© Respective Importance of Scatter, Attenuation, Collimator Response and Partial Volume Effect Corrections for Accurate Quantification in 123I Dopamine Receptor Imaging

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Abstract

We studied the relative importance of scatter correction (SC), attenuation correction (AC), depth-dependent collimator response (CC) and partial volume effect corrections (PVE) for accurate quantitative 123I brain SPECT. 123I activity was simulated in the putamen, caudate nuclei and background of the numerical Zubal brain phantom. Monte Carlo simulations including scatter, attenuation and collimator response effects were performed. The impact of all corrections was studied by reconstructing the projections using 29 schemes involving 2 reconstruction methods (FBP and OSEM), 3 SC (ideal, 20%, Jaszczak), 3 AC (ideal, iterative Chang, OSEM), 1 CC (frequency-distance principle) and 1 PVE correction (anatomically guided pixel-by-pixel algorithm). For each processing scheme, spatial resolution, binding potential (BP) and errors in striatal and background activity estimates were calculated. Results demonstrate: 1) the crucial role of CC for improved spatial resolution hence improved binding potential estimates; 2) the inaccurate striatal activity quantitation using SC+CC+AC only (errors ≥50%); 3) the essential and effective role of PVE correction for accurate striatal activity quantitation (errors <13%). In conclusion, SC, AC and CC all help improve relative and absolute quantitation, but PVE correction is essential for absolute quantitation of striatal activity. PVE correction is effective provided high resolution anatomical information is available.

I. Introduction

Quantitative brain SPECT for neuroreceptor imaging is especially challenging given the small size of the structures of interest. On the other hand, the issues of scatter and attenuation are less severe in brain SPECT than in cardiac imaging because the brain is a relatively small and homogeneous attenuating medium. In order to better assess the role of attenuation, scatter and limited spatial resolution in 123I neuroreceptor brain SPECT, we studied the respective effect of scatter correction (SC), attenuation correction (AC), corrections for depth-dependent collimator response (CC) and partial volume effect (PVE), with a particular emphasis on PVE. Indeed, unlike in PET, PVE correction has not received much attention in brain SPECT yet.

II. Material and Methods

To permit a detailed investigation of the different phenomena affecting 123I brain SPECT, Monte Carlo simulations (PHG code [1]) were performed using the three-dimensional numerical Zubal brain phantom [2]. 123I activity was set in the putamen (370 kBq/ml), caudate nuclei (222 kBq/ml) and background (bgd, 37 kBq/ml). The effects of collimator response, scatter and attenuation were simulated. A set of 128 projections 128x128 was obtained over 360° with a parallel beam geometry, a pixel size of 2.2mm and a radius of rotation of 25cm. Ten million photons were generated and 0.5 million events were detected in the projections between 143 and 174 keV (20% energy window centered on 159 keV). Images of unscattered and scattered photons were created.

The impact of the different corrections was investigated by reconstructing the projections using 29 different schemes involving 2 reconstruction methods, 3 SC, 1 CC, 3 AC and 1 PVE correction.

For all reconstruction schemes, the number of iterations of the iterative algorithms was adjusted so that the signal to noise ratio (SNR) measured as the ratio between the mean and the standard deviation in a background region was equal to 3.

Reconstruction was performed either using filtered backprojection (FBP, ramp filter) or using Ordered Subset Expectation Maximization (OSEM) [3].

Regarding scatter correction, the conventional 20% energy window (143-174 keV for 123I) was used. In addition, the images corresponding to the Jaszczak (JAS) subtraction (Compton window =[90-110 keV] and k=0.35) were obtained. To mimic ideal scatter correction, the projections of primary photons only were considered (PRIM).

Depth-dependent collimator response was compensated for using the frequency-distance principle (FDP) [4]. The detector response function was modeled as a Gaussian point spread function with a full width at half maximum (fwhm) varying linearly with the distance to the collimator.

Three approaches of attenuation correction were considered: ideal correction corresponding to the data simulated without attenuating medium, and two iterative schemes: iterative Chang as described in [5] and OSEM (OSEM-A). For both algorithms, the attenuation map used for the simulations was considered, without simulating any blurring or noise in this map.

Correction for partial volume effect was performed using an anatomically guided pixel-by-pixel algorithm (APA) [6]. To estimate the activity concentration in a compartment r (e.g., caudate nucleus), APA assumes that any other physiological compartment r' (e.g. background or putamen) has a known uniform activity concentration $A_{r'}$ and that all compartments r and r' are anatomically defined by their spatial support X_r and $X_{r'}$. The image that would be obtained had only the compartments r' other than r be present is estimated by convolving the image of the activity distribution corresponding to all compartments r' by the 3D point spread function h of the imaging system. This image is subtracted from the observed image I to get the image I' representing the specific contribution of compartment r. On the other hand, the binary image representing the spatial support of compartment r

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is convolved by h to get an image of the pixel-by-pixel weights (lower than 1) of compartment r in the observed image I. Finally, in all pixels for which the weight of compartment r is non-zero, the pixel value in I' representing the specific contribution of compartment r is divided by the weight of compartment r to get the activity due to compartment r in that pixel. When estimating the activity in the caudate nucleus compartment, these operations can be expressed as:

$$I_{caud} = \frac{I - h * A_{putamen} X_{putamen} - h * A_{bgd} X_{bgd}}{h * A_{caud}} = \frac{I'}{h * A_{caud}}$$

where * represents convolution.

We implemented APA in two ways: one rather "ideal" (PVi), one more "realistic" (PVr). In both cases, we assumed that the 5 compartments of our phantom (2 putamens, 2 caudate nuclei and the background) were anatomically known since their spatial supports were available from the simulated phantom. In the "ideal" implementation, we considered the true putamen and the bgd activities to estimate the caudate nuclei activity and similarly, we considered the true caudate nuclei and the bgd activities to estimate the putamen activity. In the "realistic" implementation, we took the mean activity values measured from caudate nuclei and bgd ROIs on the images not corrected for PVE as A_{caud} and A_{bgd} to estimate the putamen activity and similarly, we took the mean activity values measured from the putamen and bgd ROIs in the images not corrected for PVE to estimate the caudate nuclei activity corrected for PVE. In all cases, the system response function h was modeled using a stationary 3D Gaussian isotropic kernel with FWHM equal to 1.32 cm.

For each reconstructed image I resulting from a specific processing scheme, 3 parameters were measured: 1) spatial resolution estimated by determining the FWHM of the 2D Gaussian function g that minimized the root mean square error between I and the simulated activity distribution convolved by g in the striatal region; 2) percent errors in putamen, caudate nucleus and bgd activity. The 3D ROIs used for absolute activity quantitation were the exact anatomical regions derived from the simulated activity distribution map. The 3D ROI used for background measurement was a large cylindrical region drawn below the striata as shown on fig 1; 3) binding potential value (BP) defined as (striata - bgd)/bgd activity ratio (true value = 9 in putamen and 5 in caudate nucleus).

III. Results and Discussion

First, the impact of the corrections on the three evaluation criteria was assessed (Tables 1). Next, the performances of the different correction methods were compared.

A. Spatial resolution

Neither scatter correction alone, nor attenuation correction alone, nor combined scatter and attenuation corrections improved spatial resolution substantially in the reconstructed slices (maximum change less than 2 mm) (Table 1). Spatial resolution was only substantially improved when performing the FDP collimator response correction: this correction improved spatial resolution by almost 8.6 mm as compared to performing no correction (22.2 mm with 20%+OSEM vs. 13.6 mm with 20%+FDP+OSEM) (Table 1). Similarly combining FDP and attenuation corrections improved spatial resolution from 24.2 mm with 20%+OSEM-A down to 14.6 mm with 20%+FDP+OSEM-A. These improvements in spatial resolution were clearly visible on the resulting images (Fig. 2). These results show that performing a collimator response correction does improve spatial resolution for an equivalent SNR.

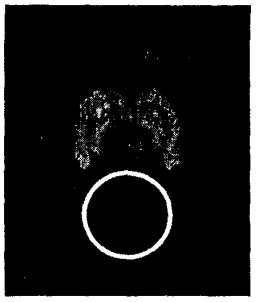

Figure 1: caudate nucleus, putamen, and background ROIs drawn on a reconstructed slice and used for the assessment of quantitative accuracy.

B. Absolute activity quantitation

The corrections required for accurate absolute activity quantitation strongly depended on the size of the considered organ. In the background, which can be considered as a large compartment, the effects of variable collimator response and partial volume effect were negligible and the major phenomena affecting quantitation were scatter and attenuation. Without any correction, the background activity was underestimated by 62% (Table 1). Correcting for scatter alone did not reduce this error (underestimation > 67% on average in PRIM+OSEM and JAS+OSEM) because attenuation is the major effect affecting absolute activity quantitation. Correcting for attenuation alone yielded an activity overestimation of about 26% because scatter was still present in the data. Attenuation correction had to be combined with scatter correction to achieve reliable activity estimate in the background (average errors of +3% in Table 1 for SC+AC). Collimator response and partial volume effect corrections did not substantially affect absolute activity quantitation in the background (underestimation of 1% on average in PRIM+FDP+OSEM-A and JAS+FDP+OSEM-A).

For small structures such as the striata, activity was also largely underestimated without any correction (by 88% on average in the caudate nucleus and putamen, Table 1). Similar to what was observed for the background, correcting for scatter alone did not improve accuracy (underestimation > 89% on average in PRIM+OSEM and JAS+OSEM). Correcting for attenuation alone decreased the bias from 88% to 59%. Unlike what was observed for large structures, combining scatter and attenuation corrections was not enough to yield accurate quantitation, as the underestimation remained on average greater than 64%. Correcting for collimator response further reduced the bias from 64% to 54% on average in

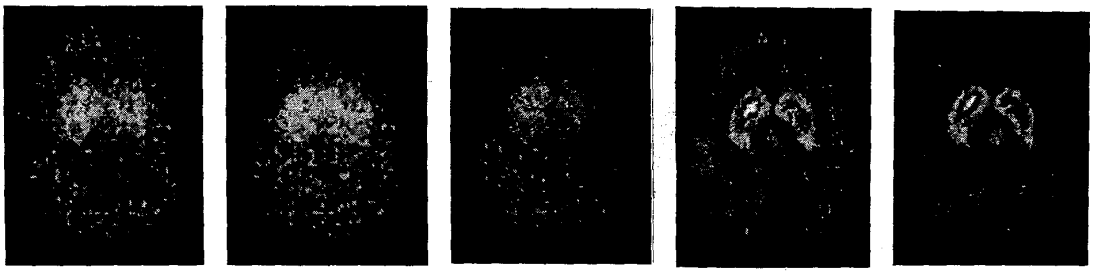

Figure 2: images resulting from: None (20%+OSEM), AC (20%+OSEM-A), SC+AC (PRIM+OSEM-A), CC+AC (20%+FDP+OSEM-A) and SC+CC+AC (PRIM+FDP+OSEM-A).

PRIM+FDP+OSEM-A and JAS+FDP+OSEM-A. This residual 54% underestimation after scatter, attenuation and collimator effect corrections was due to the partial volume effect of the imaging system. Performing partial volume effect compensation in addition of all other corrections led to biases less than +11% on average (Table 1).

In summary, in the background, corrections for scatter and attenuation were sufficient to estimate the activity with errors less than 4%. However, estimation of striatal activity with errors less than 14% required correcting for scatter, collimator response, attenuation and partial volume effect.

C. *Binding potential*

Binding potential is a contrast measurement. Table 1 shows that scatter correction or attenuation correction alone did not make the binding potential estimate more accurate. Indeed, the difference in attenuation between the background and the striata was not enough for attenuation correction to affect the contrast between those two areas. Scatter correction alone did not affect BP because without attenuation correction, the effect of scatter correction is negligible, as already shown in cardiac configurations [7].

Collimator response correction alone increased the binding potential value by about 50% with respect to no correction in the caudate nucleus and putamen (Table 1). However binding potential was still seriously underestimated (by 68% on average) when applying 20%+FDP+OSEM (Table 1).

Combining scatter and attenuation corrections only slightly improved BP compared to no correction (average underestimation of 79% without correction as compared to 76% in average for S+A methods) (Table 1). Performing collimator correction in addition to SC+AC reduced the bias affecting BP estimates from about -76% with SC+AC to about -63% for SC+AC+CC. Nevertheless, BP was still underestimated by 63% on average with SC+AC+CC processing schemes. The crucial correction for reducing this large bias in BP estimate was partial volume effect correction. Combining PVE correction with SC+CC+AC decreased the bias from -63% to +12% (Table 1).

D. *Comparison of the correction methods*

Analyzing the results obtained for the different correction methods (Table 1) allowed us to compare the performances of different approaches that can be used to compensate for a single effect and to determine how well the correction methods work compared to ideal corrections.

As results obtained with the JAS correction were close to the results obtained using primary photons, JAS could be considered as reliable for this imaging configuration.

Comparing the results obtained for the "ideal" (PVi) and "realistic" (PVr) PVE corrections, we found that the "realistic" PVE correction performed quite well compared to the "ideal" correction. For example, bias in absolute striatal activity was on average 10% for PVr and 5% for PVi, BP bias was on average 12% for PVr and 6% for PVi. APA therefore appears as a valuable approach for PVE compensation, provided high resolution anatomical information is available.

Figure 2 presents an example of reconstructed slice resulting from different processing schemes: no correction (20%+OSEM), AC (20%+OSEM-A), SC+AC (PRIM+OSEM-A), CC+AC (20+FDP+OSEM-A) and SC+CC+AC (PRIM+FDP+OSEM-A). Only FDP correction improved the visual aspect of the images. Although the signal-to-noise ratio was about 3 for all these reconstructed images, the images corrected for the collimator response by FDP appeared less noisy. This is explained by differences in noise frequency which was not accounted for in the definition of signal-to-noise ratio we used to determine the noise magnitude.

The greater the number of corrections involved, the more critical the choice of each correction method. For instance, when performing attenuation correction alone, caudate activity varied by 1.3% and spatial resolution varied by 3.8% depending on the attenuation correction method. When considering scatter and attenuation corrections, error in caudate activity estimates varied by 3.9% while spatial resolution varied by 7.7% depending on the scatter and attenuation corrections that were applied. This is because the imperfections inherent to each correction get amplified as the number of corrections that are involved increases.

Table 1: parameter values as a function of the processing scheme.

Corrections	Methods	Res (mm)	Putamen error (%)	Caudate error (%)	Bgd error (%)	Putamen BP	Caudate BP
None	20%+OSEM	22.2	-90	-86	-62	1.6	1.1
AC	20%+OSEM-A	24.2	-66	-52	+26	1.6	1.2
	20%+Chang	24.2	-65	-51	+18	1.9	1.5
SC	PRIM+OSEM	20.4	-91	-88	-69	1.8	1.2
	JAS+OSEM	22.3	-90	-87	-64	1.6	1.1
CC	20%+FDP+OSEM	13.6	-86	-84	-63	2.7	1.6
SC+AC	PRIM+OSEM-A	22.3	-71	-60	+1	1.8	1.3
	PRIM+Chang	20.7	-68	-58	0	2.0	1.4
	JAS+OSEM-A	23.6	-70	-57	+5	1.8	1.4
	JAS+Chang	21.1	-67	-56	+4	2.1	1.5
CC+AC	20%+FDP+OSEM-A	14.6	-54	-45	+23	2.7	1.6
	20%+FDP+Chang	13.4	-50	-43	+23	3.0	1.7
SC+CC+AC	PRIM+FDP+OSEM-A	12.7	-59	-53	-3	3.2	1.9
	PRIM+FDP+Chang	11.7	-56	-50	-3	3.5	2.0
	JAS+FDP+OSEM-A	13.1	-56	-49	+2	3.2	1.9
	JAS+FDP+Chang	11.9	-53	-47	+3	3.5	2.0
SC+CC+AC+PVE	PRIM+FDP+OSEM-A+PVr		+6	+7	-3	10.1	5.6
	JAS+FDP+OSEM-A+PVr		+13	+13	+2	10.1	5.6
	PRIM+FDP+Chang+PVr		+17	+12	-3	11.1	6.0
	JAS+FDP+Chang+PVr		+24	+20	+2	11.1	6.0
Ideal Correction			0	0	0	9	5

Table 2: parameter values as a function of the processing partial volume effect correction.

Corrections	Methods	Putamen error (%)	Caudate error (%)	Bgd error (%)	Putamen BP	Caudate BP
SC+CC+AC+PVEr	PRIM+FDP+OSEM-A+PVr	+6	+7	-3	10.1	5.6
	JAS+FDP+OSEM-A+PVr	+13	+13	+2	10.1	5.6
	PRIM+FDP+Chang+PVr	+17	+12	-3	11.1	6.0
	JAS+FDP+Chang+PVr	+24	+20	+2	11.1	6.0
SC+CC+AC+PVEi	PRIM+FDP+OSEM-A+PVi	+1	-12	-3	9.5	4.5
	JAS+FDP+OSEM-A+PVi	+9	-2	+2	9.7	4.7
	PRIM+FDP+Chang+PVi	+11	-4	-3	10.5	4.9
	JAS+FDP+Chang+PVi	+20	+6	+2	10.7	5.2
Ideal Correction		0	0	0	9	5

IV. CONCLUSION

In summary, the results of this simulation study show that:

1) combining attenuation and scatter corrections only is enough to properly estimate activity in large compartments such as background whereas striatal activity and binding potential remain largely underestimated when performing only these two corrections (errors >54% for striatal activity and >62% for BP on average).

2) depth-dependent collimator correction significantly improves spatial resolution (more than 9 mm improvement) yielding a concomitant reduction of the biases affecting striatal activity estimates. However, depth-dependent collimator response is not sufficient for properly estimating striatal activity. Without PVE correction, striatal activity remains underestimated by about 50% or more.

3) anatomically guided partial volume effect correction is very effective at restoring activity in small regions and makes both relative (BP) and absolute quantitation (bgd and striatal activity) quite accurate (errors less than 13%).

4) results did not differ much depending of the specific correction used for compensating a given phenomenon and most corrections were fairly effective.

SC, AC and CC all help improve relative and absolute quantitation, but PVE correction is the key correction for accurate estimation of BP and striatal activity. Anatomically guided PVE correction seems to be a promising approach for quantitation in neuroreceptor brain SPECT provided high resolution anatomical information is available. In the study we reported here, we assumed that the anatomical map was perfectly known, was properly registered with the functional data and that anatomical structures were properly segmented. Studies about the influence of imperfect anatomical information, misregistration between anatomical and functional data and segmentation errors are under way in our laboratory.

V. REFERENCES

[1] Harrisson and al., "Preliminary experience with the photon history generator module of a public-domain simulation system for emission tomography," *Conf. Rec. Nucl. Sci. Symp.*, vol. 2, pp.1154-1158, 1993.

[2] Zubal and al., "Computerized three dimensioal segmented human anatomy, " *Med. Phys.*, vol. 21, pp.299-300, 1994.

[3] Hudson and al., "Accelerated image reconstruction using ordered subsets of projection data," *IEEE Trans. Med. Imaging*, vol 13, pp. 601-609, 1994.

[4] Xia and al., "Fourier correction for spatially variant collimator blurring in SPECT," *IEEE Trans. Med. Imaging*, vol 14, pp.100-115, 1995.

[5] Riddell and al., "The approximate inverse and conjugate gradients: non-symmetrical algorithms for fast attenuation correction in SPECT," *Phys. Med. Biol.*, vol 40, pp. 269-281, 1995.

[6] Müller-Gärtner and al., "Measurement of radiotracer concentration in brain gray-matter using positron emission tomography - MRI-based correction for partial volume effects", *J. Cereb. Blood Flow Metab*, vol 12, pp. 571-583, 1992.

[7] El Fakhri and al., "Relative Impact of scatter, collimator response, attenuation and finite spatial resolution correction in cardiac SPECT" (in press), *J. Nucl. Med.*, vol 41, 2000.