

Unfolding of the Measured Spectra and Determination of Correction Factors of a Free Air Ionization Chamber Using EGS4 Simulations

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Abstract

The responses of NaI detector and HPGe detector for incident photons up to 662 keV were calculated using EGS4 simulations. The calculated spectra were normalized to the measured spectra after being smoothed using cubic spline fit at highest energies, and were unfolded. The unfolded one of a measured spectrum with NaI detector at a distance 100 cm away from the Cs-137 source shows that the measured one was contributed remarkably from the surrounding materials at low energy region. The measured spectra obtained by HPGe detector with a maximum energies 63 keV and 83 keV were also unfolded. No significant difference is seen in the shapes of spectra between the measured and the unfolded ones. In a free air ionization chamber of 24 cm × 24 cm × 46 cm, a ratio of loss of ionizations and a ratio of secondary ionizations were calculated at incident photon energy from 10 keV to 300 keV in 10 keV steps using EGS4 simulations. The ratio of loss of ionization to the total ionization which shows no applicable value up to 130 keV of incident photon energy, rises up from 130 keV to 220 keV and slightly decreases between 220 keV and 260 keV and then increases again up to 300 keV. On the other hands, the ratio of secondary ionizations decreases monotonously with the increase of photon energy.

1 Introduction

Generally, the radiation spectrum that we measure from the detector is much different from the one that arrives at the detector from the radiation source. We call the former one a measured spectrum and the latter one a real spectrum. Photon beam radiated from the source interact with the atoms of the materials while they are traveling through the medium to the detector, and inside the detector before they are measured. Thus the measured energy spectrum can be significantly different from the one radiated from the source due to the contribution of the scattered photon. While the characteristics and limitations of the radiation measurement system make it very difficult to measure a real spectrum, it is also possible to obtain a spectrum very close to the real one by using a software in which all the characteristics of measurement system are considered.[1,2,3,4] One of the most powerful tools currently known so far is a computer simulation using EGS4 code.[5] Using this code, we can calculate an energy absorption spectrum for the NaI or HPGe detectors for the incident photon beam with the energy ranging from a few keV to hundreds of GeV. The energy spectrum thus calculated at many different values of energy can then be compared with the measured spectrum through an interpolation in order to simulate the real spectrum, which is called unfolding of the measured spectrum.

In this paper, the results of unfolding procedure of the spectrum measured by 3 in. × 3 in. NaI detector at 100 cm away from the Cs-137 source and that by 9 mm × 5 mm HPGe detector at 100 cm away from the X-ray generator are presented.[4,6] The result of the calculations of a ratio of loss

of ionizations and a ratio of secondary ionizations for a free air ionization chamber when the incident photon beam is applied is also presented.[7,8,9] The dimension of the inner volume of the free air chamber used in this calculation is 24 cm \times 24 cm \times 46 cm and the incident photon energy ranges from 10 keV to 300 keV.

2 Unfolding of the Measured Spectrum

2.1 Unfolding of spectrum measured with NaI detector

A gamma-ray spectrum was measured by 3 in. \times 3 in. NaI detector at 100 cm away from the Cs-137 source and analyzed. [Fig.1] The photon beam emitted from Cs-137 are mostly 662 keV gamma-rays with small portion of 32 keV X-ray, but the measured spectrum shows a strong peak at 662 keV with a broad background at low energy region.[4] The strong peak around 662keV appears to be contributed by 662 keV photons. A pulse height distributions which were calculated using EGS4 code with incident photon energy 662 keV are redistributed using a Gaussian distribution function with a FWHM (full wave half maximum) 7 %. [Fig.1.(A)] After the highest energy peak was normalized to the measured peak, the normalization result is compared with the measured spectrum. The result shows an excellent agreement in shape for the calculated and measured one at the photon energies above 450 keV. This explains that there was no other incident photons with energy above 450 keV except 662 keV photons from the Cs-137. On the other hand, in low energy regions below 450 keV, the spectrum does not match well with the measured one. The result of measured strength subtracted by the calculated one using EGS4 code at 662 keV is shown in Fig.1(B). The remaining part is considered to be contributed by the secondary scattered photons from the surrounding materials. Divided the normalized intensity by the detecting ratio at 662 keV, the unfolded intensity at 662 keV could be obtained. This unfolded strength at 662 keV is considered as an intensity of the photons which arrived at the detector with that energy.

To unfold the remaining strength, pulse height distributions at 11 energies were calculated at incident photon energies from 50 keV to 500 keV. [Fig.1.(C)] The simulated spectra for the other energies were obtained by the interpolation method. The calculated spectra were redistributed using a Gaussian distribution function with a FWHM 7% except the highest energy peaks. The highest energy peaks were not redistributed because of the convenience of normalizing the peaks to the remaining spectrum. With the same method as was applied at 662keV peak, the intensity of the highest energy of a calculated spectrum at next energy was normalized to that of the highest energy of a remaining spectrum. Starting from the highest energy, the whole spectrum of a calculated one was multiplied by the same normalization factor and was subtracted from the remaining spectrum. Then the unfolded intensity at the highest energy can be obtained by dividing the intensity of a measured peak at that energy by a peak detecting ratio. This process was repeated in a descending order down to zero energy. The unfolded spectrum is shown in Fig.1.(D). The results show that 68% of whole strength are from the Cs-137 source, and 32% are contributed by the surrounding materials.

2.2 Unfolding of spectrum measured with HPGe detector

The continuous energy X-rays produced by a X-ray generator with maximum energies 63 keV and 82 keV, were measured by using a HPGe detector (9 mm diameter, 5 mm thickness and 5.23 g/cm³ density for Ge crystal, 0.5 mm thick Be window, and 1 cm thick Al case), and was analyzed using the same unfolding method as that of Cs-137 gamma-ray. However, in this procedure the Gaussian distribution function was not applied to the simulated spectrum because of a very good resolution of about 0.5 keV, which is less than the energy bin used in the calculation.[Fig.2] Due to the secondary scattered photons coming from the surrounding materials, the measured spectrum has different energy distribution from the one emitted from the source. The spectra measured by HPGe detector with maximum energies at 63 keV and 82 keV are shown in Fig.3. The unfolding procedure has been performed to obtain the simulated spectra using EGS4 code with the incident photon energies

from 5 keV to 85 keV in 5 keV step and several of them are given in Fig.2. Since there is no significant peak in the measured spectra at the high energy region, like 662 keV peak in a spectrum by NaI detector, the intensity of the highest energy of a calculated spectrum was normalized to the intensity of the highest energy of a measured spectrum, and was subtracted from the measured spectrum. The other steps are the same as in NaI detector. The unfolded spectra which were arrived at the detector are given in Fig.3.(C) and Fig.3.(D).

3 Determination of correction factors of a Free Air Ionization Chamber using EGS4 Simulations

Free air ionization chamber plays an important role in a measurement of gamma ray exposure. An air filled ionization chamber is well matched to this application because an exposure is expressed in terms of the amount of ionization charge created in air. One of the quantities to describe an exposure is **kerma** (kinetic energy released in material). [6,7,8,9] [Fig.4.(A)] Kerma is a sum of transferred kinetic energy to the charged particles per unit mass at a point of interest by radiation. It is expressed as

$$K = \frac{dE_{tr}}{dm}, \quad \text{where unit is } 1 \text{ Gy} = 1 \text{ J/kg}$$

$$= \frac{I}{v \cdot \rho_o} \cdot \frac{W}{e} \cdot \frac{1}{1-g} \cdot \Pi K_i$$

where I : ionization current (A)

v : sensitive volume (cm^3)

$\frac{W}{e}$: required energy to make an ion pair (33.97 eV/pair)

ρ_o : specific gravity of dried air at STP (1.293×10^{-3})

$\Pi K_i = K_{sc} \cdot K_e \cdot K_a \cdot K_s \cdot K_p \cdot K_l \cdot K_h$

where K_{sc} = secondary scattered photo ionization factor(e_4)

K_e = loss of ionization correction factor(e_5)

K_a = diminishing factor due to air between the defining plane and collector

K_s = ion recombination correction factor

K_p = polarity effect of collecting electrons

K_l = diaphragm penetration correction factor

K_h = humidity correction factor.

As we see from the above equation, there are several parameters to be determined to calculate kerma. Among the parameters, we calculated a ratio of loss of ionizations (K_e) and a ratio of secondary ionizations (K_{sc}) for a free air ion chamber composed of 24 cm \times 24 cm \times 46 cm, at photon's incident energies from 10 keV to 300 keV with 10 keV steps for the 0.1 mm diameter beam using EGS4 simulations.

3.1 1 Determination of a ratio of loss of ionizations

As X-ray beam passes through the inner volume of a free air chamber occupied by air, they collide with air particles and make various kinds of interactions. Some of them ionize air particles by photo-absorption or Compton scattering and produce pairs of free electron (recoiled electron) and positive ion. The recoiled electron has kinetic energy almost equivalent to one which X-ray loses in the first interaction subtracted by the binding energy of the recoiled electron to the atom. These recoiled electrons interact with air particles and ionize them until they lose all the energy they possess.

Theoretically, all the electrons produced in the volume can be collected by applying a high voltage between the top and bottom plates surrounding the volume. However, some of the recoiled electrons happen to hit the plates of a chamber before losing all the kinetic energies. This phenomenon causes a loss of ionization current and should be corrected by theoretical calculation. In this study, the incident photons with energy from 10 keV to 300 keV have been used in this simulation in 10 keV step. The photons entered into the volume through a 0.1 mm diameter hole and passed 46 cm distance before they reach the guard strips in the backside. The sensitive volume (0.1 mm diameter, 10 cm long) locates in the middle of the chamber, 18 cm away from front wall and 12 cm away from the side walls. [Fig.4.(A)] We tried to trace all the electrons and photons that were produced in the volume until they lose all their energies or go out of the volume completely. The ratio of energy absorbed from ionized electrons in the plates of a chamber to the total energy absorbed in the air inside the chamber, which is defined as a ratio of loss of ionization was obtained and the results are given in Fig.4.(B). In the incident photon energy below 130 keV, the ratio is negligible, in other words, no electrons with the energy less than 130 keV produced by primary scattering process could reach the plates. The ratio exhibits increase starting from 130 keV up to 220 keV, slight decrease up to 260 keV and another increase up to 300 keV.

3.2 Determination of a ratio of secondary ionization

Besides the interactions described in section 3.1, some of the primarily scattered photons collide with air particles again and ionize them outside of the sensitive volume. This process is called secondary ionization, and thus the electrons produced in this process should not be taken into count and the contribution due to it should be corrected. To do this, we followed the photon's track in EGS4 simulations and summed the energies transferred from the photon to the air particles when it occurred outside the sensitive volume. The relative ratio of this energy to the total energy absorbed by air particles inside the chamber was calculated for the incident photon energies from 20 keV to 300 keV in 10 keV steps. The results are given in Fig.4.(C). In the photon energy below around 20 keV, the ratio is about 0.8% and the ratio decreases monotonously as the photon energies goes up to 300 keV, yielding the ratio of 0.2% at 300 keV.

4 Summaries

Monte Carlo simulation using EGS4 was used in unfolding process and in determining the correction factors of free air ionization chamber. For the spectrum measured by NaI detector at 100 cm away from the Cs-137, the calculations smoothed with Gaussian distribution and cubic spline show that the measured spectrum was contributed strongly by the surrounding materials at low energies. For the spectrum measured by HPGe detector at 100 cm away from the X-ray generator, the pulse height distributions obtained with EGS4 simulations were normalized to the measured spectra without curve fit because of a good energy resolution of X-ray. The comparison explains that the energy spectrum of the incident photons is also continuous like the measured ones. In a free air ionization chamber composed of a parallel plate with a distance between the two plates, 24 cm, the loss of ionizations to the total ionization is negligible up to 130 keV of incident photon energy. Whereas, the ratio of secondary ionizations which are dominant at low energy decreases monotonously as the energy increases. At incident photon energies lower than 290 keV, the ratio of secondary ionizations is larger than the ratio of loss of ionizations. At energies higher than 290 keV, the ratio of loss of ionizations is dominant.

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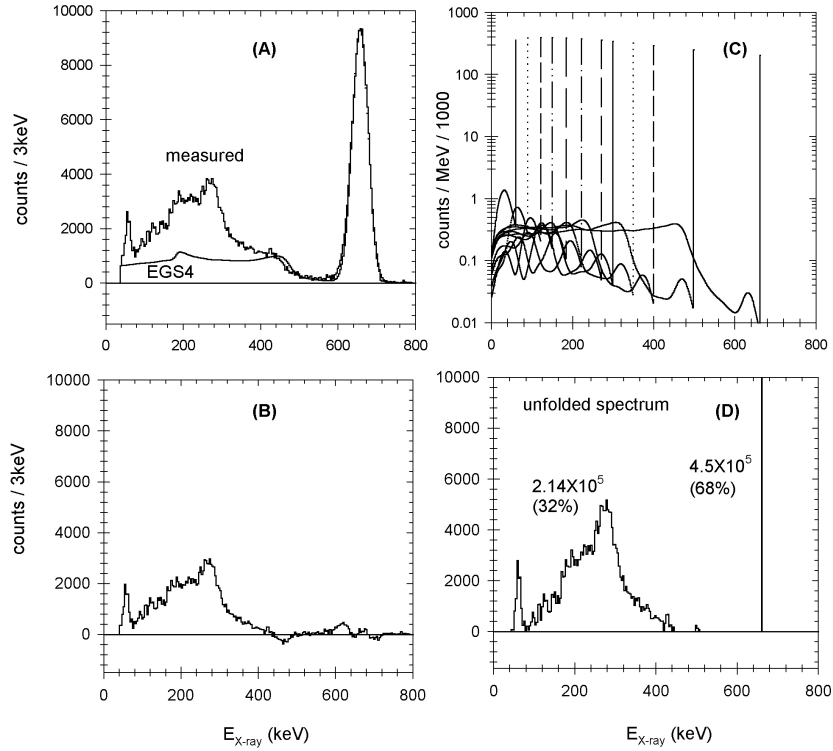


Figure 1: (A) A spectrum measured with a NaI(3" x 3") detector at 100 cm away from a radiation source Cs-137 is compared with a spectrum obtained using EGS4 simulations for 662keV incident photons. (B) Measured strength subtracted by the simulated strength. A small portion of the strength above 430 keV were neglected in the unfolding process. (C) Calculated spectra for a NaI (3 in. X 3 in.) detector using EGS4 code at different incident photon's energies. (D) Unfolded energy spectrum of photons that arrived at the detector. The number of 4.5×10^5 means the number of the incident photons that arrived at the detector with 662 keV from Cs-137 and 2.14×10^5 means the number of photons scattered from the surrounding materials. The numbers in the parenthesis mean the relative strengths.

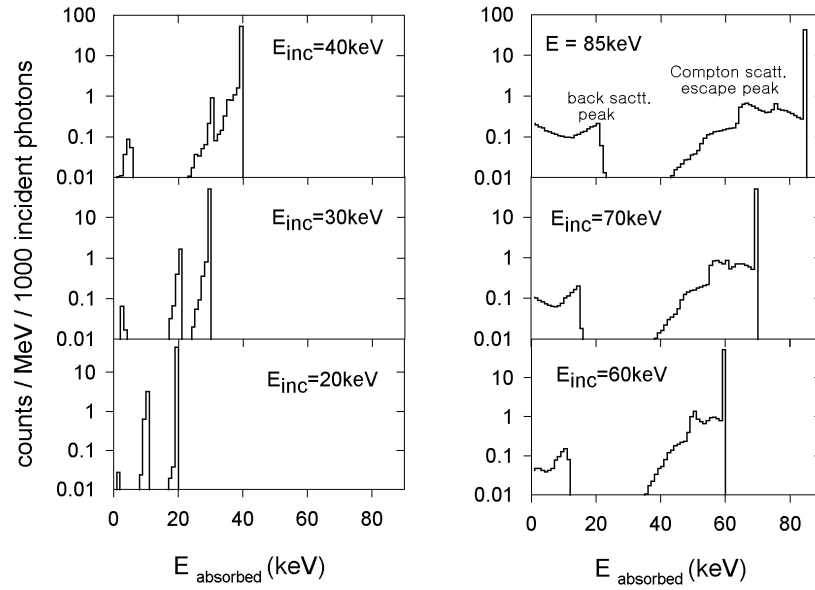


Figure 2: Calculated spectra using EGS4 code for the HPGe detector at different incident photon's energies. Totally, 17 spectra obtained at the energies from 5keV to 85keV in 5keV steps were used for interpolation.

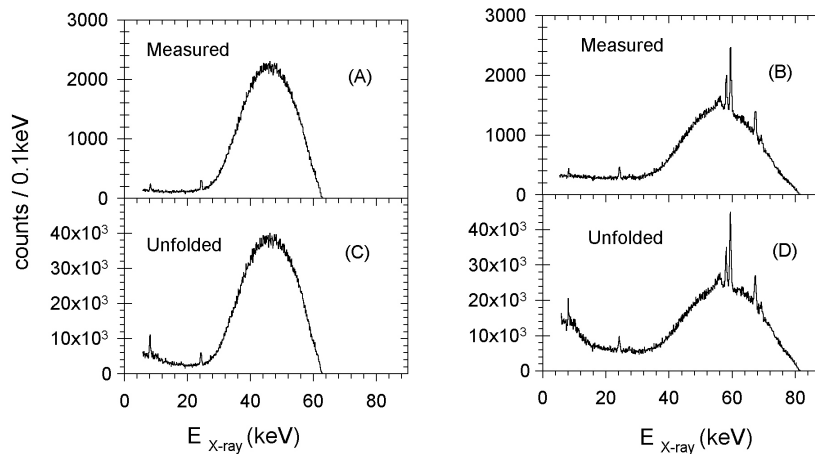


Figure 3: (A) Measured spectrum with a HPGe detector for the continuous X-rays of energies upto 63 keV. (B) Measured spectrum with the same HPGe detector for the continuous X-rays of energies upto 82 keV. (C) Unfolded spectrum for measured spectrum (A). (D) Unfolded spectrum for measured spectrum (B).

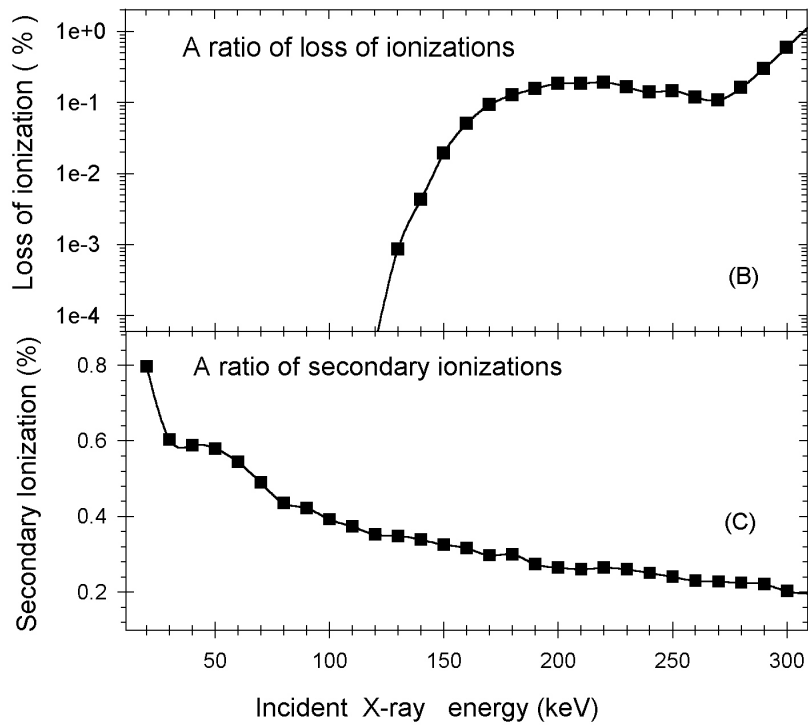
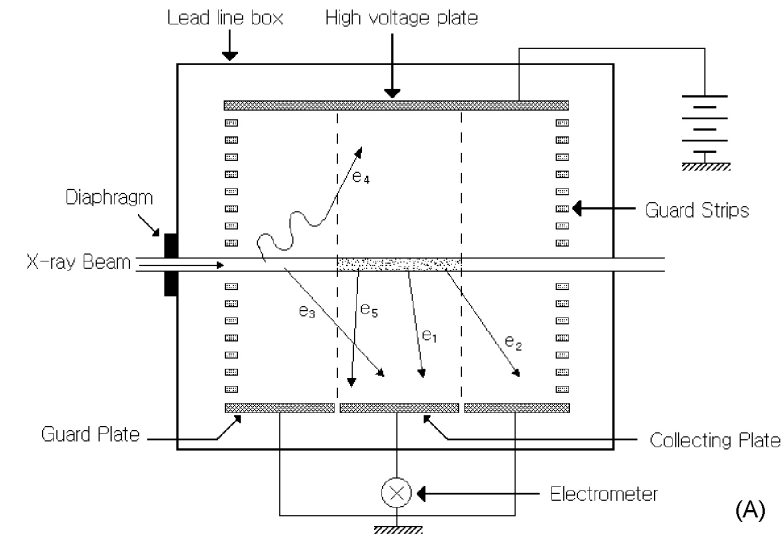


Figure 4: (A) Diagram for the free air ionization chamber. Incident photon beams pass through the 0.1mm diameter hole. The energies used in this simulation are from 10 keV to 300 keV in 10 keV step. (B) A ratio of loss of ionizations to the total air ionizations inside the chamber. (C) A ratio of air ionizations by the secondary scattered photons to the total air ionizations.