Effect of Misalignment Between Transmission and Emission Scans on SPECT Images

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Attenuation coefficient maps (μ maps) are a useful way to compensate for nonuniform attenuation when performing single-photon emission computed tomography (SPECT). We have previously reported that brain SPECT images could be improved by using a μ map constructed with transmission data and the iterative expectation maximization (EM) algorithm. However, if transmission and emission data are acquired separately, patient movement between the transmission and emission scans may cause misalignment of the μ map and the emission data. The effect of such misalignment on SPECT images reconstructed using the EM algorithm was investigated using both a thorax phantom, incorporating nonuniform attenuation, and clinical brain SPECT data. We found that misalignment between transmission and emission scans produced large errors, with a 2-pixel shift of the μ map causing an error of about 13% in the reconstructed activity level. These findings suggest that precise alignment of the μ map and the emission data is needed, and that simultaneous transmission and emission data acquisition should be strongly recommended to achieve this.

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Single-photon emission computed tomography (SPECT) is widely used in diagnostic nuclear medicine. The major factors that reduce the quality and accuracy of SPECT images are photon attenuation, a geometric detector response, and scatter radiation, and much effort has been spent on attempts to solve these problems (*1,2*).

We have previously reported that image reconstruction using an attenuation coefficient map (μ map), obtained with transmission data and the expectation maximization (EM) algorithm (*3*), can both improve the image quality and the accuracy of brain SPECT (*4*).

However, if transmission and emission data are acquired separately, patient movement during the interval between transmission and emission imaging may lead to misalignment of the μ map and the emission data.

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The purpose of this study was to investigate the effect of misalignment between transmission and emission scans on SPECT images reconstructed using the EM algorithm. To do this, we used both a thorax phantom, incorporating nonuniform attenuation, and clinical brain SPECT data.

MATERIALS AND METHODS

Phantom Study

Figure 1 shows the phantom (a simplified model of a transverse section of the human thorax) and the distribution of the activity sources and attenuation coefficients used in the simulation study. Regions 0, 1, 2, and 3, labeled by subscripts in the figure, simulate lung, blood pool, myocardium, and vertebra, respectively. C_0, C_1, C_2, and C_3 are the source activities in regions 0, 1, 2, and 3, respectively, while μ_0, μ_1, μ_2, and μ_3 are the attenuation coefficients. The lengths of the major and minor axes of the phantom were 30 cm and 20 cm, respectively. The outer and inner radii of Region 2 were 4 cm and 2 cm, respectively, and the center of Region 2 was located at a point 5 cm along the x-axis and 4 cm along the y-axis from the center of the phantom. Region 3 had a radius of 1.5 cm, and its center was located at −7 cm along the y-axis from the center of the phantom. In the present study, μ_0, μ_1, μ_2, and μ_3 were set at 0.06, 0.15, 0.18, and 0.3 cm^{-1}, respectively, while C_0, C_1, C_2, and C_3 were 100, 0, 300, and 0 counts/pixel. Emission projection data were obtained by calculating projection ray-sums analytically from the model's geometry shown in Fig. 1 for 64 equally spaced angles over 360°, using line integrals that allowed for the effect of attenuation. The 64 projection bins (each 0.6 cm long) produced a total length of 38.4 cm per projection. The μ map was assumed to be equal to the attenuation coefficient distribution shown in Fig. 1.

Clinical Study

The scans obtained from a 40-yr-old male with luxury perfusion (*5*) due to subacute cerebral infarction were used. Data were acquired using a four-headed SPECT scanner (Hitachi Medical Co., Tokyo, Japan) (*6*), and transmission data acquisition was performed with a radioactive flood

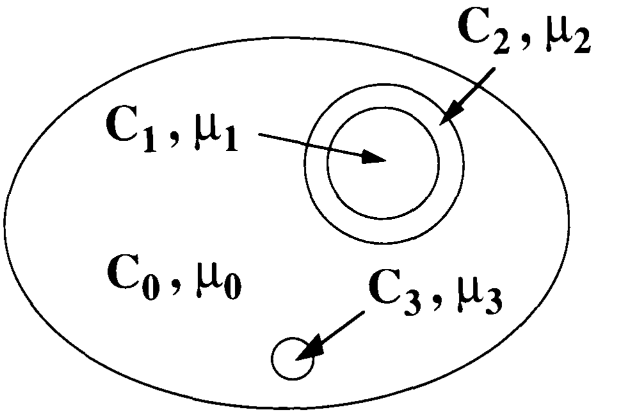

FIG 1. The thorax phantom used in the present study. C_0, C_1, C_2, and C_3 are the source activities, while μ_0, μ_1, μ_2, and μ_3 are the attenuation coefficients in Regions 0, 1, 2, and 3, respectively.

source attached to one of the four gamma camera heads instead of the collimator (*4*). Transmission projection data were acquired in 64 views over 360° for 30 sec/view using a 64 × 64 matrix, a low-energy general-purpose collimator, and a radioactive flood source containing about 185 MBq (5 mCi) of ^{99m}Tc-pertechnetate.

Following transmission data acquisition, the patient was injected with about 740 MBq (20 mCi) of ^{99m}Tc-hexamethylpropyleneamine oxime (HMPAO). About 5 min later, emission projection data were acquired in 64 views over 360° for 20 sec/view using a 64 × 64 matrix and a four-headed gamma camera equipped with a low-energy high-resolution collimator. The pixel size was 4.0 mm × 4.0 mm. The patient was asked to remain as still as possible throughout the transmission and emission data acquisition procedures. The method used to produce the μ map was described in our previous paper (*4*).

Image Reconstruction

Image reconstruction was performed using the iterative EM algorithm (*3*) and the μ map. The details of the image reconstruction method were also described in our previous paper (*4*). In the present study, the number of iterations was set at 50 when using the EM algorithm. Calculations were performed using a FACOM M-770/6 computer (8.5 MIPS) (Fujitsu, Tokyo, Japan).

Effect of Misalignment

To investigate the effect of misalignment between transmission and emission scans, the μ maps were manipulated as follows. Although misalignment due to patient movement can include both rotational and translational errors, only translational misalignment was investigated in the present study. Misalignment was produced by shifting the μ map upward or downward in the vertical plane and to the left or right in the horizontal plane, relative to the position of the emission data.

Evaluation of Misalignment Error

To quantitatively evaluate the degree of image distortion caused by misalignment, the misalignment error was calculated using the following equation.

$$\text{Error} = \frac{\sum_i \sum_j |C_{ij} - C'_{ij}|}{\sum_i \sum_j C_{ij}} \times 100(\%) \qquad \text{Eq. 1.}$$

C_{ij} is the image at pixel (i, j) following reconstruction without misalignment, and C'_{ij} is the image at pixel (i, j) after reconstruction with misalignment. This method evaluates the global image distortion. In addition, the error in regional activity was evaluated as $|C_{ij} - C'_{ij}|/C_{ij} \times 100$ (%).

RESULTS

The results obtained in the phantom study are shown in Figures 2 and 3. Figure 2 illustrates the effect of misalignment in the horizontal direction on the reconstructed SPECT images. In Figure 2A, SPECT images are shown as a function of the horizontal shift (dx). Figure 2B shows profiles through the site indicated by the arrows in the upper left image of Figure 2A, with profiles being shown for the situation where dx = 0 pixels (solid line), dx = +2 pixels (dotted line), and dx = −2 pixels (dashed line).

Figure 3 illustrates the effect of misalignment in the vertical direction. The reconstructed SPECT images are shown as a function of the vertical shift (dy) in Figure 3A, while Figure 3B shows profiles through the arrowed site in the upper left image of Figure 3A for dy = 0 pixels (solid line), dy = +2 pixels (dotted line), and dy = −2 pixels (dashed line). A 2-pixel shift of the μ map produced as much as a 47% error in regional activity in the simulated myocardium (Region 2 in Fig. 1).

Results obtained in the clinical study are shown in Figures 4 and 5. As in the phantom study, Figure 4A shows SPECT images as a function of horizontal shift (dx), and Figure 4B shows profiles through the arrowed site in the upper left image of Figure 4A for dx = 0 pixels (solid line), +2 pixels (dotted line), and −2 pixels (dashed line).

Likewise, Figure 5A shows the images as a function of vertical shift (dy), and Figure 5B shows profiles through the arrowed site in the upper left image of Figure 5A for dy = 0 pixels (solid line), +2 pixels (dotted line), and −2 pixels (dashed line). A 2-pixel shift of the μ map produced up to a 12% error in regional activity in the cerebral cortex.

As can be seen from Figures 4A and 5A, image distortion becomes more severe toward the edges of an object. Even if the μ map was misaligned by only 2 pixels, the image distortion was visually detectable (Figs. 4A and 5A) and could thus cause false-positive diagnostic results.

Tables 1 and 2 summarize the errors due to misalignment calculated using Equation 1 in the phantom and clinical studies, respectively. A mean increase in error of about 5.5%

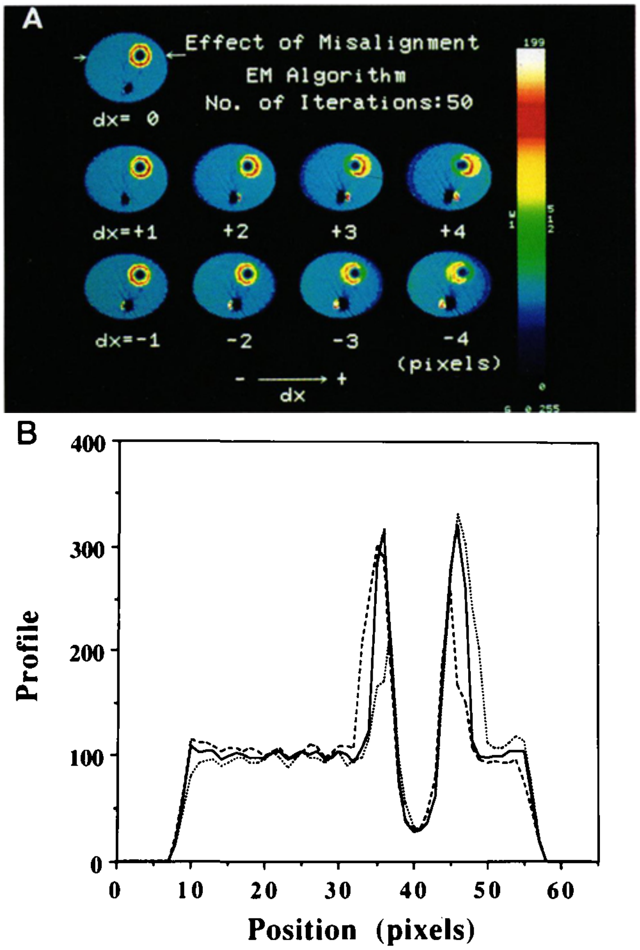

FIG. 2. (A) Reconstructed SPECT images as a function of horizontal shift (dx) in the phantom study. The numbers show the horizontal shift in pixels. (B) Changes in image profile due to misalignment in the horizontal direction. Position of the profile is shown by arrows in the upper left image in (A). The effect of a horizontal shift (dx) of 0, +2, and −2 pixels is shown. —— : dx = 0 pixels, ----- : dx = +2 pixels, and – – – : dx = −2 pixels.

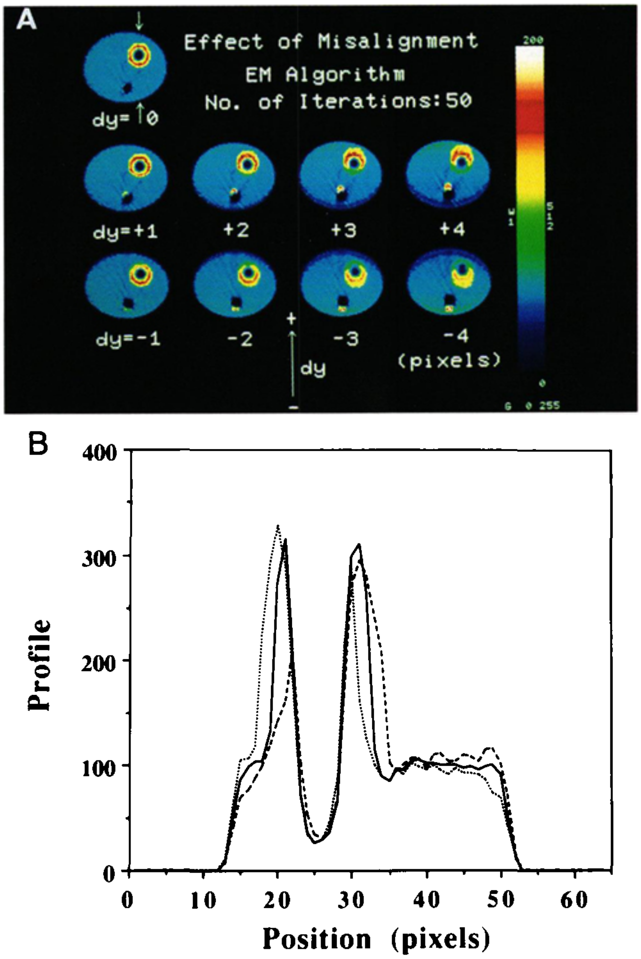

FIG. 3. (A) Reconstructed SPECT images as a function of vertical shift (dy) in the phantom study. The numbers show the vertical shift in pixels. (B) Changes in image profile due to misalignment in the vertical direction. Position of the profile is shown by arrows in the upper left image in (A). The effect of a vertical shift (dy) of 0, +2, and −2 pixels is shown. —— : dy = 0 pixels, ----- : dy = +2 pixels, and – – – : dy = −2 pixels.

was observed per 1 pixel shift in both studies. In addition, a 2-pixel shift of the μ map caused a 13% error in both studies, although there were some differences between the errors caused by horizontal shift and vertical shift.

DISCUSSION

We have previously reported that brain SPECT images could be improved by using a μ map produced with transmission data and the EM algorithm (*4*). The usefulness of this method in cardiac SPECT imaging has also been reported by Tsui et al. (*7*). However, when transmission and emission data are acquired separately, misalignment due to patient movement often occurs, and we considered it important to determine the magnitude of the effect produced by such misalignment error. In this study, we therefore investigated the effect of misalignment between transmission and emission scans using a thorax phantom incorporating nonuniform attenuation as well as clinical brain SPECT data. Although the phantom we used was very simple, it was considered to be appropriate for this type of study.

Huang et al. (*8*) investigated the effects of inaccurate attenuation correction on quantitation in positron emission tomography (PET), using both computer simulation and theoretical analysis, followed by experimental verification with phantom measurements. They reported that errors as large as 14% in the reconstructed activity level could be caused by a 5-mm shift in object location. McCord et al. (*9*) also reported that a 2-cm shift between attenuation and emission scans produced up to a 30% change in regional activity in myocardial FDG scans obtained using PET.

Our study also demonstrated that misalignment between transmission and emission scans produced large errors in SPECT images reconstructed using the EM algorithm (Figs. 2–5). For example, a 2-pixel shift of the μ map caused an error of about 13% in the reconstructed activity level (Tables 1 and 2). The errors simulated in this study would be similar in magnitude to those that might realistically occur in

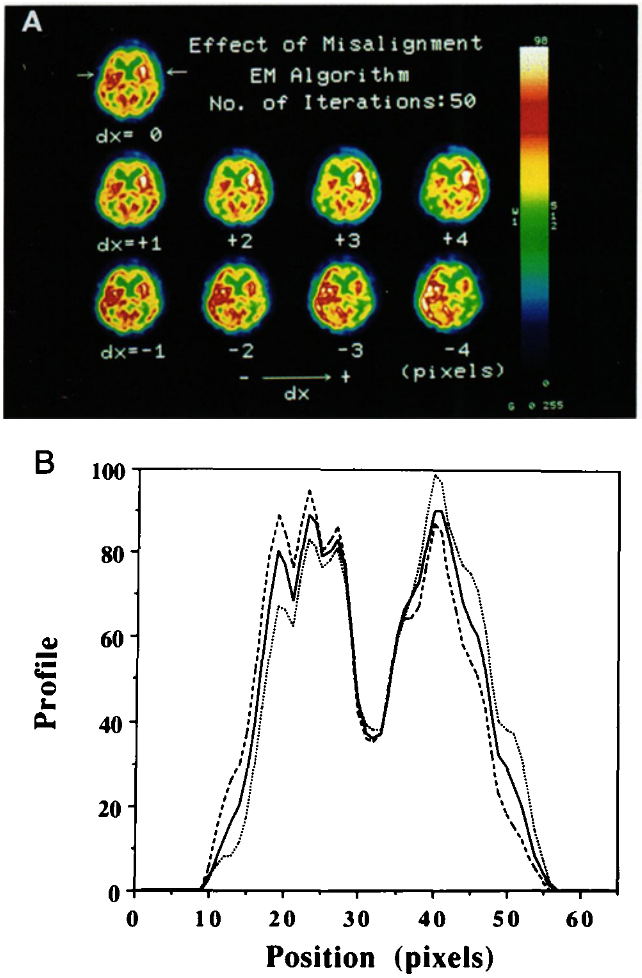

FIG. 4. (A) Reconstructed SPECT images as a function of horizontal shift (dx) in the clinical study. The numbers show the horizontal shift in pixels. (B) Changes in image profile due to misalignment in the horizontal direction. Position of the profile is shown by arrows in the upper left image in (A). The effect of a horizontal shift (dx) of 0, +2, and −2 pixels is shown. —— : dx = 0 pixels, ----- : dx = +2 pixels, and – – – : dx = −2 pixels.

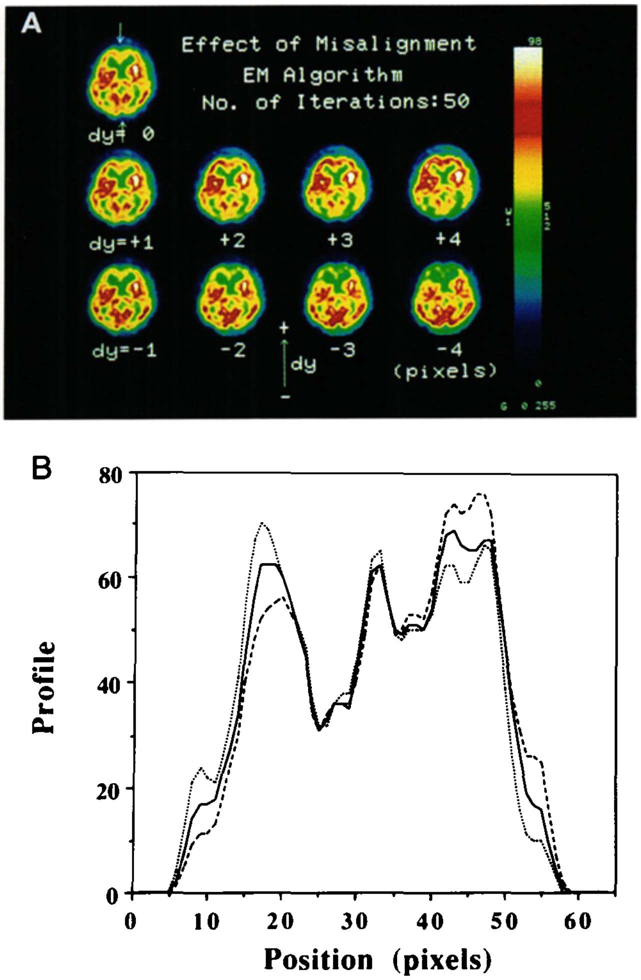

FIG. 5. (A) Reconstructed SPECT images as a function of vertical shift (dy) in the clinical study. The numbers show the vertical shift in pixels. (B) Changes in image profile due to misalignment in the vertical direction. Position of the profile is shown by arrows in the upper left image in (A). The effect of a vertical shift (dy) of 0, +2, and −2 pixels is shown. —— : dy = 0 pixels, ----- : dy = +2 pixels, and – – – : dy = −2 pixels.

SPECT imaging, and such errors could easily lead to qualitative and quantitative misinterpretation of SPECT data.

When the μ map was assumed to be uniform in the simulation study, i.e., μ_0, μ_1, μ_2, and μ_3 in Figure 1 were all 0.15 cm^{-1}, the error in myocardial regional activity (Region 2 in Fig. 1) was decreased to about one third of that obtained using a nonuniform μ map (data not shown). This finding suggests that the magnitude of regional image distortion due to misalignment is strongly related to the degree of heterogeneity of the μ map, with regional image distortion increasing as the μ map becomes more heterogeneous. Accordingly, misalignment between transmission and emission scans may be more severe in cardiac SPECT imaging than in brain SPECT imaging, due to the more heterogeneous attenuation coefficient distribution in the thorax (*7*).

The simplest approach to overcoming problems related to misalignment between transmission and emission scans is to minimize any movement of the patient in the interval between transmission and emission measurements. As stated by Ter-Pogossian (*10*), this can be achieved by a combination of several approaches. First, the patient will be less inclined to move if placed in a comfortable position during

TABLE 1. Misalignment Error in the Thorax Phantom Study

Shift value (pixels)	Horizontal shift (% error)	Vertical shift (% error)
+1	7.4	7.7
+2	12.5	13.5
+3	17.1	19.1
+4	21.6	24.2
−1	7.3	7.7
−2	12.5	13.1
−3	17.7	18.6
−4	22.2	23.6

Note: Misalignment error was calculated using Equation 1.

TABLE 2. Misalignment Error in the Clinical Study

Shift value (pixels)	Horizontal shift (% error)	Vertical shift (% error)
+1	7.2	6.4
+2	13.3	11.5
+3	18.3	15.5
+4	23.2	19.4
−1	7.2	6.4
−2	13.2	11.5
−3	18.3	15.3
−4	23.3	19.1

Note: Misalignment error was calculated using Equation 1.

the examination. Another simple way to reduce movement is the use of a restraining tape or a plastic foam restraining device molded to the patient's anatomy. As also pointed out by Ter-Pogossian (*10*), a crucial factor in minimizing patient movement is reducing the examination time. When transmission and emission data are acquired separately, extra imaging time is naturally needed for the transmission study (about 32 min in our protocol), and this considerably increases the discomfort of the patient. Accordingly, simultaneous acquisition of transmission and emission data (*11,12*) is strongly recommended. The use of multi-detector SPECT systems allows transmission and emission data to be acquired simultaneously, and makes it possible to obtain a μ map in an acceptable imaging time (*12,13*).

Incorrect μ values and the statistical noise in the μ map will also affect the accuracy of the reconstructed SPECT images. However, Huang et al. (*8*) showed that these factors have less influence than errors due to misalignment between transmission and emission scans. To minimize the effect of incorrect μ values and statistical noise, a high quality μ map is necessary. Recently, the use of a cone-beam collimator has been proposed in order to improve μ map quality (*14*), and it is anticipated that such an approach can produce sufficiently accurate μ maps. Detailed analysis of the effects of these other factors is currently underway.

In conclusion, misalignment between transmission and emission scans produces large errors in SPECT images reconstructed using the EM algorithm. Thus, great care is needed to ensure precise alignment between the μ map and the emission data, and simultaneous acquisition of transmission and emission data is strongly recommended for this purpose.

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