Misalignment Between PET Transmission and Emission Scans: Its Effect on Myocardial Imaging

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Patient movement between PET scanning sequences can produce misalignment between attenuation and emission scans. Such misalignment introduces errors in the emission image. This study evaluates the severity of these errors and their effect upon quantitation of regional myocardial activity. Myocardial FDG scans from 14 patients were reconstructed with simulated translational, rotational and out-of-plane patient movement. Eight myocardial regions from each patient were examined to determine the effect such misalignment might have on regional myocardial activity. A 2-cm shift between attenuation and emission scans produced up to a 30% change in regional activity. Some regions of the myocardium increased while others decreased for a given magnitude and direction of shift, producing anomalous regional myocardial inhomogeneities in the image. Such changes could easily cause qualitative and quantitative misinterpretations. We present data permitting the reader to assess the magnitude of this effect in his/her own clinical setting.

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Positron emission tomography (PET) is frequently used to measure myocardial perfusion and metabolism. An important advantage of PET for this purpose is its ability to measure accurately both relative and absolute activity concentrations. This ability is due in part to the fact that a practical method exists which, in principle, allows PET scans to be corrected for attenuation effects. Failure to make this correction, or inaccuracies in the correction, can lead to both absolute and regional errors in the myocardial image.

The potential errors that can occur when attempting to correct for attenuation have been described in detail by Huang et al. (*1*). Huang also performed simulation and phantom studies showing how such errors could influence PET brain imaging. In practice, great care is needed to perform an accurate attenuation correction even in a small and relatively homogeneous structure like the brain. Accurate attenuation correction in the thorax is an even more difficult problem due to much larger attenuation correction factors (*2*) and due to the presence of sharp boundaries between regions with greatly differing attenuation values (e.g., lung and tissue). This paper applies some of Huang's methodology to a specific problem of myocardial imaging. Namely, how misalignment between the actual and assumed attenuation media can affect myocardial scans. The goal was to investigate how patient motion (either translations or rotations) which may occur during the time between the attenuation scan and emission imaging (*3*), might affect both the regional and absolute appearance of the myocardial image. The data show the degree to which absolute and regional isotope distributions will be distorted if such misalignment due to movement occurs. Such motion is not uncommon, for example, during the 30-min interval between FDG injection and FDG imaging. The results of this paper allow the reader to assess how much motion can be tolerated in practice and indicate that small shifts in body position can cause rather large distortions in the apparent regional distributions of myocardial activity.

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METHODS

All studies were performed on the 21 slice Positron Corporation PC6.5 whole-body scanner (*4*). The scanner utilizes BGO crystals and has an inplane resolution of 6.5 mm FWHM, 5.1 mm separation between slices, 13 mm FWHM axial resolution and an overall sensitivity of 130 kcps/μCi/cc (20 cm cylindrical phantom total coincidence efficiency). The machine produces sinograms consisting of 120 projections spaced at 1.5° intervals. Each projection was binned into 256 intervals of 1.7 mm each.

Attenuation Measurements

Transmission (T) scans were performed either with a fillable ring source of ^{18}F (average 2.3 mCi) or with a ^{68}Ge (average 1.8 mCi) rotating rod source and fan beam as described below. The rotating rod was a 6.0 mm outer diameter stainless steel tube 15.0 cm long with a wall thickness of 1.2 mm. The rotating rod spanned the entire axial length of the scanning volume and rotated continuously (10 rpm) around the patient aperture at a radius of 28.0 cm. An electronic "mask" inhibited all coincidences, except those whose lines were colinear with the rotating rod position at the time of detection. Data acquired from the rotating rod were not corrected for randoms, because the randoms were insignificant due to the electronic mask. Data acquired with the ring source were corrected for randoms, which averaged approximately 15% of the total events for the attenuation scan with the ring. Both ring and rod attenuation methods gave similar results, except that the ring required a longer imaging time to achieve the same degree of statistical accuracy due to randoms and scatter. Attenuation scan acquisition times averaged 37 min for the ring and 20.5 min for the rod, yielding 203 million events for the ring and 33 million events for the rod.

To normalize the T scans, blank (B) ring or rod scans were performed under exactly the same conditions as the transmission scan except that the field of view was clear of all attenuating objects. Acquisition time for the 1.8 mCi blank rod scan averaged 26 min, yielding 140 million events. The blank ring was acquired for an average of 5 hr the evening prior to the patient study (because it was also used as a detector normalization scan). The initial blank ring activity ranged from 0.5 to 1.1 mCi, yielding an average of 529 million events. From the sinograms of the T and B scans, a sinogram of attenuation correction factors (ACF) was calculated for each projection line, as the ratio between the B sinogram and the T sinogram, and appropriately normalized.

Patient Data

Data from 14 human thoracic scans were studied. Three subjects had coronary artery disease, seven subjects had hypertrophic cardiomyopathy and four were normal subjects. Ten of the subjects were studied using the rod attenuation method and four (all of them HCM subjects) with the ring attenuation method. Again, the results presented in this paper were not dependent on type of attenuation source used. Data were obtained as follows. First, the B scan was obtained. Immediately following the B scan, the subject was positioned in the scanner and the T scan was obtained. There was a 30-min delay, during which the patient remained in the same position in order that measurements unrelated to this paper could be made (myocardial blood flow measurements using ^{15}O). Following the delay, 5 mCi of FDG were intravenously injected and a list-mode acquisition scan was performed for 60–75 min. The FDG emission images were created by formatting the list-mode data into a single interval of 30–45-min duration, beginning 30 min postinjection. The typical emission scan contained 28M counts. Emission data were corrected for randoms (*5*), scatter [using a deconvolution technique (*6*)] and attenuation, and then reconstructed using standard filtered backprojection (a Hanning filter with a cutoff of 2.9 cm^{-1} and order 0.75), yielding 6.5 mm FWHM inplane resolution.

Misalignment

To investigate misalignments effects (such as might be produced by patient motion) between the T scan and the emission scan, either the emission sinogram or the ACF sinogram were manipulated as described below. Both rotational and translational misalignments could be investigated in this way. It should be emphasized that this sinogram manipulation scheme produces exactly the effect that would have been obtained had the subject actually moved to the new position.

Several types of inplane translational misalignments were investigated. Inplane misalignments were produced in the up/down (i.e., anterior/posterior) direction and in the left/right (i.e., lateral) direction. In addition, certain oblique shifts (along a 45° and a 135° line) were produced by allowing various (equal) combinations of lateral and anterior/posterior translations. To produce translational misalignments, the emission sinogram with all corrections applied except attenuation, was reorganized according to the shift desired. Note that for translation, no change was made to the ACF sinogram. Rotational misalignments, on the other hand, were produced by moving entire rows of the ACF sinogram without altering the emission sinogram. Each row of the sinogram corresponded to a projection angle 1.5° greater than the one before it. Thus, by moving the last row of the ACF sinogram to row 1 and all other rows (n) to rows n + 1, a negative 1.5° rotation could be obtained. Positive rotations were obtained in a similar manner. Rotational misalignments were produced from 0° to ±36° in increments of 9°. For clarity, all results are expressed as apparent motion of the patient with respect to the original transmission image.

Image Analysis

Each set of 21 emission images was visually examined. One slice was selected as roughly representing the transaxial slice which passed through the center of the left ventricle. A region of interest (ROI) was drawn around the myocardium in this slice and on one or two adjacent slices on either side of this slice. These myocardial ROIs were then divided into eight pie-shaped annular sectors, each subtending the same angle (Fig. 1). On average, each sector included approximately 160 pixels (4.6 cm^2).

The mean activity concentration in each sector was calculated without any misalignment. These data are referred to as "aligned" data. The mean activity for each sector from images reconstructed with various misalignments are referred to as "misaligned" data. The percent difference of the mean value in each sector between aligned and misaligned data were calculated as:

$$\%\text{ sector difference} = 100\times(\text{misaligned} - \text{aligned})/\text{aligned}. \quad \text{Eq. 1}$$

This %sector difference for each sector was then averaged over the three or four contiguous slices to give a mean %sector difference (MSD).

RESULTS

Figure 2 illustrates the change in observed sector activity concentrations as a function of simulated object motion to the left, right, up or down. These data are the average data from all 14 subjects. In this figure, a motion to the right refers to the effect that would occur had the subject moved to his own right, relative to the position of the attenuation scan. Sectors 5, 6 and 7 (the postero-lateral free wall sectors) are seen to increase in apparent activity concentration by about 14% for a 1-cm shift of the patient to his right and increase by about 28% for a 2-cm shift to the right. At the same time, sectors 4 and 8 increase only about half this much, while the septal sectors either remain the same (sector 1) or decrease slightly (sectors 2 and 3, the more posterior septal sectors). A shift of the subject to his left produces similar, but slightly more extreme, and of course reversed, effects. A 1-cm shift of the subject to the left causes the free wall sectors (5, 6 and 7) to decrease by over 16%, while the septal sectors (1, 2 and 3) remain nearly unchanged, and the antero-apical sector drops by about 7%. Therefore, significant absolute changes in activity concentration occur in the myocardium, and, perhaps more importantly, these changes are not uniform in the myocardium. A shift of the patient to his right will cause

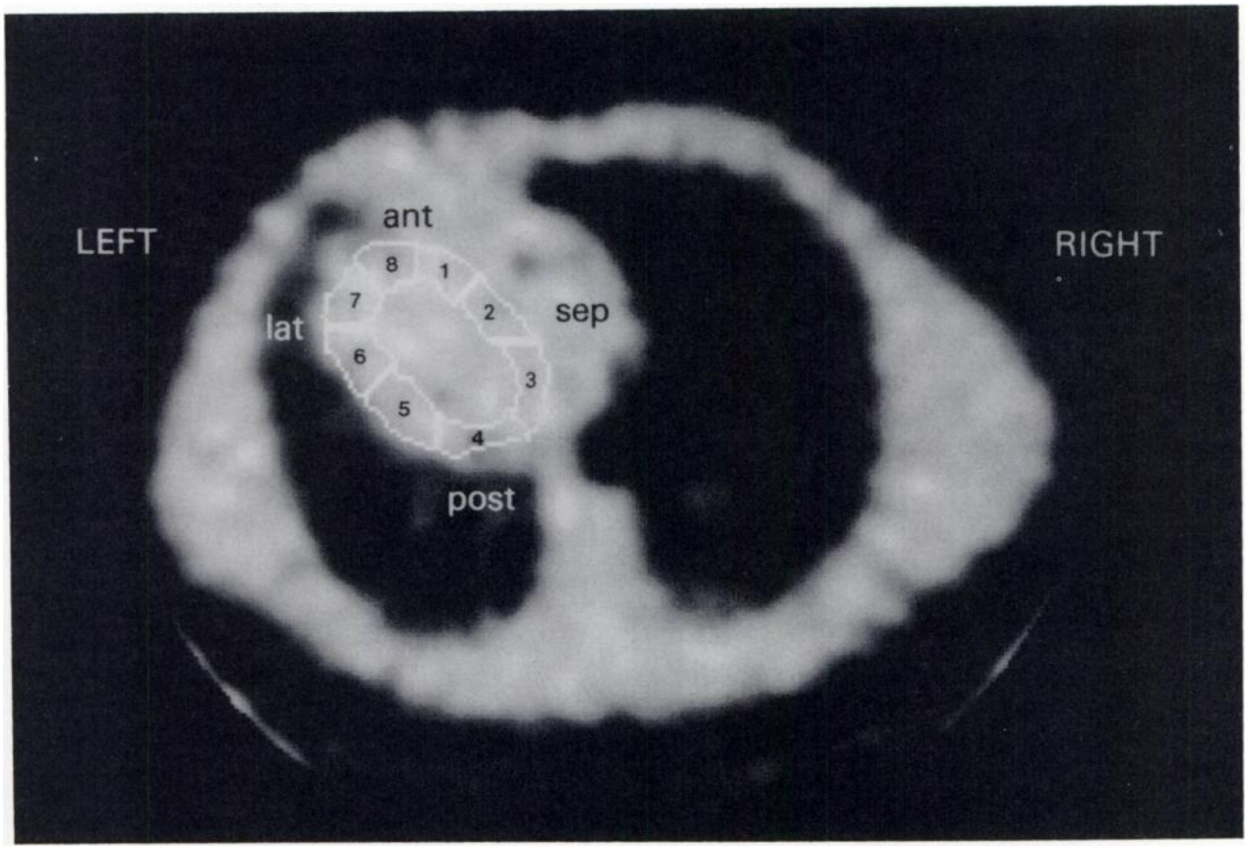

FIGURE 1. A transmission image of the thorax at the mid-left ventricular level of a typical patient. The myocardial ROI drawn on the corresponding emission image is shown segmented into eight subregions. Note that the view was obtained by looking down on the transaxial slice from above. This is the orientation used in all subsequent figures.

the free wall to get hotter with respect to the septum, while a shift to the left will cause the opposite effect. In order to better visualize these regional effects, the data for a 2-cm shift to the right or left are presented as images in Figure 3. In this figure, it is assumed that a subject has a perfectly uniform myocardial distribution of activity concentration (Fig. 3E). If the subject were to move 2 cm to his left or right, or 2 cm up or down (compared to the attenuation scan), this uniform activity distribution will be reconstructed as an image with regional inhomogeneities. The intensity scale has been adjusted to exaggerate the effects and allows the reader to easily determine the actual magnitude of the effects from the labeled intensity bar on the right of Figure 3.

Regional effects for up/down translations (i.e., as though the bed had been moved up or down after the attenuation scan) are shown in Figure 2B. Upward shifts by the patient of 1 and 2 cm produces 8% and 13% increases, respectively, in the apparent activity in the posterior region (sectors 4, 5 and 6). For the same upward shifts, the activity in the anterior sectors (1 and 8) decreases 9% and 19%. Over this same range of motion, the free wall region (sector 7) and the more posterior septal region (sector 3) have an overall decrease of only a few percent, while the changes in sector 2 are about half that of the anterior sectors. Effects observed in the myocardium for a downward shift are slightly larger and the reverse of the effects for all upward motion. The anterior region increases are 8% for a 1-cm downward shift and 16% for a 2-cm shift. Activity changes in the septal region (sector 2) are only half as much as the anterior region and the posterior region decreases 13% and 28%. A portion of the freewall (sector 6) decreases 8% and 18% for 1- and 2-cm downward shifts and sectors 3 and 7 decrease only a few percent.

Figure 4A shows the effect of slight rotations on the activity measured in each myocardial sector. A counterclockwise rotation is a motion that would occur had the subject turned his body by raising the right shoulder, while simultaneously lowering the left during an emission scan. For a rotation of 18°, the free wall region (sectors 5 to 7) decrease an average 24%, while the anterior region (sectors 1 and 2) increase 8%. The decrease in the antero-apical region (sector 8) is 6%, the posterior region (sector 4) decreases 16% and the septal region remains relatively unchanged. For a −18° rotational (clockwise) shift, the antero-apical region decreases 15%, the anterior region (sectors 1 and 2) decrease 8%, whereas the free wall sectors (4, 5 and 6) increase 11%. The remaining regions (sectors 3 and 7) decrease by less than a percent. For completeness, Figures 2C–D show the effects of combined left or right and up or down motion.

When positioning a patient, the subject is asked to hold

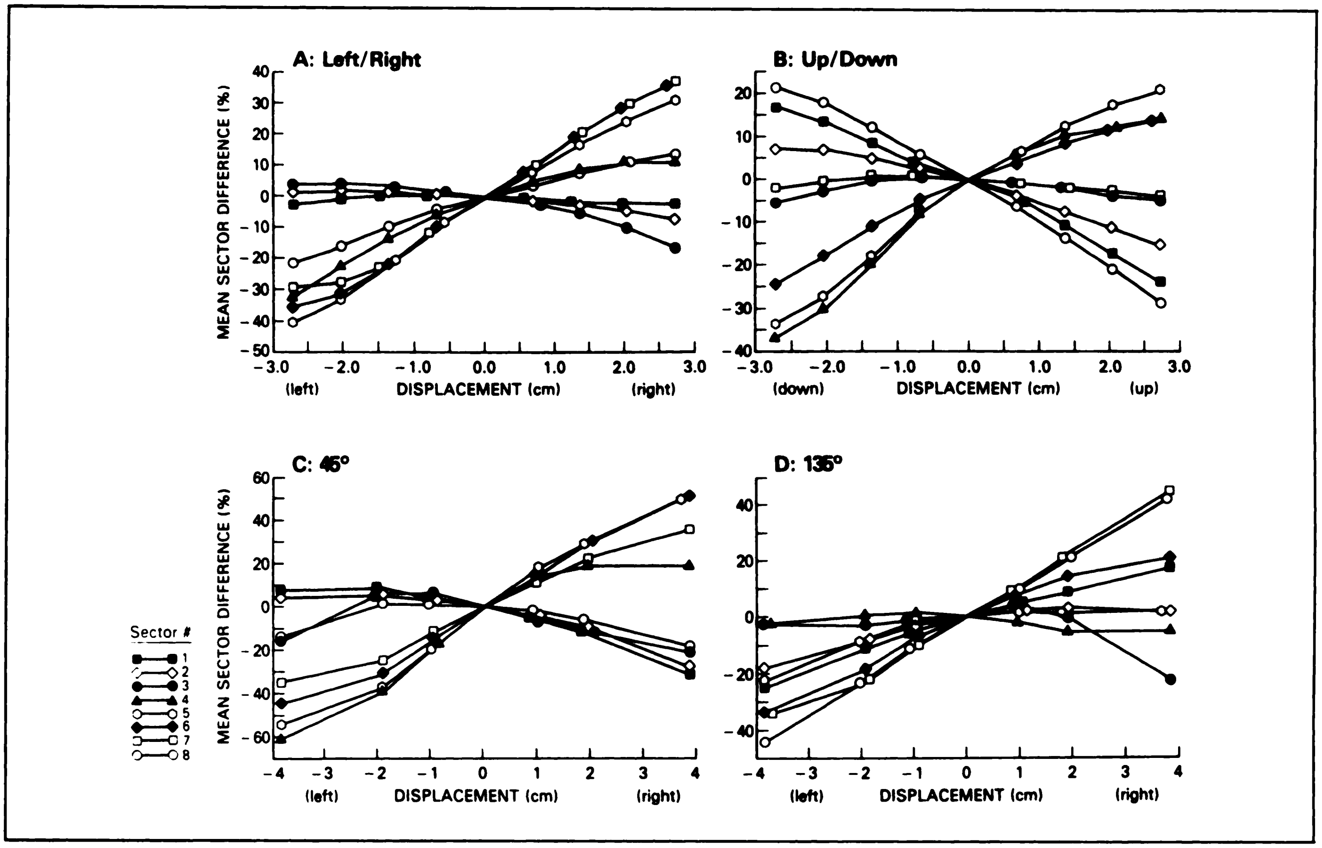

FIGURE 2. Changes due to misalignment are shown for each of eight sectors averaged over all subjects. Each panel shows one of four possible misalignments along (A) right/left lateral, (B) anterior/posterior and (C) shifts along a 45° line and (D) along a 135° line relative to the right/left lateral axis. The directions shown on each abscissa indicate the direction to which the emission data have been shifted relative to the transmission data.

his arms perpendicular to his body or over head, in order to remove the arms from the field of view. In this position, the subject's inner arms may press on the gantry, tending to draw the subject further into the gantry, causing a possible axial misalignment between the transmission and emission. As seen in Figure 4B, caudal shifts of the subject relative to his attenuation scan result in an overall increase of activity in all regions, except for the posterior region (sector 4), which for a 2-cm caudal shift decreases only a few percent. The region beginning at the free wall (sectors 6, 7 and 8) and including the antero-apical region (sectors 1 and 2) shows about a 10% increase in activity. The remaining regions (sectors 3 and 5) increase 7% and 5%, respectively. A 2-cm cephalad shift causes the posterior region (sectors 3 and 4) to increase 5% and the antero-apical region (sectors 7 and 8) to decrease 18%. The same 2-cm cephalad shift results in a decrease in the free wall (sectors 5 and 6) of 7% and 13% and a decrease in the anterior region (sectors 1 and 2) of 6% and 1%.

DISCUSSION

Some patient movement almost inevitably occurs between the time of attenuation scan and the time of cardiac emission imaging. This motion may result in misalignment between the attenuation scan and the emission scan. We have presented data which show quantitatively and qualitatively what the effects of such misalignment can be. From this data, the reader should be able to determine how much of a misalignment can be tolerated, and what effect such motion may have on myocardial transaxial images. Figures 2, 3 and 4A show that even small inplane misalignments can cause rather serious errors in absolute quantitation. For a given misalignment, some sectors increase in apparent activity and others decrease. This causes an otherwise homogeneous distribution to become markedly inhomogeneous. This is apparent in Figure 3, which shows exactly such regional effects for a 2-cm lateral misalignment.

All of the general features of Figures 2 through 4 can be understood on the basis of the location of the various cardiac sectors in relation to the body surface and, most importantly, in relation to the lungs. For example, consider the case in which the patient shifts slightly to his own left between the transmission scan and the emission scan. The free wall of his ventricle in the emission scan is now in the region of the lungs in the transmission scan. While this does not affect left/right projection rays, it does affect the

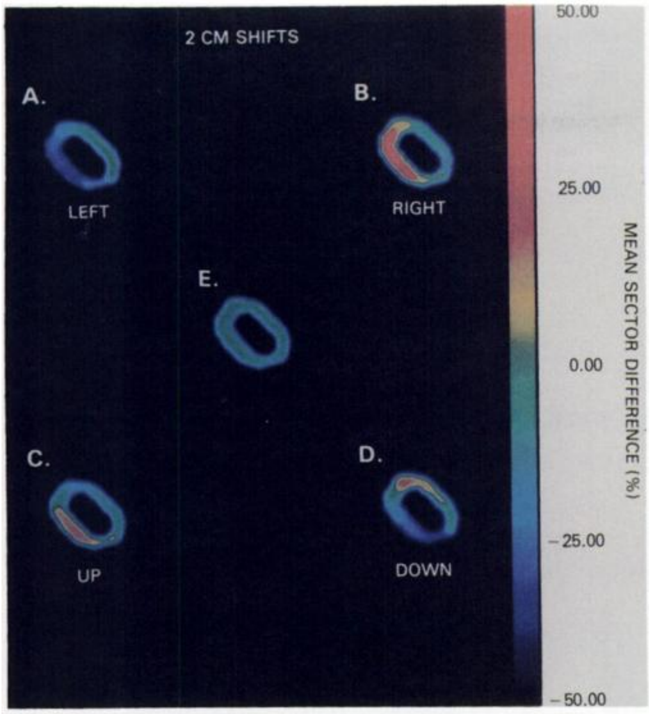

FIGURE 3. Effects of a 2-cm misalignment on an otherwise uniform myocardial distribution of activity. Regional changes of apparent activity in the myocardium are shown for 2.0 cm shifts of the emission data (A) left, (B) right, (C) up and (D) down relative to the transmission data. (E) Center image shows initial uniform myocardial distribution. Colors indicate percentage of apparent increase or decrease from initial activity. These data are extracted from the results of Figure 2.

correction applied to projection rays in the more vertical direction. The photons emitted from the free wall of the ventricle which travel in the up/down (i.e., anterior/posterior) directions are mistakenly thought to have travelled through a large distance of lung tissue. This causes the attenuation correction to be too low in these projections, resulting in an erroneous drop in reconstructed activity in the free wall for motions to the subjects left. The septal wall, on the other hand, still lies within the original cardiac outline, and so does not appreciably change. This is exactly the effect observed in Figure 2. The effect from all the other motions can be explained in a similar fashion.

Axial displacements (i.e., displacements along the z-axis) appear from Figure 4B to cause slightly less distortion per centimeter of motion than do the equivalent x and y motions. This is probably in part due the z-axis resolution (12.5 mm) is twice as large as the x and y resolution. A second reason may be the fact that motion in the z direction does not produce as large a movement of myocardial tissue into the lung field as do x and y movements.

It should be noted that it is possible that the subjects studied here may also have unintentionally moved slightly between the attenuation and emission scan. Such motion would mean that the "aligned" data presented here was already to some extent misaligned. This, however, would not appreciably change any of the general features of the data presented, and would roughly correspond to a shift in what constitutes the "zero" position in Figures 2 and 4. Similarly, the results depend very little on the absolute accuracy of the attenuation scans, because only the differences between aligned and unaligned data are of interest.

It should also be pointed out that the data presented here are an average of 14 subjects. There may well be significant subject to subject variations depending on the details of body habitus, etc. The data here should be taken only as a general indication of what the average magnitude of effects of misalignments may be. Finally, the effects of motion during the transmission scan or during the emission scan have not been addressed here. They will be a combination of the effects presented plus additional blurring and motion artifacts.

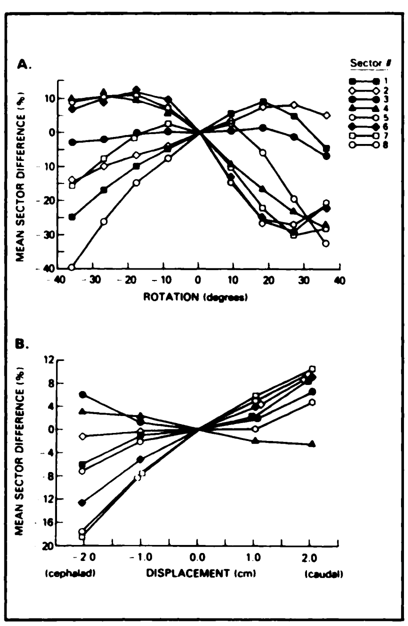

FIGURE 4. Absolute % changes of the myocardial sectors due to simulated (A) rotational and (B) z-axis misalignments between emission and transmission data. The sector values are averages of the 14 patients used in this study. Displacements and directions refer to the amount the emission data have been shifted relative to the transmission. Positive angles represent a counter-clockwise rotation of the emission data.

CONCLUSION

It is seen that patient motion occurring between the attenuation scan and the emission scan can produce large errors in myocardial imaging. Even left/right translations as small as 1 cm can cause appreciable absolute and relative errors in myocardial regional activity. Rotational or z-axis shifts can also cause large errors. If, however, the motions are kept small—perhaps less than 1 cm for left/right shifts, less than 5° for rotational shifts and 1 cm or less for z-axis shifts—then the absolute and relative regional errors may be kept under 10%. Imposing such limits may well require that more attention be paid to the often ignored issues involved in adequate subject restraint. The data show, however, that unless adequate attention is paid, serious misinterpretations of data could ensue.

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EDITORIAL

Misalignment Between PET Transmission and Emission Scans: Effect on Myocardial Imaging

The paper by McCord et al. is an interesting and useful investigation which draws attention to a too often overlooked source of artifacts in PET examinations of the myocardium. It is probably obvious that a misalignment between transmission measurements of the thorax utilized in correcting emission images of the myocardium would yield artifacts in the corrected images. The merit of this article is that it describes these artifacts with reference to the type of misalignment (left to right, cephalad to caudal, various degrees of rotation, etc.) quantitates the effects thus observed, and particularly shows that these effects are different in different sectors of the myocardium. It is now important to take the next step and consider, and eventually apply, means for overcoming this difficulty.

Since the problem is created by a misalignment between transmission and emission measurements, one could remove the problem by doing away with the attenuation measurement altogether. This, as we all know, would severely distort the images obtained due to the variability of the attenuation experienced by the annihilation photons as they encounter different absorbers and would impair the usefulness of any study relying on static images. On the other hand, this approach would, in many instances, not affect measurements based on the variation as a function of time of the activity in different segments of the myocardial, such as wash in or wash out studies, this with the additional advantage of doing away with the noise contribution of the attenuation measurement. Parenthetically, misalignment between transmission and emission measurements would not affect a wash out study.

Another intriguing approach to the solution of this problem is the simultaneous acquisition of emission and transmission measurements, as proposed and demonstrated by Thompson et al. (*1*) in PET imaging of the brain. One of the weaknesses of this otherwise ingenious approach is that PET detectors, under simultaneous measurements, are subjected to the need of acquiring data for two measurements with a concomitant contribution of various sources of noise randoms, and of dead time from both measurements. So far, with present equipment, this approach does not seem to be practical for myocardial imaging, but deserves further investigation.

Another possible solution would be to verify the proper alignment of the transmission and emission measurements through the use of some frame of reference common to both measurements. In cases of misalignment, the transmission sinograms could be suitably displaced by a method similar to the one described in the paper under discussion. At this time, a convenient common frame of reference does not come to mind, but could probably be developed.

Perhaps the easiest way, at least at this time, to overcome the problem is to minimize, as much as possible, any displacement of the patient between the transmission and emission measurements. This can be achieved by the combination of several approaches. In the first place, the patient will be less inclined to move if he or she is in a comfortable position during the examinations. This can be easily achieved in many of the existing PET imaging systems which put, perhaps, less strain on the patient than mentioned in the McCord et al. article (. . . tending to draw the patient into the gantry . . .). Another easy approach towards minimizing patient motion is use of a plastic foam restraining device molded to the patient's anatomy (this approach has been used at Washington University). A crucial factor in minimizing patient motion is to reduce the length of the examination. While this is obviously either difficult or perhaps impossible for emission measurements, there is no reason why the transmission measurement cannot be carried out with a sufficient amount of activity in the attenuation source to collect statistically adequate data in a short period of time. The rotation of the patient can be considerably minimized by supporting the patient's arms in comfortable arm-

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