PET imaging with yttrium-86: comparison of phantom measurements acquired with different PET scanners before and after applying background subtraction

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Abstract. Quantitative imaging with the positron emitter ^{86}Y is the method of choice to determine the uptake and dosimetry of ^{90}Y-labelled radiopharmaceuticals. To examine the quantitative accuracy of positron emission tomography findings with ^{86}Y, this non-pure positron emitter was evaluated in a cylindrical phantom with rods of Teflon, water and air and measured with three different scanners: ECAT EXACT (2D/3D), ECAT HR+ (2D/3D) and PC4096+ (2D). After standard reconstruction, ^{86}Y radioactivity measured with the ECAT EXACT and related to the true radioactivity varied between 0.84 and 0.99 in 2D and between 0.93 and 1.20 in 3D from the first to the last acquisition (eight half-life times later). The water and Teflon rods exhibited considerable amounts of reconstructed radioactivity – 21% in 2D and 67% in 3D for water and 65% and 147%, respectively, for Teflon – compared with the actual ^{86}Y radioactivity of the phantom. For the ECAT HR+ similar results were obtained in 3D, but there were even greater overestimations in 2D. Measurements with the PC4096+ showed rather small errors, with 10% for water and 20% for Teflon. To correct for the background of γ-coincidences, sinograms were analysed and an experimental percentage of the background was subtracted from the sinograms. In order to minimise the errors in reconstructed radioactivity, the subtraction value had to be different for the individual scanners and modes. Our results demonstrate that ^{90}Y/^{86}Y-based dosimetry for bone and red marrow must be regarded with caution if it is derived from regions of interest over the bone, the density of which is similar to that of Teflon. To obtain more reliable estimates, an appropriate background correction must be applied and tailored individually with respect to the scanner and acquisition mode.

Keywords: Yttrium-86 – PET imaging – Phantom measurements – BGO scanner

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Introduction

Quantitative positron emission tomography (PET) imaging with ^{86}Y allows patient- and compound-specific dose estimation for therapies with ^{90}Y-labelled radiopharmaceuticals [1, 2, 3]. The non-pure positron emitter ^{86}Y is, however, not an ideal PET isotope, because 67% of its decays are accompanied by additional γ-rays with energies from 200 to 3,000 keV that are mostly emitted simultaneously with positron emissions and the subsequent annihilation photons. These γ-rays increase scatter and random events and produce γ-coincidences between a γ-ray and an annihilation photon. Most single photons have energies above 1 MeV and may be recorded after having lost part of their energy by Compton scattering. Other γ-rays with energies of 626 keV and 447 keV, with an abundance of 32% and 17%, respectively, are directly accepted by the PET scanner energy window, which ranges from 350 keV to 650 keV. The resulting large number of non-true coincidences evoke a low-frequency background noise that decreases the contrast in reconstructed images and may lead to erroneous quantitation of the ^{86}Y radioactivity concentration in individual regions of interest (ROIs), thus resulting in false ^{90}Y organ doses. The aim of this study was to assess the quantitative accuracy of PET measurements using different scanners and acquisitions, i.e. 2D versus 3D modes. Further-more, we examined the outcome of background subtraction applied to the sinograms before image reconstruction [4]. Such a background correction was recently also suggested in the case of ^{76}Br, another non-pure positron emitter [5]. The chosen approach shares similarities with correction schemes already applied in the early days of PET, when the counts detected outside the object were subtracted in order to correct for random and scattered coincidences [6].

Materials and methods

Phantom. All tests used a cylindrical phantom of 20 cm length and 22 cm diameter which had three inserts, a solid cylinder of Teflon and two fillable rods each with a diameter of 5 cm. One of the tubes was filled with water and the other remained empty (air). Teflon, water and air were selected because of their different densities (2.2, 1.0 and 0.001 g cm^{-3}, respectively), resulting in different attenuation coefficients for 511 keV (0.18, 0.095 and 0.004 cm^{-1}, respectively).

PET measurements and data analysis. Before the first emission scan with the Siemens/CTI scanner ECAT EXACT [7], a 10-min transmission scan was performed with the phantom filled just with water. Then the phantom was filled with an aqueous solution of 70 MBq (corresponding to 15 kBq/ml) ^{86}Y, as determined by γ-spectroscopy, and repositioned in the centre of the field of view. Emission data each with 100 million coincidences were acquired with the ECAT EXACT in 2D mode and in 3D mode. Then the phantom was transported to another PET site where additional measurements were performed with two BGO scanners: a Siemens/CTI scanner ECAT HR+ [8] in 2D and in 3D mode and a GE/Scanditronix PET scanner PC4096+ [9] operating only in 2D mode. These measurements were done with a specific activity of 4–5 kBq/ml ^{86}Y.

In order to assess the influence of different specific activities on quantification, additional measurements in 2D and 3D mode were performed on the ECAT EXACT scanner after refilling and exact repositioning of the phantom with a radioactivity concentration of 4 kBq/ml.

All corrections and reconstructions were done with clinical standard settings. These procedures, especially the corrections for random and scatter coincidences, were scanner specific: On both Siemens/CTI scanners, random coincidences were detected in a delayed coincidence window and subtracted during acquisition. The random correction for the PC4096+ was software based and derived from the single count rates. For all scanners, scatter correction of 2D data was performed according to the method introduced by Bergström et al. [10]. 3D scatter correction for the Siemens/CTI scanners was done using the image-based approach suggested by Watson [11] and implemented in the CTI software package 7.2. The scatter and random corrected data were reconstructed with filtered back-projection. ROI evaluation was performed on transaxial slices using the MPITool (ATV GmbH Erftstadt, Germany). An ROI template of six circles with diameters between 10 mm and 18 mm was defined. Three ROIs were placed in the warm ^{86}Y area between the cold rods and one ROI in the centre of each of the cold inserts. The size of the ROIs was small enough to prevent partial volume effects. For each ROI, results were averaged over adjacent +/-10 transaxial planes and decay corrected in respect to the filling time.

Using a MATLAB program, sinograms were analysed to determine a mean background of coincidences seen outside the phantom. Figure 1 compares typical projection lines of the 2D sinogram data when the phantom was filled with ^{86}Y and ^{18}F, respectively, and projection lines of a point source scanned with the ECAT HR+ in air and water. Both examples support the idea of subtracting a constant background from the originally recorded sinogram. As the background consists of γ-coincidences and scattered events, the latter of which is at least partly corrected by the normal scatter correction, we varied the subtracted value between 0% and 100% of the background found in the sinograms. To judge the outcome, a figure of merit (FOM) was defined, which is calculated by evaluating (a) the radioactivities measured in the cold rods (A_{MT} = Teflon ROI, A_{MW} = water ROI, A_{MA} = air ROI) in relation to the radioactivity measured in the ^{86}Y area (A_{MY} = ^{86}Y ROI) and (b) the absolute value of the relative difference between A_{MY} and the true radioactivity in the ^{86}Y area A_{TY}:

$$\mathrm{FOM} = (|A_{MT}/A_{MY}| + |A_{MW}/A_{MY}| + |A_{MA}/A_{MY}| + |(A_{MT} - A_{TY}/A_{TY}|)/4$$

The FOM of an ideal background correction would be zero.

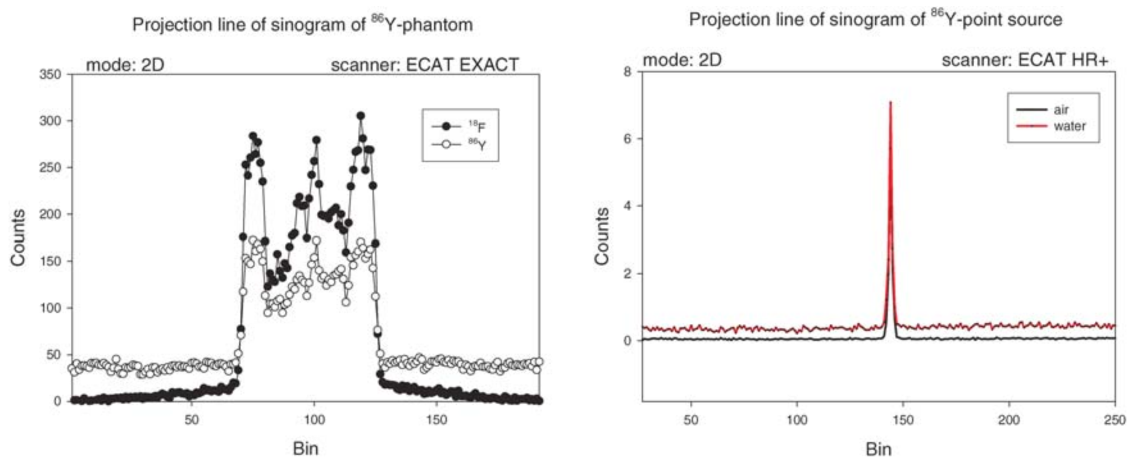


Fig. 1. *Left:* projection line of sinogram from a phantom scan with ^{86}Y and ^{18}F, ECAT EXACT 2D mode; ^{86}Y shows a constant background outside the phantom. *Right:* projection line of sinogram of a point source of ^{86}Y in water and in air, ECAT HR+ 2D mode; ^{86}Y in water leads to a constant background over all bins

Table 1. Reconstructed radioactivity in cold rods related to the measured ^{86}y-radioactivity. The optimum figure of merit is underlined

Scanner/mode	Background subtraction (%)	Teflon-ROI/ ^{86}Y-ROI	Water-ROI/ ^{86}Y-ROI	Air-ROI/ ^{86}Y-ROI	^{86}Y-ROI/ ^{86}Y-True	Figure of merit
EXACT/2D	0	0.70	0.22	–0.03	0.99	0.240
	25	0.56	0.17	0.00	0.94	0.197
	50	0.41	0.12	0.03	0.90	0.164
	75	0.24	0.06	0.06	0.85	0.126
	100	0.05	0.00	0.10	0.81	<u>0.085</u>
HR+/2D	0	1.07	0.41	–0.10	1.17	0.437
	25	0.78	0.32	–0.03	1.10	0.307
	50	0.49	0.22	0.02	0.97	0.190
	75	0.12	0.09	0.08	0.85	<u>0.111</u>
	100	–0.34	–0.07	0.17	0.72	0.212
PC4096+/2D	0	0.23	0.09	0.07	1.09	0.117
	50	–0.05	–0.01	0.09	0.99	<u>0.043</u>
	100	–0.31	–0.11	0.12	0.92	0.156
EXACT/3D	0	1.45	0.51	–0.14	1.20	0.574
	25	1.24	0.42	–0.14	1.06	0.462
	50	0.97	0.33	–0.09	0.94	0.360
	75	0.62	0.21	–0.03	0.83	0.258
	100	0.22	0.06	0.01	0.72	<u>0.141</u>
HR+/3D	0	1.47	0.56	–0.21	1.51	0.688
	25	1.08	0.43	–0.12	1.39	0.505
	50	0.70	0.31	–0.06	1.17	0.310
	75	0.18	0.13	0.03	0.95	<u>0.097</u>
	100	–0.65	–0.15	0.16	0.67	0.324

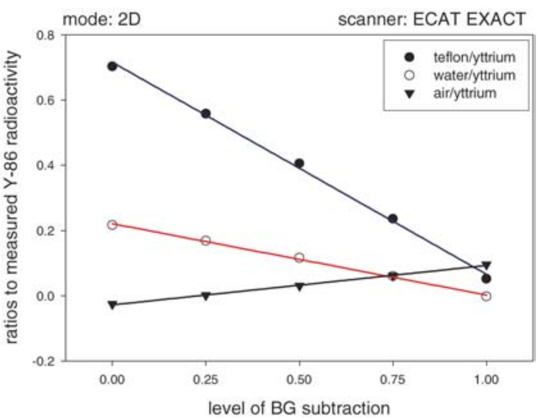
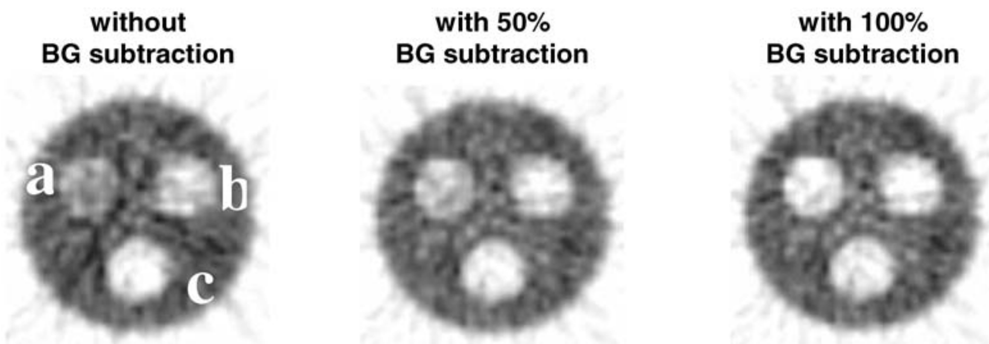


Fig. 2. Influence of the level of background (BG) subtraction on amounts of virtual radioactivity in cold rods related to measured ^{86}Y radioactivity. On ECAT EXACT (2D mode) the decreases are strongly linear to the percentage of BG subtraction

Results

The decay-corrected ^{86}Y radioactivity measured with the ECAT EXACT was dependent on the actual amount of ^{86}Y radioactivity within the phantom: the measured/true ratios were 0.84 (2D) and 0.93 (3D) for 15 kBq/ml and 0.99 (2D) and 1.20 (3D) for 4 kBq/ml. At a radioactivity concentration of about 5 kBq/ml, the corresponding ratios for the ECAT HR+ were 1.17 (2D) and 1.51 (3D), and for the PC4096+, 1.09 (2D). Considerable amounts of reconstructed ^{86}Y radioactivity were found within the Teflon and water rods, especially in the 3D mode. (Table 1, columns 3 and 4, no BG subtraction). In the 2D mode there were great differences between the different scanners. The overestimations of the ^{86}Y radioactivity in the Teflon and water rods could be reduced by background subtraction applied to the sinograms; however,

Fig. 3. Outcome of different background subtraction levels in a 2D measurement with the ECAT EXACT at 4 kBq/ml ^{86}Y-radioactivity concentration. Reconstruction with filtered back projection , cold inserts: *a*, Teflon; *b*, water and *c*, air



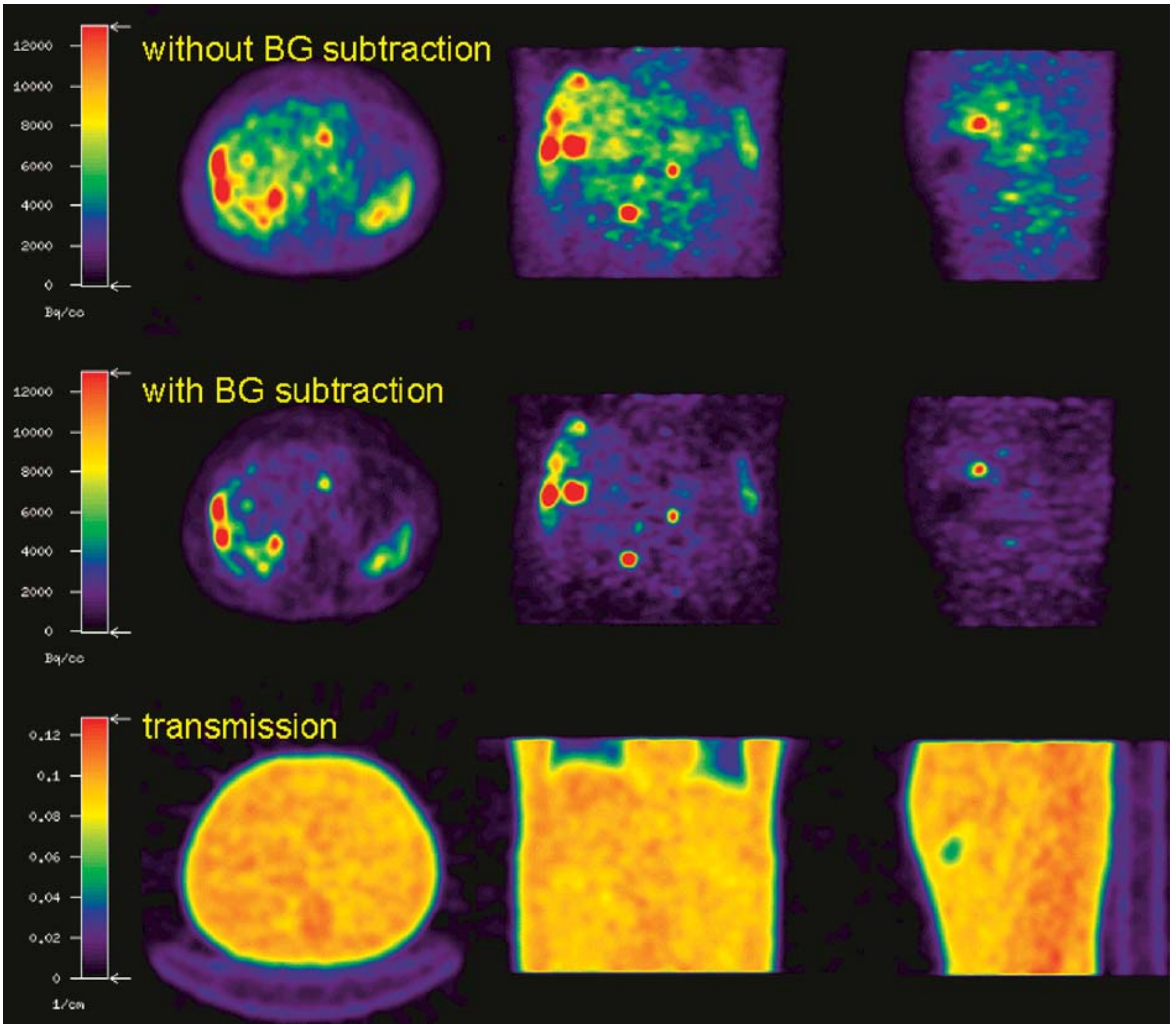


Fig. 4. ^{86}Y-DOTATOC PET from patient data in transaxial, coronal and sagittal views, ECAT EXACT, 2D mode, two bed positions. *Upper row:* original image, non-negligible radioactivity in spine and high background. *Middle row:* BG subtraction on sinogram prior to reconstruction. In addition to the better delineation of the multiple hepatic metastases, radioactivity in spine is reduced (12-fold). *Lower row:* corresponding transmission image

this procedure leads to increased values within the rod with air. Figures 2 and 3 show examples for this situation. Table 1 details the outcome for the different background subtractions. The optimum percentage of subtracted background as indicated by the figure of merit differs between the scanners, but not in respect to the modes of a given scanner.

Discussion

The data presented here demonstrate and confirm that quantitation of ^{86}Y-labelled radiotracers is possible, but must be regarded differently to the standard procedures as applied to ^{11}C, ^{13}N, ^{15}O or ^{18}F. In particular, measurements with the present scanner generation might yield significant errors if the data acquisition and processing is not performed adequately. There are also considerable differences between present devices such as the ECAT EXACT and the ECAT HR+. The decisive variation between the scanners operated in 2D mode is due to the design of the septa, so that random, scattered and γ-coincidences are rejected to a different extent.

The correction for the γ-coincidences is mandatory to reduce errors in the quantitation of ^{86}Y to an acceptable degree. As already pointed out by Pentlow et al. [4], this should be done on the basis of sinograms. The γ-coincidences may cause an overestimation of ^{86}Y radioactivity, but are also responsible for an extraordinary error in bone tissue, the high attenuation of which was simulated using Teflon. Here the erroneous γ-coincidences are amplified by the attenuation correction. This fact became clear when no attenuation correction was applied and Teflon ROIs showed similar data to water ROIs. The errors in hot and cold ROIs were reduced by a simple subtraction of counts within the sinograms, which showed a constant background outside the phantom. It is, however, necessary to adapt the percentage of background subtraction to the individual scanner. Interestingly, in this regard there was no difference between the 2D and 3D modes. The figures of merit defined here try to elucidate an optimum percentage of background subtraction. If the error in cold areas is minimised, the inaccuracy in radioactive areas may be corrected by a calibration correction factor. The dependence of the quantitation of ^{86}Y on the radioactivity concentration was correspondingly observed by Lubberink et al. [5] in the case of ^{76}Br, another non-pure positron emitter. These authors suggest a possibly inaccurate dead-time correction of such data.

In conclusion, our results show that quantitation of ^{86}Y-labelled radiotracers is feasible. If individual correction for the γ-coincidences is supplied adequately for each scanner, errors in bone-ROIs may be avoided. Although preliminary results in ^{86}Y imaging of patient data [12] demonstrated that the radioactivity in the vertebral column found in uncorrected data disappeared after applying the proposed background subtraction (Fig. 4), further improvement of the correction algorithm based on studies with more realistic phantoms seems necessary.

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