A Procedure for Patient Repositioning and Compensation for Misalignment Between Transmission and Emission Data in PET Heart Studies

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A procedure for patient repositioning and compensation for misalignment between transmission and emission data in positron emission tomography (PET) heart studies has been developed. Following the transmission scan (TR1), patients are moved from the scanner bed for the administration of the tracer, and repositioned when ready for the emission scan (EM1). A short postinjection transmission scan (TR2) is performed at the end of the EM1 study. TR1 and TR2 images are compared to recognize misalignment between transmission and emission studies. TR1 sinograms are compensated for misalignment to allow for a proper attenuation correction. The procedure has been tested on phantom and [^{18}F]FDG PET heart studies. Misalignments down to 2.5 mm translation and 1 degree rotation in the transaxial plane and 4 mm in the axial direction can be recognized and compensated for. The procedure is suitable for clinical purposes, allowing reduction of patient time on the scanner bed, increased patient comfort and significant increase of patient throughput.

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Quantitative positron emission tomography (PET) studies require accurate compensation for the attenuation of annihilation photons in the patient's body. Measured attenuation correction performed following a transmission scan is now generally used in whole-body studies. It assumes a perfect match between transmission and emission studies. Misalignment is particularly critical in whole-body studies where attenuation correction (AC) is crucial due to the presence of heterogeneous tissues (muscle, bone, lung, etc.) (*1–3*).

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Three alternative acquisition protocols are currently employed:

1. Transmission scans are performed before tracer administration and patients must remain motionless until the end of the emission scan. This is difficult, especially for heart patients who may find it uncomfortable to lie on the scanner bed for a long time.
2. Transmission scans are performed before tracer administration. Patients are removed from the bed at the end of the transmission scan and then repositioned for the emission scan. The use of such repositioning techniques makes the examination less tiring and more comfortable for the patient. Repositioning techniques require the use of external landmarks, such as radioactive sources or laser beams, to recognize the patient's spatial position. The accuracy of repositioning is, however, limited by complex and continuous movements of the heart, chest and skin, with respect to internal organs.
3. Transmission measurements are performed after tracer administration, and before, during or after the emission scan (*4–10*). These techniques employ specially designed rotating sources, hardware and software control during acquisition, which allows for the removal of most scattered and random coincidences as well as most emission counts from the transmission data. The implementation of these techniques is not simple and may also be limited by positron emission tomograph performance, especially in relation to nonlinearity effects caused by the high count rate concentrated on the detectors close to the source.

The aim of this work is to develop a procedure which can be used with all PET scanners to increase patient comfort, recognize and compensate for misalignment between transmission and emission studies and make efficient use of scanner time.

MATERIALS AND METHODS

PET Scanner

A Siemens ECAT 931/04-12 (Siemens-CPS Knoxville, TN) whole-body scanner was used. The system consists of four rings of bismuth germanate detectors yielding seven transaxial images with a slice thickness of 6.7 mm. Images were reconstructed using a filtered backprojection algorithm with a Hann filter (0.5 cycles/pixel, cutoff frequency) on a 256 × 256 matrix (pixel size: 2.5 mm) for transmission images and on a 128 × 128 matrix (pixel size: 1.5 mm) for emission images respectively. Measured AC was performed using ring sources filled with ^{68}Ge.

Fluorine-18-Deoxyglucose Acquisition Protocol and Repositioning Technique

The proposed acquisition protocol for PET [^{18}F]FDG heart studies consists of the following steps:

1. Blank Scan (BL1).
2. Patient Positioning. Three laser beams were projected and then marked with a felt pen onto the patient's skin for later recognition (hours or even days later).
3. Transmission Scan (TR1): Two spatially consecutive acquisitions were performed to cover the whole heart (10 min for each position, ~8–10M counts/direct plane depending on the individual patient dimensions).
4. Tracer Injection. The patient was removed from the scanner at the end of the TR1 scan for the injection of the tracer.
5. Patient Repositioning. Forty minutes after radiopharmaceutical injection (uptake time), the patient was repositioned on the scanner bed.
6. Emission Scan (EM1). Two spatially consecutive emission scans (15 min for each position) were performed.
7. Postinjection Transmission Scan (TR2). A single postinjection transmission scan (2 min) was acquired, matching the first position of the TR1 scans, at the end of the EM1 study.

Correlation-Compensation (C-C) Procedure

The procedure to recognize and compensate for misalignment between transmission and emission studies consists of the following.

Processing TR2 Data. The TR2 scan is degraded by the emissive radiotracer contribution. Compensation is performed by subtracting the emissive (EM1) contribution from the transmission data (TR2) to generate a compensated transmission scan (PTR2) as follows:

$$[\text{PTR2}] = [\text{TR2}] - \text{acf}\cdot[\text{EM1}] \qquad \text{Eq. 1}$$

where: [ ] is the pixel-by-pixel sinogram matrix operation and acf is the AC factor for the presence of the transmission source between patient and detectors for the different scan lengths between TR2 and EM1 and for radioactive decay.

The resulting attenuation map (PTR2) is not quantitatively accurate in terms of absolute attenuation coefficients and the reasons for this are essentially related to statistical noise. If PTR2 data were used for AC, the noise propagation effect into emission images would not be acceptable (*1*). Furthermore, when counting statistics in a transmission scan are very low (as in the PTR2 case), the resulting attenuation coefficients are wrong (overestimated) when compared to the true values (*11*). Finally, noise in PTR2 data is increased by the subtraction of the emissive contribution (*8*), therefore previous considerations become even more critical.

However, the reconstructed PTR2 images are not used for AC, but only for alignment purposes, based on the recognition of anatomical structures.

Testing the Accuracy of Patient Repositioning. Based on a threshold technique, the edges of anatomical structures (body, heart, lungs) are extracted from the TR1 images and the resulting binary images are superimposed onto the PTR2 images. Edge detection is performed only on TR1 images (~8–10M counts/direct plane). At such counting statistics, edges can be properly extracted. A preliminary evaluation of the accuracy of patient repositioning is thus performed by visual inspection. In fact, if a misalignment is present, it can be recognized because all edges appear consistently misplaced. A very different finding would be observed in case of a local mismatch due to statistical noise effect in TR2 images. Because TR2 is performed immediately after the EM1 study, we assume that misalignment between TR1 and PTR2 is an estimate of misalignment between TR1 and EM1.

Misalignment is then quantitatively assessed, using a bi-dimensional correlation program based on a least squares approach. A cross-correlation coefficient is calculated between the two reconstructed TR1 and PTR2 images according to the following equation (*12*):

$$cc_{X,Y} = \frac{\sum_{i,j} f_{i-x,j-y} g_{i,j} - fgN}{(F - f^2N)^{1/2}(G - g^2N)^{1/2}}, \qquad \text{Eq. 2}$$

where $cc_{X,Y}$ is the cross-correlation coefficient; f is the comparison image (TR1); g is the reference image (PTR2); F and G are the mean values of f and g, respectively, used for the normalization of $cc_{X,Y}$ to 1; N is the number of points where f and g are defined; and X and Y are the spatial ranges on which the correlation test is performed.

TABLE 1
Calculated (X, Y, Z, Φ) versus True (x, y, z, ϕ) Misalignments Parameters for Two Selected Phantom Measurements

TR2 M counts/ direct planes	Cross-correlation coefficient	X* mm	Y* mm	Z* mm	Φ* degree
10	0.9975	5.0	2.5	6.7‡	9
7.5	0.9904	5.0	2.5	6.7‡	9
3.5	0.9889	5.0	2.5	6.7‡	9
2.0	0.9816	5.0	2.5	6.7‡	9
0.9	0.9606	5.0/7.5§	2.5	0/6.7‡§	8/9§
0.4	0.9386	5.0/7.5§	0/2.5§	0/6.7‡§	8/9§
TR2 M counts/ direct planes	**Cross-correlation coefficient**	**X† mm**	**Y† mm**	**Z† mm**	**Φ† degree**
10	0.9982	2.5	2.5	0.0	3
7.5	0.9918	2.5	2.5	0.0	3
3.5	0.9895	2.5	2.5	0.0	3
2.0	0.9824	2.5	2.5	0.0	3
0.9	0.9668	2.5	0/2.5§	0.0	2/3§
0.4	0.9384	0/2.5§	0/2.5§	0.0	2/3§

* True displacement parameters: x = 6.0 mm, y = 2.5 mm, z = 4 mm, ϕ = 9.

† True displacement parameters: x = 2.5 mm, y = 2.5 mm, z = 4 mm, ϕ = 3.

‡ 6.7 mm as z parameters correspond to the thickness of one slice.

§ The two values correspond to fluctuations among planes.

The cross-correlation coefficient is calculated repeatedly for each set of parameters X, Y, Φ, Z in the range X, Y = 0, ±1 . . . ±(X_{max}, Y_{max}), Φ = 0, ±1 . . . Φ_{max}, and Z = 0, ±1 . . . Z_{max}. X, Y = 0, ±1 . . . ±(X_{max}, Y_{max}), Φ = 0, ±1 . . . Φ_{max}, and Z = 0, ±1 . . . Z_{max}. In practice, in order to save computing time, the ranges over which the correlation test is performed is limited. This is based on preliminary information obtained from the qualitative assessment of the misalignment between TR1 and PTR2 studies. The value of the cross-correlation coefficient is maximum for the set of parameters (X, Y, Φ, Z) which produces the best match between the two images.

Compensation Procedure. Compensation for misalignment has to be performed on patient data, excluding the bed contribution, present in the transmission sinograms. For this purpose, a transmission scan of the scanner bed (TR1B) must be acquired in the same position (height) as during the patient study (usually a reference position). The bed contribution can be removed from the TR1 sinogram data according to the following equation:

$$[PTR1] = ([TR1]\cdot[BL1])/[TR1B]\cdot dcf, \qquad \text{Eq. 3}$$

where PTR1 corresponds to a transmission sinogram relative to "pure" patient transmission data and dcf is a correction factor accounting for the different scan length among TR1, BL1, TR1B and for the ^{68}Ge radioactive decay. Misalignment between transmission and emission studies is then recovered by processing the PTR1 data according to the set of parameters (X, Y, Φ, Z) which maximize the correlation coefficient. Translation in the x and y direction can be corrected by modifying the sinusoidal law of the detected events in the sinograms. Rotation ϕ can be corrected by shifting the rows of the sinograms. A translation in the z direction can be corrected by shifting the planes of the study.

Finally the bed scan can then be reinserted into the modified PTR1. The resulting data can be used to make a new map of attenuation coefficients, where misalignment between TR1 and EM1 studies has been corrected. Emission images can now be reconstructed using appropriate AC factors.

Validation of the C-C Procedure

Effect of Noise on the Correlation Procedure. The dependence of the correlation procedure on the noise in the TR2 images was assessed using an anthropomorphic phantom (Rando, Alderson Research Laboratories) simulating the human chest. A TR scan was acquired to simulate TR1 scan in clinical studies (~10M counts/direct plane). Six sets of TR2 scans were then acquired at different total collected counts (from ~10M counts/direct plane to ~0.4M counts/direct plane). Each complete set was acquired at different axial positions moving the bed in the z direction with a step of 2 mm from 0 to 8 mm, to simulate a displacement in z direction. Translation (x, y) and/or rotation (ϕ) movements of the phantom, in the axial plane with respect to the TR1 phantom position were simulated in the reconstruction procedure by setting offsets in the x and y direction in the range from 0 to 15 mm and rotation angles in the range from 0 to 15 degrees.

Phantom Studies. A heart phantom inserted into a bigger phantom simulating the human thorax was used (Capintec RH-2 heart phantom). A first transmission scan was acquired (TR1, ~10M counts/direct plane) with the phantom in a reference

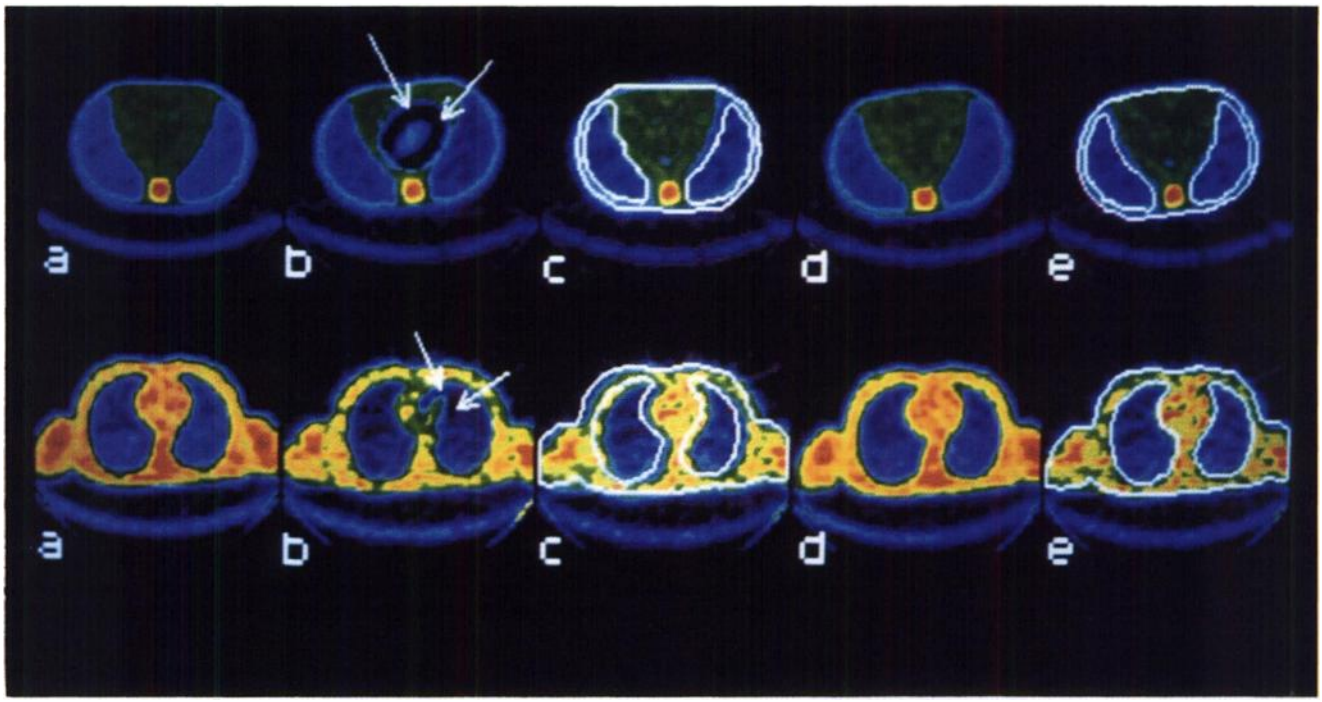

FIGURE 1. (Top) Application of the C-C program on a selected TR image from the thorax/heart phantom experiment for a translation misalignment between TR and EM studies respectively. Images are labeled as follows: (a) TR1 image (reference position). (b) Correspondent TR2 image. Note how the emissive contribution from the heart chamber (which is radioactive during the TR2 study) generates a severe artifact on the TR attenuation coefficients map (arrows). (c) Phantom edges extracted from TR1 and superimposed on TR2 image, after data processing, according to Equation 1 (PTR2). Repositioning error is evident as misalignment between the two images. (d) TR1 image after correction for misalignment. (e) Phantom edges extracted from TR1 after correction for misalignment and superimposed on PTR2 image. The repositioning error is now compensated. (Bottom) Application of the C-C program on a heart patient study. Images are labeled as before.

position. The heart wall of the phantom was then filled with homogeneous radioactive solution of ^{18}F in water, while the heart chamber was filled with water. An initial emission study (EM1) was acquired with the phantom in the same position as in the TR1 study. The phantom was then moved to a new position and a second emission scan (EM2) followed by a short transmission scan (TR2, ~1M counts/direct plane) were performed. Seven different misaligned positions were considered. All the EM2 scans were corrected for radioactive decay with respect to EM1. EM1 and EM2 images were then reconstructed using the original TR1 data to compensate for radiation attenuation. ROIs were drawn on the heart wall of the phantom in all the studies and profiles (ROIs average counts versus ROIs number) were generated. Differences in radioactivity distribution in the heart wall, caused by the change of position of the phantom in all EM2 studies with respect to the TR1 study, were estimated by comparing average counts in correspondent ROIs in each EM2 with respect to EM1 reference images. The C-C procedure was then applied to each misaligned set of data. Differences in radioactivity distribution in all the compensated EM2 images with respect to EM1 were then measured with the same ROI analysis as before.

Patient Studies. The C-C procedure was also tested on eight patients undergoing [^{18}F]FDG heart studies for clinical purposes. The patients were informed and written consent was obtained in each case. All the patients were positioned on the scanner bed with their arms extended and fastened to the chest. Patients were asked to remain motionless from the beginning of the TR1 scan to the end of the EM1 scan, and their position was monitored.

At the end of the EM1 scan, the patients were asked to change their original position to simulate a misalignment. The displacement was evaluated in the range of 1–2 cm translation and 2–3 degree rotation in the transaxial plane. An EM2 scan and a TR2 scan, misaligned with respect to TR1 and EM1, were immediately acquired. Data analysis was performed like in phantom studies.

RESULTS

Validation of the C-C procedure

Effect of Noise on the Correlation Procedure. Results from the Rando phantom studies are shown in Table 1 for two selected misalignment configurations. The cross-correlation coefficient depends on the noise in the TR2 studies, decreasing when the noise in TR2 increases. Despite this effect, the accuracy of the correlation program, in terms of maximum errors in the estimation of the X, Y, Φ and Z parameters, is not sensitive to the noise in the data down to ~1M counts/direct plane. In fact, at this noise level, the results oscillate and are not consistent for all planes (Table 1). The maximum errors found for all the configurations are: x = 2.5 mm, y = 2.5 mm, ϕ = 1°, z = 4 mm. These values are also representative of the minimum misalignment between TR1 and TR2 which can be recognized by the correlation technique. Given these results, a short TR2 scan of at least ~1M counts/direct plane is adequate to recognize misalignment between TR1 and TR2 studies. In patient studies, this corresponds to a transmission scan of at least 2 min, taking the variability of patient dimensions into account.

Phantom Studies. The application of the C-C procedure on a selected slice for the experimental thorax/heart phantom studies is presented in Figure 1 (top). Correspondent emission images of the heart are shown in Figure 2 (top). Accuracy of the correlation program was confirmed in all the experiments (Table 2). Artifacts generated by the misalignment between transmission and emission studies (arrows in Figure 2) are corrected by the C-C procedure. The efficacy of the compensation procedure was quantitatively verified by the ROI analysis, as shown in Figure 3 (left). Errors caused by misalignment in radioactivity distribution of up to 30% were reduced, after the application of the compensation procedure, to less than 8%, which is comparable to the statistical fluctuations in the reference study (EM1). This result was found for all experiments analyzed.

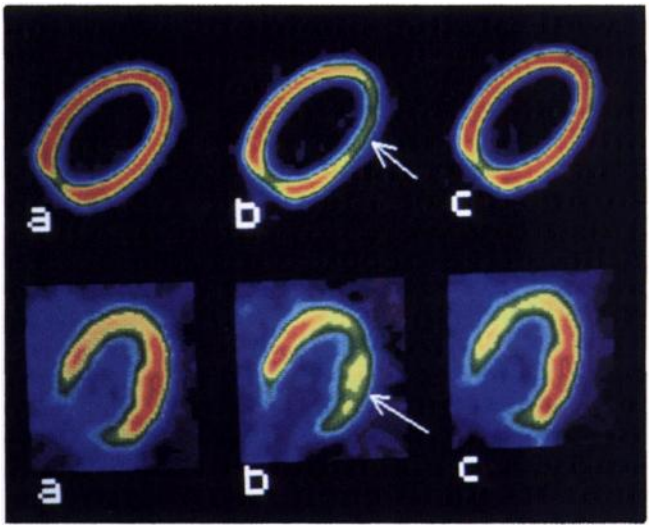

FIGURE 2. (Top) Emission images for the thorax/heart phantom experiment showing the efficacy of the C-C procedure for a translation misalignment between TR and EM studies. Images are labeled as follows. (a) Selected heart image from EM1 study. (b) The correspondent slice from EM2 study: severe artifacts caused by misalignment between TR and the EM studies can be observed (arrows). (c) The same EM2 image after the application of the C-C procedure: artifacts have disappeared and radioactivity distribution is now very similar to that in EM1 study. (Bottom) EM images from a [^{18}F]FDG heart patient study showing the efficacy

TABLE 2
Accuracy of the Correlation Program: True (x, y, ϕ) and Calculated (X, Y, Φ) Misalignments for Seven Thorax/Heart Phantom Studies

True displacement parameters			Calculated displacement parameters		
x mm	y mm	ϕ degree	X mm	Y mm	Φ degree
+2.5	−6.0	−3.0	+2.5	−7.5	−3.0
−3.5	−3.5	−2.8	−5.0	−5.0	+3.0
−4.5	−2.0	−3.8	−5.0	−2.5	−4.0
+12.0	0.0	+6.0	+10.0	+0.0	+5.0
+15.0	+9.0	+12.0	+12.5	+7.5	+13.0
+17.0	0.0	0.0	+15.0	0.0	0.0
+28.0	+12.0	+8.0	+30.5	+12.5	+7.0

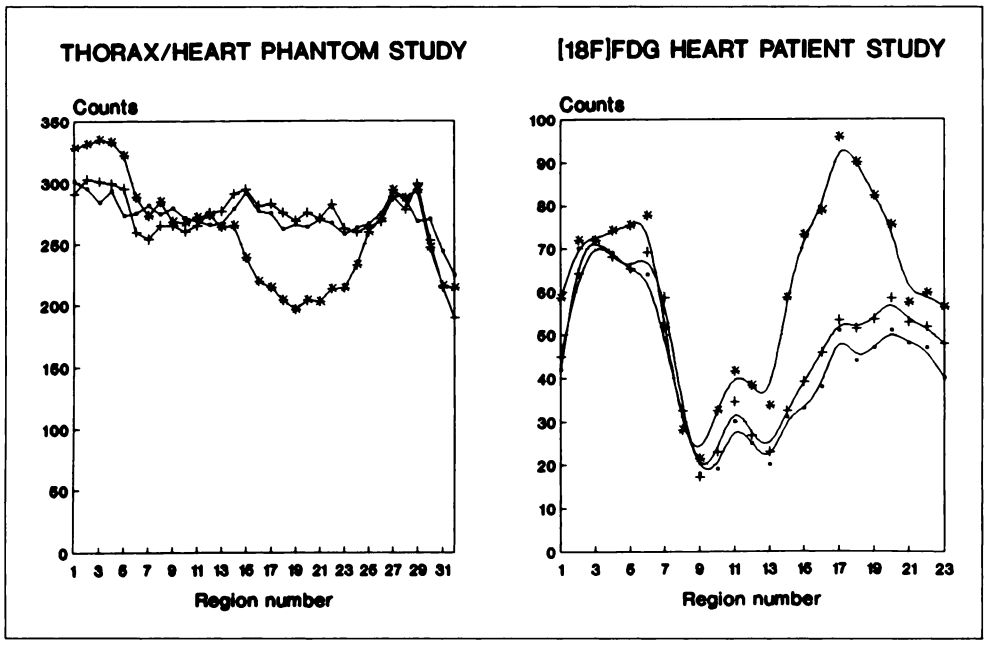

FIGURE 3. Graphical representations of the activity distribution in the heart walls for a selected image from the heart/thorax phantom experiment (left) and for a [^{18}F]FDG patient heart study (right). Average counts are plotted versus ROI number. (.) reference EM1 study, (*) uncorrected data (misalignment between TR1 and (EM1) and (+) recovered data after compensation for misalignment.

Patient Studies. The C-C procedure proved to be effective in all evaluated [^{18}F]FDG PET heart patient studies. The application of the C-C procedure on patient data is reported in Figure 1 (bottom) for a selected transmission slice. The corresponding heart image of radioactivity distribution is shown in Figure 2 (bottom). As can be seen, the pattern of radioactivity distribution of the tracer was reestablished after the application of the C-C procedure. Results from the ROI analysis in Figure 3 (right) showed that the mean percentage error was reduced from 40% (misaligned data) to 10% (compensated data). The residual error can be attributed to incomplete compensation of the TR1 data and to the variations of [^{18}F]FDG uptake in the myocardium due to the difference in time between the first and second emission study.

DISCUSSION AND CONCLUSIONS

An important requirement in quantitative PET studies is an accurate match of transmission data, needed to compensate for radiation attenuation in the body, and emission radioactivity data. The C-C procedure used in this study is sensitive to 2.5 mm displacements (x and y directions) and 1 degree rotation in the transaxial image plane and 4 mm as axial shift. Within this degree of accuracy, for both phantom and [^{18}F]FDG patient studies, misalignment errors of up to 30%–40% were compensated to within 10%.

A limitation of the technique is related to the intrinsic hypothesis of considering the patient as a rigid body. In fact, arm movement with respect to the thorax does change attenuation conditions and cannot be accounted for. Arms extended behind the head might be preferable, but this is uncomfortable for the patient. A system needs to be devised to 'rigidly' fix the arm position to the body. Furthermore, the C-C program is bi-dimensional so rotations around the x- and y-axis cannot be compensated.

The following considerations concerning the feasibility of implementing such a technique in a clinical environment can be made:

1. Generality. The technique is very general and can be implemented with any PET scanner.
2. Dosimetry. The short TR2 scan is responsible for an increase in radiation dose to the patient. However, the dose resulting from a 2-min transmission is negligible with respect to the total dose from the PET study (*11,13*). When repeat PET studies are required, at different times or different days (e.g., rest/stress, perfusion ^{13}N-ammonia/metabolism [^{18}F]FDG protocols), the procedure proposed here allows for a single transmission scan to be acquired and applied to different emission studies by proper repositioning of the patient. Radiation doses from multiple long transmission scans can thus be replaced with the much lower dose of multiple 2-min transmission scans.
3. Patient Comfort. The increase in patient comfort, achieved by reducing the time on the scanner bed, reduces the probability of patient motion during the scan. Patients can be removed from the bed during the waiting time, such as the decay of ^{13}N-ammonia and uptake of [^{18}F]FDG in combined flow/metabolic studies.
4. Time. The correlation program takes about 15 min on a μVaxII computer, while 15 min are usually required by the compensation procedure for the correction of transmission data and by the reconstruction algorithm for the generation of a new set of emission images (14 slices) properly corrected for

attenuation. The program can be run off-line, in batch mode, without occupying scanner time.

5. Patient Throughput. The repositioning technique allows the implementation of optimized daily protocols. Patient studies can be interleaved and a better use of scanner time is achieved.

In conclusion, this procedure for patient repositioning and correction for misalignment between transmission and emission PET heart studies is advantageous, especially for clinical purposes.

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