Investigation of the Air Kerma Response of Spherical Ionization Chambers for Unfolded Pulse Height Distributions of $^{60}$Co and $^{137}$Cs using the EGS4 Monte Carlo Code

Kook Jin CHUN$^{1,8}$ and Gwang Ho YOO$^{2}$

Air kerma response/Monte Carlo simulation/EGS4 code/Spherical ionization chamber/Mass energy-absorption coefficient ratio/Stopping power ratio/Wall correction factor/Non-uniformity correction factor/Scattering/Energy pulse height distribution/Unfolding.

Data required for the determination of the absolute air kerma rate for $^{60}$Co and $^{137}$Cs gamma-rays using spherical cavity chambers were calculated using the EGS4 Monte Carlo system. Mass energy-absorption coefficient ratio and the stopping power ratio were calculated for a 10 cm$^3$ primary standard graphite-walled ionization chamber from the unfolded energy pulse height distributions of $^{60}$Co and $^{137}$Cs sources. Wall correction factors and non-uniformity correction factors for two graphite and one air equivalent plastic walled ionization chambers were also calculated with EGS4 code. The wall correction factors were compared with those determined by an experimental extrapolation method.

To check the accuracy of the calculations the results were compared with those obtained from other primary standard laboratories such as NIST and NRCC. For a 10 cm$^3$ graphite ionization chamber, the mass energy-absorption coefficient ratios were 0.99917 for $^{60}$Co and 1.0004 for $^{137}$Cs. The values differed by 0.02~0.05 % for $^{60}$Co and 0.11 % for $^{137}$Cs from those of two laboratories. The stopping power ratios were 0.99984 for $^{60}$Co and 1.0087 for $^{137}$Cs. Comparison with NIST values showed differences of 0.06 % for $^{60}$Co and 0.04 % for $^{137}$Cs.

The wall correction factors were obtained and they were different by 0.6~1.1 % for $^{60}$Co and $^{137}$Cs compared to the experimental linear extrapolation method. These values were compared with Monte Carlo derived values from other laboratories.

The non-uniformity correction factors were also calculated and they differed from unity, the traditional value used in most standard national metrology laboratories.

INTRODUCTION

In the field of radiation dosimetry, various types of ionization chamber have been used as a primary standard of air kerma for ionizing photons. For photon energies between 10 and 300 keV, the primary standard instrument for the measurement of air kerma is traditionally a Free Air Chamber (FAC). For photon energies above 300 keV the FAC is not a practical instrument because the range of the recoiled electrons generated in air becomes large. For $^{60}$Co we would require a Free Air Chamber the size of the irradiation room. Instead, thick-walled ionization chambers are used, based on the assumptions of Bragg-Gray cavity theory.$^{1,2}$ The definition of a thick-walled chamber is that for a particular incident photon energy all the secondary electrons that contribute to the ionization in the cavity are produced in the wall (i.e. there is charged particle equilibrium).

The purpose of the present paper is to investigate the air kerma response of a number of spherical ionization chambers for $^{60}$Co and $^{137}$Cs gamma-rays using the EGS4 Monte Carlo system. The spherical ionization chambers used in the study were 1 cm$^3$ and 10 cm$^3$ graphite wall chambers and a 3.6 cm$^3$ air equivalent plastic wall chamber.

One difference from other such studies is that we did not use a Monte Carlo simulation of the source geometry to determine the energy spectrum at the chamber, nor did we use published spectra (e.g. from another standards laboratory with a similar irradiator). Instead we applied an EGS4 unfolding code$^{3}$ to the pulse height distributions measured
by an HPGe detector. The detailed procedure for unfolding the measured pulse height distributions is described in one of the authors’ previous works.\(^6\) One advantage of this technique is that one does not need to have a detailed knowledge of the source capsule and irradiation geometry.

In the determination of air kerma using a cavity chamber one of the most important correction factors is for the presence of the chamber walls. There have been extensive discussions in recent years on such wall correction factors determined by the traditional method of measuring ionization current as a function of wall thickness and extrapolating linearly to zero wall thickness versus that obtained by theoretical calculations using Monte Carlo methods.\(^5\)\(^-\)\(^9\) Since it was suggested that the traditional approach of obtaining the wall correction factors is inappropriate,\(^7\) we calculated the correction factors for the attenuation and scattering of the photons in the walls of the chambers by Monte Carlo simulation using EGS4 code.

THEORY

The fundamental equation for air kerma rate \(K_{\text{air}}\) for a graphite-walled chamber is given by

\[
K_{\text{air}} = \frac{I}{\nu \rho} \cdot \left( \frac{W}{e} \right)_{\text{air}} \cdot \left( \frac{\mu_{\text{em}}}{\rho} \right)_{\text{G}} \cdot \left( \frac{S}{\rho} \right)_{\text{air}} \cdot K_{\text{wall}} \cdot K_{\text{m}} \cdot \prod_i K_i,
\]

where \(I\) is the ionization current resulting from the collection of the ions produced in the air of the cavity, \(\left( \frac{W}{e} \right)_{\text{air}}\) is the average energy spent to produce an ion pair in dry air, \(g\) is the fraction of energy lost by bremsstrahlung, \(\left( \frac{\mu_{\text{em}}}{\rho} \right)_{\text{G}}\) is the ratio of mass energy-absorption coefficients for air to graphite (wall material), \(\left( \frac{S}{\rho} \right)_{\text{air}}\) is the ratio of the restricted mass stopping powers for graphite and air, \(K_{\text{wall}}\) is the correction factor for the attenuation and scatter in the wall, \(K_{\text{m}}\) is the correction factor for the axial non-uniformity of the photon beam due to using a point source instead of an ideal parallel beam and \(\prod_i K_i\) is the product of other correction factors (e.g., corrections for leakage current, scattered radiation contribution from the chamber stem, loss of ionization due to recombination, presence of water vapor in the air) to be applied to the standard chamber. \(\nu\) is the sensitive volume of the chamber in which the charge is collected and \(\rho\) is the air density under the measurement condition. Physical constants such as \(\left( \frac{W}{e} \right)_{\text{air}}\) and \(g\) are usually taken from standard data sets and in this case the values recommended by Consultative Committee on Ionization Radiation (CCRI)\(^{10}\) for dry air were used. Mass energy-absorption coefficients of both air and graphite were taken from the data published by Seltzer\(^{11}\) for the \(^{60}\)Co and \(^{137}\)Cs photon energies. Stopping power values for graphite and air were taken from the data for electrons in graphite and air in ICRU report 37.\(^{12}\) The cut-off energy \(\Delta\) based on Spencer-Attix theory is the minimum value of the electron kinetic energy which can just cross the cavity of the chamber – electrons with an energy less than \(\Delta\) are considered to deposit their energies locally. Electrons created by photon interactions with energies below \(\Delta\) are not included in the calculation of the stopping power ratio. \(\Delta\) is usually derived from mean chord length, which is related to the csda (continuous-slowing-down-approximation) of the electron range in air. For the spherical ionization chamber, the mean chord length is \(4/3\) times the radius of the chamber cavity. More detailed explanation of \(\Delta\) is given by National Institute of Standards and Technology (NIST)\(^{13,14}\) and values of csda for standard temperature and pressure are in ICRU report 37.\(^{12}\) \(\Delta\) usually depends on the size and geometry of the chamber cavity.

The wall correction factor \(K_{\text{wall}}\) is usually the most important and the largest correction term in the estimation of the air kerma response of the ionization chamber. The traditional way to determine wall correction factor, \(K_{\text{wall}}^{\text{exp}}\) has been a multiplication of two parameters, \(K_{\text{wall}}^{\text{exp}} = K_{\text{extrap}} \cdot K_{\text{cop}}\). \(K_{\text{extrap}}\) is obtained by measuring the ionization current as a function of additional wall thickness which is added to the chamber (from its minimum build-up thickness of 2 mm for \(^{137}\)Cs and 4 mm for \(^{60}\)Co) and extrapolating linearly to zero wall thickness. \(K_{\text{cop}}\) is the correction factor which accounts for the fact that the center of electron production, which contributes to electron energy deposition in the cavity, is not on the surface of the cavity, but inside the surface, closer to the radiation source. However, there has been a suggestion from National Research Council of Canada (NRCC)\(^{5-9}\) that \(K_{\text{cop}}^{\text{exp}}\) is incorrect and one should use \(K_{\text{wall}}^{\text{MC}}\) instead. Bielajew reported\(^{17}\) that the wall correction factor from Monte Carlo calculation can differ by as much as 1 % for the spherical ionization chambers from that obtained by the traditional linear extrapolation measurement and thus, nonlinear extrapolation should be applied to resolve this difference. He concluded that the nonlinear extrapolation method led to reasonable agreement with the result obtained by Monte Carlo calculation and thus the traditional linear extrapolation method should be regarded with suspicion for all type chambers.

Monte Carlo calculation of the wall correction factor is expressed as \(K_{\text{wall}}^{\text{MC}} = K_{\text{air}} \cdot K_{\text{sc}}\), where \(K_{\text{air}}\) is the correction factor for attenuation in the wall, \(K_{\text{sc}}\) is the correction factor for the scattering from the walls. If the interaction positions

are given, the effect of the mean position of interaction can be included in the attenuation factor. In that case, the product of an attenuation factor in the wall and the factor of scattering becomes a wall correction factor and we need not to calculate the factor of center of electron production $K_{\text{eff}}$.\(^{(15)}\)

The correction factor $K_{\text{an}}$ reflects the axial non-uniformity of the photon fluence, which arises from the difference between the real point source beam and an ideal parallel beam.\(^{(16)}\) Some primary standard laboratories have taken $K_{\text{an}}$ to be 1.000 by assuming that the effective point of measurement can be the geometrical center of the chamber due to the symmetry of the chamber. This consideration has been supported by the argument that the energy deposited to the cavity of the chamber by electrons produced due to a point source photon beam is higher than that of a parallel beam, but this overestimate can be compensated by the decrease of diverging electron fluence and the energy in the cavity remains almost the same. However, analytical calculation\(^{(16)}\) showed that the non-uniformity correction was not unity. Later, Monte Carlo calculation further demonstrated that $K_{\text{an}}$ varied up to a 0.75% difference from unity.\(^{9}\) This means that the energy deposited to the cavity of the chamber for a parallel beam is not exactly the same for a point source beam and the non-uniformity correction factor should be estimated by Monte Carlo calculation.

**IONIZATION CHAMBER DESCRIPTION AND EXPERIMENTAL SETUP**

The chambers used in the measurement and calculations are spherical type ionization chambers. The spherical ionization chamber was chosen for this study for the following reasons: 1) the photon beam can be approximated to be uniform and parallel, 2) the symmetry of the spherical geometry allowed the employment of the approximation that the angular distribution of the electrons entering the cavity is isotropic, 3) the chamber geometry is easier and simpler for Monte Carlo simulation than other types of ionization chamber, 4) the geometrical symmetry provided no angular dependence of the chamber position on the horizontal plane to the incident photon beam in the measurement of air kerma, 5) machining of the spherical head (two hemispherical shells) and the estimation of the volume of the head are simple and straightforward.

Three spherical ionization chambers were used in the study and were designated as GR1, AE3 and GR10, respectively, according to the wall material and nominal sensitive volume of the chamber. GR1 represents the graphite chamber with 1 cm$^3$ sensitive volume, AE3 the air equivalent plastic chamber with 3.6 cm$^3$ and GR10 the graphite chamber with 10 cm$^3$. Figure 1 shows the pictures and diagrams of the chambers. GR10 was fabricated at the Institute for National Measurement Standards (INMS), National Research Council of Canada (NRCC) for the purpose of the absolute measurement of air kerma rate for $^{60}$Co and $^{137}$Cs gamma-rays. The other two are commercial ionization chambers. The minimum build-up wall thicknesses for the three chambers are GR1 = 2.00 mm graphite, AE3 = 2.25 mm C-552 and GR10 = 2.00 mm graphite. The dimensions of the spherical ionization chambers are given in Table 1.

UT 145 graphite with a density of 1.7779 g/cm$^3$ was used for the construction of base caps of GR10 and additional graphite build-up caps. The inner and outer diameter of the graphite head is 25.99 mm and 27.96 mm leading to the wall thickness of 0.99 mm. The electrode is made of the same graphite and is 1 mm in diameter and 21.5 mm long. The sensitive volume of the chamber cavity was determined by

**Table 1.** Dimensions of GR1, AE3 and GR10 spherical chambers used in the study.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Sensitive Volume (cm$^3$)</th>
<th>Outer Diameter (mm)</th>
<th>Inner Diameter (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR1</td>
<td>0.944</td>
<td>12.70</td>
<td>16.71</td>
<td>2.01</td>
<td>1.80</td>
</tr>
<tr>
<td>AE3</td>
<td>3.60</td>
<td>19.56</td>
<td>19.06</td>
<td>0.25</td>
<td>1.76</td>
</tr>
<tr>
<td>GR10</td>
<td>9.175</td>
<td>27.96</td>
<td>25.99</td>
<td>0.99</td>
<td>1.78</td>
</tr>
</tbody>
</table>
the weighing method corrected for the volume of the electrode measured by high accuracy measuring machine at the machine shop in Korea Research Institute of Standards and Science (KRISS). Another mechanical volume measurement was done at INMS, NRCC to provide a comparison. In the weighing method used at KRISS the volume of the cavity is given by the weight difference of the spherical head of the chamber between that if filled with water and that if filled with air, divided by the density of the water. The value and the combined systematic uncertainty of the sensitive volume were 9.1753 cm$^3$ and 0.21%.

For the determination of the gamma-ray spectra a HPGe detector was used to measure the pulse height distribution from very low intensity $^{60}$Co and $^{137}$Cs sources mounted inside each irradiator. The standard sources could not be used, as the intensity was too high for the spectrometer. For the $^{60}$Co irradiator we mounted a $^{60}$Co ‘dummy’ source in place of the visible light-beam diaphragm inside the irradiator. With the standard source this places the low intensity source in exactly the same position as the real source would be when it is used for irradiations. The ‘dummy’ source has activity of the order of 10$^7$ Bq, which is sufficient to measure a pulse height distribution. The capsule including the dummy source has the same material and shape as that of the main source in the irradiator (to reproduce scatter). The same measurement procedure was carried out to obtain the pulse height distribution of $^{137}$Cs using its dummy source in the $^{137}$Cs irradiator. The assumption then is that these unfolded spectra are the same as for the real sources used for the ion chamber measurements.

For the experimental determination of the wall correction factor the chambers were placed at the center axis of the beam on the reference plane which is 1 m distance from the actual $^{60}$Co and $^{137}$Cs sources in each irradiator and measurement of the ionization current with adding wall thickness up to 10 mm was performed.

CALCULATIONS

Unfolded pulse height distributions and electron energy spectra

The real pulse height distribution functions are obtained by unfolding the measured distributions using monoenergetic response functions calculated with the EGS4 Monte Carlo simulation code$^9$ for incident photon energies from 10 keV to 1400 keV in 10 keV steps.

In the calculations of the response functions, the cutoff energy was set to 1 keV for photons, and 10 keV for electrons and positrons. All the particles with kinetic energy lower than the cutoff energy were assumed to transfer all their kinetic energy to the medium and to have been converted to electrical signals. The directions of the incident photons were chosen randomly along the radial direction from the source so that the photons hit the front surface of the detector almost uniformly.

The measured pulse height distribution consists of $N$ values of energy bin of $n_i$ ($i = 1, \ldots, N$) counts for each bin, starting from the highest energy bin and going to the lowest energy bin. By dividing the count of a bin of the highest energy $E_N$ by the full energy absorption efficiency from the simulated pulse height distribution, the unfolded count for the bin of the energy $E_N$ is obtained. This unfolded count is a number of photons that arrived at the surface of a detector with the incident energy $E_N$. The simulated pulse height distribution can be obtained in 1 keV steps for the incident photons with energy $E_N$ from the previously calculated response functions using an interpolation method. To normalize the simulated pulse height distribution to the measured one at the highest energy bin, the count of each energy bin in the simulated pulse height distribution should be multiplied by the same full energy absorption efficiency. This count of each bin in the normalized pulse height distribution should be subtracted from the count of each corresponding bin in the measured pulse height distribution. The remaining measured pulse height distribution is then made up of the pulse height distributions caused by the photons of which energies are from $E_{N-1} = E_N - \Delta E$ to the lowest energy, where $\Delta E$ is the energy difference between the bins. The unfolded count of the next highest energy bin is obtained by replacing the highest energy $E_N$ by $E_{N-1}$, the full energy absorption efficiency for the energy $E_N$ by that for $E_{N-1}$, and doing the same calculation. By repeating this process down to the lowest energy bin, we can deduce the whole energy distribution of the incident photons, the unfolded pulse height distribution that arrived at the front surface of a detector. This process is an unfolding technique of the measured pulse height distribution.

The unfolded pulse height distribution functions $\phi_{\text{ph}} (E)$ are given in Fig. 2 and for more detail see Reference (4).

The next step is to determine the spectrum of secondary electrons in the air cavity of the chamber. The EGS4 code tracks the secondary electrons produced by photon interactions in the chamber walls and extracts the pulse height distributions, $\Phi_d (E)$, of the electrons that pass through the inner surface of the wall to enter the cavity. The calculated spectra of electrons, $\Phi_d (E)$, for GR10 from the photon pulse height distributions of the $^{60}$Co and $^{137}$Cs are given in Fig. 2.

Mass energy-absorption coefficient ratios of air to graphite and stopping power ratios of graphite to air

The mass energy-absorption coefficient ratio of air to graphite is defined as,

$$\left( \frac{\mu_{\text{air}}}{\rho} \right)_{\text{air}} \frac{\mu_{\text{air}}}{\rho} \left( \frac{\mu_{\text{air}}}{\rho} \right)_{\text{air}} = \int_{E=0}^{E_{\text{max}}} \phi_{\text{ph}} (E) \frac{\mu_{\text{air}}}{\rho} \left( \frac{\mu_{\text{air}}}{\rho} \right)_{\text{air}} dE,$$

Air Kerma Response was Estimated using EGS4 Code

\[
\begin{align*}
\text{where } & \left( \frac{\mu_{\text{air}}}{\rho} \right) \text{ and } \left( \frac{\mu_{\text{GR10}}}{\rho} \right) \text{ are mean mass energy-absorption coefficients of air and graphite. } \\
\Psi_{\text{ph}}(E) \text{ is the energy fluence spectrum of incident photons that arrived at the outer surface of the sphere with kinetic energy } E, \text{ and } E_{\text{max}} \text{ is the maximum kinetic energy of the incident particle. } \\
\Phi_{\text{ph}}(E) \text{ is a product of } \Psi_{\text{ph}}(E) \text{ and } E, \text{ where } \Phi_{\text{ph}}(E) \text{ is a pulse height distribution of incident photons (determined in this case by unfolding the measured pulse height distribution of photons). The mass energy-absorption coefficients are taken from Seltzer.}^{11} \\
\text{The stopping power ratio of graphite to air was given by the following equation }^{13} \\
\left( \frac{S}{\rho} \right)_{\text{air}} = \frac{\int_{E=\Delta}^{E_{\text{max}}} \Phi_{\text{ph}}(E) \left( \frac{L}{\rho} \right)_0 \, dE + \Phi_{\text{ph}}(\Delta) \left( \frac{S_{\text{air}}}{\rho} \right)_0 \cdot \Delta}{\int_{E=\Delta}^{E_{\text{max}}} \Phi_{\text{ph}}(E) \left( \frac{L}{\rho} \right)_{\text{air}} \, dE + \Phi_{\text{ph}}(\Delta) \left( \frac{S_{\text{air}}}{\rho} \right)_{\text{air}} \cdot \Delta},
\end{align*}
\]

\[
\begin{align*}
K_{\text{wall}} &= K_{\text{air}} \cdot K_{\text{air}}, \\
\text{where } & \sum_{i=1}^{n} E_{i,j} \cdot e^{\text{air}_{ij}} \\
K_{\text{air}} &= \frac{\sum_{i=1}^{n} E_{i,j}}{\sum_{i=1}^{n} E_{i,j}},
\end{align*}
\]

\[137\text{Cs}, 100\text{cm from irradiator}

\begin{align*}
60\text{Co}, 100\text{cm from irradiator}
\end{align*}

Fig. 2. Graphs of the measured and unfolded pulse height distribution for $^{60}\text{Co}$ and $^{137}\text{Cs}$ sources located inside an irradiator, 1 m away from the chamber. The numbers of percentage represent a relative ratio of counts of the main peaks to the total counts. Calculated mass energy-absorption coefficient of air to graphite for GR10 is 0.99917 for $^{60}\text{Co}$ and 1.0004 for $^{137}\text{Cs}$. Calculated electron spectra entering the inner surface of GR10 chamber by the unfolded incident photons are shown at the bottom. The stopping power ratio of graphite to air is 0.99984 for $^{60}\text{Co}$ and 1.0087 for $^{137}\text{Cs}$. 

where $E_{i,p}$ is the energy deposited in the cavity by an electron released by the $i$th primary photon interaction, $E_{i,sc}$ is the energy deposited in the cavity by the electrons released by the second and higher order scattered photons arisen from the $i$th primary photon, $\mu_i$ is a linear attenuation coefficient of photons in the wall and $l_i$ is the path length of a photon in the wall to the first interaction point [Fig. 3]. The weight in equation (5) is to compensate the attenuation of the incident photon due to an interaction in the wall material that generates a secondary electron. This weighted sum energy corresponds to the energy that the electron generated in the primary interaction would deposit to the cavity air if the attenuation of photons were zero in the wall. Thus the correction factor $K_{cc}$ for the attenuation of photons in the wall is the ratio of the sum of the weighted energies to the total

\[ K_{cc} = \frac{\sum_i E_{i,p}}{\sum_i (E_{i,p} + E_{i,sc})} \tag{6} \]
The Japan Radiation Research Society

Air Kerma Response was Estimated using EGS4 Code

Fig. 5. Measured data (+), linear fit (solid line), calculated data (o) and non-linear fit (dashed line) of the response as a function of wall thickness for AE3 with $^{60}\text{Co}$ and $^{137}\text{Cs}$. $K_{\text{exp}}$ factor of 0.995 for $^{60}\text{Co}$ and 0.999 for $^{137}\text{Cs}$ was multiplied to the experimental values to determine $K_{\text{wall}}$. A minimum wall thickness is 4.25 mm for $^{60}\text{Co}$ and 2.25 mm for $^{137}\text{Cs}$.

the primary photons. The deposited energy in the cavity is increased by the electrons generated by scattered photons. This increase can be corrected for by taking the ratio of the energy deposited in the cavity by the electrons generated by primary photons to the total energy deposited by the electrons generated by both primary and scattered photons.

In the calculation, the thicknesses of added walls were chosen to be equal to those used in the experiment and the calculated data points were fitted to a non-linear response equation to determine the wall correction factor. The response equation developed by Bielajew\(^{2,17}\) is given by

$$R(t) = a_0 + a_1f(\alpha),$$

where $t$ is the wall thickness, $a_0$ and $a_1$ are the coefficients to be obtained by fitting equation (7) to the data points used for the non-linear fit. The slope function, $f(\alpha)$ is given by:

$$f(\alpha) = [1 + (1 + 1/2\alpha) \ln(1 + 2\alpha)]/2,$$

where $\alpha$ is $r/t$, and $r$ is the inner radius of the chamber cavity. For the best fit of the data points to equation (7), a least-square fitting routine that minimizes the weighted sum of the squares of the deviations $\chi^2$ \(^{18}\) was used. The Monte Carlo data and non-linear fits are plotted with circles and dashed lines in Fig. 4–6.

Non-uniformity correction factor

The equation for the non-uniformity correction is given as

$$K_{\text{in}} = \frac{D_{\text{air}}}{D_{\text{point}}},$$

where $D_{\text{air}}$ is the energy deposited by both primary and scattered photons per unit fluence of incident photons to the air in the cavity for a parallel or point source beam.\(^{13}\) This method is a very straightforward approach to obtain the correction factor without using complicated routines, however it is valid only when the wall of a chamber is thick enough to exclude the electrons generated by the secondary interactions outside the chamber and the cavity is small enough so as not to perturb the secondary electron fluence.

EXPERIMENT

The experimental estimation of the wall correction factor using linear extrapolation $K_{\text{extrap}}$ was done for GR1, AE3 and GR10 chambers by making ionization current measurement with changing wall thicknesses at 1 m distance from both $^{60}\text{Co}$ and $^{137}\text{Cs}$. For GR1 and GR10, four additional graphite build-up caps of thickness of 2 mm, 4 mm, 6 mm and 8 mm
were used for the measurement. Minimum wall thickness for the measurement was 4 mm for $^{60}$Co and 2 mm for $^{137}$Cs. The base wall thickness of AE3 was 0.25 mm and an additional cap was added to meet the TCEP (transient charged particle equilibrium) condition and the minimum wall thickness was 4.25 mm for $^{60}$Co and 2.25 mm $^{137}$Cs. The estimated $K_{\text{extrap}}$ values are multiplied by $K_{\text{ep}}$ factors of 0.995 and 0.999 for $^{60}$Co and $^{137}$Cs$^{5}$ to determine $K_{\text{ep}}$. The extrapolation data and the linear fits to the chambers are shown with cross hairs and solid lines in Fig. 4–6.

RESULTS AND DISCUSSION

The unfolded pulse height distributions for $^{60}$Co and $^{137}$Cs dummy sources in the irradiators at 100 cm are given in Fig. 2. The broad peaks around 200 keV for both $^{60}$Co and $^{137}$Cs appear to be due to photons scattered in a backward direction in the irradiator. The weak peaks near 75 keV are from the characteristic X-rays of lead.

The mass energy-absorption coefficients of air to graphite for the GR10 graphite ionization chamber calculated for the $^{60}$Co and $^{137}$Cs dummy sources in the irradiators at 1 m are 0.99917 and 1.0004, respectively. Our value differed by 0.05 % for $^{60}$Co when compared with that given by NRCC.$^{17}$ GR10 was fabricated by NRCC with same design of their spherical ionization chamber (nominal volume is 10 cm$^3$) using the same graphite.$^{20}$ For reference, the values given by NIST$^{15}$ for the similar size spherical chambers are shown in Table 2.

To calculate the stopping power ratio of graphite to air, the electron spectra that enter the cavity of the chamber were calculated using the EGS4 code from the photon pulse height distribution of the $^{60}$Co and $^{137}$Cs dummy sources with cut-off energy of 34.4 keV. The values were 0.99984 and 1.0087 [Fig. 2 and Table 2]. The values given by NIST were 1.0004 with 32.7 % scattered photon contribution to the mono-energetic $^{60}$Co pulse height distribution in a $10 \times 10$ cm$^2$ field and 1.0091 with 35 % for $^{137}$Cs. The scattered photon contribution to our unfolded pulse height distribution was 28.1 % for $^{60}$Co and 35.95 % for $^{137}$Cs in the same field size. Comparison with NIST values showed a difference of 0.06 % for $^{60}$Co and 0.04 % for $^{137}$Cs. Another comparison with the NRCC value calculated in an unspecified field condition showed a difference of 0.12 % for $^{60}$Co. It was shown$^{19}$ that use of a realistic $^{60}$Co pulse height distribution instead of a mono-energetic 1.25 MeV spectrum increases the value of the stopping power ratio by only 0.14 %, therefore the calculated values given here for the ‘dummy’

Fig. 6. Measured data (+), linear fit (solid line), calculated data (o) and non-linear fit (dashed line) of the response as a function of wall thickness for GR10 with $^{60}$Co and $^{137}$Cs. $K_{\text{ep}}$ factor of 0.995 for $^{60}$Co and 0.999 for $^{137}$Cs was multiplied to the experimental values to determine $K_{\text{ep}}$. A minimum wall thickness is 4 mm for $^{60}$Co and 2 mm for $^{137}$Cs.
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Table 2. Mass energy-absorption coefficient ratios of air to graphite and stopping power ratios of graphite to air for GR10 chamber in the $^{60}$Co and $^{137}$Cs obtained at KRISS using EGS4 Monte Carlo calculation and values from NIST$^{13}$ and NRCC.$^{17}$

<table>
<thead>
<tr>
<th>Source</th>
<th>KRISS</th>
<th>NIST</th>
<th>NRCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{\mu_{en}}{\rho}$</td>
<td>$\frac{S}{\rho}$</td>
<td>$\frac{\mu_{en}}{\rho}$</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>0.99917</td>
<td>0.99984</td>
<td>0.9990</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>1.0004</td>
<td>1.0087</td>
<td>0.9993</td>
</tr>
</tbody>
</table>

† 10 × 10 cm$^2$ rectangular field with 32.7% scattered beam ($^{60}$Co), ‡ 35% scattered beam ($^{137}$Cs).

* Cut-off energy is 34.4 keV for GR10 chamber.

Sources will be very close to the real situation. The results are given in Table 2.

Comparison of the wall correction factor between the experimental linear extrapolation, $K_{wall}^{exp}$, and Monte Carlo calculation, $K_{wall}^{MC}$, has been made for three ionization chambers. The non-linear fit to the calculated data showed more rapid increase than the linear fit to the measured ones as wall thickness goes to zero, which was expected. The results of the $\chi^2$ calculation of the non-linear fit to the calculated data and the coefficients $a_0$ and $a_1$ for the three chambers are listed at Table 3.

$K_{wall}^{exp}$ showed a difference of about 1% from $K_{wall}^{MC}$ for both $^{60}$Co and $^{137}$Cs. The difference was 0.59% for GR1, 0.55% for AE3 and 1.07% for GR10 with $^{60}$Co and 0.69% for GR1, 0.62% for AE3 and 0.84% for GR10 with $^{137}$Cs, respectively. The comparisons between $K_{wall}^{MC}$ and $K_{wall}^{exp}$ values for three chambers are tabulated in Table 4.

The studies of the wall correction factor for a similar size spherical ionization chamber (about 10 cm$^3$) were also reported by NIST$^{13}$ and NRCC.$^{20}$ As the comparison of $K_{wall}^{MC}$ is not a significant matter unless the designs of the chambers were exactly the same, our comparison was only done with NRCC value. For $^{60}$Co, our value of $K_{wall}^{MC}$ is 1.0253, which is 0.52% from the NRCC value (1.020). The reason for this discrepancy can be explained by the following argument.

The difference between the NRCC value and ours appeared to come from the application of the different pulse height distribution-NRCC used a point source model of incident photon and a spectrum including all scattered photons$^{20}$-and the different thickness of the minimum wall (4 mm vs. 3 mm for $^{60}$Co) of the chamber to the calculation.

For $^{137}$Cs, the minimum wall thickness to determine the wall correction factor was 2 mm while NRCC used a thickness of 3.73 mm$^{17}$ for 10 cm$^3$ chamber. Therefore, the direct comparison of the wall correction factor determined by the application of different minimum wall thickness could not be made. Instead, we further calculated the wall correction factors with the minimum wall thickness of 4 mm for the

Table 3. Results of non-linear fitting procedure of the calculated data points to equation (7). The common uncertainty of 0.25% from the calculation of response was used.

<table>
<thead>
<tr>
<th>$^{60}$Co</th>
<th>Ionization Chamber</th>
<th>$\chi^2$</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$K_{wall}^{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR1</td>
<td>0.151</td>
<td>1.0258</td>
<td>-0.439 × 10$^{-2}$</td>
<td>1.0189</td>
<td></td>
</tr>
<tr>
<td>AE3</td>
<td>0.134</td>
<td>1.0404</td>
<td>-0.591 × 10$^{-2}$</td>
<td>1.0260</td>
<td></td>
</tr>
<tr>
<td>GR10</td>
<td>0.329</td>
<td>1.0279</td>
<td>-0.419 × 10$^{-2}$</td>
<td>1.0253</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$^{137}$Cs</th>
<th>Ionization Chamber</th>
<th>$\chi^2$</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$K_{wall}^{MC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR1</td>
<td>0.069</td>
<td>1.0197</td>
<td>-0.594 × 10$^{-2}$</td>
<td>1.0163</td>
<td></td>
</tr>
<tr>
<td>AE3</td>
<td>0.570</td>
<td>1.0283</td>
<td>-0.713 × 10$^{-2}$</td>
<td>1.0194</td>
<td></td>
</tr>
<tr>
<td>GR10</td>
<td>0.408</td>
<td>1.0259</td>
<td>-0.673 × 10$^{-2}$</td>
<td>1.0210</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Wall correction factors for $^{60}$Co and $^{137}$Cs gamma-rays obtained by EGS4 Monte Carlo calculation and linear extrapolation to experimental values*.

<table>
<thead>
<tr>
<th>Source</th>
<th>Ionization Chamber</th>
<th>$K^{\text{MC}}_{\text{wall}}$ (EGS4)</th>
<th>$K^{\text{exp}}_{\text{wall}}$ (experiment)*</th>
<th>$K^{\text{MC}}<em>{\text{wall}} / K^{\text{exp}}</em>{\text{wall}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>GR1</td>
<td>1.0189</td>
<td>1.0129</td>
<td>1.0059</td>
</tr>
<tr>
<td></td>
<td>AE3</td>
<td>1.0260</td>
<td>1.0203</td>
<td>1.0055</td>
</tr>
<tr>
<td></td>
<td>GR10</td>
<td>1.0253</td>
<td>1.0144</td>
<td>1.0107</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>GR1</td>
<td>1.0163</td>
<td>1.0093</td>
<td>1.069</td>
</tr>
<tr>
<td></td>
<td>AE3</td>
<td>1.0194</td>
<td>1.0131</td>
<td>1.062</td>
</tr>
<tr>
<td></td>
<td>GR10</td>
<td>1.0210</td>
<td>1.0125</td>
<td>1.084</td>
</tr>
</tbody>
</table>

* Experimental value was multiplied by the factor 0.995 for $^{60}$Co and 0.999 for $^{137}$Cs.

comparison with NRCC. For GR10, our value is 1.0325 and differs by 0.10 % from NRCC value (1.0313).

The non-uniformity correction factors for GR1, AE3 and GR10 ionization chambers were also calculated from equation (9). Calculations of $K_m$ for $^{60}$Co resulted in a correction not significantly different from unity. For GR10, comparison with the NRCC value (0.9991) which was determined by a Monte Carlo calculation20 showed a 0.13 % difference. $K_m$ for the three chambers deviated by a 0.01--0.04 % from unity. On the other hand, $K_m$ differed by more than 0.4 % from unity for the GR1 chamber with $^{137}$Cs. No comparison with other primary standard laboratory has been made because there was no measurement result for spherical ionization chamber with $^{137}$Cs available. The results of calculations are listed in Table 5.

Table 5. Correction factor for axial non-uniformity of the beam calculated from equation (9).

<table>
<thead>
<tr>
<th>Source</th>
<th>Ionization Chamber</th>
<th>$K_m$ (EGS4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>GR1</td>
<td>0.9999</td>
</tr>
<tr>
<td></td>
<td>AE3</td>
<td>0.9999</td>
</tr>
<tr>
<td></td>
<td>GR10</td>
<td>1.0004</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>GR1</td>
<td>0.9954</td>
</tr>
<tr>
<td></td>
<td>AE3</td>
<td>0.9987</td>
</tr>
<tr>
<td></td>
<td>GR10</td>
<td>0.9984</td>
</tr>
</tbody>
</table>

SUMMARY

Data required to determine the absolute air kerma rate for $^{60}$Co and $^{137}$Cs beams using a cavity chamber primary standard have been calculated using the EGS4 Monte Carlo simulation code.

In this paper, we made the first attempt at using the unfolded pulse height distribution to calculate four parameters of the air kerma response for spherical ionization chambers. These parameters have been demonstrated to be very close to the real situation in more clear and detailed fashion using EGS4.

The mass energy-absorption coefficient ratio and the stopping power ratio were calculated for a 10 cm$^3$ graphite-walled ionization chamber from the unfolded energy spectrum of the pulse height distributions of $^{60}$Co and $^{137}$Cs sources and were compared with those from NIST13 and NRCC.17 Since the design of GR10 chamber was almost the same with the 10 cm$^3$ of NRCC,20 the comparison was mainly made with NRCC values. The mass energy-absorption coefficient ratio shows good agreement with the NRCC value, with difference of 0.05 % for $^{60}$Co for GR10 chamber. The stopping power ratios with cut-off energy of 34.4 keV were 0.99984 with 28.10 % scattered photon contribution for $^{60}$Co pulse height distribution in a 10 × 10 cm$^2$ field and 1.0087 with 35.95 % for $^{137}$Cs. Our values showed the difference of 0.06--0.12 % from those of NIST and NRCC for $^{60}$Co and 0.03 % from the NIST value for $^{137}$Cs.

Wall correction factors and non-uniformity correction factors for two graphite and one air equivalent plastic walled ionization chambers were also calculated with EGS4 code. The wall correction factors were compared with those determined by an experimental linear extrapolation method. $K^{\text{exp}}_{\text{wall}}$ showed a difference of about 1 % from that given by Monte Carlo calculation, $K^{\text{MC}}_{\text{wall}}$. The difference was 0.59 % for GR1, 0.55 % for AE3 and 1.07 % for GR10 with $^{60}$Co and 0.69 % for GR1, 0.62 % for AE3 and 0.84 % for GR10 with $^{137}$Cs.

For 10 cm$^3$ chamber, our value of $K^{\text{MC}}_{\text{wall}}$ was 1.0253, which is 0.52 % difference from the NRCC value for $^{60}$Co appeared to result from the application of a different pulse height distribution and a different minimum wall thickness of the chamber to the calculation.

For $^{137}$Cs, the direct comparison of the wall correction factor with NRCC could not be made because the different minimum wall thickness was applied to the calculation of the wall correction factor. However, the calculation of the wall correction factor with changing the minimum wall thickness to 4 mm showed that the calculated value (1.0325) differed by 0.12 % from NRCC value (1.0313) for 10 cm$^3$ chamber.

Calculations of non-uniformity correction factors showed that they were not equal to unity for all three chambers and the effective points of the measurements were not exactly at the center of the chambers. $K_m$ was not estimated by the point source but by the pulse height distribution of the dummy source which has a real dimension and thus the point source beam approximation can not be expected to work perfectly in our case.

In this study, EGS4 code has been used for Monte Carlo calculation. Recently, EGSnrc has been proposed21 for better and more accurate calculation of air kerma response of the ionization chambers independent of the wall material.
However, EGS4 can still be considered as a good code to calculate the ionization chamber response to the photon beams with the proper choice of ESTEPE (electron step size for energy loss) depending on the wall material. According to NRCC, for a graphite wall ionization chamber, EGS4/PRESTA agrees with EGS4rc within 0.2% at ESTEPE of 0.15 in terms of ionization chamber response to $^{60}$Co gamma-rays. For the laboratories using a graphite-walled ion chamber as a primary standard, it seems reasonable to use EGS4/PRESTA in the calculation of the data for the chamber response to gamma-ray.

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