Evaluation of Detection Characteristics for Scanning-Type Whole-Body Counter

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Abstract. As an alternative to the phantom used for calibrating whole-body counters, in this study the Monte Carlo simulation was used to evaluate peak efficiencies for a whole-body counter installed at the JNC, to examine the validity of using the simulation technique to calibrate the whole-body counter. Prior to simulating a phantom, the sensitive region of the crystal in the Ge detectors which are used with the whole-body counter, was evaluated by assuming dead layers in the simulation. The phantom was then simulated based on the determined configuration of the sensitive region. As a result, the calculated peak efficiencies were fairly consistent with the measured ones. For an entire body scanning measurement, the discrepancy between the measurement and the simulation was within 4% for peak energies ranging from 81.0 keV to 1460.8 keV. The simulation technique is therefore both effective and practical for situations that are difficult to be simulated by a phantom.

1. Introduction
A whole-body counter is used to determine the total content of radionuclides within a body. The counter consists of a γ-ray spectrometer with shielding, and the measured object is a person. In order to obtain peak efficiencies, an anthropomorphic phantom that contains known activity is required. Standardized phantoms, which meet the physical characteristics of a representative subject, are generally used and are also recommended in national standards [1]. However, in order to evaluate the dose accurately in the case of serious internal contamination, a more realistic phantom is necessary, but it is difficult to fabricate a realistic phantom in practice for each case. Therefore, the uncertainty of peak efficiency remains an issue for measurement with a whole-body counter. Monte-Carlo simulations may provide an alternative method of calibration using a phantom, and some papers have already demonstrated their effectiveness and potential [2]-[5]. The main advantage of such simulations is that peak efficiencies can be obtained for various body sizes of subjects and even for organs or tissues that are difficult to be simulated by a phantom. Recent progress in computer technology also enables more complex and realistic simulations to be performed.

In this paper, a simulation was performed to obtain peak efficiencies for a whole-body counter equipped with scanning germanium (Ge) semiconductor detectors at the Japan Nuclear Cycle Development Institute (JNC). Some papers reported application of the Monte-Carlo simulation to a whole-body counter equipped with a thallium-activated sodium iodide [NaI(Tl)] but there have been very few studies on counters equipped with Ge detectors. In this study, we examined the reliability of calibration using the Monte-Carlo simulation for our whole-body counter and set out to obtain useful information regarding detection characteristics.

2. Materials and Methods
2.1. Experiments
The JNC developed a whole-body counter having dual Ge detectors which scan along the body axis of a subject. The whole-body counter is shown in Figure 1. The counter is shielded within a room having steel walls, ceiling and floor that are 20 cm thick, and internal dimensions of 200 (height) × 200 (width) × 250 (length) cm. The detectors are n-type high-purity germanium (HPGe) closed-ended coaxial detectors with 50% nominal efficiency (EG&G Ortec Model, GMX-50S) and are collimated by lead of 3 cm thickness in order to improve the positional resolution. The driving of the Ge detectors is controlled by software. The scanning range and speed can be selected arbitrarily from 0 cm (head side) to 190 cm (foot side) and from 1 cm/min to 20 cm/min respectively.

The phantom used in this study consisted of 11 cylindrical vessels which were uniformly filled with radioactivity in a composite with soft tissue-equivalent density. The radionuclides contained in the composite were 133Ba, 137Cs, 60Co and 40K, the major peaks of which cover an energy range to obtain a
peak efficiency curve. The activities, elemental composition and density of the phantom were certified by the manufacturer. The relative intrinsic errors of the activities were 5%. The walls of the vessels were 5 mm-thick polymethyl methacrylate, and the vessels were covered with 5 mm-thick polyvinyl chloride. The dimensions of the vessels are shown in Table 1. In the study, response functions of the detectors for the phantom were measured to obtain peak efficiencies, which were compared with those of the simulation. The phantom was fixed on the bed of the whole-body counter and measurements were performed with the Ge detectors at different locations and scanning along the entire phantom. The peak analysis of the response functions was performed using commercially available software (Gamma Studio system, Seiko EG&G Co., Ltd.).

2.2. Monte-Carlo simulation
Peak efficiencies of the phantom were evaluated by the Monte-Carlo simulation, using the MCNP4C code [6]. This code provides a general-purpose program that can simulate photon interactions with associated electron transport and production of X-ray and Bremsstrahlung radiation. It uses continuous-energy data libraries over a wide range of energies for various cross sections and scattering angles.

In order to evaluate peak efficiencies for the phantom with the whole-body counter, it is necessary to build a proper model. In this calculation, the entire system of the whole-body counter except for the shielding was modeled as accurately as possible. However, it is difficult to determine the detailed structure of each part of the Ge detector, and in particular the precise dimensions of the sensitive region of the Ge crystal. Therefore, in this study a convenient method was used to determine the sensitive region of the crystal, as described later.

The number of the history of the simulation was determined properly to reduce statistical uncertainties. The Monte-Carlo energy-bin width was set at 0.5 keV so that the conditions were the same as in the measurement. Photons were assumed to be isotropic in case of calculations for the phantom, i.e. to be uniformly distributed within volume sources. No variance reduction technique was used.

In this study, a pulse height tally, which is provided with the MCNP4C code, was used for evaluating peak efficiencies. Peak efficiency was obtained from the probability in the energy bin of interest and was corrected by subtracting the average of the probabilities in both sides of the energy bin as Compton continua. A folding technique with a Gaussian distribution was not used in the simulation since a comparison of measured response and simulated response function was not the objective of this study. Calculations were performed for major peak energies of nuclides contained in the phantom: 81.0, 276.4, 302.9, 356.0, 383.9, 661.6, 1172.5, 1332.5 and 1460.8 keV.

2.2.1. Modelling of the Ge detectors
The calculation geometry of the Ge detector is shown in Figure 2. The geometry was assumed to be composed of multilayer cylinders. The crystal dimensions are given in Table 2 according to the manufacturer’s data. However, the actual sensitive region is not the whole of the crystal volume. In this study, dead layers with uniform thickness were assumed to exist at the outer and inner surfaces of the crystal. An n-type germanium detector has an outer electrode of p+ contact and an inner electrode of n+ contact. Typically, the former is about 0.3 µm thick and the latter is about 1 mm thick respectively [7]. It was thought that dead layers exist around the regions of the electrodes [8].

The objective of the procedure is not to determine the precise structure of the dead layers, but to evaluate the sensitive volume in order to calculate the phantom. A similar approach assuming dead layers was described elsewhere [9].

2.2.2. Calculation of peak efficiencies for the phantom
The peak efficiencies of the phantom were obtained by

$$\varepsilon_{\text{eff}} = \frac{\sum A_k \cdot \varepsilon_k}{\sum A_k}$$  \hspace{1cm} (1)
where, $\varepsilon_W$ is the peak efficiency for the whole parts of the phantom, and $A_k$ and $\varepsilon_k$ are the activity contained in the $k$-th part and the peak efficiency of it, respectively. $\varepsilon_W$ varies with the location of the Ge detectors and was calculated at different locations as shown in Figure 3. The peak efficiency of an entire body scanning measurement, $\varepsilon_S$, was obtained by

$$
\varepsilon_S = \frac{\left( \varepsilon_W (1) \right)}{2} + \sum_{i=2}^{11} \varepsilon_W (i) + \frac{\varepsilon_W (11)}{2} \nonumber
$$

where, $\varepsilon_W (i)$ is $\varepsilon_W$ at the $i$-th calculated position as shown in Figure 3. The number of history was determined to be 2 million per part of the phantom so the relative error of $\varepsilon_W (i)$ was within several percent.

3. Results and Discussions

3.1. Determination of dead layer thickness in crystal

To determine the dead layer thickness of the crystal, the relationship between calculated peak efficiency and dead layer thickness was obtained by the simulation. Since a photon with low energy does not penetrate a deep region of the crystal, the dead layer thickness of the outer surface was evaluated using the 81.0 keV of $^{133}$Ba, and that of the inner surface was evaluated using the 1332.5 keV of $^{60}$Co. The neck part of the phantom, which was positioned on the bed of the whole-body counter along the center-line of the Ge detector, was used because its diameter is closer to that of the end cup than other volume sources available. Table 3 gives the results of the dead layer thickness evaluated by the simulation.

Using the dead layer thickness shown in this table, the peak efficiencies of other energies were calculated for the neck and the head part of the phantom. As a result, the discrepancy of the measured and calculated peak efficiencies was within several percent.

3.2. Simulations for the phantom

The calculation of the phantom was performed based on the configuration of the Ge detectors described above, and the peak efficiencies summed for both Ge detectors were used for comparison between the measurement and the simulation.

Figure 4 compares the measured and calculated peak efficiencies $\varepsilon_W$ for different locations of the Ge detectors. The 81.0 keV of $^{133}$Ba and the 1332.5 keV of $^{60}$Co are shown in this figure. Although discrepancies of $\varepsilon_W$ can be seen for some locations of the detectors, the average was within about 10% for calculated energies. The uncertainties in the positioning of the phantom or uniformity of the radioactivity in the composite would be the main causes of these discrepancies. The variation of $\varepsilon_W$ as shown in Figure 4 was a response obtained from the phantom filled with radioactivity uniformly throughout an entire body and seems to be reflected by active volume in the detectable view of the Ge detector.

A scanning measurement is not only effective but also practical for identifying body content profile for a whole-body counter with limited detectors. According to the ICRP’s biokinetic models, incorporated radionuclides move to various organs or tissues with time. Therefore, an understanding of the body content profile would be useful for a more precise evaluation. The Monte-Carlo simulation is expected to provide suitable counting efficiencies reflecting the body content profile.

Figure 5 compares the calculated and measured peak efficiencies $\varepsilon_S$ for an entire body scanning measurement. The error bars are indicated only for the measurement values. As shown, the calculated peak efficiencies were in fairly good agreement with the measured ones, within 4% for calculated energies. The peak efficiency at 150 keV is indicated only for calculation in order to obtain a proper peak efficiency curve.

4. Conclusions

Peak efficiencies for a whole-body counter equipped with Ge semiconductor detectors were evaluated using the MCNP4C code. In preparation for simulating the phantom, the sensitive volume of the crystal in the Ge detectors was determined by adjusting the dead layer thicknesses around electrodes in the simulation so that the calculated peak efficiencies were consistent with the measured ones using a
part of the phantom. The phantom was simulated based on the detector’s modelling mentioned above. As a result, the simulation for a scanning measurement was in fairly good agreement with the measurement, within 4% for energies ranging from 81.0 keV to 1460.8 keV. The result shows the validity of using the Monte-Carlo simulation to evaluate peak efficiencies for a whole-body counter equipped with Ge detectors, and the simulation technique was proved to be effective for calibrating a whole-body counter instead of an expensive phantom. In addition, the simulation is expected to provide suitable peak efficiencies reflecting body content profile.

References
FIG.1 The whole-body counter with scanning Ge detectors.
(The detector is installed under the bed for a subject.)

FIG.2 Modeling of the Ge semiconductor detector.
FIG. 3 Locations of the Ge detectors for calculation to obtain the peak efficiency for an entire body scanning measurement.
FIG. 4 Comparison of calculated and measured peak efficiencies, $\varepsilon_p$, for different locations of detectors.
FIG. 5 Comparison of calculated and measured peak efficiency, $\varepsilon_S$ for an entire body scanning measurement.
Table 1 Specifications of the phantom used in this study.

<table>
<thead>
<tr>
<th>Section</th>
<th>a (cm)</th>
<th>b (cm)</th>
<th>H (cm)</th>
<th>Active Vol. (liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>22</td>
<td>©</td>
<td>22</td>
<td>6.2</td>
</tr>
<tr>
<td>Neck</td>
<td>11</td>
<td>©</td>
<td>11</td>
<td>0.65</td>
</tr>
<tr>
<td>Breast</td>
<td>32</td>
<td>22</td>
<td>22</td>
<td>9.4</td>
</tr>
<tr>
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<td>22</td>
<td>22</td>
<td>10.0</td>
</tr>
<tr>
<td>Hip</td>
<td>32</td>
<td>22</td>
<td>22</td>
<td>10.0</td>
</tr>
<tr>
<td>Arm</td>
<td>11</td>
<td>©</td>
<td>51</td>
<td>3.0</td>
</tr>
<tr>
<td>Thigh</td>
<td>16</td>
<td>©</td>
<td>30</td>
<td>4.2</td>
</tr>
<tr>
<td>Leg</td>
<td>12</td>
<td>©</td>
<td>41</td>
<td>3.0</td>
</tr>
</tbody>
</table>

a: length of major axis
b: length of minor axis
H: height of cylinder

Table 2 Dimensions of the Ge semiconductor detector as specified by the manufacturer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detector #1</th>
<th>Detector #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal diameter</td>
<td>63.8</td>
<td>65.3</td>
</tr>
<tr>
<td>Crystal length</td>
<td>73.3</td>
<td>77.3</td>
</tr>
<tr>
<td>End cap to crystal distance</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Absorbing layer (end cap) of beryllium</td>
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<td>0.5</td>
</tr>
<tr>
<td>Dead layer on the outer surface of crystal</td>
<td>0.0003</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 Evaluated dead layer thickness

<table>
<thead>
<tr>
<th>Detector</th>
<th>Outer surface</th>
<th>Inner surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>4.76e-2 mm</td>
<td>2.75 mm</td>
</tr>
<tr>
<td>#2</td>
<td>3.97e-2 mm</td>
<td>2.09 mm</td>
</tr>
</tbody>
</table>