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Quantification of F-18 FDG PET Images in Temporal Lobe Epilepsy Patients Using Probabilistic Brain Atlas

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A probabilistic atlas of the human brain (Statistical Probabilistic Anatomical Maps: SPAM) was developed by the international consortium for brain mapping (ICBM). It is a good frame for calculating volume of interest (VOI) in many fields of brain images. After calculating the counts in VOI using the product of probability of SPAM images and counts in FDG images, asymmetric indices (AI) were calculated and used for finding epileptogenic zones in mesial temporal lobe epilepsy (mTLE). FDG PET images from 18 surgically confirmed mTLE patients and 22 age-matched controls were spatially normalized to the average brain MRI template of ICBM. Counts from normalized PET images were multiplied with the probability of 12 VOIs from SPAM images in both temporal lobes. Finally AI were calculated on each pair of VOIs, and compared with visual assessment. If AI of mTLE patients were not within 2.9 standard deviation from those of normal control group ($P < 0.008$; Bonferroni correction for $P < 0.05$), epileptogenic zones were considered to be found successfully. The counts of VOIs in the normal control group were symmetric (AI < 4.3%, paired *t* test $P > 0.05$) except for those of the inferior temporal gyrus ($P < 0.001$). By AIs in six pairs of VOIs, PET in mTLE had deficit on one side ($P < 0.05$). Lateralization was correct in only 14/18 of patients by AI, but 17/18 were consistent with visual inspection. In three patients with normal AI, PET images were symmetric on visual inspection. The asymmetric indices obtained by taking the product of the statistical probability anatomical map and FDG PET, correlated well with visual assessment in mTLE patients. SPAM is useful for the quantification of VOIs in functional images. © 2001 Academic Press

Key Words: **positron emission tomography; statistical probabilistic anatomical mapping; probabilistic brain atlas; temporal lobe epilepsy; quantification; volume of interest.**

INTRODUCTION

F-18 FDG (fluoro-deoxyglucose) interictal PET is one of the useful methods for detecting and lateralizing the epileptogenic focus in patients with mesial temporal lobe epilepsy. Visual assessment is a widely used approach in clinical situation, but the results are dependent on observers according to experience (Drzezga *et al.,* 1999). Sometimes objective data is needed to support what we feel but are not sure of, in case of subtle decreased metabolism.

To make objective data, sampling using regions of interest (ROIs) method is traditionally introduced to quantify the activity of PET images. Working with fixed ROIs (e.g., elliptical, rectangular, etc.) is the common method of sampling the regions. However, defining ROIs using fixed figures presents the same problem, that it is not fully objective. (1) Results vary depending upon who draws the ROIs, (2) or vary from image to image due to intersubject variability. (3) Moreover, the process is very time-consuming when a large number of ROIs are involved.

To solve these problems, voxel based approaches, such as statistical parametric mapping (SPM) were introduced (Signorini *et al.,* 1999; Van Bogaert *et al.,* 2000), and these methods facilitate the interpretation of PET brain images in a clinical setting. However, if we are interested in a specific area such as the hippocampus, another method is needed because the methods does not contain information about anatomical structures.

Recently, many kinds of brain mapping methods have been developed including automated registration and segmentation. One of them is statistical probabilistic anatomical mapping (SPAM) and it was designed to overcome cross-subject variations in brain structure, as a project of the international consortium for brain mapping (ICBM). SPAM consists of 98 brain structures including multiple cortical gyri, white matter, cerebrospinal fluid, etc. Most of the studies that have used SPAM have concerned anatomical differences and volume measurements in MRI images, but application to

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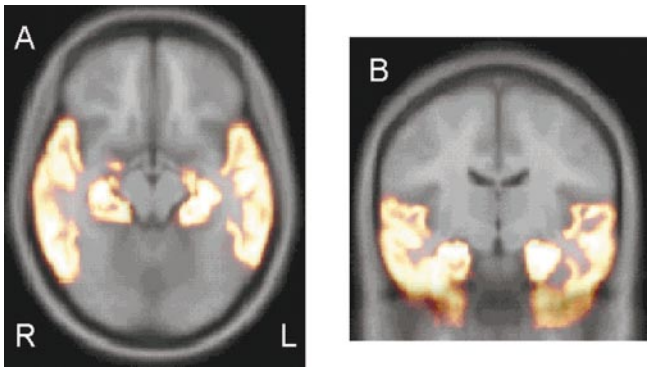

FIG. 1. Integrated images of six pairs of SPAM used for the VOIs of the temporal lobe. Figures show 3-D areas of the both temporal lobes overlaid upon normal average brain MRI template. The temporal lobe shown consisted of the superior, middle, inferior temporal gyrus, hippocampus, parahippocampal gyrus, and amygdala. (A) Transverse image; (B) coronal image; R, right; L, left.

functional images has also been suggested (Penhune *et al.*, 1996).

We applied SPAM to the PET images of patients with mesial temporal lobe epilepsy to determine whether quantifying a PET study with SPAM is useful to support visual assessment in a clinical situation.

MATERIALS AND METHODS

Patients and Controls

Eighteen patients with drug resistant mesial temporal lobe epilepsy (TLE) were selected, who had undergone temporal lobectomies at Seoul National University Hospital and had good surgical outcomes. The patients were followed up for 1.3 ~ 4.1 years with a seizure free state (mean follow up period: 2.5 ± 0.8 years), and all were of Engel class 1 (Engel 1993). The mean age of the patients was 29 ± 9. Eleven were men and seven were women. Ten patients had right TLE and the other eight left TLE.

The initial presurgical evaluation of epileptic patients included history and neurological examination. All patients were monitored with audiovisual-scalp EEG and underwent F-18 FDG PET. MRI was performed in all patients and revealed either hippocampal sclerosis or atrophy in patients with mesial TLE. In patients who had discordant results from noninvasive studies, intracranial EEG were performed to determine the epileptic focus.

Twenty-two healthy volunteers underwent FDG PET as a control group. They were of mean age 28 ± 9. Sixteen were men and six were women. All the subjects had no history of neurological or psychological disease and were not taking any drugs, known to affect PET studies. Informed consent was obtained from each volunteer after he or she was given an explanation about the purpose and procedures of this study.

PET Imaging

For those subjects undergoing PET, 370 MBq (10 mCi) of F-18 FDG was injected intravenously, with eyes open and the room lights dimmed. Images were acquired about 30 min after tracer injection with a CTI ECAT Exact 47 PET camera (Siemens, Knoxville, TN). After taking a transmission scan for 5 min with a Ge-68 rod source, the emission scan was performed for 25 min in 2-dimensional mode.

Emission scan images were reconstructed using a back-projection method with a Shepp–Logan filter (cut-off frequency of 0.35), and the attenuation effects were corrected with transmission images. The resolution (FWHM) of the PET camera was 6.2 × 6.2 × 4.3 mm and the dimension of the image matrix was 128 × 128.

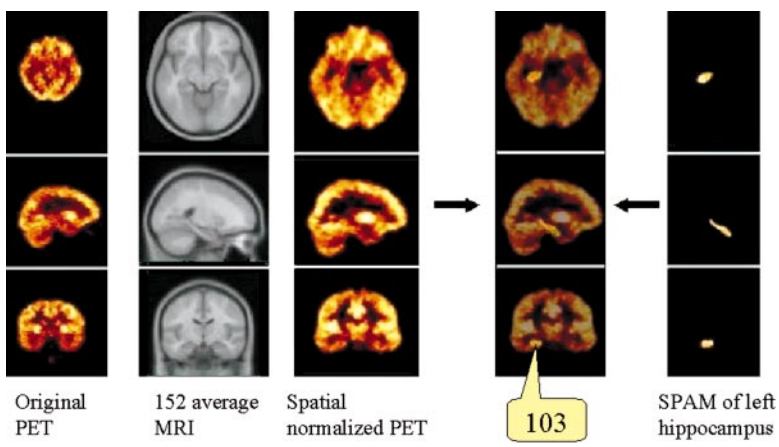

FIG. 2. After the PET was spatially normalized into average MRI template, the counts from the PET were multiplied by the probability of each VOI of SPAM. Then counts were normalized with average gray matter counts. These figures are examples of the left hippocampus; probability-weighted average PET count of the left hippocampus was 103. PET, positron emission tomography; MRI, magnetic resonance imaging; SPAM, statistical probabilistic anatomical mapping; VOI, volume of interest.

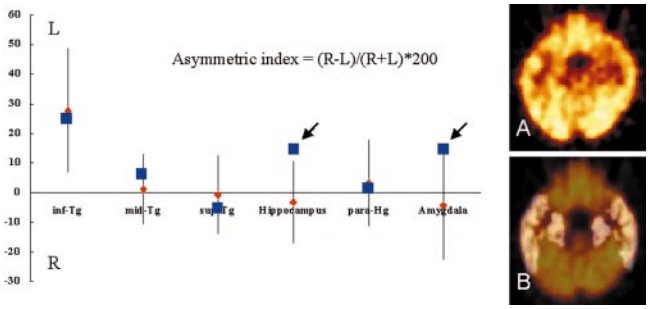

FIG. 3. Asymmetric indices (AIs) of normal control group (red rhomboid) and a 23-year-old male patient with medial temporal lobe epilepsy (blue square, Patient No. 13 in Table 1). The VOI (volume of interest) counts in normal control group were symmetric (AIs $<$ 4.3%), except for those of the inferior temporal gyrus. The confidence interval of normal control group was corrected with Bonferroni method ($P = 0.008$). AIs of the hippocampus and amygdala in patient showed deficit on left side (indicated), which was consistent with the visual finding (A). The patient was proven to have an epileptic focus in the left temporal lobe after surgery. (B) An overlaid SPAM of the temporal lobe on the patient's spatially normalized PET. inf-Tg, inferior temporal gyrus; mid-Tg, middle temporal gyrus; sup-Tg, superior temporal gyrus; para-Hg, parahippocampal gyrus; R, when AI was negative, epileptogenic focus was in right temporal lobe; L, when AI was positive, epileptogenic focus was in left temporal lobe.

Registration of PET Images with SPAM

We applied the Statistical Probabilistic Anatomical Map (SPAM) images of ICBM to calculate PET count objectively. SPAM consists of 98 vol of interest (VOIs) images, including bilateral cortical gyri, and each image consists of the probability from 0 to 1 that belong to specific region.

FDG PET images were count normalized and spatially normalized with a 12-parameter affine (linear) transformation to a T1-weighted brain MRI template using SPM99b (Wellcome Department of Cognitive Neurology, London, UK). The template we used in this study was an average MRI image from 152 young normal volunteers of the International Consortium for Brain Mapping (ICBM). The counts from normalized PET images were multiplied by the probability from 98 VOIs of SPAM using a program we developed with Matlab (Mathworks Inc., Sherborn, MA).

Calculation of Asymmetric Indices

We selected six pairs of VOIs to represent the temporal lobe. These consist of the superior temporal gyrus, middle temporal gyrus, inferior temporal gyrus, hippocampus, parahippocampal gyrus, and the amygdala in each hemisphere (Fig. 1).

We obtained the probability-weighted counts for the right (R) and the left (L) VOIs (Fig. 2). Asymmetric indices (AI) were calculated using the equation $(R - L)/(R + L) \times 200$. We compared normalized PET counts in each pair of VOIs obtained from the normal controls using a paired t test to find out whether they were symmetric or not. $P = 0.05$ was considered significant. We calculated mean and standard deviation (SD) of AIs from the normal control group in each pair of VOIs.

Comparison with Visual Assessment

A PET image was determined to indicate epileptogenic zone if any one of the PET counts in the six pairs of VOIs was not within 2.9 SD from those of the normal controls. T value of 2.9 was calculated to correct for multiple comparison with Bonferroni method (degree of freedom: 21). We used 0.008 (=0.05/6) as a corrected P value for comparison of six ROI. If all the AIs in six pairs of VOIs were within 2.9 SD of normal control, we assumed the PET images as normal. If the VOIs were of variable sidedness, it was concluded that lateralization was not possible.

Two experienced nuclear medicine physicians examined transverse, coronal, and sagittal PET images blinded to the clinical findings, final diagnosis and the results from the VOI data, determined the area of decreased FDG uptake and decided the epileptogenic zone by consensus.

Lateralization determined by VOI criteria was then compared with the surgical diagnosis and visual assessment results.

RESULTS

Normal Control Group

Probability weighted normalized PET counts were obtained from six pairs of VOIs in the normal control group. No significant differences were found between the VOI counts of the right and left sides (paired t test $P > 0.05$) except for those of the inferior temporal gyrus ($P < 0.001$). In case of the inferior temporal gyrus, the counts of the left side (55 ± 5) were less than those of the right (73 ± 6). In terms of AI, 5 pairs of VOI were symmetric (AI $-3.3 \sim 4.3\%$), and the inferior temporal gyrus was asymmetric ($28 \pm 7\%$) (Fig. 3).

Patient Group

By AIs of VOI excluding or including inferior temporal gyrus, PET in TLE patients had deficit on ether side of temporal gyrus ($P < 0.05$). Because a certain VOI had always deficit on one side, there were no cases that lateralization was not possible. Lateralization was correct in 14 among 18 patients by AI, and was consistent with visual inspection in all the patients except one (Table 1). Four patients were normal in terms of AI. In three patients with normal AI, PET images were symmetric on visual assessment. Another patient showed decreased metabolism in his right temporal lobe on visual assessment.

TABLE 1

Lateralization by Asymmetric Index versus Surgical Results and Visual Assessment

Patients	Sex/age	Inf T	Mid T	Sup T	HF	PHg	Amy	Surgical results	PET findings
1	F/32				R			R. TLE	R. TLE
2	M/19		R	R	R	R	R	R. TLE	R. TLE
3	M/20		R		R			R. TLE	R. TLE
4	M/26		R	R	R	R	R	R. TLE	R. TLE
5	M/26							R. TLE	R. TLE
6	M/31		R	R			R	R. TLE	R. TLE
7	M/44		R		R	R		R. TLE	R. TLE
8	F/23	L	L	L	L		L	L. TLE	L. TLE
9	F/26				L			L. TLE	L. TLE
10	F/33		L		L			L. TLE	L. TLE
11	F/55				L			L. TLE	L. TLE
12	M/19		L		L			L. TLE	L. TLE
13	M/23				L		L	L. TLE	L. TLE
14	M/24	L	L	L	L			L. TLE	L. TLE
15	M/35				L			L. TLE	L. TLE
16	F/25							R. TLE	WNL
17	F/41							R. TLE	WNL
18	M/30							R. TLE	WNL

Note. Inf T, inferior temporal gyrus; Mid T, middle temporal gyrus; Sup T, superior temporal gyrus; HF, hippocampus; PHg, parahippocampal gyrus; Amy, amygdala; TLE, temporal lobe epilepsy; WNL, within normal limit; R, counts of right volume of interest are decreased 2.9SD more than those of normal control group; L, counts of left volume of interest are decreased 2.9SD more than those of normal control group.

Computing Time

It took less than 10 min for each subject to normalize PET images using SPM99b with an IBM-compatible personal computer (Pentium III 600 MHz CPU and 128 Mb memory). Probability-weighted counts were calculated using the MATLAB program in batches for multiple subjects, and calculation took less than 1 min per subject.

A Case of Mesial Temporal Lobe Epilepsy

A 23-year-old male patient (Patient No. 13 in Table 1) had suffered from uncontrolled complex partial seizures for five years. MRI showed left hippocampal atrophy and interictal FDG PET showed decreased metabolism in the left medial temporal lobe. With the diagnosis of left mesial temporal lobe epilepsy, left anterior temporal lobectomy was performed. The patient has been seizure free for 3 years.

Asymmetric indices (AIs) of the hippocampus and amygdala indicated the left temporal lobe as epileptogenic zone (Fig. 3). This was consistent with the visual assessment, on which decreased metabolism was found in left anterior temporal lobe (Fig. 3A), especially in the medial part.

DISCUSSION

Functional brain imaging like PET is one of the most important methods of investigating brain function and neuropsychological diseases in the field of neuroscience and medicine. It is well known that F-18 FDG PET studies show decreased glucose metabolism in epileptogenic foci (Kuhl, 1978). Interictal FDG PET effectively detects hypometabolic brain zones that are sites of onset for seizures in patients with temporal lobe epilepsy (TLE). Several studies have reported a sensitivity of 62 ~ 85% for the diagnosis of temporal lobe epilepsy by FDG PET (Henry *et al.*, 1993; Won *et al.*, 1999), but results vary according to observers (Drzezga *et al.*, 1999).

Drawing regions of interest (ROIs) on 2 dimensional slices of PET image have been used to quantify metabolic activity and to support visual assessment (Henry *et al.*, 1990). Asymmetric index by comparing counts of regions with their contralateral counterparts was found to be the most sensitive marker of hypometabolism in patients with TLE (Theodore *et al.*, 1988). However, reporting techniques based on ROI analysis are also varying according to drawers, not fully objective, and time consuming. To overcome this shortcoming, a variety of observer-independent analysis methods have been studied, including statistical parametric mapping (SPM) and 3-dimensional stereotactic surface projections (Drzezga *et al.*, 1999). SPM is now widely used for analyzing functional brain images, and is applied to FDG PET (Signorini *et al.*, 1999), especially in temporal lobe epilepsy (Van Bogaert *et al.*, 2000). They reduced observer variability but the methods were still not fully objective. They rely upon voxel based statistical values of counts, and do not contain area information. Finally, observers must determine where the area

of decreased metabolism belongs. This is particularly difficult when the areas concerned are on small structures. During SPM processing, data from small structures are blurred out by a partial volume effect combined with a smoothing process, which is capable of downgrading significant values to the insignificant.

In our study, six patients with mesial temporal lobe epilepsy were found to have hypometabolism only in small structures like the amygdala and hippocampus. When we processed PET data using SPM, we failed to locate a decreased area around the medial temporal lobe in three patients who had deviated AI only in the hippocampus or amygdala. On the other hand, SPAM methods have a problem when the ROI is too large. Decreased count levels were not detected in the anterior temporal lobe using SPAM, which were found in SPM. We used predefined VOI for temporal lobe such as superior, middle, and inferior temporal gyri. They covered the area of temporal lobe from anterior to posterior section. Small deficit only in anterior temporal lobe could be within normal range due to average effect by the normal counts of the posterior section. We should develop a specific VOI of anterior temporal lobe to find out small deficit confined to anterior temporal lobe.

In our study, the SPAM based method did not increase the sensitivity of lateralizing the epileptic zones, but 17 of 18 cases were consistent with visual assessment. Because we determined that lateralization was possible if any one of 6 ROI is not between the confidence interval of normal controls, we corrected for multiple comparison with the Bonferroni method. We used 0.008 (=0.05/6) as a corrected P value rather than 0.05. When P value had been changed from 0.05 to 0.008, a few AIs of some patients came to be within the symmetric range. However, results on lateralization did not change except one. In this case (Patient No. 5), the patient had AI of -14.5 in the hippocampus, and it is the only ROI with asymmetry, when we did not consider correction for multiple comparison ($-12.5 \sim 6.4$ for $P < 0.05$). After Bonferroni correction, it came to be within normal range ($-17.2 \sim 10.6$ for $P < 0.008$).

We applied SPAM with F-18 FDG PET and quantified the probability-weighted normalized counts of VOIs in 22 normal controls. The counts of VOIs in normal controls were symmetrical except for those of the inferior temporal gyrus. The counts of the left inferior temporal gyrus were decreased (AI = 28%). We reviewed the SPAM images overlaid on an average brain MRI template, and found that the probabilistic map of the left inferior temporal gyrus was not confined to gray matter, and tended to include more an area of CSF under the left temporal lobe (Fig. 1B). Because glucose metabolism of CSF is very low, the counts of the left inferior temporal gyrus was underestimated. We speculate that the lower border of the inferior temporal gyrus is variable, edge detection algorithm for making SPAM data would have failed to line out the correct border in some of the MRI data.

One of the limitations of this study is that the SPAM used was not based on a Korean MRI template if there is an ethnic difference between oriental and occidental people. During spatial normalization, areas are likely to be distorted if the structures are very different from those of the template. If the atrophied volume in the hippocampus is enlarged to fit into a normal template, the partial volume effect might be accentuated. To solve this problem, a variety of templates have been developed, such as templates of old normal people, and those with Alzheimer's disease, schizophrenia, etc. (Thompson *et al.*, 2000). These templates were produced using a continuum mechanical model and contain more information about the cortical gyri than the average blurred template of ICBM. For more accurate quantification without the partial volume effect, SPAM should be modified in every subject by using a nonlinear fitting program like ANIMAL (Automatic Nonlinear Image Matching and Anatomical Labelling) (Collins and Evans, 1999).

To obtain accurate counts, PET should be fit more precisely into SPAM. Since the SPAM data originates from MRI, its spatial resolution is higher than that of PET. When information on gray matter is important, as was the case in this study, gyri by SPAM should be well matched with those of PET. However, in our study, while the gyri of the temporal lobe by SPAM were well confined to the gray matter, the gyri by PET were blurred out and involved a wider area than the SPAM templates (Fig. 3B). Because PET has lower resolution than MRI, gray matter counts are blurred out into adjacent areas, such as the CSF and white matter, and the value is correspondingly decreased. To solve this problem in PET, partial volume correction (PVC) might be performed as in many previous studies (Meltzer *et al.*, 1990, 1999; Rousset *et al.*, 1998). PVC methods require the precise determination of structural information from MRI. It would be better to correct partial volume effects using the subject's own MRI data, especially to measure PET counts in small structures such as the hippocampus and amygdala.

In patients with temporal lobe epilepsy, partial volume effects occurs not only by the lower resolution of PET but also by the lesions itself. Partial volume effect is induced by relatively small volume of structures in patients with the hippocampal atrophy. Without PVC, deficit in the hippocampus on PET maybe overestimated. If we make individualized SPAMs through nonlinear registration to patient's own volume MRI and multiply probabilities of individualized SPAMs with the counts of PET data without spatial normalization, we could obtain more accurate data. Unfortunately, 3-D volume MRI data were not available because they were not stored in our institution several years ago when the patients' PET data were collected. Develop-

ment of the methods to make an automatic and objective individually parceled anatomical atlas after PVC would be a next strategy.

To improve our SPAM based ROI methods, (1) we should correct for partial volume effect, (2) use a more ethnically and/or disease-wise appropriate template, (3) and develop an appropriate individualized anatomical map.

SPAM is useful for the quantification of VOIs in the PET data of patients with mesial temporal lobe epilepsy. It gives us fully automated objective data, reduces the time required and supports decision making in the clinical setting. This method can be applied not only to TLE but also to various other diseases like Alzheimer's, and many other psychological diseases, and it can be applied to other functional images like SPECT.

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REFERENCES

Collins, L., and Evans, A. C. 1999. ANIMAL: Automatic nonlinear image matching and anatomical labelling. In *Brain Warping* (A. W. Toga, Eds.), pp. 133–142. Academic Press, San Diego.

Drzezga, A., Arnold, S., Minoshima, S., Noachtar, S., Szecsi, J., Winkler, P., Romer, W., Tatsch, K., Weber, W., and Bartenstein, P. 1999. ^{18}F-FDG PET studies in patients with extratemporal and temporal epilepsy: Evaluation of an observer-independent analysis. *J. Nucl. Med.* **40:** 737–746.

Engel, J., Jr. 1993. Clinical neurophysiology, neuroimaging, and the surgical treatment of epilepsy. *Curr. Opin. Neurol. Neurosurg.* **6:** 240–249.

Evans, A. C., Collins, D. L., and Holmes, C. J. 1996. Computational approaches to quantifying human neuroanatomical variability. In *Brain Mapping: The Methods* (A. W. Toga, C. John, and J. C. Mazziotta, Eds.), pp. 343–361. Academic Press, San Diego.

Henry, T. R., Engel, J., Jr., and Mazziotta, J. C. 1993. Clinical evaluation of interictal fluorine-18-fluorodeoxyglucose PET in partial epilepsy. *J. Nucl. Med.* **34:** 1892–8.

Henry, T. R., Mazziotta, J. C., Engel, J., Jr., Christenson, P. D., Zhang, J. X., Phelps, M. E., and Kuhl, D. E. 1990. Quantifying interictal metabolic activity in human temporal lobe epilepsy. *J. Cereb. Blood Flow Metab.* **10:** 748–757.

Mazziotta, J. C., Toga, A. W., Evans, A., Fox, P., and Lancaster, J. 1995. A probabilistic atlas of the human brain: Theory and rationale for its development. The International Consortium for Brain Mapping (ICBM). *NeuroImage* **2:** 89–101.

Meltzer, C. C., Kinahan, P. E., Greer, P. J., Nichols, T. E., Comtat, C., Cantwell, M. N., Lin, M. P., and Price, J. C. 1999. Comparative evaluation of MR-based partial-volume correction schemes for PET. *J. Nucl. Med.* **40:** 2053–2065.

Meltzer, C. C., Leal, J. P., Mayberg, H. S., Wagner, H. N., Jr., and Frost, J. J. 1990. Correction of PET data for partial volume effects in human cerebral cortex by MR imaging. *J. Comput. Assist. Tomogr.* **14:** 561–570.

Penhune, V. B., Zatorre, R. J., MacDonald, J. D., and Evans, A. C. 1996. Interhemispheric anatomical differences in human primary auditory cortex: Probabilistic mapping and volume measurement from magnetic resonance scans. *Cereb. Cortex* **6:** 661–672.

Rousset, O. G., Ma, Y., Wong, D. F., and Evans, A. C. 1998. Pixel- versus region-based partial volume correction in PET. In *Quantitative Functional Brain Imaging with Positron Emission Tomography* (R. E. Carson, M. E. Daube-Witherspoon, and P. Herscovitch, Eds.), pp. 67–75. Academic Press, San Diego.

Signorini, M., Paulesu, E., Friston, K., Perani, D., Colleluori, A., Lucignani, G., Grassi, F., Bettinardi, V., Frackowiak, R. S. J., and Fazio, F. 1999. Rapid assessment of regional cerebral metabolic abnormalities in single subjects with quantitative and nonquantitative [^{18}F]FDG PET: A clinical validation of statistical parametric mapping. *NeuroImage* **9:** 63–80.

Theodore, W. H., Fishbein, D., and Dubinsky, R. 1988. Patterns of cerebral glucose metabolism in patients with partial seizures. *Neurology* **38:** 1201–1206.

Thompson, P., Woods, R., Mega, M., and Toga, A. 2000. Mathematical/computational challenges in creating deformable and probabilistic atlases of the human brain. *Hum. Brain Mapp.* **9:** 81–92.

Van Bogaert, P., Massager, N., Tugendhaft, P., Wikler, D., Damhaut, P., Levivier, M., Brotchi, J., and Goldman, S. 2000. Statistical parametric mapping of regional glucose metabolism in mesial temporal lobe epilepsy. *NeuroImage* **12:** 129–138.

Won, H. J., Chang, K-H., Cheon, J-E., Kim, H. D., Lee, D. S., Han, M. H., Kim, I-O., Lee, S. K., and Chung, C-K. 1999. Comparison of MR imaging with PET and ictal SPECT in 118 patients with intractable epilepsy. *Am. J. Neuroradiol.* **20:** 593–599.