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Accurate scatter correction for transmission computed tomography using an uncollimated line array source

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We investigated scatter correction in transmission computed tomography (TCT) imaging by the combination of an uncollimated transmission source and a parallel-hole collimator. We employed the triple energy window (TEW) as the scatter correction and found that the conventional TEW method, which is accurate in emission computed tomography (ECT) imaging, needs some modification in TCT imaging based on our phantom studies. In this study a Tc-99m uncollimated line array source (area: 55 cm × 40 cm) was attached to one camera head of a dual-head gamma camera as a transmission source, and TCT data were acquired with a low-energy, general purpose (LEGP), parallel-hole collimator equipped on the other camera head. The energy spectra for 140 keV-photons transmitted through various attenuating material thicknesses were measured and analyzed for scatter fraction. The results of the energy spectra showed that the photons transmitted had an energy distribution that constructs a scatter peak within the 140 keV-photopeak energy window. In TCT imaging with a cylindrical water phantom, the conventional TEW method with triangle estimates (subtraction factor, $K = 0.5$) was not sufficient for accurate scatter correction ($\mu = 0.131$ cm^{-1} for water), whereas the modified TEW method with $K = 1.0$ gave the accurate attenuation coefficient of 0.153 cm^{-1} for water. For the TCT imaging with the combination of the uncollimated Tc-99m line array source and parallel hole collimator, the modified TEW method with $K = 1.0$ gives the accurate TCT data for quantitative SPECT imaging in comparison with the conventional TEW method with $K = 0.5$.

Key words: attenuation correction, TEW scatter correction method, uncollimated transmission CT source, SPECT, quantification

INTRODUCTION

IN SINGLE PHOTON EMISSION COMPUTED TOMOGRAPHY (SPECT) imaging, it is important to perform both accurate, scatter and attenuation corrections for quantification of source activities, and many investigations have focused on their corrections.[1–12] For attenuation correction, transmission computed tomography (TCT) data are useful to obtain quantitative SPECT image counts.[12–22,24,25] We have also studied attenuation corrections using the combinations of a line source and a symmetrical fan beam collimator,[21] a narrow plate source and asymmetric fan beam collimator,[22] and a wide line array source and a parallel-hole collimator.[23,25] However, as the last attenuation correction method employs an uncollimated transmission source, accurate correction for scattered photons through the body is required in TCT imaging.[14,15,18,19,24,25] So, to remove scatter from TCT data we employed the triple energy window (TEW) scatter correction method which

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was proposed by Ogawa et al.[2,5] The goal of this study was to investigate the energy distribution of scattered photons in a parallel-hole collimator TCT imaging with a Tc-99m uncollimated transmission source and to accurately correct for scatter included in attenuation coefficient maps for that TCT imaging circumstance using the TEW method.

MATERIALS AND METHODS

All data acquisitions were performed with a dual-headed gamma camera (GCA-7200A/DI, Toshiba, Japan) and a nuclear medicine computer system (GMS-5500/DI). Each camera head was equipped with a low-energy, general purpose (LEGP), parallel-hole collimator. Two line array sources including Tc-99m (140 keV) solutions of 222 MBq (LAS-A, 21 cm × 18 cm) and 1.11 GBq (LAS-B, 55 cm × 40 cm) were used as uncollimated transmission sources (Fig. 1). Each line array source consisted of a uniform activity line source placed at intervals of 5 mm. The line array source LAS-A was stuck on a cardboard (30 cm × 21 cm), and the line array source LAS-B was housed in an acrylic plate of 10 mm thickness. For scatter correction in Tc-99m TCT data, a triple energy window (TEW) mode (24% main energy window at 140 keV and 7% lower sub-energy window) was considered.

A. Measurement of energy spectra for transmission acquisition

For transmission acquisition, the multiple 1 keV-width-images between 61 keV and 170 keV (110 images with 64 × 64 matrix, a zoom factor of 2.0, and a pixel size of 4.3 mm) were measured for the water equivalent material thicknesses of 0, 5, 10 15, 20, 25, and 30 cm (30 cm × 30 cm, Tough water phantom, Kyoto Kagaku, Japan, $\mu = 0.152\ cm^{-1}$ for 140 keV) using the uncollimated source, LAS-A (Figs. 2A and 2B). The data acquisition time was varied from 5 to 15 min according to the thickness of the attenuating materials. All the data were corrected for Tc-99m time decay. In order to obtain energy spectra for transmission, a region of interest (ROI) (50 × 45 pixels) was set on all the images.

We obtained energy spectra of scatter in the following manner. Scatter count $S(d)$ at thickness d is given by

$$S(d) = T(d) - P(d) \qquad (1)$$

where $T(d)$ is the total measured count and $P(d)$ is the primary (non-scattered) count. Using the theoretical attenuation coefficient μ_a and the primary count $P(0)$ at $d = 0$, $P(d)$ is represented by

$$P(d) = P(0)\exp(-\mu_a d) \qquad (2)$$

From Eqs. (1) and (2), energy spectra of scattered photons for various water equivalent material thicknesses were calculated. In this study, we considered the count measured in air as the primary count $P(0)$ and used the theoretical attenuation coefficient μ_a of $0.152\ cm^{-1}$ for water equivalent material.

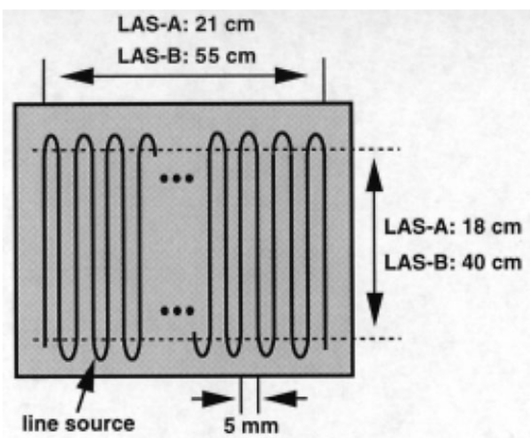

Fig. 1 Line array sources.

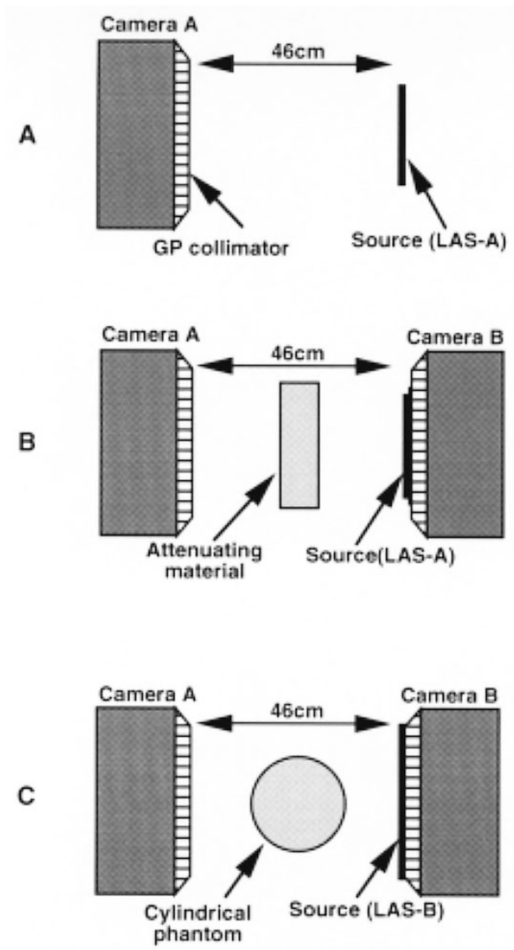

Fig. 2 Transmission data acquisition using a dual-head gamma camera with a parallel hole collimator and uncollimated line array source (LAS). A: energy spectrum measurement in air. B: energy spectrum measurement through the attenuator. C: TCT data acquisition.

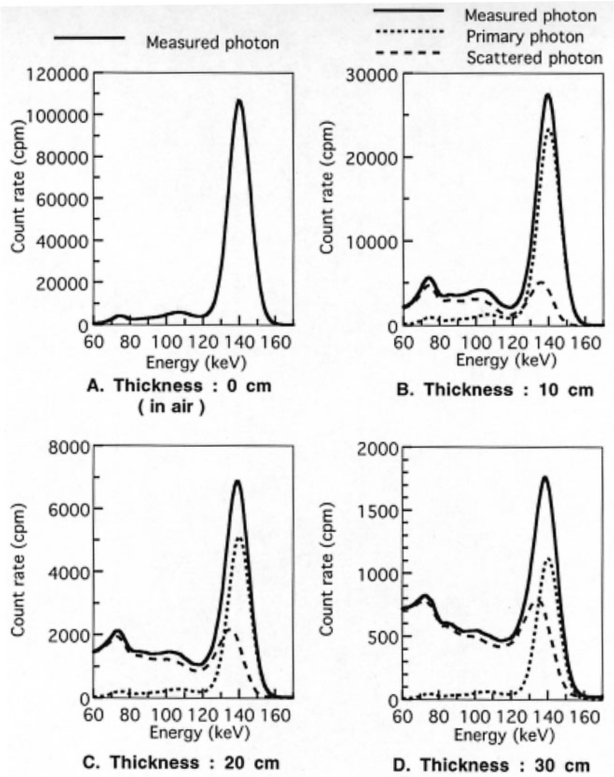

Fig. 3 Energy spectra measured for various thicknesses of attenuating materials.

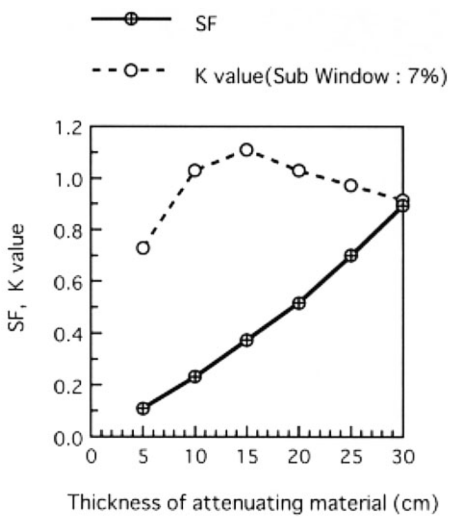

Fig. 4 Scatter fraction and *K*-value for the TEW method in transmission imaging.

B. TEW method for scatter correction in TCT and ECT imaging

1. Conventional TEW method

The scatter count within the main energy window is estimated by a linear interpolation between the two adjacent sub-windows:

$$Cp = Cm - Cs \tag{3}$$

where Cp is the estimated primary count, Cm is the count within the main energy window and Cs is the estimated scatter count. The scatter count Cs is calculated by

$$Cs = K \cdot (Cl/Wl + Cu/Wu) \cdot Wm \tag{4}$$

where Cl and Cu are the counts within a lower sub-energy window and an upper sub-energy window, respectively, Wm, Wl, and Wu are the widths of a main energy window, a lower sub-energy window, and an upper sub-energy window, respectively, and K is the subtraction factor. Conventionally, the triangle scatter approximation using a lower sub-energy window counts alone ($K = 0.5$ and $Cu = 0$) is employed for Tc-99m emission imaging.

2. Modified TEW method

From Eq. (4), the K value is determined according to scatter contribution on measurements of transmission energy spectra,

$$K = Cse/(Cl/Wl + Cu/Wu)/Wm \tag{5}$$

where Cse is the scatter count estimated from Eqs. (1) and (2).

C. Transmission CT (TCT) imaging

For a cylindrical water phantom with 20 cm-diameter, TCT scans were performed in 128 × 128 matrices with a pixel size of 4.3 mm and in 60 views over 360° using the uncollimated source, LAS-B (Fig. 2C). Total acquisition time was 20 min. A planar blank image for reconstruction of the attenuation coefficient map was acquired for 5 min. After two-dimensional Butterworth filtering (order of 8 and cutoff frequency of 0.1–0.14 cycles/pixel) for transmission data, TCT images were reconstructed by a filtered backprojection with a ramp filter.

RESULTS

A. Analyses of transmission energy spectra

Energy spectra for various thicknesses of attenuating materials are shown in Figure 3. The energy resolution was 10% at 140 keV from the measurement in air and the full energy window width covering the photopeak was 24% (123–157 keV) at 140 keV. As the thickness of the attenuating materials increased, scattered photons increased and the scatter peak was constructed within the photopeak. The center of the scatter peak was 136 keV (scatter angle 26.8°), 135 keV (30.1°), and 134 keV (33.2°) for the thicknesses of 10 cm, 20 cm, and 30 cm, respectively.

B. Determination of the best subtraction factor *K* for TCT imaging

The TEW method accurately corrects scatter in emission CT (ECT) imaging, but for TCT imaging using uncollimated external sources the TEW method using Eq. (3) and Eq. (4) with $K = 0.5$ has great errors in estimation of scattered counts within the photopeak. Therefore, to overcome this underestimation by the conventional TEW method, we investigated the subtraction factor K that accurately estimates transmission scatter including that within the photopeak.

The scatter fraction (SF), defined as the ratio of scattered counts to primary counts, and the subtraction factor K are plotted against the thickness of attenuating materials for the combination of the main energy window width (24%) and the lower sub-energy window width (7%) in Figure 4. The SF values were 0.23, 0.52, and 0.89 for the attenuating material thickness of 10, 20, and 30 cm, respectively. For the thickness range of 10 cm to 30 cm, the mean K value was 1.012. These values were about two times greater than the conventional K value, 0.5 in ECT scatter correction.

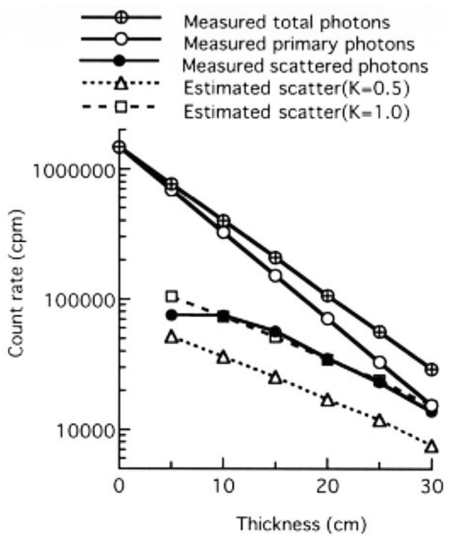

Fig. 5 Comparison between estimated and measured scattered photons' count rates for various thicknesses of attenuating materials.

Figure 5 shows the comparison between estimated scatter counts and measured (true) scatter counts. The TEW method with $K = 0.5$ was not sufficient to estimate the true scatter counts, but the TEW methods with $K = 1.0$ estimated the true scatter counts accurately for the wide range of the attenuating materials thickness (10 cm–30 cm).

C. Attenuation coefficient images of cylindrical water phantom

Attenuation coefficient images of the cylindrical water phantom (20 cmϕ) with and without scatter correction (SC) are compared in Figure 6. Attenuation coefficient images without SC had the low mean value of 0.114 cm^{-1}.

The TEW method with $K = 0.5$ gave inaccurate attenuation coefficient images with 0.127 cm^{-1}, but the attenuation coefficient value of 0.153 cm^{-1} by the TEW method with $K = 1.0$ was very close to the true attenuation coefficient of 0.154 cm^{-1} for water.

DISCUSSION

For attenuation correction in SPECT imaging, the method that assumes a uniform attenuator causes inaccurate quantification for non-uniform attenuator. So, the non-uniform attenuation correction techniques based on TCT imaging have been investigated.[12–22,24,25] We have also studied such non-uniform attenuation correction techniques with the combination of a line source and a symmetric fan beam collimator on the triple-head gamma camera,[21] and the combinations of a narrow plate source and an asymmetric fan beam collimator[22] and a large plate source and a parallel-hole collimator[23,25] on the dual-head gamma camera. In TCT images with the combination of a line source and a fan beam collimator, there are very few photons which are scattered within the attenuator.[11,12,17,19,20,24] However, the combination of an uncollimated source and a parallel-hole collimator causes a large number of scattered photons in TCT images and gives inaccurate attenuation coefficient maps.[14,15,18,19,24,25]

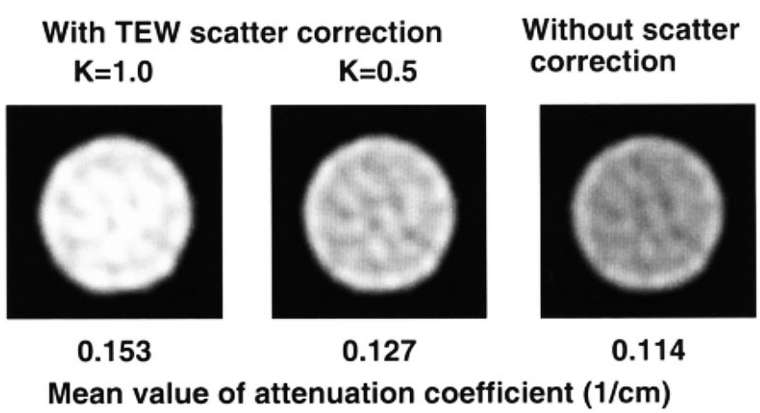

Fig. 6 Reconstructed attenuation coefficient images with or without the TEW scatter correction method.

Even when an uncollimated line source is used for TCT imaging, a fan-beam collimator makes transmission scatter fraction very low.[11] However, the results of our transmission energy spectrum measurements showed that the combination of an uncollimated Tc-99m source and a parallel-hole collimator makes a scatter energy peak between 134 and 136 keV within the photopeak of Tc-99m. This means that when the 140 keV photons pass through the attenuators, a lot of scattered events with small angles are generated and are accepted with the parallel-hole collimator. We tried to apply the TEW method to remove these scattered photons included in TCT images. The TEW method using a trapezoidal formula ($K = 0.5$ in Eq. 4) is effective in scatter correction for ECT imaging,[2,5] but we found that this conventional TEW method was not sufficient to remove scatter included in TCT data. From our analyses of the energy spectra, the appropriate K value was about 1.0 for the main energy windows of 24% (Fig. 5). We applied the TEW method with $K = 1.0$ to TCT imaging for a cylindrical water phantom (uniform attenuator, 20 cmϕ) and obtained the accurate attenuation coefficient maps for uniform water in comparison with the TEW method with $K = 0.5$ (Fig. 6).

An attenuation compensation method using the combination of an uncollimated line array source and a parallel hole collimator was proposed by Ichihara et al.[12] This method has many advantages in comparison with other attenuation correction methods based on TCT with external sources.[12] However, our experimental data showed that the ratio of the raw image count rates at the attenuation area (inside the attenuator) and the non-attenuation area (about 160 counts/20 sec/pixel, outside the attenuator) was about 0.07 for 20 cm water thickness and 0.02 for 30 cm water thickness. These ratios became smaller after scatter correction with the TEW method. In order to increase the count rate at the attenuation area, the longer TCT scan time or much line source activity is preferable, but increases the exposure dose to the patient. Therefore, with respect to the accuracy of TCT data, patient exposure, and the detector system's dead time, we think that a non-uniform line array source which has high activity distribution around the source center may be appropriate as an uncollimated external source. Now, we are investigating the effect of a non-uniform line array source experimentally, as compared with a uniform line array source.[25]

CONCLUSIONS

1. Scattered photons transmitting through the object have a peak within the main energy window: scatter peak at 135 keV (scatter angle 30°) in the water thickness of 20 cm.

2. In the water thickness of 20 cm the contribution of the total scatter counts was about 34% (scatter fraction: 0.52) of the total counts for the 24% main energy window.

3. For the TCT imaging with the combination of the uncollimated Tc-99m line array source and the parallel hole collimator, the TEW method with the subtraction factor $K = 1.0$ gives accurate attenuation coefficient data in comparison with the $K = 0.5$.

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