PET/CT NEMA Body Phantom Image Reconstruction Study Using 2 mm Voxel Size for Improved Image Quality

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Abstract

Background

PET/CT imaging is widely used in oncology and provides both metabolic and anatomic information. Because of the relatively poor spatial resolution of PET/CT imaging technique the detection of small lesions is limited. The low spatial resolution introduces the partial-volume effect (PVE) which negatively affects images both visually and quantitatively. The aim of our research was to investigate the effect of 4 mm and 2 mm voxel size on image quality and on detection of small spheres.

Methods

We used the NEMA body phantom with six fillable spheres. The spheres and background were filled with a solution of ^{18}F -FDG, in ratio spheres vs background 2:1, 3:1, 4:1 and 8:1. In all images reconstructed with 2 mm and 4 mm voxel size the contrast recovery coefficient (CRC), contrast to noise ratio (CNR) in standardized uptake value (SUV) were evaluated.

Results

For phantom spheres ≤ 13 mm, we found significant higher CRC, SUV and CNR using small-voxel reconstructions. CRC and SUV did not differ for large spheres (≥ 17 mm) using 2 mm and 4 mm voxel size. On the other hand, CNR for large spheres (≥ 17 mm) was significantly decreased in 2 mm voxel size images compared to the 4 mm.

Conclusion

According to our results, the reconstruction with 2 mm voxel size can improve precise lesion localization, image contrast, and image quality.

1. Introduction

Positron emission tomography combined with computed tomography (PET/CT) is widely used for staging and tumor response assessment in oncology [1], [2], [3]. PET/CT provides both metabolic and anatomic information and allows detection, localization and characterization of the lesions [4], [5]. In majority of PET/CT scanners image reconstruction is traditionally performed using the 4 mm voxel size [6], [7], [8]. This relatively large voxel size affects image quality by limiting the image spatial resolution, which prevents detection of small metabolically active lesions [9], [10], [11]. The poor spatial resolution additionally introduces the partial-volume effect (PVE) negatively affecting images both visually and quantitatively. PVE arises from the discrete representation of the reconstructed images on a grid of voxels. The distribution of radioactivity on the PET images is accordingly displayed by the voxels and it is possible that the contours of the visible lesions exceed the size of the real metabolically active lesion in the body. As a result of PVE smaller lesions lose the signal and in the larger areas around the lesions the image is smoother [9], [10], [11], [12]. Therefore, the lesions in the image appear larger but less active compared to the real accumulated activity in the lesions. The PVE can be reduced by using a smaller voxel size in image reconstruction process. Smaller voxel sizes have already been studied in evaluation of diagnostic PET/CT scans as well as in pilot phantom studies. Li et al. [13] demonstrated that 2 mm voxel size allows detection of more lymph nodes and had better image-quality output compared to 4 mm voxel size. Koopman et al. [14] analyzed National Electrical Manufacturers Association (NEMA) body phantom and patient images, and reported that the use 2 mm voxel size significantly improves contrast recovery coefficient (CRC) and signal to noise ratio (SNR) of spheres with diameter less than 13 mm and small pathological lesions in patients. The same group further concluded that the small-voxel PET/CT improves the sensitivity of visual lymph node characterization and provides a higher detection rate of malignant lymph nodes [15].

Previous studies evaluated the image quality on images reconstructed with 2 mm and 4 mm voxel size with NEMA phantom with a high sphere/background ratio. The goal of our study was to explore the effect of different voxel size on the image quality systematically at a set of different lower and higher sphere/background ratios. This was evaluated on a NEMA body phantom PET/CT image, reconstructed with 2 mm and 4 mm voxel size, with calculation of maximum and mean contrast

recovery coefficient (CRCmax and CRCmean), quantitative evaluation of the obtained data (SUVmax and SUVmean) and contrast to noise ratio (CNRmax and CNRmean).

2. Materials And Methods

Measurements were performed with the NEMA International Electrotechnical Commission (IEC) body phantom. The NEMA body phantom consists of the background compartment with a volume of 9.300 ml and six fillable spheres with diameters of 10, 13, 17, 22, 28, and 37 mm. Filling of the phantom with 18-FDG solution was repeated four times, to obtain sphere / background radioactivity ratio of 2:1, 3:1, 4:1 and 8:1. Each time, the phantom was scanned on a Siemens Biograph mCT PET/CT scanner combining patented lutetium oxyorthosilicate (LSO) PET system with time-of-flight (TOF) technique and a 128-slice CT. The NEMA body phantom scan acquisition protocol included a low dose (120 kV; 25 mA) non-enhanced CT scan for the attenuation correction, followed by a 10 min per one bed position 3D PET acquisition.

The four PET scans were reconstructed using a Siemens True-X-TOF iterative algorithm (2 iterations, 21 subsets) which incorporates point-spread-function (PSF) and TOF correction (SIEMENS ultra HD PET®). Each image was reconstructed using 4 mm and 2 mm voxel dimensions and zoom 1. For 4 mm voxel size a 200 x 200 matrix, whereas for 2 mm voxel size a 400 x 400 matrix was used.

Quantitative image analysis was performed on OASIS SEGAMI processing software. In each NEMA body phantom image we drew circular ROIs around the spheres, using the known sphere diameters, as well as regions of interest (ROIs) in the background compartment, using the known diameters of the largest sphere. In these ROIs we determined mean and maximum activity concentration in becquerel/mililiter (Bq/ml), and mean and maximum SUV.

We calculated CRC mean/maximum as the ratio between measured concentration (CAm) and true concentration (CA_t):

$$CRC = \frac{CA_m}{CA_t} \quad \text{Eq.(A.1)}$$

We also determined CNR mean/maximum, as a measure of the signal level in the presence of noise:

$$CNR = \frac{SUV - BG_a}{SD_{bg}} \quad \text{Eq.(A.2)}$$

where SUV is a mean/maximum measured FDG SUV in the phantom spheres, BG_a is the average measured SUV in the background and SD_{bg} is the standard deviation of the SUV in the background.

Comparison between different voxel sizes

We analyzed CRC, CNR and SUV values independently in three ways: for spheres with diameters ≤ 13 mm, for spheres with diameters ≥ 17 mm, and for all spheres together, respectively.

Normality of the distribution of values was assessed using the Shapiro-Wilk test. Median, minimum and maximum values were calculated. We assessed differences between measurements in images with 2 mm and 4 mm voxel sizes using the Wilcoxon signed-rank test for paired samples.

All statistical analysis was performed using IBM SPSS Statistics for Windows, version 25 (IBM Corp., Armonk, N.Y., USA) and was considered significant for p < 0.05. GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, California USA, www.graphpad.com) was used to create the artwork.

3. Results

NEMA body phantom images reconstructed with 2 mm and 4 mm for all radioactivity concentration ratios in spheres vs. background are presented in Fig. 1.

Visual comparison of the images clearly shows enhanced contrast in smaller spheres (≤ 13 mm) in images reconstructed with 2 mm compared to 4 mm voxel size. The sphere with diameter 10 mm in ratio 1:2 was not visible in the images and was therefore not used in the following quantitative analyzes.

Measurements of CNR, CRC and SUV in all six phantom spheres for all radioactivity ratios are given in Tables 1–3 and graphically presented in Fig. 2. Median, minimum and maximum values for these parameters are in Tables 4–6.

Table 1

CNRmax, CNRmean, of six NEMA body phantom spheres filled in radioactivity concentration ratio spheres/background 2:1, 3:1, 4:1, 8:1 for both 2 mm and 4 mm voxel size reconstructions, including relative changes in %.

	CNRmax						CNRmean					
	NEMA body phantom sphere diameter (mm)						NEMA body phantom sphere diameter (mm)					
Ratio 2:1	10	13	17	22	28	37	10	13	17	22	28	37
2 mm	N/A	6.28	9.45	10.12	15.17	12.67	N/A	2,00	3.83	6.00	5.50	6.61
4 mm	N/A	5.94	10.14	13.14	17.94	15.14	N/A	0.80	2.20	7.80	6.60	13.40
%	N/A	9	4	-13	-8	-9	N/A	6	16	-20	-15	-10
Ratio 3:1												
2 mm	12.08	25.92	29.08	34.08	33.08	31.58	4.75	10.08	14.08	20.25	18.42	20.25
4 mm	9.48	24.88	35.08	41.48	39.88	37.88	3.88	7.48	16.48	20.28	21.88	23.48
%	39	16	-6	-7	-6	-5	5	7	4	0	-4	0
Ratio 4:1												
2 mm	12.24	27.54	33.35	33.05	34.24	35.80	8.58	13.02	15.36	19.80	21.24	22.57
4 mm	10.75	27.37	38.25	37.25	39.75	38.62	6.87	11.87	18.00	22.12	24.37	25.37
%	30	9	-5	-4	-7	0	10	3	-14	-4	-4	-1
Ratio 8:1												
2 mm	81,00	126.83	133.83	125.00	121.83	130.67	51.50	51.67	75.50	81.00	86.00	91.00
4 mm	73.95	124.95	163.75	162.15	150.95	156.75	49.75	51.55	91.15	98.95	103.95	110.95
%	32	-1	-3	-7	-4	-2	5	1	-1	-1	0	-1
*N/A - not applicable												

Table 2

CRCmax, CRCmean, of six NEMA body phantom spheres filed in ratio spheres/background 2:1, 3:1, 4:1, 8:1 for both 2 mm and 4 mm voxel size reconstructions, including relative changes in %.

	CRCmax Bq/ml						CRCmean Bq/ml					
	NEMA body phantom sphere diameter (mm)						NEMA body phantom sphere diameter (mm)					
Ratio 2:1	10	13	17	22	28	37	10	13	17	22	28	37
2 mm	N/A	0,55	0,63	0,65	0,76	0,71	N/A	0,44	0,51	0,61	0,69	0,66
4 mm	N/A	0,53	0,61	0,67	0,76	0,72	N/A	0,43	0,50	0,59	0,69	0,66
%	N/A	4	4	-3	0	-0.5	N/A	3	3	1	0	0
Ratio 3:1												
2 mm	0,46	0,67	0,73	0,81	0,79	0,77	0,33	0,45	0,57	0,71	0,71	0,70
4 mm	0,41	0,61	0,74	0,82	0,81	0,77	0,32	0,43	0,56	0,69	0,73	0,71
%	15	11	-1	-0.5	-1	0	3	5	2	1	-2	-1
Ratio 4:1												
2 mm	0,43	0,71	0,82	0,82	0,84	0,87	0,29	0,44	0,61	0,74	0,74	0,74
4 mm	0,38	0,66	0,83	0,82	0,86	0,84	0,28	0,41	0,58	0,76	0,77	0,75
%	13	8	-1	0	-2	3	3	5	3	-2	-3	-1
Ratio 8:1												
2 mm	0,59	0,87	0,92	0,86	0,84	0,89	0,30	0,49	0,71	0,71	0,81	0,81
4 mm	0,47	0,86	0,93	0,92	0,87	0,90	0,27	0,46	0,67	0,82	0,79	0,82
%	24	1	-2	-7	-3	-1	11	6	6	-14	1	-2
*N/A - not applicable												

Table 3
SUVmax, SUVmean, of six NEMA body phantom spheres filed in ratio spheres/background 2:1, 3:1, 4:1, 8:1 for both 2 mm and 4 mm voxel size reconstructions, including relative changes in %.

	SUVmax						SUVmean					
	NEMA body phantom sphere diameter (mm)						NEMA body phantom sphere diameter (mm)					
Ratio 2:1	10	13	17	22	28	37	10	13	17	22	28	37
2 mm	N/A	1.39	1.58	1.62	1.92	1.77	N/A	1.13	1.24	1.37	1.34	1.38
4 mm	N/A	1.31	1.52	1.67	1.91	1.77	N/A	1.05	1.12	1.40	1.34	1.68
%	N/A	6%	4%	-3%	0.5%	0%	N/A	8%	10%	2%	0	18%
Ratio 3:1												
2 mm	1.76	2.59	2.78	3.08	3.02	2.93	1.32	1.64	1.88	2.25	2.14	2.25
4 mm	1.51	2.28	2.79	3.11	3.03	2.93	1.23	1.41	1.86	2.05	2.13	2.21
%	16%	14%	-0.5%	-1%	-0.5%	0	7%	16%	1%	10%	0.5%	2%
Ratio 4:1												
2 mm	2.11	3.49	4.01	4.01	4.09	4.23	1.78	2.18	2.39	2.79	2.92	3.04
4 mm	1.87	3.2	4.07	3.99	4.19	4.1	1.56	1.96	2.45	2.78	2.96	3.04
%	12%	9%	-2%	0.5%	-3%	3%	14%	11%	-3%	0.5%	-2%	0
Ratio 8:1												
2 mm	5.78	8.62	9.04	8.51	8.32	8.85	4.1	3.71	5.54	5.87	6.17	6.47
4 mm	4.71	7.26	9.2	9.12	8.56	8.85	3.50	3.26	5.57	5.96	6.21	6.56
%	24%	16%	-2%	-7%	-3%	0	17%	13%	-0.5%	-1.5%	-1%	-1.5%
*N/A - not applicable												

Table 4

Median, Minimum and maximum values of CNRmax and CNRmean over all background vs spheres ratio for all spheres, spheres ≤ 13 mm and spheres ≥ 17 mm. The values are given for images reconstructed with 2 mm and 4 mm voxel size.

	N	Mediana	Minimum	Maximum
CNRmax 2 mm	23	33.08	6.28	133.83
CNRmax 4 mm	23	37.88	5.94	163.75
CNRmean 2 mm	23	18.42	2.00	91.00
CNRmean 4 mm	23	20.28	0.80	110.95
CNRmax 2 mm; ≤ 13 mm	7	25.91	6.28	126.83
CNRmax 4 mm; ≤ 13 mm	7	24.88	5.94	124.95
CNRmean 2 mm; ≤ 13 mm	7	10.08	2.00	51.50
CNRmean 4 mm; ≤ 13 mm	7	7.48	0.80	49.95
CNRmax 2 mm; ≥ 17 mm	16	33.35	9.45	133.83
CNRmax 4 mm; ≥ 17 mm	16	38.44	10.14	163.75
CNRmean 2 mm; ≥ 17 mm	16	20.03	3.83	91.00
CNRmean 4 mm; ≥ 17 mm	16	22.01	2.20	110.95

Table 5

Median, Minimum and maximum values of CRCmax and CRCmean over all background vs spheres ratio for all spheres, spheres ≤ 13 mm and spheres ≥ 17 mm. The values are given for images reconstructed with 2 mm and 4 mm voxel size.

	N	Mediana	Minimum	Maximum
CNRmax 2 mm	23	33.08	6.28	133.83
CNRmax 4 mm	23	37.88	5.94	163.75
CNRmean 2 mm	23	18.42	2.00	91.00
CNRmean 4 mm	23	20.28	0.80	110.95
CNRmax 2 mm; ≤ 13 mm	7	25.91	6.28	126.83
CNRmax 4 mm; ≤ 13 mm	7	24.88	5.94	124.95
CNRmean 2 mm; ≤ 13 mm	7	10.08	2.00	51.50
CNRmean 4 mm; ≤ 13 mm	7	7.48	0.80	49.95
CNRmax 2 mm; ≥ 17 mm	16	33.35	9.45	133.83
CNRmax 4 mm; ≥ 17 mm	16	38.44	10.14	163.75
CNRmean 2 mm; ≥ 17 mm	16	20.03	3.83	91.00
CNRmean 4 mm; ≥ 17 mm	16	22.01	2.20	110.95

Table 6
Median, Minimum and maximum values of SUVmax and SUVmean over all spheres, spheres ≤ 13 mm and spheres ≥ 17 mm. The values are given for images reconstructed with 2 mm and 4 mm voxel size

	N	Mediana	Minimum	Maximum
SUVmax 2 mm	23	0.77	0.43	0.92
SUVmax 4 mm	23	0.77	0.39	0.94
SUVmean 2 mm	23	0.66	0.30	0.81
SUVmean 4 mm	23	0.67	0.27	0.82
SUVmax 2 mm; ≤ 13 mm	7	0.60	0.43	0.87
SUVmax 4 mm; ≤ 13 mm	7	0.54	0.39	0.86
SUVmean 2 mm; ≤ 13 mm	7	0.44	0.30	0.46
SUVmean 4 mm; ≤ 13 mm	7	0.42	0.27	3.26
SUVmax 2 mm; ≥ 17 mm	16	0.82	0.63	0.92
SUVmax 4 mm; ≥ 17 mm	16	0.82	0.61	0.94
SUVmean 2 mm; ≥ 17 mm	16	0.71	0.52	0.81
SUVmean 4 mm; ≥ 17 mm	16	0.70	0.50	0.82

In the small spheres (≤ 13 mm) CRC values were significantly higher in the images reconstructed using the 2 mm compared to the 4 mm voxel size (CRCmax: $p = 0.018$, CRCmean: $p = 0.018$). On the other hand, CRC did not differ between the two voxel sizes for large spheres (≥ 17 mm) (CRCmax: $p = 0.140$, CRCmean: $p = 0.918$) and for all spheres (CRCmax: $p = 0.338$, CRCmean: $p = 0.107$).

SUV value was significantly higher in images reconstructed with 2 mm compared to 4 mm voxel size for small spheres (≤ 13 mm) (SUVmax: $p = 0.018$, SUVmean: $p = 0.018$), but did not differ for large spheres (≥ 17 mm) (SUVmax: $p = 0.124$, SUVmean: $p = 0.362$) nor for all spheres (SUVmax: $p = 0.279$, SUVmean: $p = 0.159$).

Also CNR was found significantly higher in reconstruction with 2 mm voxel size compared to 4 mm for small spheres (≤ 13 mm) (CNRmax ($p = 0.018$) and CNRmean ($p = 0.018$)). In addition, CNR was elevated in 2 mm images when analyzing all spheres in all ratio spheres vs. background reconstructed (CNRmax: $p = 0.004$, CNRmean: $p = 0.01$). However, in larger spheres (≥ 1.7 mm) CNR was significantly decreased in 2 mm voxel size images compared to the 4 mm (CNRmax: $p < 0.001$, CNRmean: $p = 0.001$).

The comparison of CRC, CNR and SUV between the two voxel sizes is graphically presented in Fig. 3.

4. Discussion

Most of PET scanners worldwide use 4 mm voxel size reconstruction in clinical practice, which reflects in limited image spatial resolution. Relatively poor spatial resolution represents an aggravated localization and quantification of small lesions. In present investigation we scanned and analyzed NEMA body phantom with various sphere vs. background radioactivity concentration ratios to demonstrate that detection and quantification of small lesions with PET/CT TOF scanning can be improved if reconstruction with 2 mm voxel size is used.

We compared image quality in reconstruction with 2 mm and 4 mm voxel sizes, by calculating SUV, CRC and CNR values for NEMA body phantom spheres over all sphere vs. background radioactivity ratios. We found significant increase of mean and

maximum CRC, SUV and CNR values of spheres with diameter 10 mm and 13 mm in images reconstructed with 2 mm voxels size, in comparison to 4 mm. In larger spheres and spheres of all sizes, no statistical differences in SUV and CRC were found between different voxel sizes. Nevertheless, CNR was found significantly higher for spheres of all sizes, but significantly lower in large spheres, in images with 2 mm voxel sizes compared to 4 mm.

These findings clearly demonstrate that 2 mm voxel size PET reconstruction allows more precise semi-quantitative reconstruction and assessment of PET images, especially in lesions with diameter smaller than 13 mm which are most challenging in clinical diagnostics.

We also confirmed the findings in the previous publications that despite the increase in noise using the 2 mm voxel size, the image quality is improved. [13], [14], [15]. Our results are in line with Koopman et al [14], who demonstrated on NEMA body phantom that the use 2 mm voxel size significantly increases SUV (max and mean) and significantly improves CRC and the SNR of small spheres with diameter less than ≤ 13 mm. They also analyzed 66 18F-FDG PET positive lesions in the chest and upper abdominal region. For all 18F-FDG PET positive lesions, the average SUVmean and SUVmax increase using the 2 mm voxel size (17 % and 32 %). At lesions with volume less than 0.75 mL, the average increase was 21% and 44%. Moreover, averaged over all lesions, the mean and maximum SNR increased by 20% and 27%. For lesions less than 0.75 mL, these values increased up to 23% and 46%. The same group later extended their research included 61 benign and 169 malignant lymph nodes and concluded that small-voxel PET/CT improves the sensitivity of visual lymph node characterization and provides a higher detection rate of malignant lymph nodes [15].

The study by Li et al. [13], who similarly demonstrated on 39 patients in which 18FDG PET/CT was performed for assessment of lymph node metastases in head and neck squamous cell carcinoma, that matrix size is important factor influencing lesion detect ability. In their study the 2 mm reconstructions with PSF and TOF provided the best overall performance in terms of quantitation over the different lesion size and concluded that 2 mm voxel size detected more lymph nodes, had a higher sensitivity for lesion detection, and a better image-quality output in comparison with 4 mm voxel size.

Previous studies analyzed the impact of 2 mm voxel size reconstruction on image quality in one sphere vs. background ratio of NEMA body phantom. In our study we extended the research to systematically evaluate CRC, SNC and SUV for different sphere vs. background ratios to simulate the conditions in the patient lesions where the accumulation of RP is differently intense.

The reason for improvements in CRC, CNR and increased SUV using 2 mm voxel size are improved spatial resolution and PVE of PET scanner which reduces the apparent activity concentrations in imaging of smaller lesions [16]. However, the limited spatial resolution results in a spillover of activity distribution into neighboring voxels or regions in the image which in the case of small spheres decreases measured VOI activity in contrast to larger spheres with the same activity concentration. The measured lower concentration in small spheres (diameter < 13 mm) on 4 mm voxel size indicates that smaller volumes are indeed more affected by partial volume effects and when using the 2 mm voxel size this effect is reduced. On the contrary partial volume effect affects minimally the largest sphere (diameter 37 mm). Nevertheless, although the small 2 mm voxel size improves the resolution, it may produce high fluctuations of the signal that increase the noise because of lower number of counts per voxel. In contrast, large 4 mm voxel size produces homogeneous images, however, with low spatial resolution. The image noise in 2 mm voxel size images can be compensated by using an iterative True-X reconstruction algorithm which incorporates PSF and TOF correction [7], [8], [17]. The TOF information does not directly lead to a higher image spatial resolution, but provides images with higher signal to noise ratio (SNR), which improves the detections of small lesions with relatively low activity [5], [8], [18]. The resolution modeling of PSF leads to higher and more uniform spatial resolution over the transaxial field of view (FOV) [19], [20].

Conclusion

In summary, we have analyzed CRC, CNR and SUV in the spheres of NEMA body phantom images with a set of FDG radioactivity ratios in spheres vs. background. Our results confirmed the findings of the previous studies and further proved that the use of 2 mm voxel size improves localization of smaller volumes with various radioactivity concentrations in PET

which can be advantageous in diagnostic assessment of small lesions improving precise lesion localization, contrast, and image quality. These interesting observations are worth further exploration in relation to clinical studies such as parathyroid adenomas in patients with suspected primary hyperparathyroidism.

List Of Abbreviations

Positron emission tomography combined with computed tomography (PET/CT),

Partial-volume effect (PVE),

Contrast recovery coefficient (CRC),

Signal to noise ratio (SNR),

Contrast to noise ratio (CNR)

Standardized uptake value (SUV)

National Electrical Manufacturers Association (NEMA),

International Electrotechnical Commission (IEC),

Lutetium oxyorthosilicate (LSO),

Time-of-flight (TOF),

Point-spread-function (PSF),

Regions of interest (ROIs),

Becquerel/mililiter (Bq/ml),

Measured concentration (C_{Am}),

True concentration (C_{At}),

Maximum contrast recovery coefficient (CRC_{max}),

Mean contrast recovery coefficient (CRC_{mean}),

Maximum contrast to noise ratio (CNR_{max}),

Mean contrast to noise ratio (CNR_{mean}).

Declarations

1. Ethics approval and consent to participate:

The study does not include patient data and therefore does not require the approval of the ethics committee.

2. Consent for publication:

The study does not include patient data and therefore no consent is required.

3. Availability of data and materials:

All results and materials are listed in the article.

4. Competing interests:

The authors declare that they have no competing interests.

5. Funding:

There were no sources of funding for the research.

6. Authors' contributions:

SR: performed the all imaging and analize of NEMA phantom, and was a major contributor in writing.

PT: contributor in writing, review and editing.

LJ: Writing - analize of NEMA phantom, review and editing.

KZ: Writing - Review and editing.

LL: Writing - Review and editing.

All authors read and approved the final manuscript.

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References

1. Derlin T, Grünwald V, Steinbach J, Wester H-J, L. Ross T. Molecular Imaging in Oncology Using Positron Emission Tomography. *Dtsch Ärztebl Int.* 2018 Mar;115(11):175–81.
2. Simianu VV, Varghese TK, Flanagan MR, Flum DR, Shankaran V, Oelschlager BK, et al. Positron emission tomography for initial staging of esophageal cancer among medicare beneficiaries. *J Gastrointest Oncol.* 2016 Jun;7(3):395–402.
3. Juweid ME, Stroobants S, Hoekstra OS, Mottaghy FM, Dietlein M, Guermazi A, et al. Use of Positron Emission Tomography for Response Assessment of Lymphoma: Consensus of the Imaging Subcommittee of International Harmonization Project in Lymphoma. *J Clin Oncol.* 2007 Feb 10;25(5):571–8.
4. Schöder H, Erdi YE, Larson SM, Yeung HWD. PET/CT: a new imaging technology in nuclear medicine. *Eur J Nucl Med Mol Imaging.* 2003 Oct;30(10):1419–37.
5. Townsend DW. Dual-modality imaging: combining anatomy and function. *J Nucl Med Off Publ Soc Nucl Med.* 2008 Jun;49(6):938–55.
6. Kolthammer JA, Su K-H, Grover A, Narayanan M, Jordan DW, Muzic RF. Performance evaluation of the Ingenuity TF PET/CT scanner with a focus on high count-rate conditions. *Phys Med Biol.* 2014 Jul 21;59(14):3843–59.
7. Conti M. Focus on time-of-flight PET: the benefits of improved time resolution. *Eur J Nucl Med Mol Imaging.* 2011 Jun;38(6):1147–57.
8. Boellaard R, Delgado-Bolton R, Oyen WJG, Giammarile F, Tatsch K, Eschner W, et al. FDG PET/CT: EANM procedure guidelines for tumour imaging: version 2.0. *Eur J Nucl Med Mol Imaging.* 2015 Feb;42(2):328–54.
9. van der Vos CS, Koopman D, Rijnsdorp S, Arends AJ, Boellaard R, van Dalen JA, et al. Quantification, improvement, and harmonization of small lesion detection with state-of-the-art PET. *Eur J Nucl Med Mol Imaging.* 2017 Aug;44(Suppl 1):4–16.

10. Fukui MB, Blodgett TM, Meltzer CC. PET/CT imaging in recurrent head and neck cancer. *Semin Ultrasound CT MR*. 2003 Jun;24(3):157–63.
11. Tarantola G, Zito F, Gerundini P. PET instrumentation and reconstruction algorithms in whole-body applications. *J Nucl Med Off Publ Soc Nucl Med*. 2003 May;44(5):756–69.
12. Le Pogam A, Hatt M, Descourt P, Boussion N, Tsoumpas C, Turkheimer FE, et al. Evaluation of a 3D local multiresolution algorithm for the correction of partial volume effects in positron emission tomography. *Med Phys*. 2011 Sep;38(9):4920–3.
13. Li C-Y, Kloth S, Sadick H, Weiss C, Hoermann K, Schoenberg SO, et al. Effect of time-of-flight technique on the diagnostic performance of 18F-FDG PET/CT for assessment of lymph node metastases in head and neck squamous cell carcinoma. *J Nucl Med Technol*. 2014 Sep;42(3):181–7.
14. Koopman D, van Dalen JA, Lagerweij MCM, Arkies H, de Boer J, Oostdijk AHJ, et al. Improving the detection of small lesions using a state-of-the-art time-of-flight PET/CT system and small-voxel reconstructions. *J Nucl Med Technol*. 2015 Mar;43(1):21–7.
15. Koopman D, van Dalen JA, Arkies H, Oostdijk AHJ, Francken AB, Bart J, et al. Diagnostic implications of a small-voxel reconstruction for loco-regional lymph node characterization in breast cancer patients using FDG-PET/CT. *EJNMMI Res*. 2018 Jan 16;8(1):3.
16. Meechai T, Tepmongkol S, Pluempitiwiriawej C. Partial-volume effect correction in positron emission tomography brain scan image using super-resolution image reconstruction. *Br J Radiol*. 2015 Feb;88(1046):20140119.
17. Lee YS, Kim JS, Kim KM, Kang JH, Lim SM, Kim H-J. Performance measurement of PSF modeling reconstruction (True X) on Siemens Biograph TruePoint TrueV PET/CT. *Ann Nucl Med*. 2014 May;28(4):340–8.
18. Lois C, Jakoby BW, Long MJ, Hubner KF, Barker DW, Casey ME, et al. An assessment of the impact of incorporating time-of-flight information into clinical PET/CT imaging. *J Nucl Med Off Publ Soc Nucl Med*. 2010 Feb;51(2):237–45.
19. Rogasch JM, Steffen IG, Hofheinz F, Großer OS, Furth C, Mohnike K, et al. The association of tumor-to-background ratios and SUVmax deviations related to point spread function and time-of-flight F18-FDG-PET/CT reconstruction in colorectal liver metastases. *EJNMMI Res [Internet]*. 2015 May 6 [cited 2020 Nov 25];5. Available from: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4427576/>
20. Akamatsu G, Ishikawa K, Mitsumoto K, Taniguchi T, Ohya N, Baba S, et al. Improvement in PET/CT image quality with a combination of point-spread function and time-of-flight in relation to reconstruction parameters. *J Nucl Med Off Publ Soc Nucl Med*. 2012 Nov;53(11):1716–22.

Figures

Figure 1

NEMA body phantom, filled in the radioactivity concentration ratio sphere/background 2:1, 3:1, 4:1, 8:1, and reconstructed with 2 mm voxel size (top row) and 4 mm voxel size (bottom row).

Figure 2

Measurements of CNR (top row), CRC (middle row) and SUV (bottom row) in all six phantom spheres for all radioactivity ratios with 2 mm and 4 mm voxel size.

Figure 3

Graphically presented CRCmean, CNRmean and SUVmean between the 2 mm and 4 mm voxel sizes.