Detection and Correction of Patient Motion in SPECT Imaging

Qin-sheng Chen, Philippe R. Franken, Michel Defrise, Marc H. Jonckheer, and Frank Deconinck

Experimental Medical Imaging Laboratory, Department of Nuclear Medicine, Vrije Universiteit Brussels, Brussels, Belgium

We have developed an approach to detect and correct patient motion that occurs during SPECT imaging. The detection of patient motion is based on frame-to-frame matching, using phase-only matched filtering (POMF). The correction procedure has been designed to correct any translational patient motion and alert the operator to other kinds of patient movement. The precision in correcting translational motion is less than 1 pixel in the axial direction and less than 2 pixels in the lateral direction. Experiments on phantom and patient data have demonstrated that our approach is a reliable, accurate, and sensitive method for detecting and correcting patient motion in SPECT imaging.

J Nucl Med Technol 1993; 21:198–205

In single-photon emission computed tomography (SPECT), the data acquisition requires 20–40 min. During this period, the patient must lie still to guarantee the image quality. Nevertheless, patient movement has frequently been reported in clinical applications (*1–6*). Patient movement during the data acquisition results in misalignment of the projection frames, which degrades the reconstruction image and may even introduce false defects. Since patient motion is unmodeled, it is difficult to restore the degraded image after reconstruction. Therefore, the ability to detect and correct for patient motion in the acquired data is useful in the quality control of SPECT imaging.

Patient movements may be roughly divided into two classes, namely, abrupt movement and gradual movement (*3*). Abrupt movement is due to a sudden position change of the organ to be imaged, e.g., a voluntary or an involuntary patient movement, while gradual movement probably results from a smooth and continuous movement of the organ, e.g., upward creep of the heart in exercise cardiac imaging.

For reprints contact: Q. S. Chen, Experimental Medical Imaging Laboratory, NUGE, AZ-VUB, Laarbeeklaan 101, B-1090, Brussels, Belgium.

In order to achieve high quality SPECT images, four kinds of techniques have been employed to detect patient motion:

- Cine mode (movie) display
- Sinogram display
- The measure of frame-to-frame cross-correlations
- Tracking of the object (heart) center in frames

The cine mode and sinogram displays are quality control displays of patient motion and are widely used. One problem with using these two techniques is that the quantitative measure of motion cannot be easily and objectively achieved. Although the measure of frame-to-frame cross-correlation developed by Eisner, Noever, et al. (*1,2*) provides an automatic, quantitative, and objective means to evaluate the presence and amount of patient movement, this technique is not totally reliable. Since the matching surface of a cross-correlation, around the maximum in parameter space, is rather broad, and noise may bias the correlation peak (*7*), some detected maxima of the cross-correlations between SPECT frames may be ill-defined. This can result in incorrect estimations of patient motion. Another drawback is that the cross-correlation approach cannot detect gradual movements (*3*).

In order to correct both the abrupt and gradual motion in exercise thallium-201 (^{201}Tl) cardiac SPECT imaging, Geckle, Frank, et al. developed a procedure to track and realign the "centre of heart," a kind of gravity center of the perfusion, in the projection frames (*3*). The efficacy of Geckle's approach depends on the accuracy in locating the center of heart. Since the shape of a patient's heart is not symmetric, the nuclide perfusion in the heart may not be homogeneous, and attenuation of the thorax is nonuniform, the centers of the heart in the projection frames may not coincide with an inherently invariant point, i.e., the gravity center of the perfusion in the three-dimension imaging space. Tracking and realigning the unreliable center of the heart in the projection frames will not always yield correct realignments and will sometimes introduce further misalignments. According to Geckle's report (*3*), 8% of the cardiac SPECT images that underwent this motion-correction procedure were judged to be worse than the images without such a motion correction. Furthermore, since this procedure, even in the absence of patient or organ movement, shifts the data to account for center of rotation errors, unnecessary and incorrect realignments of projection frames will be made.

In this paper, we present a new approach to detect and correct for patient motion during SPECT data acquisition. The technique used in motion detection is a phase-only matched filtering (POMF) (*8*) of the SPECT projection frames. This approach can handle both abrupt and gradual movement. After motion detection, a procedure in the approach determines whether the detected patient motion can be corrected in the acquired data. Currently, the approach can correct any translational motion, and alert the operator to other kinds of patient motion. The performance of the approach has been evaluated using phantoms and patients.

MATERIALS AND METHODS

The approach consists of two procedures, motion detection and motion correction. The detection procedure is designed to first detect any abrupt patient movements and then any gradual movement. The abrupt movements are monitored frame by frame, by matching consecutive projection frames using POMF. If there is no patient movement between two consecutive frames, their POMF matching will yield a peak whose location is coincident to the regular motion pattern owing to the rotation of the camera head. If the peak location is otherwise than described above, an abrupt patient movement is assumed. The gradual movement is detected by matching a frame to a flipped frame taken when the camera head rotates 180°, again using POMF. If a matching output peak shifts away from the coordinate origin and no abrupt movement has been detected earlier in the process, a gradual organ movement is assumed. This matching between the 180° rotated frames can also be used to confirm the detected abrupt movement. In order to examine whether all the patient movements have been correctly determined, a cumulative movement is computed as the movement between the first frame and the last frame, provided the data are acquired throughout the 360° rotation of the camera head.

Patient movement is unmodeled and may be translational, rotational, or both. A rotational movement can change the projection geometry of the frames for reconstruction, so that the motion correction may not restore the degraded image. Therefore, the motion correction procedure has been designed to correct translational patient movements and alert the operator to other uncorrectable movements.

SPECT Imaging

For each brain study, the tomographic data were obtained from 64 views, 40 sec/view, 360° rotation of the camera head, and for each heart study, from 32 views, 40 sec/view, 180° rotation of the camera head, starting from 45° right anterior oblique. In each view, the photon counts were accumulated in a 64×64 matrix with each pixel having a dimension of 6.25 mm along each coordinate. We will refer to such a matrix as a projection frame. Thus, in a SPECT study, we acquired 64 projection frames for 360° rotation or 32 projection frames for 180° rotation.

The images were reconstructed by backprojection of the acquired data using a ramp filter. After the reconstruction, the three-dimensional SPECT image was recorded in a $64 \times 64 \times 64$ matrix. Each voxel in the matrix had a physical volume of $6.25 \times 6.25 \times 6.25$ mm^3.

The Motion Pattern of a Point Source in the Projection Frames

Let (ξ, ψ, ζ) denote the imaging system coordinates and (x, y) the projection frame coordinates. The projection geometry is shown in Figure 1. A point source $P(\xi_0, \psi_0, \zeta_0)$ in the imaging space will be projected to $P'(x_i, y_i)$ in the ith projection frame, as a function of the discrete rotation angle θ_i of the camera head, where $i = 1, 2, \ldots, 32$ or 64, $A = \sqrt{\xi_0^2 + \psi_0^2}$, and $\varphi = \tan^{-1}(\psi_0/\xi_0)$.

$$\begin{cases} x_i = x(\theta_i) = A\sin(\theta_i - \varphi) \\ y_i = y(\theta_i) = \zeta_0 \end{cases} \qquad \text{Eq. 1}$$

With the increase of the rotation angle θ each time an increment $\Delta\theta = \pi/32$, the motion pattern of this point in the successive frames is a sine function on the x coordinate and a constant value on the y coordinate.

The relative displacement of the point in two consecutive frames corresponds to the discrete differential of $\Delta\theta$.

$$\begin{cases} \Delta x_i \approx A\cos(\theta_i - \varphi)\Delta\theta \\ \Delta y_i = 0 \end{cases} \qquad \text{Eq. 2}$$

Since $\Delta\theta = \pi/32 \approx 0.1$, the maximum displacement of this point in the consecutive frames will be 3 pixels along the x axis if the point source is put 32 pixels away from the rotation axis of the camera head, which is the extreme situation. In practice, the organ to be imaged would not be in the

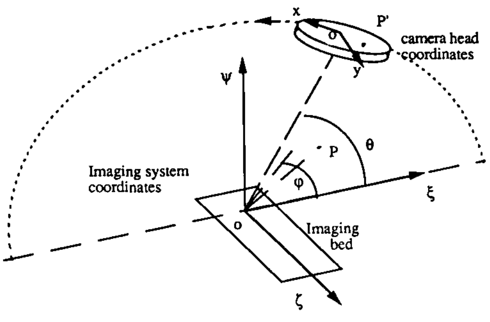

FIG. 1. Projection geometry from imaging system coordinates to projection frame coordinates. Projection of imaging system origin is at origin of projection frames.

position far from the rotation axis. Thus, the maximum displacement along the x axis may not be over 2 pixels, while the displacement along the y axis is 0.

When the camera head rotates 180° from its original angle θ_i, this point moves to:

$$\begin{cases} x_j = x(\theta_i + 180°) = -A\sin(\theta_i - \varphi) = -x_i \\ y_j = y(\theta_i + 180°) = \zeta_0 = y_i \end{cases} \quad \text{Eq. 3}$$

Without consideration of the attenuation factor, this projection frame is simply the replica of the ith frame, but flipped on the x coordinate.

Phase-Only Matched Filtering

Given a reference image r(x, y) and an image s(x, y) to be matched, their Fourier transforms, R(u, v) and S(u, v), can be computed. In POMF, the transfer function H(u, v) is a function of R(u, v), where, the amplitude of H(u, v) is a constant, while its phase is the phase of the complex-conjugate spectrum, $R^*(u, v)$ (*8*).

$$H(u, v) = R^*(u, v)/|R(u, v)|$$

$$= \exp[-j\phi_r(u, v)], \quad \text{Eq. 4}$$

where, $j = \sqrt{-1}$ and $\phi_r(u, v)$ is the phase of R(u, v).

The POMF on r(x, y) and s(x, y) is then the function,

$$f(x, y) = \text{POMF}(r(x, y), s(x, y))$$

$$= f^{-1}\{\exp[-j\phi_r(u, v)]S(u, v)\}, \quad \text{Eq. 5}$$

where, f^{-1} is the inverse Fourier transform.

Since the spectral phase preserves signal locations, which are closely correlated to the image structure, the POMF output peak is very accurate to the object displacement in the images. In addition, the output peak is much sharper than that of cross-correlation, for the phase information ignores the intensity correlation of the images, which tends to broaden the correlation peak. Applying POMF on SPECT projection frames can be expected to produce a robust and accurate detection of patient movement.

The Detection of Abrupt Movement

Let $\{P_i(x, y); i = 1, 2, \ldots, N\}$ denote N series frames of SPECT data. The POMF matching between the consecutive frames can be calculated using Equation 5:

$$f_i(x, y) = \text{POMF}(P_i(x, y), P_{i+1}(x, y));$$

$$i = 1, 2, \ldots, N-1 \quad \text{Eq. 6}$$

In each matching field, a maximum peak can be determined. Abrupt movement is revealed by the displacements of the peaks in the series' matching fields. An abrupt movement is assumed if one peak displaces ≥2 pixels along the x axis or ≥1 pixel along the y axis.

In order to examine whether all patient movements have been correctly detected and determined, a cumulative movement can be computed as the motion between the first and last frame, provided the data are acquired throughout the 360° rotation of the camera head. This matching frame in our implementation is indexed as the last frame in the series' matching frames.

$$f_N(x, y) = \text{POMF}(P_N(x, y), P_1(x, y)) \quad \text{Eq. 7}$$

The Detection of Gradual Movement

The detection of gradual movement is accomplished by matching each frame and its corresponding frame taken after 180° rotation of the camera head and flipped on the x coordinate, using POMF, where, i + 32th frame is the one after the camera head rotates 180° from the ith frame.

$$f_i(x, y) = \text{POMF}(P_i(x, y), P_{i+32}(-x, y)) \quad \text{Eq. 8}$$

In cardiac SPECT imaging, where the camera head rotates only 180° in the whole data acquisition process, the gradual movement detection is between the first and the last frame. According to the result in Equation 3, if there is no patient movement, the correlation peak in Equation 8 should stand at the origin of the matching field. Any displacement of the peak from the origin indicates a possible gradual movement, if no abrupt movement has previously been detected.

The Correction for Patient Motion

In a SPECT imaging system, the projection geometry and the reconstruction geometry have been compatibly designed. A rotational patient movement in the data acquisition may change the projection geometry. No algorithm is available to correct this change of the projection geometry and make it compatible with the reconstruction geometry. However, a translational patient movement does not violate the projection geometry. Our procedure is, therefore, designed to correct the translational movements and alert the operator to other patient motion.

The type of motion, translational or rotational, is determined by examining the magnitude of the POMF matching peaks, in Equation 6. Since a translational patient movement only moves the object and does not change the similarity between the projection frames, the peak magnitude of their POMF matching does not change much from frame to frame, while a rotational movement may ruin the similarity between the consecutive frames and diminish the matching peak. Thus, a rotational patient movement is assumed if a matching peak among the series peaks drops considerably (half of its neighboring peaks in our implementation) or disappears. On the contrary, a translational movement is assumed if a peak shifts beyond the motion pattern, but the peak magnitude is still high relative to the neighboring peaks.

When a translational movement is detected, the peak offset between the frames can be determined. Suppose a peak offset (Δx_n, Δy_n) has been detected at the nth frame. According to Equation 1, the real patient movement, under the constraint of no patient movement in the ψ direction, in the imaging coordinates (ξ, ψ, ζ), is:

$$\begin{cases} \Delta\xi = \Delta x_n / \sin\theta_n \\ \Delta\psi = 0 \\ \Delta\zeta = \Delta y_n \end{cases} \qquad \text{Eq. 9}$$

where, $\Delta\psi = 0$ indicates that the patient movement is on the bed. Then, the object in each following frame needs to be moved by the following amount:

$$\begin{cases} \Delta x_i = -\Delta\xi \sin\theta_i \\ \\ \Delta y_i = -\Delta\zeta \end{cases} \quad ; i = n+1, n+2, \ldots, N. \qquad \text{Eq. 10}$$

Multiple patient movements can also be corrected by repeating this process starting from each abrupt frame.

RESULTS

We first evaluated our motion detection and correction approach on phantom studies. Figure 2 shows the projection frames of a horn-cylinder phantom with technetium-99m-(^{99m}Tc) sestamibi. Our phantom consisted of a beaker filled with a ^{99m}Tc solution into which we inserted a water-filled Erlenmeyer flask. A typical surface of POMF matching between two consecutive frames is shown in Figure 3, where the peak position corresponds to the object displacement in the two frames. Considering the peak magnitude (PM) as the signal and the standard deviation (s.d.) of the background as the noise, the signal-to-noise ratio (SNR), defined as PM/s.d., is normally over 20. Without any patient movement during the data acquisition, the distributions of the matching peaks in the lateral and axial views, shown in Figure 4, are consistent with the deduced result in Equation 2, where the matching peak does not move in the axial direction and shifts a little (<1 pixel) in the lateral direction.

Since during the SPECT data acquisition, a patient may move at any time and in any direction on the bed, we designed several motion models to examine the motion detection procedure. The phantom movements in our investigations were obtained by moving the phantom during the SPECT data acquisitions, not by computer simulation. Figure 5 shows the transframe view (equivalent to the sinogram view) of POMF matching on SPECT data, which were moved 19 mm on the x axis and 19 mm on the y axis, at the

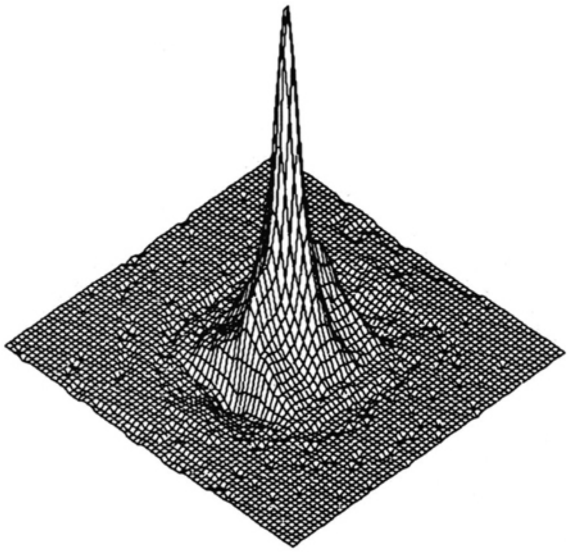

FIG. 3. Matching surface of POMF between 7th and 9th frames of the phantom data shown in Figure 2. Output signal-to-noise ratio is over 30. Full area at half maximum is 7 pixels.

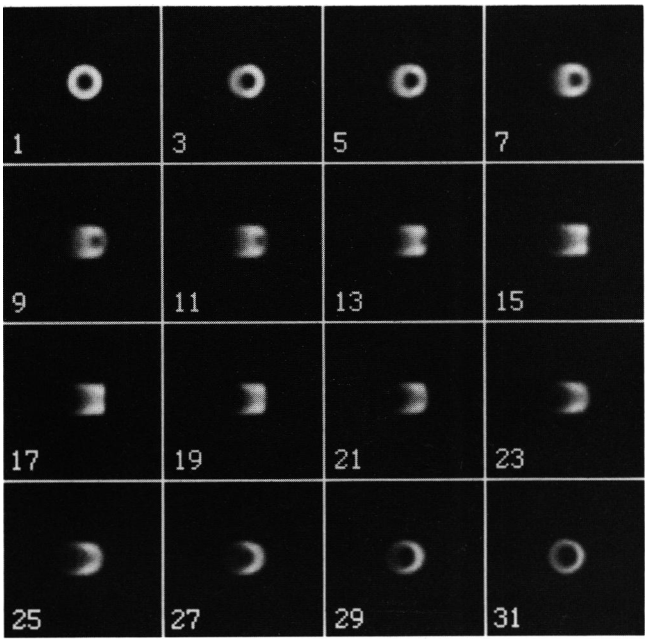

FIG. 2. Projection frames of horn-cylinder phantom with ^{99m}Tc-sestamibi.

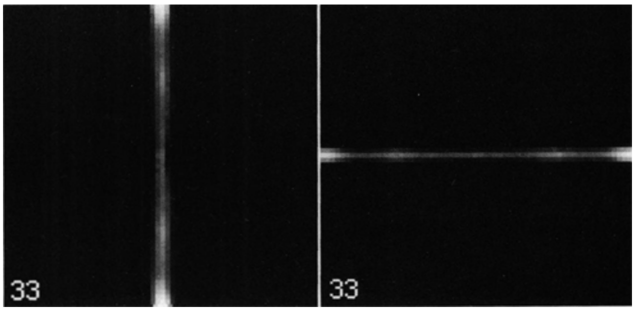

FIG. 4. Distributions of POMF matching peaks from projection frames shown in Figure 2. Left figure is lateral view of successive matching frames, in which maximum displacement of peaks from central line is less than 1 pixel. Right figure is axial view of matching frame.

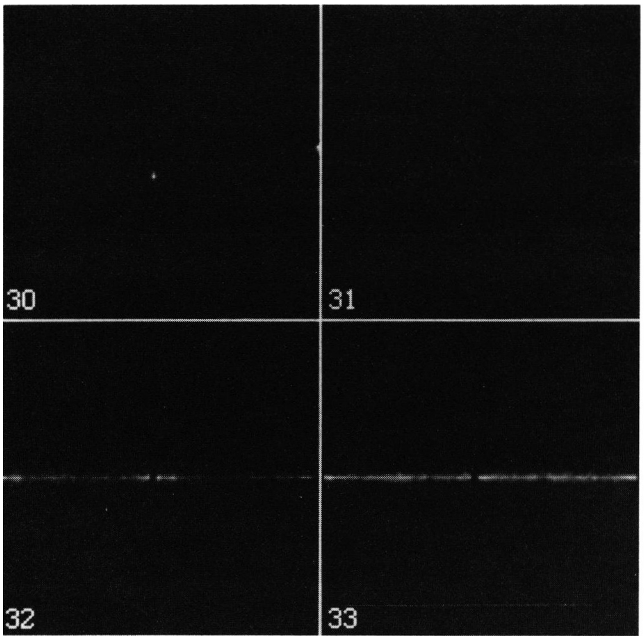

FIG. 5. Axial views of POMF matching on phantom frames which were moved 19 mm in both axial and lateral directions, between 32nd and 33rd frames. Bright spot close to center in View 30 corresponds to this movement, and other bright spot on right border of same view confirms detected movement.

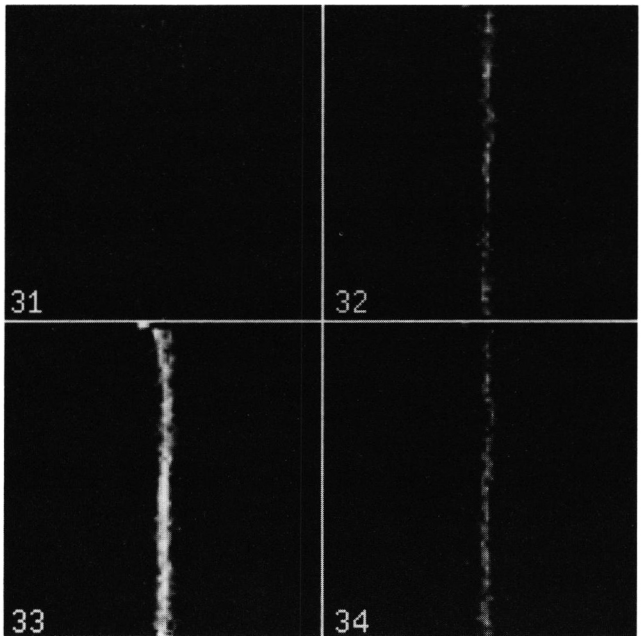

FIG. 7. Lateral views of POMF matching on phantom moved laterally 3 cm, with camera head rotated 90°. No phantom movement has been detected between 16th and 17th frames, but bright spot at top in View 33 gives a clue that phantom movement did occur during data acquisition.

33rd frame, corresponding to a camera head rotation of 180°. The bright spot located at (36, 33) in View 30, which deviates from the central line (y = 33, in Frame 33), reflects this movement: 3 pixels on the x axis and 3 pixels on the y axis. The bright spot on the right border in Frame 30, which is the match-up between the last and the first frames, confirms this detected movement.

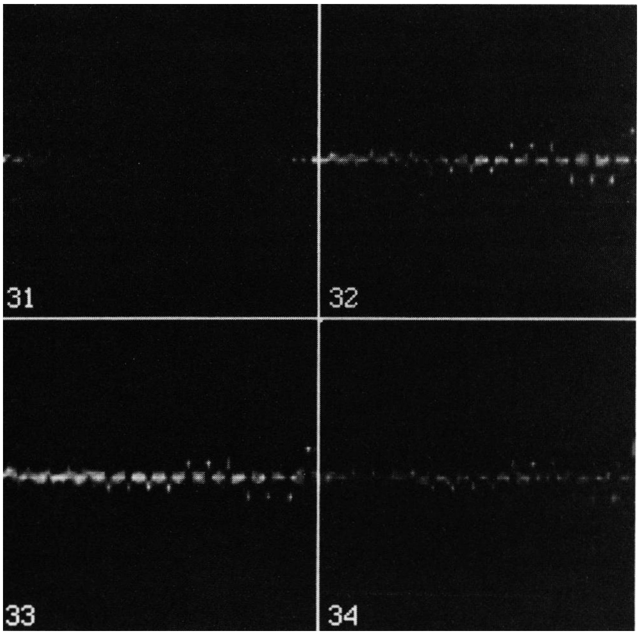

FIG. 6. Axial views of sequential movements of phantom in axial direction. All bright spots apart from central line in View 33 correspond to phantom movements.

Figure 6 demonstrates the detection of sequential movements along the axial (y) direction. During data acquisition, the phantom was moved sequentially up and down several times in the axial direction, from ±6 mm (~1 pixel) to ±37.5 mm (~6 pixels). We used a parallel-hole collimator with a 30-cm radius of rotation, and no attenuation correction was applied to the reconstruction data. The bright spots, apart from the central line in View 33, correspond to those movements. In our tests, the detectable movement in the axial direction was less than 1 pixel (6.25 mm).

Figure 7 shows the detection of a lateral movement. During data acquisition, the phantom was moved laterally 3 cm when the camera head was rotated 90°. This is the most difficult case for a motion detection program, since the lateral movement at 90° rotation has the least significance in frame-to-frame motion detection. It is indeed the case that no movement has been detected between the 16th and 17th frames, since no peak shift has been located between these two frames. However, this movement has been recorded in the data.

Figure 8 displays the tomographic reconstruction of this phantom data, where the image is degraded and a ghost artifact appears. By matching the first frame and the last frame, a lateral shift of the matching peak can be located. The bright spot at the top in Frame 33, Figure 7, which is the matching peak between the last and the first frames, indicates a possible phantom movement at 90° or 270° rotation of the camera head. By comparing the 1st and the 33rd frame (180° rotation) flipped on the x coordinate, a 5-pixel lateral movement has been detected (Fig. 9). Logically, this 5-pixel

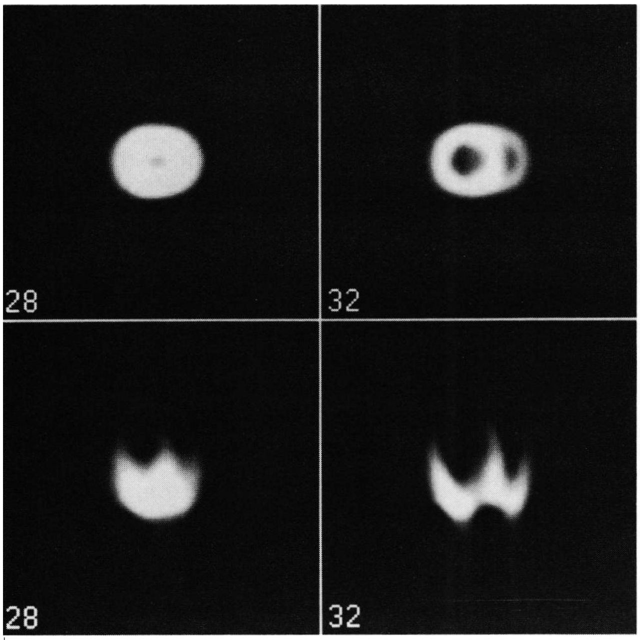

FIG. 8. Tomographic reconstruction of phantom data with 3-cm lateral movement at 90° rotation of camera head. Ghost figure appears in these images.

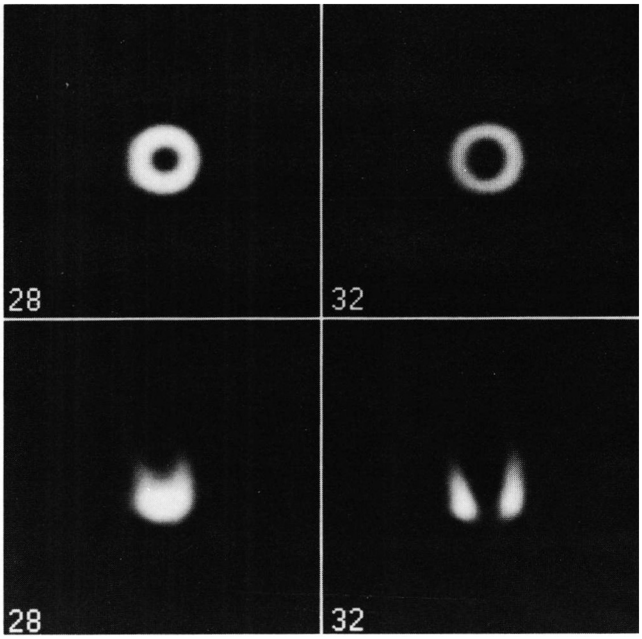

FIG. 10. Tomographic reconstruction using same phantom data as that used in Figure 8, but data have undergone motion detection and correction procedure.

lateral movement happened at 90° (17th frame). The detected movement was corrected by following Equation 10. Figure 10 shows the reconstruction image after motion correction, where the ghost has been eliminated and the image resolution improved.

In our experiments, all phantom movements ≥1 pixel in the axial direction and ≥2 pixels in the lateral direction have been correctly and reliably detected and corrected. Even if the lateral movement of the phantom occurs at 90° rotation of the camera head, the program can still locate and correct it accurately.

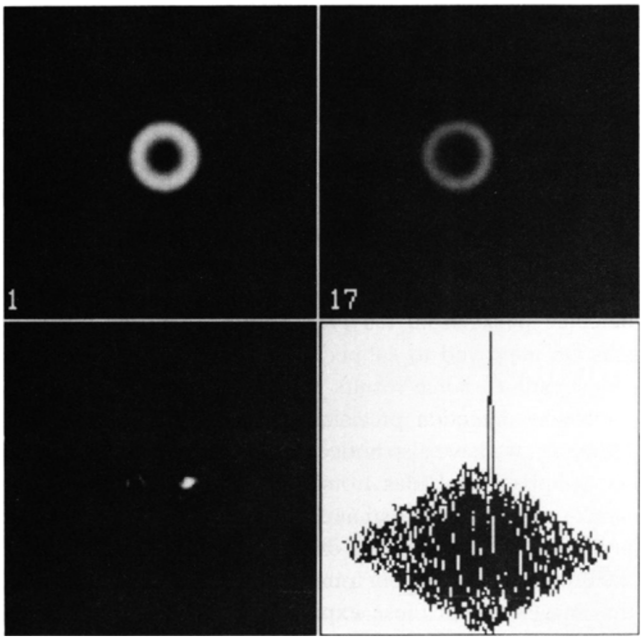

FIG. 9. POMF matching between 1st and 17th frame flipped on the x coordinate. Their matching output is shown in bottom left frame and the surface view in bottom right frame.

The patient investigation was carried out on both brain and heart studies. In order to validate the results of our motion detection process, the SPECT projection frames in each study were also examined in the cine mode by experts. Then, the results from the cine mode and our motion detection process were compared. We examined more than 15 SPECT studies using our motion detection and correction programs. All studies showed a high correlation with the cine mode displays on obvious patient motion.

Figure 11 displays the brain study of a child. The cine mode indicated several slight movements and one obvious movement, which was also detected and quantified by our detection program. The top row shows the reconstruction of the original data, and the bottom row, the reconstruction after our motion correction. The ventricle shape in the corrected image is more distinct than that in the original reconstruction image. Since the detected patient movement happened late in the study and was small (1 pixel in the axial direction), the improvement of the image quality was not large. However, the corrected image was preferred by the physicians.

Figure 12 demonstrates a cardiac study. Patient movement was seen in the cine mode and also detected by the motion detection program (2-pixel upward movement). In the top row, the short-axis view and the transaxial view of the reconstruction image are shown on the left and right, respectively; the image contrast is degraded. After motion correction, the inner heart surface is clearer, and the smudge inside

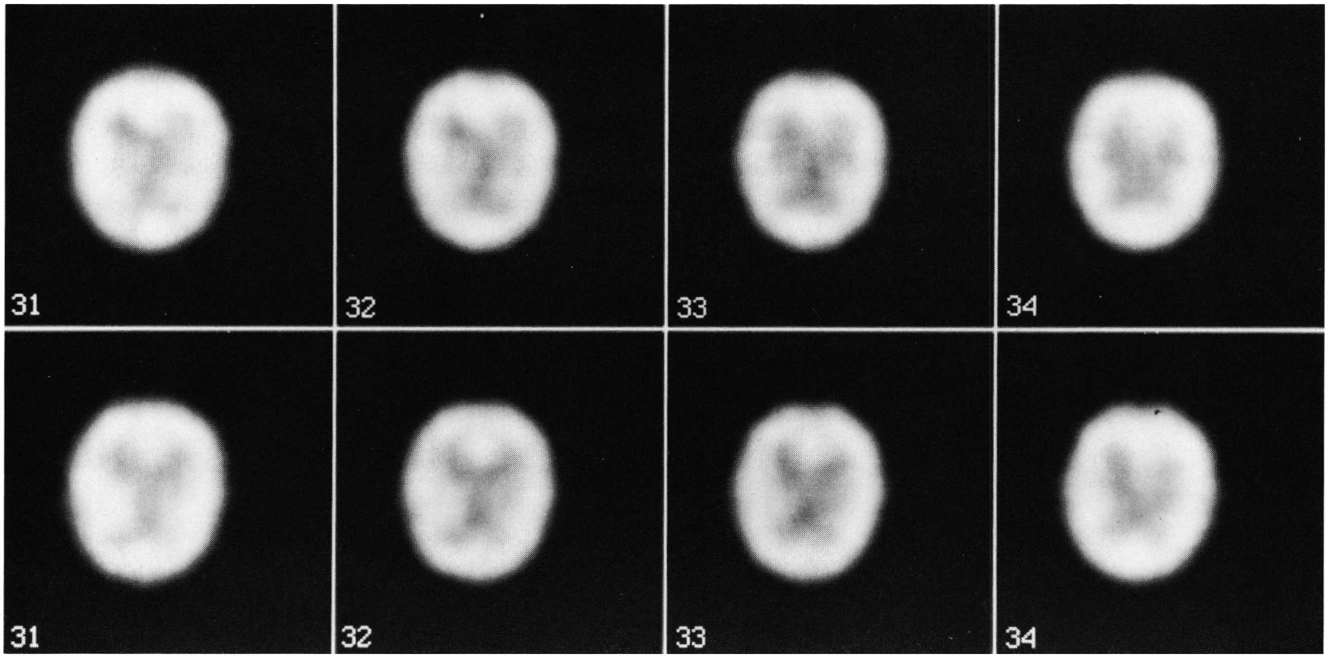

FIG. 11. SPECT images of child's brain. Top row shows reconstruction images of original data; bottom row shows reconstruction images of data that have undergone motion detection and correction procedure. Ventricle shape in corrected image is more distinct than that in original image.

the heart has been depressed (bottom row). In these images, the stomach has been masked, for its intensity is higher than the heart's intensity. The irregular zigzag shapes close to the upper right heart wall in the two short-axis views are due to the manual masks.

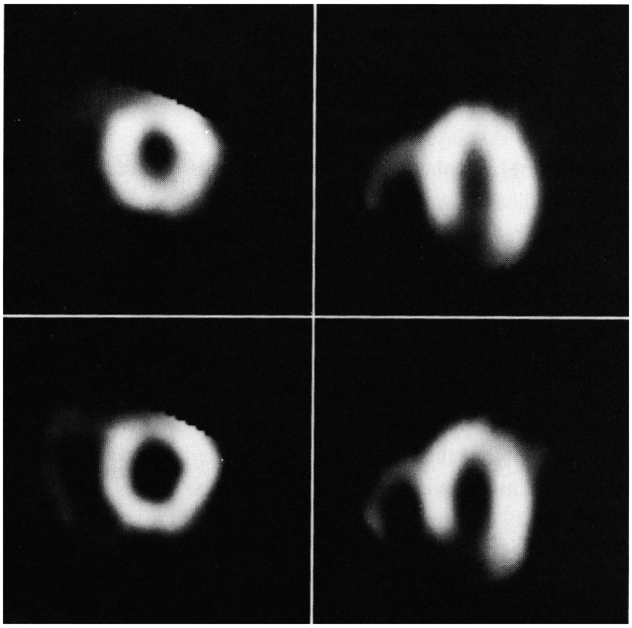

FIG. 12. Correction of patient movement in cardiac SPECT images. Top row shows reconstruction views of original data; bottom row shows reconstruction views after motion correction.

DISCUSSION

The detection of patient motion is based on the similarity between the projection frames. The matching technique used in the work is POMF. Since POMF matches object shapes by location information, rather than through image intensity (which has high spatial correlation), the matching peak between two similar images is much sharper than that produced by a cross-correlation technique (*1*). Our experiments have demonstrated that our program is very reliable and accurate in detecting patient motion during SPECT imaging. The computation of motion detection, in which the major computational part is the Fourier transformation, is very efficient. Typical computation time for fully automatic detection and correction, programmed in C language, is less than 2 min on our computer.

The precision of our motion detection is 1 pixel in the axial direction and 2 pixels in the lateral direction. By fitting the detected peaks from the projection frames, the precision may be improved to subpixel level (*1,3*). In our phantom investigations, some results have indicated a possibility of improving detection precision using the fitting technique. However, we have also noticed that some estimated peaks in the subpixel level bias from their expected positions. To handle the subpixel estimation, we have considered two problems: the slight image distortions due to the change of the projection angle from frame to frame and the low SNR in the images. From these experiments, we believe that the precision of our motion detection can be improved, but it is difficult to give a quantitative prediction before further extensive investigation.

In the cardiac study, the upward creep of the heart may follow some rules (*3,4*). In our simulation, we assumed a linear upward creep. After the motion detection, our correction consisted of moving each frame down with the same value as the increment of the heart's upward creep. Our program worked well on simulated data. Since no real cardiac data with upward creep has been collected, the efficacy of our programs on actual gradual movements has not been proved.

CONCLUSION

An algorithm has been developed to detect and correct patient motion in SPECT imaging. The technique used in the algorithm is based on phase-only matched filtering (POMF). Patient movement is monitored frame by frame, successively, on the acquired data using POMF. When the movement between one pair of consecutive frames differs from the expected regular motion pattern produced by the rotation of the camera head, a single patient movement is assumed. One may expect the patient to move on several occasions during a SPECT data acquisition, and the program detects this. In order to examine whether all movements are correctly detected and determined, a cumulative movement is computed, being the movement between the first and last frame, provided the data are acquired throughout a 360° rotation. The program then determines whether the patient movements can be corrected in the acquired data. Currently, we can identify and correct translational movements and alert the operator to other kinds of patient movements.

Since POMF matches object shapes in an image rather than the gray-scale intensity, the matching between one projection frame and its counterpart frame, taken when the camera head rotates by 180°, can be reliably determined without being affected by different attenuation factors. The matching between the 180° rotation frames not only confirms sudden patient movements, but also provides a possibility of detecting the smooth and continuous movement of an organ.

Experiments have been carried out on a series of images from a phantom, which was moved translationally and rotationally during the data acquisitions. The program works reliably and correctly on these phantom data. The precision in correcting translational movements is within 1 pixel axially and within 2 pixels laterally. Patient SPECT data have also been successfully examined by using this motion detection and correction program. The computation of motion detection, in which the major computational part is the Fourier transformation, is very efficient. A typical computation time for the fully automatic procedure is less than 2 min.

Further investigations will be focused on practical applications of our method. We hope that these programs can be integrated into the data acquisition procedure of clinical SPECT studies in order to guarantee image quality.

ACKNOWLEDGMENTS

The authors are grateful to their colleagues in the Experimental Medical Imaging Laboratory and the Department of Nuclear Medicine for their cooperation and help. Special thanks go to Mr. S. Kuijk, Mr. D. Tombeur, Prof. A. Bossuyt, Dr. C. De Sadeleer, and Ms. K. de Metz.

REFERENCES

1. Eisner RL, Noever T, Nowak D, et al. Use of cross-correlation function to detect patient motion during SPECT imaging. *J Nucl Med* 1987;28:97–101.
2. Eisner RL, Churchwell A, Noever T, et al. Quantitative analysis of tomographic thallium-201 myocardiac bullseye display: critical role of correcting for patient motion. *J Nucl Med* 1988;29:91–97.
3. Geckle WJ, Frank TL, Links JM, et al. Correction for patient and organ movement in SPECT: application to exercise thallium-201 cardiac imaging. *J Nucl Med* 1988;29:441–450.
4. Friedman J, Van Train K, Maddahi J, et al. "Upward creep" of the heart: a frequent source of false-positive reversible defects during thallium-201 stress-redistribution SPECT. *J Nucl Med* 1989;30:1718–1722.
5. DePuey EG, Garcia EV. Optimal specificity of thallium-201 SPECT through recognition of imaging artifacts. *J Nucl Med* 1989;30:441–449.
6. Cooper JA, Neumann PH, McCandless BK. Effect of patient motion on tomographic myocardiac perfusion imaging. *J Nucl Med* 1992;33:1566–1571.
7. Pratt WK. *Digital image processing*. New York: John Wiley & Sons; 1978:526–566.
8. Horner JL, Gianino PD. Phase-only matched filtering. *Applied Optics* 1984;23:812–816.