Use of Cross-Correlation Function to Detect Patient Motion During SPECT Imaging

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We have developed a procedure to detect patient motion during a tomographic acquisition. The method uses frame-to-frame cross-correlation functions of the summed profiles in the vertical and horizontal directions of the planar images. The quantitative output derived from examination of the variation of the change in the pixel value, corresponding to the maximum of the cross-correlation function at each view, provides an effective and nonsubjective means of performing quality control on the presence and amount of movement during a single photon emission computed tomographic scan. In contrast to cine mode and sinogram display, easy to interpret hard copy can be generated through this procedure.

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The extent of patient motion which can be tolerated during a tomographic acquisition and still maintain the integrity of the reconstructed tomogram has not yet been reliably established. It is clear, nevertheless, that an important part of the tomographic quality control procedure must be to ensure that patient motion during the scan is detected. One technique is to examine a cine display of the acquired planar views. This does not, however, allow for an objective quantitative estimate of the amount of motion; nor does it provide for easy generation of hard-copy outputs of any results. Sinogram displays of the acquired view data have also been used for quality control. Here again, no quantitative means of establishing the amount and type of motion is provided. This implies an inherent degree of ambiguity and subjectivity in interpretation of the results.

The motion detection method presented here is based upon an analysis of the cross-correlation functions determined between adjacent frames of the tomographic study. The same kind of formalism (*1,2*) has been used in other nuclear medicine applications to correct for misalignments of data acquired under different imaging conditions. In contrast to these studies, in tomography the view to view correlations in the data are reduced by factors other than true object displacement. These factors include effects due to attenuation, as well as the systematic change in the camera-recorded projection of any nonsymmetrical object. Even though these variables introduce potential sources of error, we have found that the correlation method still provides a sensitive and specific indication of patient motion during a tomographic scan.

THEORY

The discrete cross-correlation function $CC_N(S)$ between two one-dimensional sequences of data P_N and P_{N-1} may be written as:

$$CC_N(S) = \sum_{j=1}^{M} P_N(j) * P_{N-1}(j + S), \qquad (1.0)$$

where "M" is the number of points in the sequence and $-K \leq S \leq K$ and $P_{N-1}(j + S) = 0$ when $(j + S) < 1$ or $(j + S) > M$.

For purposes of this analysis the functions used are the summed profiles along the transaxial (x) and axial (y) directions, obtained from each planar image in the tomographic acquisition. The correlation is between the function in a given

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frame with that from the frame preceding it. "K" in Eq. (1.0) was chosen to be equal to 10. This is consistent with the assumption that any two adjacent frames should be correlated to within 10 pixels (62 mm) in any direction.

Pixel shifts between adjacent frames were determined by performing parabolic fits to the peak of the frame-to-frame correlation functions and the two neighboring points.

Before applying the algorithm to tomographic data with motion, we consider the application of Eq. (1.0) to a point source acquisition without induced motion. A point located at a distance, r, from the center of rotation of the rotating gamma camera system has a projection along the x-direction and y-direction for a view, θ, given by

$$x = xo + r \sin(\theta + \phi) \qquad (2.1)$$

$$y = yo, \qquad (2.2)$$

where xo is the pixel value of the center of rotation and ϕ is a phase factor. The value of yo is a constant which is independent of the view angle. The frame-to-frame pixel variations Δx and Δy are found from differentiation of Eq. (2.0) with respect to θ, so that

$$\Delta x = r \cos(\theta + \phi)\, \Delta\theta \qquad (3.1)$$

$$\Delta y = 0 \qquad (3.2)$$

where $\Delta\theta$ corresponds to the view sampling interval. We note that frame-to-frame correlations from a point-source acquisition can be used to detect systematic camera/gantry problems. Misalignment of the detector head during acquisition, for example, will produce deviations from Eq. (3.2). Deviations from a circular orbit (those which introduce transaxial shifts of the center of rotation in successive images) will create deviations from the sinusoidal distribution expected from Eq. (3.1).

With no motion, and for a multiple-point (e.g., patient) acquisition, Eq. (3.2) remains valid, but the variable phases and distances to the center of rotation of these points in the object make the x-axis frame-to-frame pixel shifts not predictable by analytical methods from the projection data above. In addition, the view dependent effects due to attenuation can produce x and y frame-to-frame pixel shifts which are not related to patient motion. However, as shown below, the frame-to-frame pixel shifts determined from Eq. (1.0), when applied to this situation, can still be used to detect motion.

METHODS

The technique was first applied to point source acquisitions. For this study, a technetium-99m (^{99m}Tc) point source was placed ~15 cm from the center of rotation and imaged with a rotating gamma camera interfaced to a computer system.* The radius of rotation was 20 cm. Data were acquired with 64 views over 360° into a 64 × 64 acquisition matrix.

The procedure was also applied to data obtained from tomographic thallium-201 (^{201}Tl) myocardial perfusion studies. In our institution, such data are obtained after injection of 3.5 mCi of thallous chloride at peak stress and imaging 5–10 min thereafter (stress) and then ~4 hr later (delay). Thirty-two views were acquired over a 180° arc and into a 64 × 64 matrix. Data collection time at each view was 40 sec. Each frame was uniformity corrected using data derived from a 30 million count cobalt-57 flood acquisition. For these studies the linear pixel dimension was ~6.2 mm.

The ability of the cross-correlation algorithm to detect and quantitate motion was tested by application of Eq. (1.0) to the point source data, and to the ^{201}Tl data in which motion had been computer simulated. This was accomplished by arbitrarily translating the planar images, over a specified number of views, by a known distance in the x and/or y directions. The program used to translate images was capable of integral and nonintegral shifts. If the former were used the translation was exact, while the latter applied a linear interpolation technique. Translations could be applied to any subset of frames in a sequence.

The technique was also applied to ^{201}Tl myocardial perfusion data obtained from acquisitions in which obvious motion had been detected in the rotating cine display.

RESULTS

Figures 1A and B show the results of the application of the cross-correlation function algorithm to the acquired point source data. Figures 1A and B show the resultant frame-to-frame pixel shifts in the y-(x-) direction. The small pixel shift values in Figure 1A may be indicative of a slight misalignment of the camera-gantry system used in the study. The sinusoidal distribution in Figure 1B is consistent with that expected from Eq. (3.1). In particular, the amplitude of the curve ($r\Delta\theta$) is observed to be in good agreement with the value of 2.4 predicted by Eq. (3.1).

Figure 1C shows the results from the application of the correlation technique following a 1-pixel movement of the data in the y-direction for one view (view 32) followed by a return in the next view. This motion is clearly indicated in Figure 1C by a negative deviation (motion) in view 32 followed by a positive deviation (return) in view 33. The shift of one pixel is clearly discernible in the figure.

Figure 1D shows the corresponding results following a 1-pixel movement of the data in the x-direction. Again, the correlation procedure gives results consistent with the artificially generated deviation.

Figures 2A and B show the results of the cross-correlation algorithm applied to a ^{201}Tl stress acquisition study of a normal male subject. The cine display of the planar data showed no indication of patient motion during acquisition. There is only a small variation in the view-to-view x-deviations, indicative of correlation changes induced by factors other than motion.

Figures 2C through E show the results of the algorithm applied to the same ^{201}Tl study after various combinations of x and y simulated translations (motions) were imposed on the data. Large deviations at frame values corresponding to those in which motion occurred are evident in the figures.

The algorithm was also applied to data from a ^{201}Tl study of a female subject who, during the course of data acquisition, made several sudden movements. The rotating cine display showed evidence of motion in the axial direction, with a possible indication for transaxial movement. One example of axial motion, which occurred in frame 19, is clearly visible in the 16-frame display shown in Figure 3 and detected in the frame-to-frame correlation curve shown in Figure 4.

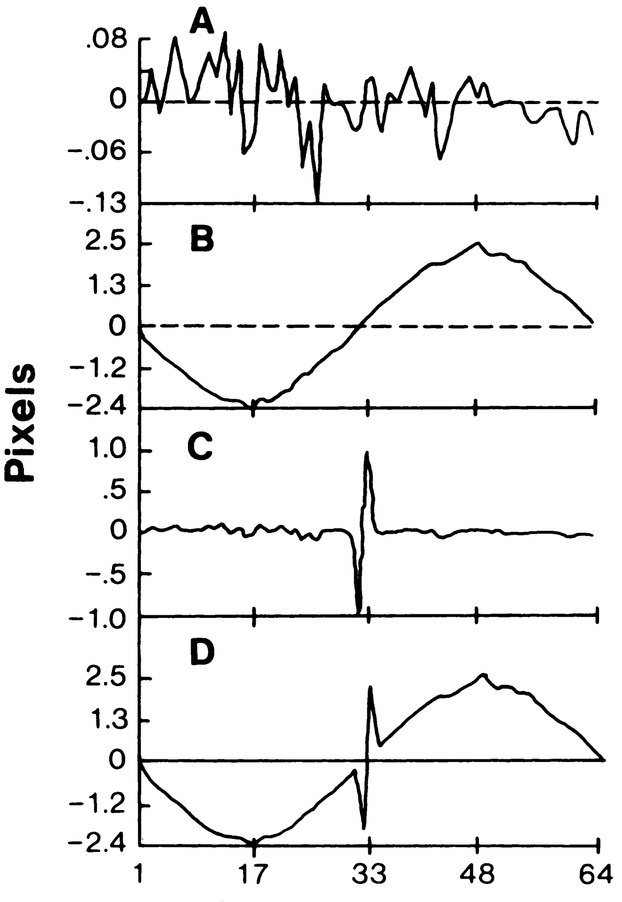

FIGURE 1
Frame-to-frame pixel shifts determined from the point source acquisition. A: In the axial (y-) direction with no induced motion. B: In the transaxial (x-) direction with no induced motion. C: In the axial (y-) direction with an induced shift of 1 pixel, followed by a 1-pixel return. D: In the transaxial (x-) direction with an induced shift of 1 pixel, followed by a 1-pixel return.

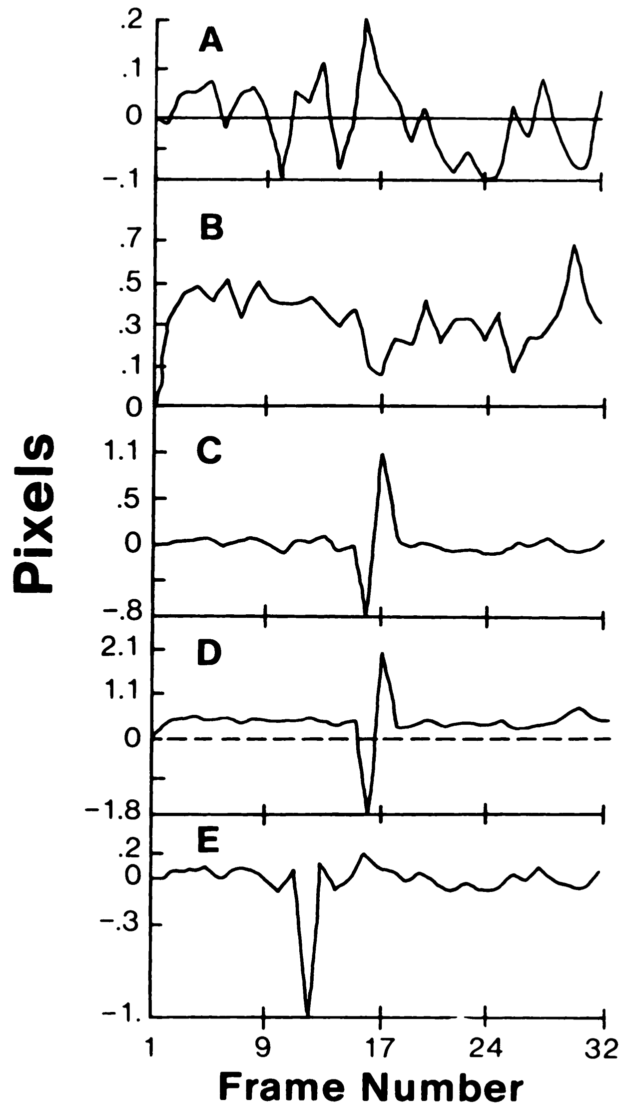

FIGURE 2
Frame-to-frame pixel shifts determined from a ^{201}Tl stress study of a normal male subject. A: In the axial (y-) direction. B: In the transaxial (x-) direction. C: In the axial (y-) direction, but following a 1 pixel translation in the axial direction, and then a 1-pixel return. D: In the transaxial (x-) direction, but following a 1 pixel translation in the transaxial direction, and then a 1-pixel return. E: In the axial (y-) direction, but following a 1-pixel nonreturning translation in the axial direction.

DISCUSSION

It should be pointed out that the curves displayed represent relative, frame-to-frame correlation results. The total pixel shift of any frame with respect to any other is therefore the integral of the curve between the two frames. Its value, however, does not represent the true total displacement, since it contains a component introduced by a systematic frame-to-frame trend, gen-

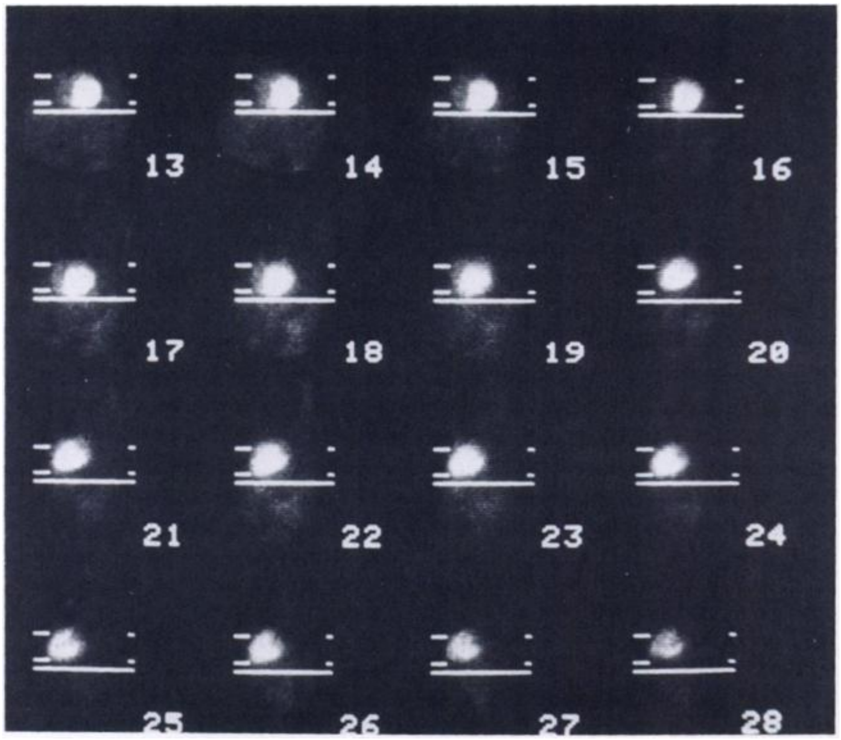

FIGURE 3
Consecutive planar views from a tomographic ^{201}Tl study of a female who made several sudden movements during the scan. Markers on images are placed at constant x-y coordinates to demonstrate movement of the heart.

erated by the varying aspects of the objects and the body habitus being imaged (see above). This trend must be subtracted to obtain the frame-to-frame displacement due to motion.

The efficacy of the procedure is subject to certain boundary conditions.

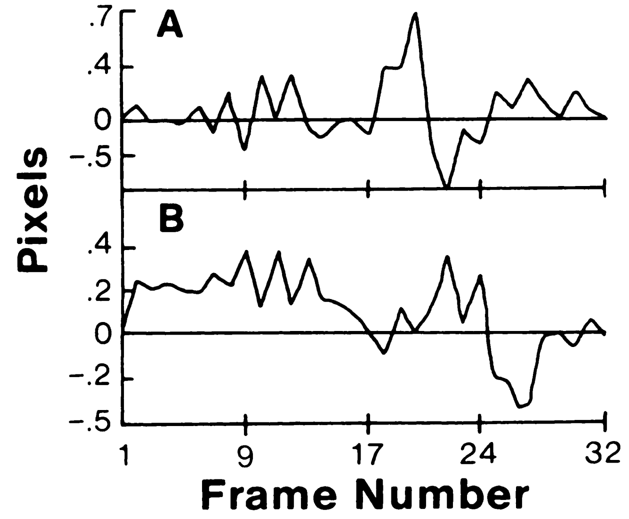

FIGURE 4
Frame-to-frame pixel shifts for data obtained from a ^{201}Tl study of a female patient. During data acquisition the subject made several sudden movements. A: In the axial (y-) direction. B: In the transaxial (x-) direction.

1. It is necessary that successive planar images are truly correlated. Any patient motion which strongly disrupts the correlation (such as a sudden twist of the body through a large angle) will result in an unpredictable determination of the amount of motion. The presence of such motion, however, can still be detected as a significant deviation in the x and/or y cross-correlation profile curve.

2. The motion detection procedure requires that there be an adequate signal to background ratio for those objects that move between frames. In scans (e.g., some delay ^{201}Tl single photon emission computed tomographic studies) with large background we have found that the algorithm underestimates the degree of motion. In these cases, improved motion detection results from subtraction of a constant background level from each frame of the tomographic study.

3. It is our experience that patient motion is composed of sudden displacements of varying magnitude; and it is these which the cross-correlation technique detects. In the unlikely event that a patient performs a smooth, continuous motion during any part of the study, the frame-to-frame correlation profiles will exhibit an offset that may or may not be significant; depending on the amplitude of the motion.

CONCLUSION

We conclude that the frame-to-frame correlation technique, applied to summed x and y profiles, represents a sensitive method for the detection of patient motion during a tomographic scan. This information can be readily stored as curves, displayed and hardcopied for presentation with the actual data being analyzed, thus providing a reliable quality control procedure.

We found that the sensitivity of the procedure for discerning motion in the transaxial (x-) direction is equivalent to using sinograms. Sensitivity in detecting returning and nonreturning motion in the axial (y-) direction is comparable only to that achieved by observing cine mode displays. Patient motion as small as 1 pixel could easily be distinguished.

NOTE

* General Electric Medical Systems (400 ACT/STAR), Milwaukee, WI.

REFERENCES

1. Singh M, Frei W, Shibata T, et al. A digital technique for accurate change detection in nuclear medical images—with application to myocardial perfusion studies using thallium-201. *IEEE Trans On Nucl Sci* 1979; NS-26:565–568.
2. Fleming JS. A technique for motion correction in dynamic scintigraphy. *Eur J Nucl Med* 1984; 9:397–402.