Evaluation of Counting Efficiency of Whole–body Counter using Voxel Phantoms

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Abstract. The calibration methods for *in vivo* measurement systems using Monte Carlo simulations and voxel phantoms have been demonstrated. The calibration data, such as counting efficiency or response function, calculated by the UCWBC code that was developed in the Japan Atomic Energy Research Institute were compared with those measured with an *in vivo* measurement system. It was found that the calibration data calculated by the UCWBC code show good agreement with measured ones. The mathematical calibration method of *in vivo* measurement systems using voxel phantoms was found to be useful for the improvement in accuracy of the measurement results.

1. Introduction

The recommendations of the International Commission on Radiological Protection (ICRP) [1,2] require greater improvement in the performance capabilities available from *in vivo* measurement systems to achieve a good individual monitoring for intakes of radionuclides. Hence, a sophisticated calibration method for *in vivo* measurement systems is of considerable practical significance in order to obtain calibration data applicable to a given subject. Several studies [3–8] have been conducted on the use of Monte Carlo simulations in calibrating *in vivo* measurement systems. It is possible to evaluate by the simulations calibration data for a radionuclide deposited in any assumed pattern relative to the detectors, taking into account geometrical and attenuation factors. In recent years, the calibration methods for *in vivo* measurement systems using Monte Carlo simulations and voxel phantoms have been demonstrated [3,5,6,8]. Voxel phantoms are anthropomorphic models generated from computed tomography (CT) or magnetic resonance imaging (MRI) sections to provide three-dimensional representations of the required body. There has been growing recognition that calibration data can be obtained under specific conditions such as real individuals in detail.

In the Japan Atomic Energy Research Institute (JAERI), some calculation codes using voxel phantoms have been developed as EGS4 [9] user codes [10]: UCPIXEL code for external dosimetry [11], UCSAF code for internal dosimetry [12] and UCWBC code for calibrating *in vivo* measurement systems. There exists a need to examine usefulness of the codes in radiological protection. The present study was performed to validate the EGS4–UCWBC code (hereinafter UCWBC code). Furthermore, the counting efficiencies for the adult voxel phantoms developed in JAERI were evaluated by the code in order to examine the differences between the counting efficiencies for practical phantoms and those for the voxel phantoms.

2. MATERIALS AND METHODS

2.1. In vivo measurement system

A whole–body counter in JAERI was applied to an object of the study. A p–type high–purity Ge (HPGe) closed–ended coaxial detector was installed in the whole–body counter in order to make a preparatory experiment for designing a precision whole–body counter [13]. The crystal of the detector (EG&G Ortec Model GEM–80205) is 73.2 mm in diameter and 85.8 mm in length. The nominal dead layer thickness on the outer surface of the Ge semi–conductor crystal is 0.7 mm. The peak efficiency, relative to that of a 76.2 mm diameter × 76.2 mm thick NaI(Tl) crystal, is 83.5 %, measured for 1,332 keV photons from a source of ^{60}Co at 25 cm; the energy resolution at 1,332 keV is 1.97 keV. The whole–body counter has a shielding that consists of a room with 200 (height) × 80 (width) × 200 (length) cm^3 of internal dimensions and 21cm thick wall of steel. The inner sides of the room are lined with 3 mm thick lead.

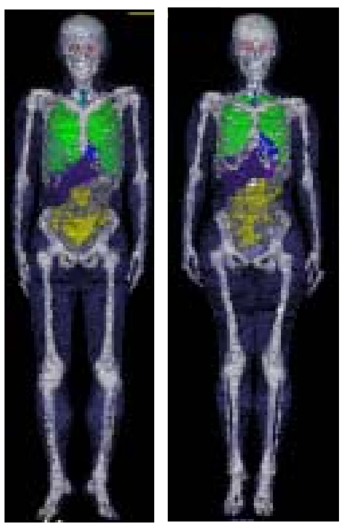
2.2. Phantoms

The whole–body counter is usually calibrated with water–filled block–shape phantoms (the height 168.0cm and the mass 58.1kg), of which size is fitted to the average size of workers in JAERI. The phantom consists of thirteen vessels of rectangular cross section, and is uniformly filled with radioactivity (^{137}Cs or ^{40}K) in aqueous solution. The walls of the vessels are made of vinyl chloride and are 5 mm in thickness. The sizes of the phantom and loaded activities of vessels are listed in Table 1. The relative intrinsic errors of activities filled in the vessels were ±5 %.

Table 1. Specification of the water–filled block–shape phantom used in JAERI

Parts	Height (cm)	Width (cm)	Length (cm)	^{137}Cs activities (Bq)	^{40}K activities (Bq)
Head	16.7	13.3	18.0	1.99×10^2	2.21×10^3
Neck	8.7	7.8	8.5	2.21×10^1	2.44×10^2
Chest	19.4	29.1	20.3	6.18×10^2	6.85×10^3
Abdomen	16.1	25.0	20.3	4.31×10^2	4.76×10^3
Arm	7.4	6.6	51.0	1.02×10^2	1.13×10^3
Pelvis	18.8	28.2	23.6	6.79×10^2	7.51×10^3
Thigh	12.7	11.4	33.0	2.35×10^2	2.60×10^3
Lower leg	8.6	7.7	37.7	1.08×10^2	1.20×10^3
Foot	16.8	8.4	6.6	3.72×10^1	4.13×10^2

In the present study, the water–filled block–shape phantom was represented as a voxel phantom whose voxel size is 1×1×1 mm^3. The voxel version of the water–filled block–shape phantom was applied to the Monte Carlo simulation to compare the calibration data between those by simulation and those by measurement. Two other voxel phantoms developed in JAERI were also used for the evaluation of calibration data. These are Japanese adult male and female phantoms, which are called "Otoko" phantom (the height 170 cm and the mass 65 kg) [11] and "Onago" (the height 155 cm and the mass 53 kg) [14], respectively. The Otoko and Onago phantoms are shown in FIG.1. The voxel phantoms were made by construction techniques developed at GSF–Forschungszentrum für Umwelt und Gesundheit [15]. The Otoko and Onago phantoms are constructed from CT data of real persons. The CT data are 512 pixel × 512 pixel resolution. The voxel size is 0.98 × 0.98 × 10.0 mm^3.



Otoko Onago

FIG. 1. Anterior three-dimensional view of the Otoko [10] and Onago [13] phantoms.

2.3. Monte Carlo simulation

Peak efficiencies of the Ge semi–conductor detector for three voxel phantoms were evaluated by the Monte Carlo simulation. The Monte Carlo simulation was carried out using the EGS4–UCWBC code. In the UCWBC code, the radiation transport of electrons, positrons and photons can be simulated, and correlations between primary and secondary particles are included. The cross–section data for photons are taken from PHOTX for EGS4 code [16,17], and the data for electrons and positrons are taken from ICRU report 37 [18,19]. The number of the history of the simulation was determined to be 10 million in order to reduce statistical uncertainties below 5%. No variance reduction technique was used. The transport cut–off energy was set as 1 keV for photon and 10 keV for electron.

The calculation geometry of the Ge semi–conductor detector was assumed to be composed of multi–layer cylinders by adopting the manufacturer's specification data. The detector's internal dimensions for the calculations are listed in Table 2. The calculation geometry of the sources, the water–filled block–shape phantom, bed and shielding were modeled to meet actual characteristics as accurately as possible (FIG.2). The water–filled block–shape, Otoko and Onago phantoms were in a standard counting position that is used with subjects. The photon sources were assumed to be monoenergetic and to be homogeneously distributed within the contents of the vessels for water–filled block–shape phantom and the Otoko and Onago phantoms.

Table 2. Properties of a Ge semi–conductor detector as specified by the manufacturer

Parameter	Dimension (mm)
Crystal diameter	73.2
Crystal length	85.8
Core hole diameter	9.2
Core hole length	76.0
End cap to crystal distance	4.0
Absorbing layer (end cap)	1.0
Dead layer on the inner surface of crystal	0.0003
Dead layer on the outer surface of crystal	0.7

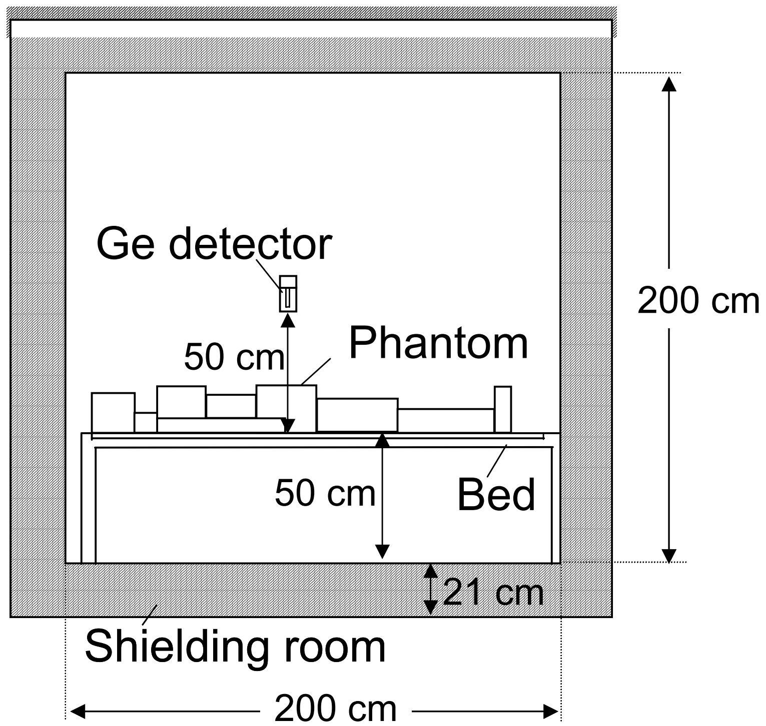


FIG. 2. Geometry of the detector and the water–filled block–shape phantom.

The peak efficiency was calculated by dividing numbers of photons in the full–energy peak area by the number of histories. The Monte Carlo bin width was set to be 0.5 keV so that it was the same condition as in the measurements. Photon energy simulated was 661 keV for ^{137}Cs and 1,461 keV for ^{40}K. Furthermore, response functions for the voxel versions of the water–filled block–shape phantoms containing ^{137}Cs and ^{40}K respectively were calculated by the UCWBC code. The response functions were folded with a Gaussian distribution using the equation (1) [20], since the effects of fluctuation in the signal of the detector are not considered in the UCWBC code:

$$G_i = \sum_{j=1}^{j_{max}} \frac{M_j}{\sqrt{2\pi}\sigma(E_j)} \cdot \int_{E_i - \frac{W}{2}}^{E_i + \frac{W}{2}} exp\left\{ -\frac{1}{2} \cdot \left[\frac{E_j - E}{\sigma(E_j)} \right]^2 \right\} \cdot dE \,, \qquad (1)$$

where M_j is the response functions calculated by the UCWBC code, E_j the average energy of the channel j, W the channel width and $\sigma(E_j)$ the standard deviation of Gaussian at energy E_j. The energy dependency of the deviation was expressed by the following equation:

$$\triangle E = a + b \cdot \sqrt{E} \,, \qquad (2)$$

where $\triangle E(=(8 \cdot \ln 2)^{1/2}\sigma(E))$ is the full width of a Gaussian distribution at half maximum (FWHM), determined by measurements, and a and b the constants.

3. Experiments

To validate the UCWBC code, *in vivo* measurements were carried out using the whole–body counter in JAERI. Peak efficiencies for two water–filled block–shape phantoms containing ^{137}Cs and ^{40}K respectively were measured with the Ge semi–conductor detector installed in the whole–body counter. The phantoms were positioned on a bed, as shown in FIG. 1. The distance between the endcap face of the detector and the bed was 50 cm. Each measurement was performed for a sufficient period (2,000sec) so that the statistical uncertainties on the full–energy peak areas were significantly small.

The peak efficiencies were calculated by dividing net count rates, which are count rates subtracted background and Compton continua of higher energy photons at these peaks from gross count rates, in the full–energy peak area by the photon emission rates from the sources.

In addition, response functions of the Ge semi–conductor detector for the water–filled block–shape phantoms containing ^{137}Cs and ^{40}K respectively were measured. The measured results by subtracting background from the measured data were compared with the calculations.

4. Results and discussion

Table 3 shows the calculated peak efficiencies for the voxel versions of the water–filled block–shape phantoms. The measured peak efficiencies for the phantom containing ^{137}Cs and ^{40}K respectively are also listed in Table 3. The peak efficiency ratios of the calculations to the measurements were 1.06 (^{137}Cs) and 1.08 (^{40}K). The calculated peak efficiencies for the phantom agree well with the measured ones for photon energies 662 keV (^{137}Cs) and 1,461 keV (^{40}K). From a comparison with the results it would appear that the calculations exhibit slightly positive deviations from the measurements. The discrepancies between the calculated and measured peak efficiencies are mainly attributed to the experimental conditions such as the source activity, in which the relative intrinsic errors are not small. Consequently, the above results confirmed that the UCWBC code could be useful for calibrating *in vivo* measurement systems. The calculated peak efficiencies for the Otoko and Onago phantoms are also shown in Table 3. The peak efficiencies for the Otoko and Onago phantoms are about 1.3 times greater than those of the water–filled block–shape phantoms. These discrepancies are probably due to the geometry effects, in particular the effective distances between the phantoms and the Ge semi–conductor detector. This fact indicates that the peak efficiencies for the water–filled block–shape phantoms are not always best for all subjects in JAERI.

Table 3. Comparison of peak efficiencies for the water–filled block–shape phantom, Otoko and Onago phantoms containing ^{137}Cs and ^{40}K

Energy	water–filled block–shape		Otoko	Onago
	Calculation	Experiment		
662 keV (^{137}Cs)	2.33×10^{-4}	$2.20\times10^{-4}\pm4.0\times10^{-5}$	2.93×10^{-4}	3.04×10^{-4}
1,461 keV (^{40}K)	1.72×10^{-4}	$1.59\times10^{-4}\pm2.8\times10^{-5}$	2.08×10^{-4}	2.15×10^{-4}

Figures 2 and 3 show the calculated and measured response functions of the Ge semi–conductor detector for the water–filled block–shape phantoms containing ^{137}Cs and ^{40}K respectively. The statistic deviations at a peak of the calculated response function prior to the folding were 2.07 % (^{137}Cs) and 2.41 % (^{40}K). These results are in good agreement with the measurements. The response functions between the backscatter peaks and the Compton edges and the characteristic X–rays emitted by the lead of the shielding room are reproduced by the calculations. In the calculations, the response in the regions between the Compton edges and the absorption peaks are slightly lower than the experimental results. The discrepancies between the calculations and the measurements are mainly due to the source conditions and the counting statistic. Consequently, it is possible to conclude that the calculated results represent all important interactions that take place within the Ge semi–conductor detector.

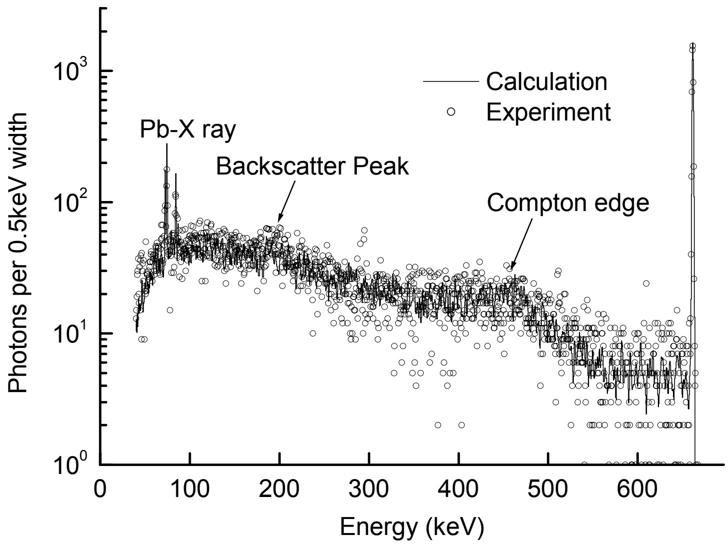


FIG. 3. Comparison of the measured and calculated response functions for the water–filled block–shape phantoms containing ^{137}Cs in solution.

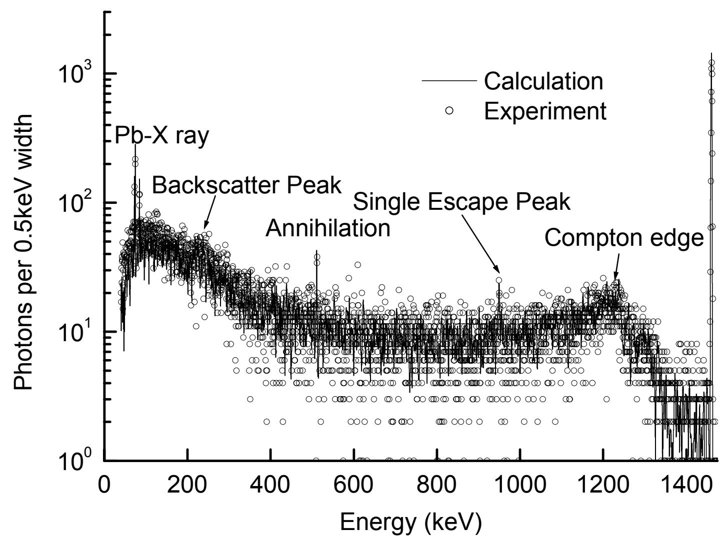


FIG. 4. Comparison of the measured and calculated response functions for the water–filled block–shape phantoms containing ^{40}K in solution.

5. Conclusions

The calibration methods for *in vivo* measurement systems using Monte Carlo simulations and voxel phantoms have been shown to be quite applicable to a contemporary whole–body counter with a Ge semi–conductor. The EGS4–UCWBC code developed in JAERI was found to be very useful for improving in accuracy of *in vivo* measurement results. The calibration data by the EGS4–UCWBC code can adequately reproduce those by measurements.

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