Title
A DETAILED MONTE CARLO STUDY OF MULTIPLE SCATTERING CONTAMINATION IN COMPTON TOMOGRAPHY AT 90 DEGREES

Permalink
https://escholarship.org/uc/item/5120n405

Author
Guerra, A. Del

Publication Date
1982-03-01
A DETAILED MONTE CARLO STUDY OF MULTIPLE SCATTERING CONTAMINATION IN COMPTON TOMOGRAPHY AT 90 DEGREES

Alberto Del Guerra, Ronaldo Bellazzini, Guido Tonelli, Renzo Venturi, and Walter R. Nelson

March 1982

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
A DETAILED MONTE CARLO STUDY OF MULTIPLE SCATTERING CONTAMINATION IN COMPTON TOMOGRAPHY AT 90 DEGREES

Alberto Del Guerra\(^{(1,+)}\), Ronaldo Bellazzini\(^{(2)}\), Guido Tonelli\(^{(2)}\), Renzo Venturi\(^{(3)}\), and Walter R. Nelson\(^{(4)}\)

Abstract

A low dose technique has been recently proposed for tomographic studies of the lung, which makes use of a gamma camera to detect 90° Compton scattered photons from external planar gamma source. In this paper we present a detailed Monte Carlo study of this technique. A 20 x 20 x 20 cm\(^3\) water phantom was simulated as a target and a large gamma camera equipped with imaging collimator as a detector. The multiple scattering contamination of the single scattered signal was studied as a function of the source-detector geometry and of the incident energy, in the range 100 to 500 keV. The multiple to single scatter ratio has an approximate \(1/E^{0.7}\) dependence and increases almost linearly with the phantom depth and the transversal thickness at 90°. Simulation has been also performed with a 16 x 16 x 10 cm\(^3\) sawdust phantom of 0.3 g/cm\(^3\) density; the Monte Carlo results agree to a few percent with experimental data.

* This work was supported in part by the Director Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
+ On leave of absence from: Istituto di Fisica, Piazza Torricelli, 2, I-56100 Pisa, Italy.

(1) Lawrence Berkeley Laboratory, Univ. of California, Berkeley, CA 94720
(2) Istituto di Fisica, Piazza Torricelli, 2 Pisa I-56100 Italy and INFN, Sezione di Pisa, S. Piero a Grado, I-56010 Pisa, Italy.
(3) Gruppo Nazionale di Elettronica Quantistica e Plasmi, Sezione di Pisa Piazza Torricelli 2, I-56100 Pisa, Italy.
(4) Stanford Linear Accelerator Center, P. O. Box 4349, Stanford, CA 94305, U.S.A.

The figures were printed from originals provided by the authors.
1. **Introduction**

The use of Compton scattered radiation to produce an image of a selected volume of human tissue for diagnostic purposes was originally proposed by Lale\(^{(1)}\) and Clarke\(^{(2)}\). The principle of this technique is to irradiate a biological target with a narrow monenergetic X- or gamma-ray beam (100-2000 keV) and to detect the fluence of photons scattered into a well defined solid angle in order to obtain information on the mass density of the target. For photons of that energy Compton scattering is the dominant interaction with all tissues. Then, the fluence of single scattered photons depends linearly upon the electron density of the target. The latter is related to the mass density through the weighted average of the atomic to mass number ratio of the biological sample. Several attempts have been made to exploit Compton scanners to a narrow beam geometry, mostly for densitometry studies of selected organs or tissues, and as a tool to aid for treatment planning. A detailed bibliography may be found elsewhere\(^{(3,4)}\). The main limitations to the density resolution derive from the attenuation of the incident beam and from the contamination introduced by multiple scattering of the photons in the target\(^{(5)}\). The latter produces an undesirable signal in the detector, which arises from a volume in the target other than the irradiated one. Thus, the information on the mass density of the selected volume is altered by the material around it.

More recently\(^{(6-9)}\) several applications have been made of the Compton scattering technique, which make use of extended gamma sources and large field gamma cameras to detect 90° scattered photons. The use of a large NaI (Tl) crystal of small thickness (typically 1/2") requires the choice of a low energy (below 500 keV) gamma source in order to have a reasonable efficiency at the 90° scattered photon energy. At the CNR Institute of Clinical Physiology, this technique has currently being applied to tomographic imaging.
of the lung (7), for both routine studies and continuous monitoring of patients who cannot be transported to a TCT (e.g., those with pulmonary edema). The experimental apparatus is commonly known as the COSCAT unit. These studies are of particular interest because of the very low dose involved, about 0.5 mGy (whole body for each tomogram), as measured with TLD dosimeters on an Alderson-Rando phantom (10).

We have previously shown how it is possible to correct the data obtained with the COSCAT unit (11) for attenuation of the incident beam. In this paper we present the results of a detailed Monte Carlo study of the multiple scattering contamination. Single (S) and multiple (M) Compton scattering at 90° are calculated at various incident energies between 100 and 500 keV. The ratio M/S as a function of the target depth and of the transversal thickness is discussed. Finally a comparison of the Monte Carlo results with experimental data is presented for the case of a sawdust phantom, 0.3 g/cm³ density.

2. Monte Carlo Technique and Problem Model.

For the simulation of Compton scattering from a phantom, the general electromagnetic radiation transport code EGS (Electron-Gamma-Shower) (12) was used. Details of the simulation may be found elsewhere (3). Two different types of sources have been considered: a "pencil" beam and a collimated line source. The pencil beam is described by a Dirac delta function in position, size, and angle. The second type of source corresponds to that of the COSCAT unit: Fig. 1 shows a schematic drawing of the experimental set-up. A monoenergetic line source, having a length of 80 cm and of negligible thickness, is placed in a parallelepiped box made of lead; a slit (0.3 cm x 60 cm) located 13.7 cm from the source, determines the length of the field and the solid angle subtended. The source irradiates a frontal (or a sagittal) section of a human thorax. A gamma camera, equipped with a
high resolution imaging collimator to improve background rejection, detects the Compton scattered radiation at $90^\circ$ and produces an image of the section irradiated. In the simulation neither self-absorption in the source, nor scattering within the collimator was considered. Photons which interact in and exit from the target are scored by outputting onto magnetic tape the various quantities of interest: incident and exiting energies, coordinates and direction cosines corresponding to these photons, the number of Compton scatterings that the photon has undergone inside the phantom, and the angular details associated with each of these scatterings. The program is extremely fast as far as programs of this type are concerned. As many as 800 photons per second are generated and followed on the IBM-370/168 (that is, about 1.2 ms per photon history).

Once the Monte Carlo data have been written onto magnetic tape, a subsequent analysis program is used to simulate the detector and to histogram and plot the results of interest. The detector is a large field gamma camera equipped with an imaging collimator that only accepts events around $90^\circ$ to the phantom relative to the beam direction. Only the geometric acceptance of the collimator has been considered and no studies of edge/septum effects have been attempted. The collimator has been simulated as a series of "virtual" cylindrical holes, each centered on the exit point of the scattered photon from the target surface. A photon which is within the solid angle subtended by the hole is transmitted through and reaches the gamma camera; otherwise it is considered "absorbed" by the collimator. Various diameters of the virtual cylinders, each of length 50 mm, have been simulated between 1 mm to infinity i.e., no collimator). In the sections that follow we refer to the various sizes of the virtual collimator as $D_1$, $D_2$, ..., $D_{25}$, $D_0$, where the subscript indicates its diameter in mm. The gamma camera response has been also simulated in the following manner. The energy and the position of
the scattered photons are sampled under Gaussian distributions, taking into account the energy and spatial resolution of the gamma camera. The photons are then weighted according to the corresponding photopeak efficiency. Typical resolution data at the three energies chosen for the simulation are listed in Table 1. Analytical fits have been used in the analysis program to provide a continuous interpolation.

3. Monte Carlo Results.

In the pencil beam case, three incident photon energies (100, 279, 500 keV) were chosen. For the collimated line source case we only considered the midpoint energy (279 keV), which is the gamma line of $^{203}$Hg. In either situation the target was a $20 \times 20 \times 20$ cm water phantom. The active region of the gamma camera was $20 \times 20$ cm in the analysis program, corresponding to the target surface itself. The Monte Carlo calculation was terminated whenever a photon reached an energy corresponding to the Compton backscatter energy, except for the 500 keV case, where a higher energy cutoff was used (Table 1).

3.1 - Pencil Beam Results

In Fig. 2 we show typical calculated spectra (single and multiple scattering) for three incident photon energies and for three virtual collimators ($D_{0}$, $D_{10}$, $D_{3}$). The response of the gamma camera was not included (in this figure only). In Fig. 3 we show the multiple to single ratio, M/S, when the spectral response of the detector is included and the integration is performed over the energy window (Table 1).

We have studied the single and multiple scattering dependence on the target depth at three incident energies. Figure 4 shows the single (solid and
multiple (dashed) scattering histograms for a $D_3$-type collimator. The solid lines are exponential fits to the single scatter component. The dashed lines indicate the trend of the Compton build-up of multiple scattering events. The peak of the multiple scattering distribution moves to higher depth as the source energy increases.

3.2 - Collimated Line Source Results

A $^{203}$Hg (279 keV) collimated line source (0.3 cm $\times$ 60 cm) was simulated as described in Section 2. The energy and spatial distributions obtained for a 3 mm collimator are shown in Fig. 5. The solid and dashed histograms are for single and multiple scattering events, respectively. The spatial resolution (FWHM) for single scattering events is 7.5 mm, whereas the intrinsic resolution of the gamma camera is 5.4 mm at 180 keV (Table 1).

The dependence of the M/S ratio upon the depth into the target is shown in Fig. 6 (solid circles). On the same figure the ratio between double and single scattered photons is also plotted (open circles). The transversal thickness to the detector was 10 cm, corresponding to the line source being centered on the $20 \times 20 \times 20$ cm$^3$ target. The dependence of M/S on the transversal thickness is shown in Fig. 7, where the straight lines are fits to the Monte Carlo data at three different depths.

4. Discussion.

In absence of any collimation ($D_\infty$-type collimator), the 90° single scattering peak is spread out because the solid angle acceptance is large. This is clearly visible in Figs. 2a-c, where the multiple scattering is greater than the single component. A rather tight spatial collimation is required in order to reduce the M/S ratio to a suitable level for clinical applications. A $D_3$-type collimator is representative enough of a typical imaging collimator used with conventional gamma camera. The results for such a
collimator, plotted in Figs. 2g-i, show that the multiple scattering contamination drops by one order of magnitude at all the three energies. A dependence of the M/S ratio upon the incident photon energy can be determined from the data in Fig. 3 for D₁₀ collimators. Figure 3 also shows that M/S does not change appreciably in going from D₁₀ to D₃, and further decrease is limited by the finite energy resolution of the gamma camera. Furthermore any reduction of the collimator diameter will reduce the sensitivity of the system, leading to an increase in the dose delivered to the patient (i.e., for the same number of detected photons). A reasonable compromise between position accuracy and density resolution, which is chosen in clinical application (7), is well simulated by a D₃-type collimator.

Apart from marginal edge effects which would reflect different conditions of irradiation, it has been previously shown (see Fig. 14 of Ref. 3) that the results are very similar for the collimated line source and the pencil beam at the same energy. It is reasonable to assume that for small collimator apertures (D₃-D₁₀) the M/S ratio remains essentially the same for either source. In general, given a uniform illumination of the front face of the phantom, most of the results obtained for the pencil beam case may also be applied to extended sources.

The M₂/S data of Fig. 6 show a linear dependence with z, the depth into the phantom. This can be justified using a simple model, provided that the proper energy and spatial resolution of our collimator-gamma camera system are taken into account. To a lesser extent the M/S data can be also parametrized as linear with z. Along with the linear parametrization shown in Fig. 7, it is reasonable to assume, particularly for phantom depths less than 10 cm, that \( M/S = c₁z + c₂t_⊥ \), where \( c₁ \) and \( c₂ \) are constants, and \( t_⊥ \) is the transversal thickness to the detector.
4. **Comparison of Monte Carlo Results and Experimental Data**

A $^{203}$Hg line source defined by a $0.3 \text{ cm} \times 60 \text{ cm}$ slit (see Section 2) was used in the experiment. The target consisted of a box filled with wet sawdust having a density of $0.3 \text{ g/cm}^3$. The box was constructed out of $0.16 \text{ cm}$ thick perspex with dimensions $16 \text{ cm} \times 16 \text{ cm} \times 10 \text{ cm}$ (see insert to Fig. 8). A large-field gamma camera (TOSHIBA Jumbo Camera - GCA 202) equipped with a medium-energy, high-resolution type collimator was located at right angles to the box in order to detect scattered photons. The digital output of the gamma camera was in the form of a $64 \times 64$ matrix with a pixel size of $0.5 \text{ cm} \times 0.5 \text{ cm}$. The experimental data, however, was limited to a $32 \times 32$ matrix located well inside the acceptance field of the camera. The number of counts for each pixel was averaged over the dimensions of the matrix parallel to the linear source and rebinned into 16 bins in order to reduce the statistical errors. The data thus obtained are presented as a function of the phantom depth in Fig. 8 (solid circles).

The Monte Carlo simulation for the same $16 \text{ cm} \times 16 \text{ cm} \times 10 \text{ cm}$ sawdust box, normalized to the total number of counts between 0 and 14 cm, is shown as a histogram in Fig. 8. The statistical error associated with each of the histogram bins is of the order of $10\%$. The gamma camera performance and a $D_3$-type collimator were considered in the simulation.

The Monte Carlo calculation reasonably simulates the experiment; both include primary beam attenuation, divergence and multiple scattering effects.
In order to better understand this, two corrections were applied to the experimental data, as described in reference (11). First the raw data (solid circles), were corrected for attenuation of the incident beam (open circles) and a straight line fit was made to these points (i.e., line a) in Fig 8). Second, line b) is the result of applying the beam divergence correction to line a). A definite upward slope is clearly present, which we attribute to multiple scattering in the phantom. In fact, if we superimpose the histogram of ratio of the total \((S + M)\) to single \((S)\) scattering, obtained from the Monte Carlo simulation of this problem, the agreement is quite good.

From the results presented in Fig. 8, we may conclude that a positive linear bias as large as 25% would be introduced for such a phantom, if the multiple scattering correction is not applied. A similar qualitative trend has also been observed in different experimental conditions, i.e., narrow beam geometry and small volume target (13-15).

5. Conclusions.

In this paper we have extended the simulation of the Compton Scatter method to photon energies and geometries which are particularly suited to gamma cameras. We have extensively investigated the multiple scattering contamination in 90° Compton scattering as a function of the incident photon energy. For a \(20 \times 20 \times 20 \text{ cm}^3\) water phantom, when the detector is a gamma camera equipped with conventional imaging collimator, such a contamination at low energy (100 keV) is of the same order of magnitude as the 90° single scatter signal. The M/S ratio goes approximately as \(1/E^{0.7}\) and is rather independent of the collimator diameter in the 3 mm to 10 mm range. A linear \(^{203}\text{Hg}\) (279 keV) line source has been simulated, which is representative of that currently used in clinical applications for detecting the overall distribution of the lung density and for monitoring changes of lung pathology. The M/S ratio has been studied as a function of the depth.
into the phantom and of the transverse thickness to the detector. A linear parametrization of $M/S$ could be useful, at least for small thicknesses (less than $10 \text{ cm}^2/\text{g}$). Further work is in progress to use this linear correction for the clinical data, where high gradient density inhomogeneities are present.

Finally the use of the EGS code and the source sampling scheme has reduced the computer time limitations normally encountered in problems of this type (i.e., low efficiency simulation). Because of its versatility and modularity, the EGS code might have several other applications to similar situations, such as single photon tomography and positron tomography\textsuperscript{(16)}. 

-10-
REFERENCES


C. Giuntini, R. Guzzardi, M. Pistolesi, M.Mey and S. Solfanelli, "Evaluation of a system for 90° Compton scattering in lung


Table 1. Kinematics and typical performance of the gamma camera.

<table>
<thead>
<tr>
<th>Incident energy (keV)</th>
<th>100.0</th>
<th>279.0</th>
<th>500.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>E' (90°) (keV)</td>
<td>83.6</td>
<td>180.5</td>
<td>252.7</td>
</tr>
<tr>
<td>Backscatter energy, E'(180°) (keV)</td>
<td>71.9</td>
<td>133.4</td>
<td>169.0</td>
</tr>
<tr>
<td>Energy cutoff used in the Monte Carlo calculation (keV)</td>
<td>71.9</td>
<td>133.4</td>
<td>220.0</td>
</tr>
<tr>
<td>Photopeak efficiency at E' (90°)</td>
<td>1.00</td>
<td>0.83</td>
<td>0.60</td>
</tr>
<tr>
<td>ΔE/E (FWHM) at E' (90°)</td>
<td>0.142</td>
<td>0.111</td>
<td>0.102</td>
</tr>
<tr>
<td>Spatial resolution (FWHM) at E' (90°) (mm)</td>
<td>7.33</td>
<td>5.36</td>
<td>4.88</td>
</tr>
<tr>
<td>Energy window setting about E' (90°) (keV)</td>
<td>75-90</td>
<td>165-195</td>
<td>235-270</td>
</tr>
</tbody>
</table>
Figure Captions

1. Schematic drawing of the COSCAT apparatus: a $^{203}$Hg line source collimated to a narrow planar beam, irradiates a section of the human thorax; a large field gamma camera detects the $90^\circ$ Compton scattered photons.

2. Typical spectra of single (solid) and multiple (dashed) scattered photons for three incident photon energies (100, 279, 500 keV) and three types of collimators: a), b) and c) with no-collimation; d), e), and f) a 10 mm diameter; g), h) and i) a 3 mm diameter collimator (Note: gamma camera response not included).

3. Multiple to single scattering ratio as a function of the incident photon energy for three collimators: a) no collimation, b) 10 mm diameter and c) 3 mm diameter collimator. M/S has been integrated over the acceptance window of the gamma camera.

4. Single (solid) and multiple (dashed) scattering distributions as a function of the depth into the target for a 3 mm diameter collimator: a) incident energy 100 keV, b) 279 keV and c) 500 keV.

5. Typical results for the $^{203}$Hg line source and 3 mm diameter collimator: a) energy spectrum for single (solid) and multiple scattering (dashed); b) spatial distribution for single (solid) and multiple scattering (dashed).

6. Multiple to single scatter ratio (solid circles) and double to single scatter ratio (open circles) for the line source and a 3 mm diameter collimator. (The solid lines are linear fits to the data.)

7. Linear dependence of the multiple to single scatter ratio upon the transversal thickness to the detector for three target depths.

8. Comparison of the Monte Carlo results with the experimental data taken with a sawdust phantom (density 0.3 g/cm$^3$), as described in the insert. The solid circles are the experimental raw data and the superimposed
histogram is the Monte Carlo simulation. The open circles are the experimental data after the attenuation correction has been applied and the solid line a) is a linear fit to these points. The solid line b) is the effect of applying a further geometric correction for the beam divergence. The total to single scattering ratio, as obtained by Monte Carlo calculation, is also superimposed as a histogram (right-hand scale).
 FIG. 4

E=100 KeV

E=279 KeV

E=500 KeV

z(cm)

counts

XBL 823-8163

-20-
FIG. 5

Line source
D₃-type collimator

Counts

E(KeV)

FIG. 5
XBL 823-8162

-21-
Collimated Line Source
\( E = 279 \, \text{KeV} \)

**Figure 6**

![Graph showing the ratio of counts per unit depth into the phantom for different energy levels. The graph plots the ratio against depth into the phantom (cm). Two lines are shown, labeled \( M_x/S \) and \( M_2/S \), with error bars indicating variability.]
Collimated Line Source
E=279 KeV

$Z=1\,\text{cm}$

$Z=3\,\text{cm}$

$Z=9\,\text{cm}$

TRANSVERSAL THICKNESS (cm)

FIG. 7
Fig. 8

COUNTS x 10^2

Depth into the phantom (cm)

1.5
1.0
1.1
1.3
1.4
1.5
-2
-1.2
-1.3
-1.4
-1.5

Mean photon direction

Slit size 0.3 x 60 cm

203Hg source

XBL 823-8166
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.