

Isotropic Reconstruction of SPECT Data Using OSEM3D: Correlation with CT¹

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Rationale and Objectives. A statistical based iterative single-photon emission-computed tomography (SPECT) reconstruction algorithm (OSEM) modeling the depth-dependent collimator response in three dimensions has recently been introduced (OSEM3D). The aim of this study was to evaluate the axial shape fidelity of OSEM3D in comparison to OSEM, not taking this variable into account (OSEM2D).

Materials and Methods. SPECT and separate spiral CT were performed in a phantom containing spheres filled with In-111. In-111-pentetreotide-SPECT and separate spiral-CT imaging were also performed in 22 patients with neuroendocrine tumors. Using window settings adapting the transversal size of the SPECT hot spots to that on CT and the 50% isocontour as boundary, the three-dimensional extensions (dx, dy, dz) of the SPECT representation of the structures under study were measured. These variables were also determined for CT. Furthermore, an index of eccentricity was calculated by averaging the ratios between dz and dx and dz and dy (IE). For isotropically imaged spheres, IE is 1.

Results. For OSEM2D, IE was significantly different from 1 in the phantom data ($P < .05$); this was not the case for OSEM3D and CT. This finding was accounted for by a significantly greater dz on the OSEM2D-SPECT images. In the patient data, dz was by approximately 15.5% greater for OSEM2D than for the other two modalities ($P < .05$).

Conclusions. The use of OSEM3D avoids deformation of hot SPECT lesions in z-direction. This may be of particular importance in SPECT/CT hybrid imaging capitalizing on the exact match of both modalities.

Key Words. Single-photon emission-computed tomography; isotropic image reconstruction; image fusion; spiral computed tomography; In-111 pentetreotide.

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Iterative reconstruction of single-photon emission-computed tomography (SPECT) images has recently replaced filtered back projection (FBP) as the algorithm of first

choice (1–9). Its increasing popularity is based on the ability to accurately model imaging physics in a clinically acceptable reconstruction time (<2 minutes). The improvements in image quality are obtained by compensating for effects such as depth-dependent collimator blurring, nonuniform patient-specific attenuation, scattering, and the statistical nature of image formation. In addition, the development of more efficient and faster iterative algorithms together with advances in computer speed and memory has increased its use in daily clinical routine.

One of the most popular iterative algorithms is the ordered-subsets expectation maximization (OSEM) algorithm that is regularly used in commercially available software. It has been shown that, compared with FBP,

Acad Radiol 2006; 13:496–502

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doi:10.1016/j.acra.2005.12.004

expectation maximization algorithms are able to improve image quality and resolution (6–9). Resolution recovery is achieved by modeling the distant dependent collimator blur during the reconstruction. OSEM2D, which only recovers resolution in the transversal direction, was introduced to take advantage of the benefits of iterative reconstruction, yet sacrificing axial resolution recovery for reconstruction speed. Recently, a computationally efficient OSEM reconstruction method with three-dimensional collimator beam modeling has been introduced (Flash3D, Siemens Medical Solutions, Erlangen, Germany), which keeps reconstruction times clinically acceptable (8).

The purpose of this study was to investigate the axial shape fidelity of OSEM3D- and OSEM2D-SPECT (ie, in z-direction). For this aim, a phantom containing spheres of different size filled with indium-111 (In-111) was studied by dual-headed SPECT and multidetector spiral CT. Furthermore, data from 22 patients suffering from neuroendocrine tumors were analyzed in whom In-111 pentetotide SPECT and spiral CT also had been performed to clinically validate the findings in the phantom.

MATERIAL AND METHODS

Phantom Studies

The phantom consisted of a circular acrylic vessel of 200-mm diameter and 214-mm height and an insert with spheres of about 10-mm, 13-mm, 17-mm, 22-mm, 28-mm, and 37-mm inner active diameter. The phantom completely filled with water was scanned with CT using scanning and reconstruction parameters as indicated below. Afterwards, the spheres were filled with 0.4 MBq/mL In-111. SPECT imaging was then performed as detailed in the following section.

Patients

A database search for patients with histologically confirmed neuroendocrine tumor who were imaged using In-111 pentetotide scintigraphy between September 2002 and January 2005 yielded 53 patients. Out of these, 22 patients fulfilled the following inclusion criteria:

- Lesion clearly visible on SPECT and CT
- Performance of CT not earlier nor later than 50 days before, respectively, after the SPECT
- Availability of the digital CT data, axial slice thickness 1 mm or less

Polygonal lesions were excluded. The final study population consisted of 8 men and 14 women. The mean age of the patients studied was 67 years $\pm$ 9 (range 38–82 years). The mean time interval between CT and SPECT scans was 5.6 days $\pm$ 13.9, ranging from 1 to 47 days. The patient data used had been acquired solely for clinical and not for scientific reasons.

Data Acquisition

In both the water-filled phantom and patients, CT scans were obtained before scintigraphy using scanners with at least 10 slices (SOMATOM Sensation 10, 16, or 64; Siemens Medical Solutions, Forchheim, Germany). The CT scans were performed in the patients according to routine protocols in maximum inspiration using intravenous contrast agent and oral contrast material for abdominal scanning (10). In the phantom, the same scanning parameters were used. Image reconstruction resulted in images with a slice width of 1 mm using a 1-mm reconstruction increment with standard B30 reconstruction kernels. The windowing of the CT was adjusted appropriately and kept for all slices. Isotropic multiplanar reconstruction of CT resulting in high spatial and contrast resolution and low imaging noise was used in this study to determine the transversal and axial diameters of the lesions.

For the phantom studies, SPECT was performed using medium-energy collimators. Counts from the 20% energy windows at 172 keV and 247 keV were acquired into a 128×128 matrix using a zoom factor of 1.23 (pixel size 3.9×3.9 mm). A total of 2×30 views, each of 60 seconds' duration, were acquired over 360° .

For somatostatin receptor scintigraphy of the patients, on the average 186 MBq (150–247 MBq) In-111-pentetotide (OctreoScan, Mallinckrodt, St Louis, MO) were injected intravenously. SPECT images using a dual-head camera (e.cam, Siemens Medical Solutions, Hoffman Estates, IL) fitted with medium-energy collimators were obtained 4 hours after injection over the anatomic regions showing pathologic tracer uptake on planar scans. Counts from the 20% energy windows at 172 keV and 247 keV were acquired into a 64×64 matrix (pixel size 9.2×9.2 mm). A total of 2×30 views, each of 60 seconds' duration, were acquired over 360° .

SPECT Data Reconstruction

SPECT reconstruction was performed iteratively by using the OSEM2D (transversal distance-dependent collimator blur compensation) technique with 8 iterations and

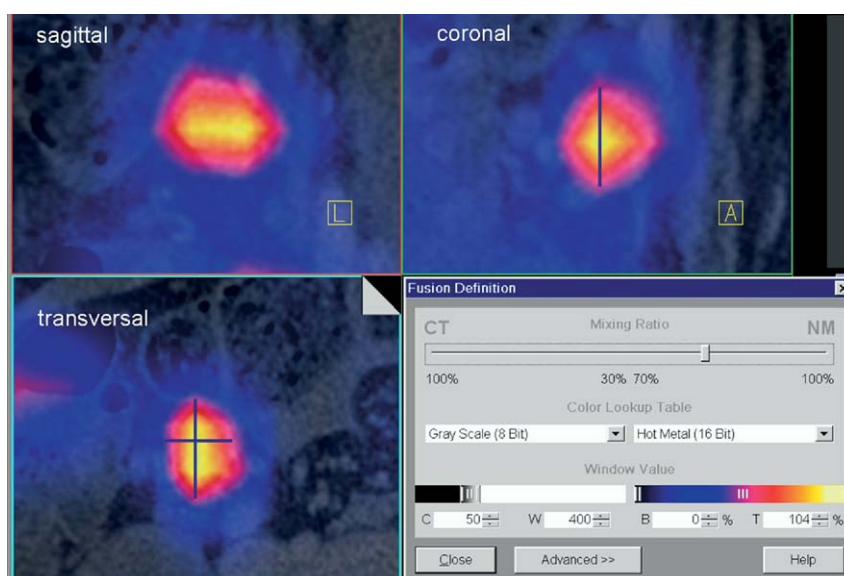


Figure 1. Image fusion of computed tomography (CT) and single-photon emission-computed tomography (SPECT) reconstructed by modeling the collimator beam in three dimensions (OSEM3D) color lookup table adjustment, and measurement of lesion extension in a patient example. Using window settings adapting the transversal size of the SPECT hot spots to that on CT and the 50% isocontour as boundary, the three dimensional extensions of the SPECT representation of the structures under study were measured. Please note that color table adjustment was performed only on the transversal images, without using the information yielded by the coronal and sagittal reconstruction (for further explanation, see text).

12 subsets. No attenuation and scatter correction was performed. Images were slightly postsmoothed with a 3D spatial Gaussian filter (full-width at half maximum 10 mm or 1.1-fold pixel width). In addition, the raw SPECT data were reconstructed using OSEM3D (transversal and axial distance-dependent collimator blur compensation) recently introduced in commercially available SPECT reconstruction software (e.soft “Flash3D,” Siemens Medical Solutions). The numbers of iterations and subsets as well as the postsmoothing parameters were identical to the OSEM2D reconstruction.

OSEM3D is an iterative SPECT reconstruction method based on OSEM. Iterative reconstruction with 3D-beam modeling has been described (1–5,7). The 3D collimator blurring was implemented into the forward and back-projection of OSEM using the identical acceptance angle (“balanced”), yet maintaining computational efficiency. OSEM2D, which has been available for some years, is similar to OSEM3D, but optimized for a two dimensional—transversal beam modeling—only. It is less computationally intensive than the 3D version and thus reconstructs faster than OSEM3D. With recent advances in computer technology and algorithmic improvements, the 3D implementation became fast enough to be used in

the clinical environment with typical reconstruction times ranging from 30 seconds to at most a few minutes depending on the chosen reconstruction parameters, matrix size, compensation methods, and desired image quality.

Data Analysis

Manual registration of the SPECT images and the CT images was performed using a commercially available 3D volume registration and fusion tool (Syngo Advanced Fusion VC20H, Siemens Medical Solutions), which allows subvoxel 3D rigid-body transformation with 6 degrees of freedom (10). Image registration focused on the lesion of interest was performed by a physician trained in CT and in SPECT. The measurement of transversal and axial lesion extension was performed with the SPECT images displayed in the hot metal color lookup table and the CT images in a normal gray scale (level 50 HU; width 400 HU) and a gamma of 1, to maintain linearity. On the transversal images, the upper cutoff window value of the hot metal color lookup table was manually adjusted so that the transition from blue to red (50% isolevel) of the lesion in SPECT fitted optimally the boundaries of the lesion on CT (Fig 1). Then, the transversal and also the axial lesion diameters were measured by software caliper

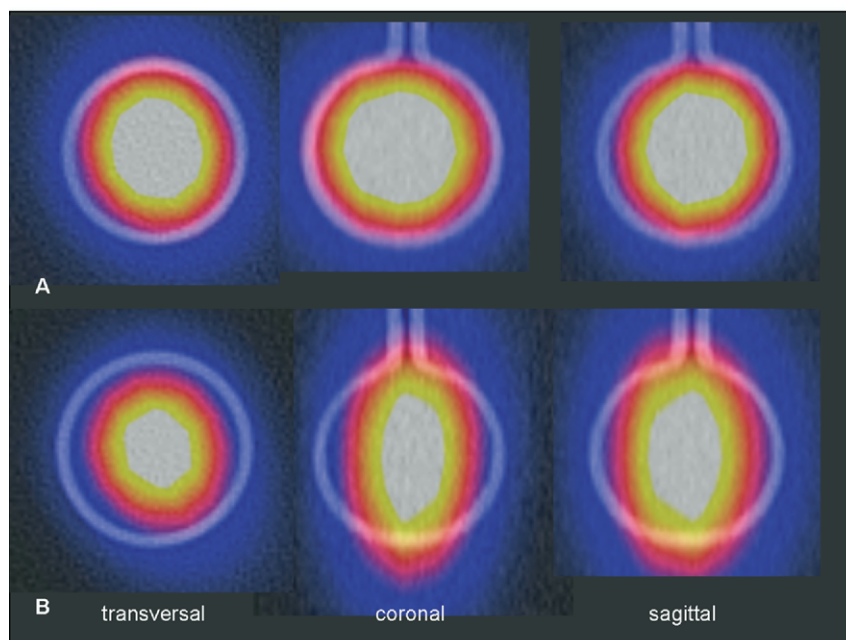


Figure 2. Computed tomography (CT) and single-photon emission-computed tomography (SPECT) images of a sphere measuring 22 mm in diameter filled with In-111 after registration of both modalities (left column: transversal slice; middle column: coronal slice; right column: sagittal slice). **(A)** The representation of the sphere reconstructed by modeling the collimator beam three dimensional (OSEM3D) exactly matches that by CT in all three dimensions. **(B)** The OSEM2D-reconstructed representation of the sphere exactly matches that by CT data in the x-axis and the y-axis. However, its diameter in the z-axis exceeds that on CT by 43%.

on both SPECT and CT images. On the SPECT images, the 50% isolevel was used as boundary for the measurements. Afterwards, the OSEM2D reconstructed SPECT images were displayed using the identical upper cutoff window values and the diameters were measured in the same way.

For further analyses, an index of eccentricity (IE) was determined for the phantom data by calculating the average of the quotient of the diameters in z-direction and x-direction and the quotient of the diameters in z-direction and y-direction: $IE = \text{average} (dz/dx; dz/dy)$.

Differences of IE from 1 were tested by performing paired *t*-tests on IE values. To assess the significance of differences in patients' lesion diameters the Wilcoxon signed-rank test was used. Significance was accepted for $P < .05$.

RESULTS

Figure 2 demonstrates the greater axial extension of lesion representation on OSEM2D-SPECT compared to OSEM3D and CT for one of the spheres studied.

In the OSEM2D phantom data, IE was significantly different from 1 (1.47 ± 0.23 ; $P < .05$); this was not the case for OSEM3D (1.03 ± 0.06 ; $P > .05$) and CT (0.98 ± 0.02 ; $P > .05$). In Fig 3, for the three sets of images, IE is plotted against the volume of the spheres; no clear-cut relationship is observed. Table 1 lists the transversal and axial extensions of the spheres contained in the phantom determined for the three sets of images. The axial diameter of the spheres was significantly greater for OSEM2D than for CT and OSEM3D. The overestimation ranged from 2% to 54%.

In Fig 4 an example of a mesenterial lymph node visible on CT with high uptake of In-111-pentetreotide is shown. The axial extension of that lesion is considerably greater on the OSEM2D- than on the OSEM3D-SPECT images.

Table 2 gives the mean values and standard deviations for the transversal and axial extension of the patients' lesions for CT and for the OSEM2D- and OSEM3D-reconstructed SPECT images. In total, 22 lesions were measured. There was no significant difference between the axial lesion diameters measured on CT and OSEM3D-

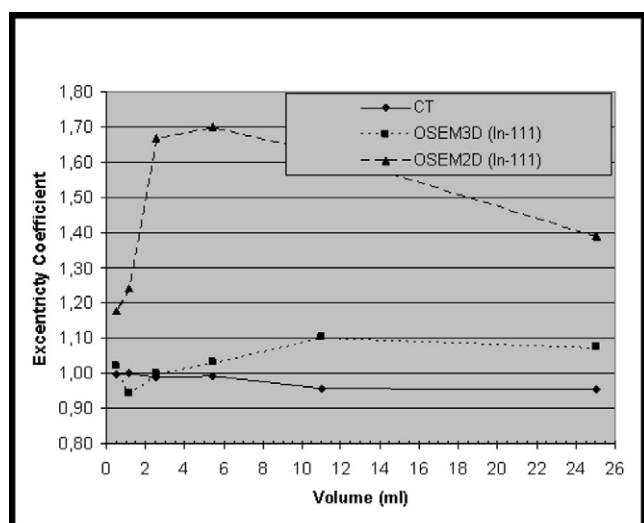


Figure 3. In the graph, the index of eccentricity is plotted against the volume for the spheres filled with In-111 separately for computed tomography (CT), single-photon emission-computed tomography reconstructed by modeling the collimator beam three dimensional (OSEM3D) and two dimensional (OSEM2D).

SPECT (3.69 ± 2.09 versus 3.71 ± 2.11 ; $P > .05$).

However, this variable was with 4.26 ± 2.18 by approximately 15% greater for OSEM2D than for the other two sets of images ($P < .05$).

DISCUSSION

A phantom study using a phantom containing spheres filled with In-111 showed that the index of eccentricity IE was significantly different from 1 for OSEM2D; this was not the case for OSEM3D and CT. This finding was accounted for by a significantly greater extension of the spheres on the OSEM2D-SPECT images in z-direction. Equivalent findings have been observed for Tc-99m (data not shown).

These observations find their explanation in the nature of the reconstruction algorithms used: in contrast to OSEM2D, OSEM3D models the collimator blurring in both the transversal and axial directions. A physical collimator hole accepts photons that impinge within a cone with some acceptance angle. Thus, with OSEM3D, depth-dependent resolution is isotropically recovered, and, in principle, a sphere should be reconstructed as a sphere after a 3D reconstruction. FBP, which does not model the collimator blur and inherently assumes the acceptance angle to be zero, also has an isotropic response, at least in the center of the field of view (7,8). These statements are

Table 1
Diameters of the Phantom Spheres and Their Images

Sphere Diameter (mm)*	Direction	CT (mm)	OSEM2D (mm)	OSEM3D (mm)
10 (9.8)	x	9.3	9.5	7.6
	y	9.4	8.1	9.0
	z	9.3	10.3	8.4
13 (13.1)	x	12.3	9.9	13.0
	y	12.1	9.3	11.9
	z	12.2	11.9	11.7
17 (17.0)	x	16.6	12.8	16.1
	y	16.8	12.6	16.5
	z	16.5	21.2	16.3
22 (21.8)	x	21.5	17.1	20.1
	y	21.6	19.0	22.0
	z	21.4	30.6	21.7
28 (27.6)	x	27.8	25.5	26.0
	y	27.8	24.4	26.8
	z	26.6	40.6	29.1
37 (36.3)	x	36.8	37.1	36.7
	y	36.8	35.5	36.8
	z	35.1	50.4	39.5

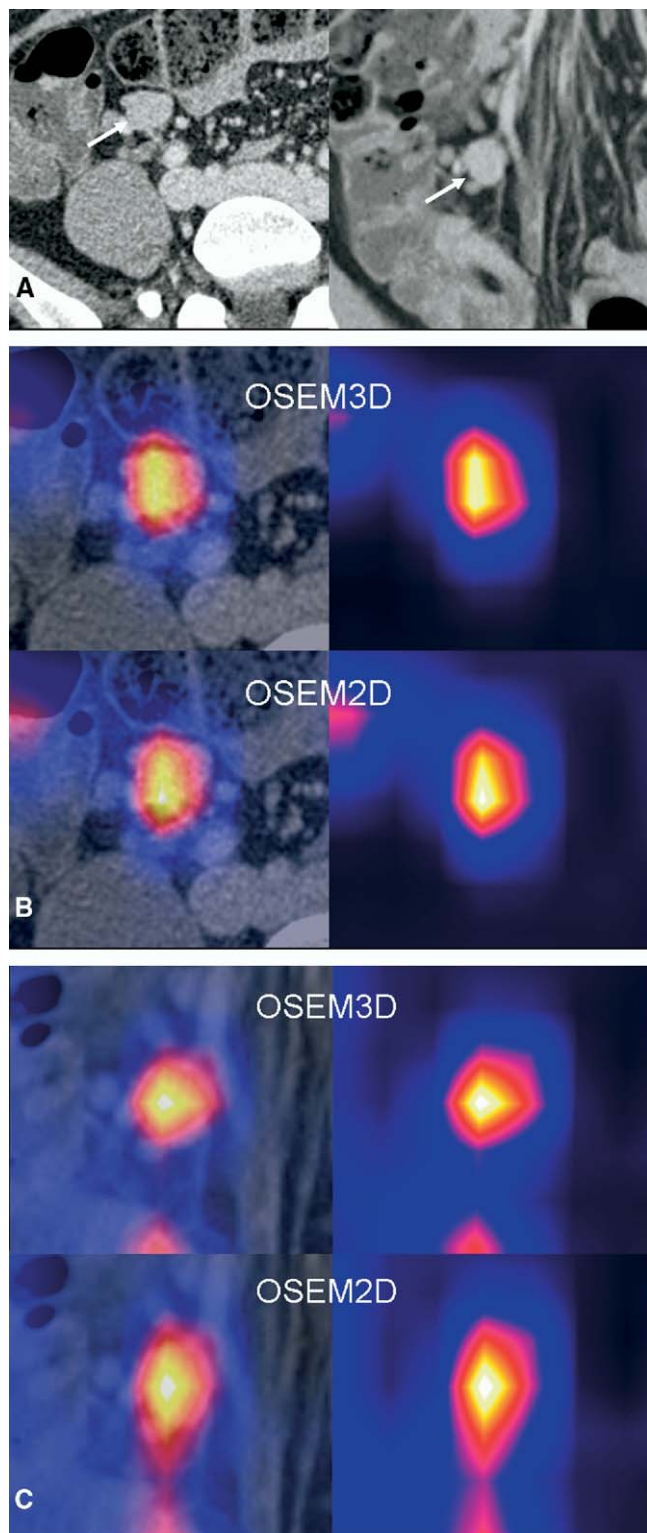
*Values in parentheses measured by the manufacturer of the phantom.

strictly true for perfect attenuation and scatter compensation. Although OSEM3D is able to accommodate nonuniform attenuation and scatter compensation, it was not used in this study, because FBP cannot compensate for attenuation and scatter and OSEM2D cannot compensate for object scattering during reconstruction. By using FBP a sphere is reconstructed as a sphere, but it is blurred and superimposed with streaks. On the other hand, a 2D modeling of OSEM only takes the collimator blurring only in the transversal direction into account, but not axially. With OSEM2D, the true physical acceptance cone for each collimator hole is modeled as an acceptance fan, and thus a sphere is deformed in the 2D reconstruction to an ellipsoid (8) as was also the case in our data.

The method of measuring lesion size is germane to this study. SPECT images do not lend themselves easily to this task because, with limited spatial resolution of SPECT, the boundaries of structures are not clear-cut, but appear blurred. When determining size in a SPECT image, one therefore has to bear in mind that the image of the lesion can be varied by changing the upper and lower cutoff values. We therefore used a standardized protocol to determine the 3D extension of the structures under study: on the transversal images, the upper cutoff window value of the hot metal color scale was manually adjusted

Table 2
Mean Values and Standard Deviation for the Images of the Patients' Lesions

Modality	Lesion Diameter Mean Value $\pm$ Standard Deviation (cm)		
	x-Direction	y-Direction	z-Direction
CT	3.30 $\pm$ 1.86	3.44 $\pm$ 1.72	3.69 $\pm$ 2.09
OSEM2D	3.19 $\pm$ 1.92	3.30 $\pm$ 1.70	4.26 $\pm$ 2.18
OSEM3D	3.23 $\pm$ 1.90	3.31 $\pm$ 1.61	3.71 $\pm$ 2.11



so that the transition from blue to red (50% isolevel) of the lesion in SPECT fitted optimally to the boundaries of the lesion on CT. These window settings were applied to the OSEM3D- as well as to the OSEM2D-SPECT images. Then, using the 50% isolevel to define lesion boundaries, we measured the diameter of the hot spots under study in x-, y-, and z-direction.

The good agreement between OSEM2D-SPECT, OSEM3D-SPECT, and CT with regard to transversal lesion diameters observed in our data is to be expected when this method is used. Its advantage is that systematic errors inherent to SPECT size measurements are homogenized for the three dimensions. Therefore, the significant greater axial extension of the OSEM2D images of the spheres proves the spatial distortion of SPECT images in z-direction.

In this context, it needs to be emphasized that our data would be misinterpreted if one assumed that it would be possible to precisely define lesion size on SPECT images. The good agreement between SPECT and CT with regard to lesion extension was achieved in our data only by adjusting structure size as it appears in SPECT to structure size visualized by CT. Therefore, an exact measurement

Figure 4. A 37-year-old female with a mesenteric lymph node metastasis of a carcinoid tumor of the cecum. **(A)** Transversal computed tomography (CT) scan (left) and corresponding coronal view (right) show an enlarged nearly spherical mesenteric lymph node adjacent to the cecum (arrows). **(B)** Transversal In-111-pentetreotide single-photon emission-computed tomography (SPECT) images reconstructed by modeling the collimator beam three dimensional (OSEM3D) (upper row) and two dimensional (OSEM2D) (lower row) fused to CT. The transversal shape of the hot spots correspond closely to the shape of the metastasis as visualized by CT. **(C)** Coronal OSEM3D- (upper row) and OSEM2D- (lower row) reconstructed In-111-pentetreotide SPECT images fused to CT. OSEM3D yields a close match to CT with regard to lesion shape; however, for OSEM2D, lesion diameter in the z-axis is by 47% higher than that measured on CT.

of size would not have been possible on the SPECT images alone (ie, without referring to the superimposed CT).

The findings of the phantom study found their confirmation in a study of patients with neuroendocrine tumors. Here again axial extension of hot spots was significantly greater when measured on OSEM2D-reconstructed SPECT images than for OSEM3D and CT.

In the patients' data, the measurement of lesion size may have been affected by artifacts caused by respiratory movements. These may affect the visualization of the axial extension of a hot spot and the quality of image fusion as has been demonstrated by registering positron emission tomography and CT (11). However, because OSEM2D- and OSEM3D-SPECT were both affected by these artifacts, they cannot account for differences in axial size yielded by the two reconstruction algorithms.

With the advent of spiral CT technology, isotropic 3D imaging has become a reality and diagnosis on CT images is no longer derived from axial slices only, but also from multiplanar reconstructed images (12). Newly introduced hybrid cameras integrate helical CT with SPECT in one gantry; thus, also SPECT can nowadays be compared with isotropic 3D images of body structure. The availability of isotropically reconstructed SPECT data is an important prerequisite for an exact localization of hot spots with reference to the matched CT data. Clearly, OSEM3D is superior to OSEM2D in this context. The ability of OSEM3D to compensate for attenuation and scatter during reconstruction will further improve the shape fidelity.

However, evidence on the possible gain in diagnostic accuracy of SPECT/spiral CT is still scarce. Preliminary data suggest that exact lesion localization may be of particular value in bone imaging for staging or in the diagnosis of the loosening of hip prostheses (13–15). Furthermore, fusion images from SPECT/spiral CT hold promise to facilitate and improve CT-guided interventions (eg, tumor biopsy or CT-guided percutaneous radiofrequency ablation of osteoid osteoma) (16–18). In particular for these purposes, the highest achievable spatial accuracy of image fusion in 3D is desirable, afforded only by isotropically reconstructed SPECT.

CONCLUSION

The use of OSEM3D avoids deformation of hot SPECT lesions in z-direction. This may be of particular importance in SPECT/CT hybrid imaging capitalizing on the exact match of both modalities.

ACKNOWLEDGMENTS

Siemens Medical Solutions, business unit SW, kindly provided the registration software package used herein. The authors are indebted to the technologists of the Clinic of Nuclear Medicine and the Institute of Radiology for technical support.

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