Use of a Germanium Detector to Optimize Scatter Correction in SPECT

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A collimated germanium detector with an energy resolution of 1 keV full width at half maximum at 140 keV was used to measure the energy spectrum of radiation emitted from a test object containing an asymmetric distribution of $^{99m}$Tc and nonuniform attenuation. Energy spectra were recorded from 24 positions around the object and convolved with Gaussian functions to simulate data that would have been acquired with a scintillation camera. The scatter fraction was computed from the convolved spectra in conjunction with a scatter-free reference spectrum. After adding appropriate Poisson noise, a technique based on maximizing the signal to noise ratio was developed to optimally subtract the scatter fraction from the recorded counts. SPECT imaging of the test object was performed to evaluate the correction technique.


In addition to the primary radiation, emitted gamma rays comprise photons that have undergone Compton scattering within the object. Although the energy of the scattered photons is lower than the energy of the primary radiation, the finite energy resolution of the detector implies that a portion of the scattered radiation will be recorded within the photopeak energy window. Inclusion of scattered photons blurs edges and reduces contrast in the emission image, thereby leading to errors in the quantitation of radioactivity distribution (1–3). In general, the blurring function due to scatter (the scatter point spread function or PSF) is spatially variant, depending on the point-to-point attenuation coefficient and activity concentration within the object. A rigorous solution to the scatter correction problem is therefore difficult to implement. Nevertheless, as higher quantitation accuracy is sought in single photon emission computed tomography (SPECT), it will become necessary to include an appropriate routine to correct for the scatter contribution (4).

Using a germanium (Ge) detector, which has a high-energy resolution so that the primary and scattered photons emanating from the object can be separated to a large extent, we have experimentally measured the scatter fraction emitted from a test object containing an asymmetric distribution of technetium-99m ($^{99m}$Tc) activity and nonuniform attenuation. Also, using measurements made with the Ge detector to simulate data that would be obtained with a scintillation camera, we have investigated the contribution of scatter to specified photpeak windows and have developed a technique to optimize a scatter correction method. The correction technique was applied to SPECT imaging of the test object. The characteristics of scattered photons observed with the Ge detector, the optimization procedure for scatter correction with signal-to-noise ratio (SNR) ramifications thereof, and results of correcting scatter in SPECT imaging of the test object are reported in this paper.

THEORY AND BACKGROUND

Two-dimensional projection images taken over a multitude of angles around the object are used to perform SPECT with a scintillation camera (5). Counts are recorded in a photpeak window whose width conforms to the energy resolution of the NaI (TI) detector used in a scintillation camera. Typically, the energy resolution of a scintillation camera ranges from 12% to 15% full width at half maximum (FWHM) for imaging $^{99m}$Tc (140 keV), and a ±10% wide window, centered on the photpeak, is normally used.

The image reconstruction algorithms upon which SPECT is based, rely on the premise that each pixel within each projection image represents a sum of all activity lying on a specific line traversing the object (6). The measured sum of activity on a specified line, called a "ray-sum", differs from...
the true line-integral of the activity due to the following two main reasons: (a) attenuation of emitted photons within the object, which reduces the measured value from the true value, and (b) inclusion of scattered photons originating from activity lying outside the specified line, that increases the measured value of the ray-sum. The following equation expresses these two factors.

\[ T = P + S \]  \hspace{1cm} (1)

In this equation, \( T \) represents the total counts recorded within a prescribed photopeak window along a specified line, \( P \) represents counts due to the primary radiation emanating from the object, which is a function of the activity and attenuation coefficient distribution along the line, and \( S \) represents counts due to the scattered photons. The ratio \( S/P \) is defined as the scatter fraction. The value of \( S \) depends on the three-dimensional activity and attenuation coefficient distribution within the object.

Ignoring \( S \), many methods have been developed to correct for attenuation losses in SPECT (5,7–9). Obviously, unless contributions from \( S \) can be removed, image quantitation will be degraded in proportion to \( S \). A simplistic solution is to undercorrect for attenuation (10), with the assumption that \( S \) compensates for a fraction of the attenuation in \( P \). However, this method cannot be quantitative because it ignores the dependence of \( S \) on the three-dimensional activity and attenuation distribution. Indeed, as described elsewhere (11), the undercorrection approach leads to an \( \sim 30\% \) error in quantitating a 6-cm cold sphere placed near the center of a 22-cm-diameter by 25-cm-long cylinder, uniformly filled with \(^{99m}\)Tc.

Iterative reconstruction techniques such as those described by Budinger and Gullberg (7) could be used to accurately correct for attenuation and scatter by using known values of the attenuation coefficients to model the photoelectric absorption and Compton scattering processes (12). Models based on Monte Carlo computational schemes to estimate the scatter fraction from a known source and attenuation description have been reported (13,14). However, in addition to being computationally tedious, this approach is limited by the accuracy of the model (4). Another approach is based on deconvolving an average scatter line spread function (15). The assumption of an average scatter blurring function, however, is reasonable only for localized sources near the center of the object with minimal surrounding background activity and uniform object attenuation. When considerable superficial activity is present, the method produces large errors (4,15) that would be compounded if the attenuation were nonuniform. An alternative approach relies on collecting counts in two energy windows—a photopeak window and a scatter window at a lower energy. The assumption is made that counts in the lower window are correlated with \( S \). Corrections are made either to the projection data, by subtracting a fraction of the counts in the lower window from the photopeak counts (3,16), or to the image by subtracting a fraction of the image reconstructed using the lower window counts from the image obtained using the photopeak counts (11).

Although the method of reconstructing separate images from the photopeak window and the scatter window is preferred by some investigators (4,11), it is our premise that the approach of correcting projection data before reconstruction is theoretically superior in achieving quantitation. Referring to Eq. (1), \( S \) depends on the three-dimensional source and attenuation distribution. Thus, the PSF attributed to \( S \) is spatially variant. The reconstruction algorithms used in SPECT, however, assume a spatially invariant PSF (6). Thus, projection data that contain \( S \) are inherently inconsistent (17) and could lead to unpredictable quantitation errors. Removing \( S \) before reconstruction avoids this problem. As described in the following sections, using data obtained with a Ge detector, we have developed a method of optimizing the two-window correction approach, where counts are subtracted before reconstruction, and have applied the technique to correct SPECT data obtained with a scintillation camera.

**MATERIALS AND METHODS**

The test object used in this study is shown in Figure 1. It consisted of a 25 cm diameter \( \times \) 28 cm tall cylindrical vessel, filled with water (up to a height of 26 cm) containing uniformly distributed 0.2 \( \mu \)Ci/ml of \(^{99m}\)Tc. Two glass cylinders of inner diameters 4 cm and 3 cm, containing 5 \( \mu \)Ci/ml and 2.5 \( \mu \)Ci/ml of \(^{99m}\)Tc, respectively, were arranged inside the main vessel as shown in Figure 1. In addition, two 25 cm long \( \times \) 2 mm thick aluminum strips, one 3.8 cm wide and the other tapered to a width of 2 cm at its midpoint, were immersed in the vessel as shown in Figure 1. The aluminum strips were used to simulate scattering by bone. The test object, thus, contained a nonuniform distribution of attenuation and activity concentration.

A 5 mm \( \times \) 5 mm in area and 6-mm-thick, high-purity Ge detector was used to perform an energy dispersive analysis of the emitted radiation. The energy resolution of the detector was 1 keV FWHM at 140 keV. The Ge detector was collimated

![Figure 1](image-url)
with a lead aperture to a field of view of 1 cm FWHM at a
distance of 10 cm from the detector so that the spatial region
from which counts were recorded would be comparable to the
resolution of typical parallel hole collimators used in SPECT.
Counts were acquired from eight equally spaced angular po-
positions covering 360° around the object, and at each angle, the
Ge detector was linearly displaced 5 and 10 cm to the left of
the central position. In this manner, a total of 24 samples of
the emitted radiation's energy spectra were accumulated in a
multichannel analyzer. Each spectrum contained 10k counts
within a 140±1 keV photopeak window. In addition, a
reference spectrum, also containing 10k counts in the photo-
peak window, was acquired from a 99m-Tc point source in air.
The reference spectrum is assumed to contain no scattered
radiation. All spectra were normalized for the change in
detection efficiency of the 6-mm-thick Ge detector as a func-
tion of energy. A plot of the 25 spectra is shown in Figure 2.
By acquiring an equal number of photopeak counts in each
spectrum, including the reference spectrum, the variations in
these spectra due to attenuation (photoelectric absorption) in
the object have been removed. The remaining differences
among these spectra are mainly due to the scattered radiation.
The small tail on the left side of the photopeak in the reference
spectrum is believed to be caused by incomplete charge col-
glection in surface channels of the Ge detector (18). As all our
analyses are based on a comparison between the test object
spectra and the reference spectrum, the effect of incomplete
charge collection is cancelled out. The peaks at the far left in
each spectrum arise from x-ray fluorescence of lead induced by the 99m-Tc source.

The 1-keV FWHM energy resolution of the Ge detector
and the ±1 keV wide photopeak window imply that a portion
of the small-angle Compton scattered photons will be recorded
under the photopeak. After compensating for the incomplete
charge collection and using the Monte Carlo results of Floyd et al. (19) to derive the shape of the energy
spectrum of the Compton scattered photons under the pho-
topeak, an extrapolation of the region lying at the left of the
photopeak indicates that the Ge photopeak contains, on the
average, ~7% counts from scattered photons. The contribu-
tion of these small-angle scattered photons to the net value of
the scatter fraction has been included in the results. However,
given the energy resolution constraint of the Ge detector, it is
not possible to experimentally study the fluctuation in this
small-angle scatter as a function of detector position, nor is it
possible to include the effects of these fluctuations, that are
expected to be relatively small, on the optimization procedure
described later.

Convolution with Gaussian Functions

In order to estimate the scatter fraction that would be
recorded if a scintillation camera were used, the Ge spectra
were convolved with Gaussian functions corresponding to the
energy resolution of a scintillation camera. In addition to
convolution with a 15% and a 12% FWHM Gaussian func-
tion, a set was also generated by convolving with a 7% FWHM
Gaussian, which is perhaps the best energy resolution that
could be attained with a NaI detector. As an example, the
spectra resulting from convolution with the 12% Gaussian
function are shown in Figure 3.

The convolved scatter-free reference spectrum provides an
estimate of the primary photons in each set. Thus, counts
from the primary and scattered photons are separable in each
spectrum, which enables us to determine the scatter fraction
within specified photopeak windows in each set. Since, on the
order of 30–40k counts were obtained within the FWHM
region of the photopeaks in these spectra, statistical fluctua-
tions are negligible. Thus, the observed fluctuations in the
scatter fraction as a function of detector position with respect
to the object reflect the source-dependent nature of the scatter
fraction.

Addition of Poisson Noise

The collimated Ge detector is roughly equivalent to a 5
mm × 5 mm pixel of the scintillation camera, and 10k counts
per pixel in the measured spectra (which produces 30–40k
counts in the convolved spectra) corresponds to an impracti-
cally high counting situation with almost no statistical error.
To include the effect of statistical noise in developing a scatter
correction method, counts within specified photopeak win-
dows of the convolved spectra were scaled down to either
1,000 or 100 total counts (which represents the order of
magnitude of counts that might be accumulated in a 5 mm ×
5 mm pixel of a scintillation camera), and Poisson noise was
then added to counts in each channel of the scaled spectra.
In Eq. (3), $C_p$ represents the true primary counts and $n$ is the total number of spectra in a given set (24 in this work). Using Eq. (2) to express $X_i$ in Eq. (3), differentiating 'y' with respect to 'a' and setting $dy/da = 0$, the following expression was obtained for 'a' to minimize 'y'.

$$a = \frac{\sum B_i (C_i - C_p)}{\sum B_i}$$

(4)

Eq. (4) was used to compute the optimized value of the parameter 'a' for each combination of photopeak and scatter window. Selection of an optimal window combination was based on the value of the SNR before and after scatter correction as described below.

In spectra used for this work, counts under a specified photopeak window fluctuate among samples of a given set due to the following two reasons: (a) Poisson noise and (b) variations in the scatter fraction with detector position. Calling the mean value of counts under a specified photopeak as the signal, and the standard deviation (sd) of fluctuations therein as the noise, the photopeak and scatter windows were optimized so that after scatter correction the mean value of the ensemble photopeak counts would be equal to the photopeak counts in the scatter-free reference spectrum, and the noise would be as low as possible, thereby producing an optimal SNR in the corrected spectra. The process of adding Poisson noise and computing optimal 'a' and SNR values was repeated 40 times for each set to generate results corresponding to the mean outcome of 40 trials.

**SPECT Data Acquisition and Reconstruction**

To test the scatter correction procedure, SPECT data were acquired from the test object and corrected before reconstruction. A small (3 cm diam x 6 cm tall) plastic bottle, filled with water containing no activity, was suspended near the mid-level of the main container to produce a cold spot in the SPECT images. The small perturbation in the activity distribution caused by this addition is not expected to have any significant impact on the scatter correction parameters. A conventional scintillation camera with an energy resolution of 15% FWHM at 140 keV, equipped with a parallel hole collimator, was used to acquire projection data from 80 equispaced angular views around 360°. The projection data were collected separately for a photopeak window and a scatter window and digitized on a 64 x 64 grid composed of 5.6 mm x 5.6 mm pixels. The windows were determined from the optimization procedure described earlier. The photopeak projection data contained ~50 counts per pixel per angular position. Two adjacent rows were summed at each angle to obtain ~100 counts per pixel, thereby conforming to the "15% energy resolution, 100 photopeak counts" example considered in the optimization procedure. The scatter window data were subtracted from the photopeak data using values of 'a' ranging from 0.1 to 0.9. A 64 x 64 transaxial image at mid-level of the object was then reconstructed using the Shepp and Logan (20) convolution and backprojection algorithm in conjunction with an attenuation correction method developed by Singh et al. (5). The attenuation correction routine assumes that the map of attenuation coefficients for the cross-section to be reconstructed is known on a corresponding grid (64 x 64 in the present work) and applies a correction to each pixel during the backprojection step at each angle of view. Also,
conjugate views were summed to produce an approximately uniform spatial resolution in the reconstructed images (5). Using an off-center $^{99m}$Tc line source in air, the spatial resolution in the reconstructed image was measured to be $1.4 \pm 0.25$ cm. The images obtained with different values of `a` were evaluated for quantitative contrast recovery in the 4 cm diameter cylinder (hot spot) and, as a test of the scatter correction technique, the value of `a` which produced the correct contrast was compared with the theoretically optimum value predicted by Eq. (4).

RESULTS

The percentage scatter fraction is plotted in Figure 4 as a function of detector position with respect to the object and energy resolution in the convolved spectra. The scatter fraction was computed from convolved spectra, prior to addition of any noise, for detector energy resolutions of 15, 12 and 7% FWHM, respectively. A symmetric ±10% wide photopeak window was used with the 15 and 12% resolution spectra and a symmetric ±7.5% window was used for the 7% case. The mean ± s.d. of the scatter fraction in percent were 66.0 ± 10.0, 43.1 ± 7.8 and 38.0 ± 5.2, respectively. A small-angle scatter contribution of 7%, which is not resolved by the Ge detector as mentioned before, has been included in the estimation of the scatter fraction.

After determining the optimal value of the parameter `a` from Eq. (4) for each combination of photopeak and scatter window, the SNR in the corrected spectra was plotted as a function of the window widths. Since no improvements were noticed with asymmetric versus symmetric photopeak windows, the results shown here are confined to symmetric photopeak windows with contiguous scatter windows. A contour plot of the SNR, corresponding to the 15% energy resolution with 100 photopeak counts (per pixel), is shown in Figure 5, which suggests a 28-keV wide photopeak window (126–154 keV) and a 32-keV scatter window (93–125 keV), for optimal correction. The value of `a` from Eq. (4) was 0.37 in this case. The optimal values of the scaling parameter `a`, window widths and the SNR values before and after scatter correction for the nine sets studied have been summarized in Table 1.

After fixing the scatter window to its optimal value (as determined from the SNR contour plots for each case), plots of the SNR before and after scatter correction are shown in Figure 6 as a function of the photopeak window for the 15% energy resolution case with 100, 1,000, and 40,000 counts. It is clear that the

![Figure 4](image)

**FIGURE 4**
The percentage scatter fraction as a function of detector position with respect to the object. Samples 1–8 correspond to eight central, equispaced angular locations around 360°; samples 9–16 to locations shifted 5 cm to the left of the central position and 17–24 to locations shifted 10 cm to the left of the central position. The top, middle, and bottom curves correspond to detector energy resolutions of 15%, 12%, and 7% FWHM respectively. A symmetric ±10% wide photopeak window was used with the 15% and 12% resolution spectra and a ±7.5% window was used with the 7% resolution spectra.

![Figure 5](image)

**FIGURE 5**
A contour plot of the signal to noise ratio (SNR) after scatter correction in the convolved spectra corresponding to 15% energy resolution and 100 photopeak counts (per pixel). The contours are plotted as a function of a symmetric photopeak window-width and a contiguous scatter window-width. The maximum SNR of 6.077 is obtained with a 28-keV wide photopeak window (126–154 keV) and a 32-keV scatter window (93–125 keV).
optimum window becomes better defined with increasing count statistics. Nevertheless, as visualized in Figure 5, an optimum window still exists at the 100 count per pixel level. Also, it is noteworthy that after optimal subtraction, the SNR in the corrected data improves for the 40,000 and 1,000 counts case and degrades only slightly with 100 counts.

Results of SPECT imaging with the test object are shown in Figure 7. The left column in Figure 7 shows, from top to bottom respectively, the mid-level transaxial image with no corrections, with attenuation correction using an attenuation coefficient of 0.15 cm\(^{-1}\) for water and 0.39 cm\(^{-1}\) for aluminum, and with attenuation and scatter correction using 'a' = 0.1. The middle and right columns show the attenuation and scatter corrected images with a = 0.2, 0.3, and 0.4, respectively (middle column) and a = 0.5, 0.7 and 0.9 respectively (right column).

The contrast in the reconstructed cross-section of the 4 cm diameter cylinder is given in Table 2. Contrast was defined as the ratio of the peak value within the hot spot to the mean background value. The background was defined as being composed of all pixels lying within the object boundary after excluding those lying within the hot and cold regions. The true contrast in the region investigated was 25.0 ± 1.2. As seen from Table 2, the experimental value of 'a' which leads to the correct contrast is ~0.35 and is in good agreement (within experimental uncertainties) with the theoretical optimal value of 0.37 obtained from Eq. (4), thereby supporting the scatter correction method reported in this work. The SNR in the SPECT images, defined as the ratio of the mean to the standard deviation among the reconstructed background pixel values, is also listed in Table 2 and shows a relatively small degradation in the SNR with optimal scatter correction.

**DISCUSSION**

The results shown in Figure 4 demonstrate the significant dependence of scatter fraction on the location of the detector with respect to an asymmetric source. Techniques to quantitatively remove scatter in SPECT must, therefore, make provisions for the three-dimensional source and attenuation dependent nature of the detected scattered radiation.

The scatter correction method described here is based on subtracting scatter from projection data before reconstruction, on the premise that it avoids the problem of data inconsistency. It is possible that inconsistencies inherent in SPECT, due to attenuation and the variation of resolution with depth, overshadow those due to scatter so that methods based on subtracting scatter after reconstruction perform equally well. Nevertheless, in our opinion, scatter correction before reconstruction is preferable because not only does it avoid the inconsistency problem but it also saves the computational effort of reconstructing an additional scatter image to be subtracted from the uncorrected image.

This investigation has demonstrated that it is possible to optimize a procedure to compensate for scatter under conditions of specified camera energy resolution and counting statistics. The results shown in Table 1, which are valid for the particular test object studied, indicate certain trends in setting optimal windows. For example, as expected, the optimal photopeak windows tend to become wider as the energy resolution of the detector degrades or if fewer counts are collected (Table 1). However, the source dependent nature of scattering implies that the actual values of the optimal windows may be different for another test object. Therefore, it is

![Figure 6](image-url)  
**Figure 6**  
Plots of the signal to noise ratio (SNR) before (dotted line) and after (solid line) scatter correction, as a function of the photopeak window for 15% energy resolution and 100, 1k and 40k counts, respectively. The width of the scatter window was fixed to its optimal value in each case. The photopeak windows, corresponding to the maximum SNR values from this figure, are listed in Table 1.

**Table 1**  
Optimized Values of the Parameter 'a', the Peak Window and Scatter Window and the Resulting Pre- and Posts scatter Correction (SNR) for Three Different Energy Resolutions and Count Statistics

<table>
<thead>
<tr>
<th>Energy Res (%)</th>
<th>Counts</th>
<th>Peak Window (keV)</th>
<th>Scatter Window (keV)</th>
<th>SNR (pre)</th>
<th>SNR (post)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>1,000</td>
<td>0.51</td>
<td>12</td>
<td>8</td>
<td>23.8</td>
</tr>
<tr>
<td>12</td>
<td>1,000</td>
<td>0.55</td>
<td>18</td>
<td>14</td>
<td>18.2</td>
</tr>
<tr>
<td>15</td>
<td>1,000</td>
<td>0.70</td>
<td>22</td>
<td>14</td>
<td>15.7</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>0.26</td>
<td>14</td>
<td>22</td>
<td>9.2</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
<td>0.42</td>
<td>18</td>
<td>18</td>
<td>9.4</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
<td>0.37</td>
<td>29</td>
<td>32</td>
<td>8.6</td>
</tr>
</tbody>
</table>
FIGURE 7
Transaxial SPECT images of the test object (shown in Figure 1) from ~350k counts at the central level after introducing a 3 cm diam × 6 cm tall cylindrical water-filled cold region as described in the text. The left column shows (from top to bottom) the transaxial image with no corrections, with attenuation correction alone, and with attenuation and scatter correction using the value of 0.1 for the scaling parameter ‘a’. The middle and right columns show the attenuation and scatter corrected images with a = 0.2, 0.3, and 0.4, respectively (middle column), and a = 0.5, 0.7 and 0.9, respectively (right column).

Table 2
Contrast and SNR Values in the SPECT Images as a Function of the Scaling Factor ‘a’

<table>
<thead>
<tr>
<th>a</th>
<th>Contrast</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 (No correction)</td>
<td>11.9</td>
<td>3.5</td>
</tr>
<tr>
<td>0.0 (attenuation correction)</td>
<td>19.6</td>
<td>2.0</td>
</tr>
<tr>
<td>0.1 (attenuation and scatter correction)</td>
<td>21.0</td>
<td>1.9</td>
</tr>
<tr>
<td>0.2</td>
<td>22.6</td>
<td>1.9</td>
</tr>
<tr>
<td>0.3</td>
<td>24.2</td>
<td>1.8</td>
</tr>
<tr>
<td>0.4</td>
<td>26.5</td>
<td>1.7</td>
</tr>
<tr>
<td>0.5</td>
<td>29.2</td>
<td>1.5</td>
</tr>
<tr>
<td>0.6</td>
<td>32.7</td>
<td>1.3</td>
</tr>
<tr>
<td>0.7</td>
<td>37.0</td>
<td>1.1</td>
</tr>
<tr>
<td>0.8</td>
<td>41.0</td>
<td>1.0</td>
</tr>
<tr>
<td>0.9</td>
<td>45.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Contrast is defined as the ratio of the peak value in the reconstructed cross-section of the 4cm cylinder to the mean value of the background. The SNR is defined as the ratio of the mean value to the standard deviation of counts in the background. The true contrast was 25.0 ± 1.2.

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REFERENCES