The determination of correction factors for free-air ionization chamber calculation using monte carlo method

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Abstract. A free-air ionization chamber is used as the primary standard instrument for absolute measurement of air kerma for of X-ray beams. The evaluation of correction factors is a key importance for establishing the standard. Photon-scattering, and diaphragm transmission and scattering were taken into the accounts to reduce some photon phenomena. On the other hand, electron-loss factor which scatter from an electrode were used for electron compensates. In this research, Correction factors were calculated for each mono-energetic photon from 2 to 60 keV for low energy x-rays and 10 to 320 keV for medium energy x-rays by EGS5 code. The calculated corrections from a mono-energetic photon of W/Mo mammography x-rays were compared between effective energy and spectrum method. There is no significant difference between two methods.

1. Introduction

Free-air ionization chamber has been used in primary standard dosimetry laboratory (PSDL) as primary standard instrument for measuring absolute air kerma rate of low and medium energy x-rays. The main principle of the free-air ionization chamber is related to the definition of kerma which is the sum of the initial kinetic energies of all the charge ionizing particles released by photons interaction at measurement volume. When photons transfer their energy to the medium, the energy transfers again to the others through atomic excitation or ionization process. Photons that emitted from x-rays generator pass through the diaphragm aperture area, the most important factor, which used to control the beam size to free-air ionization chamber. However, some photons enter to the chamber through the edge of the diaphragm and then scatter in the inner aperture before entering to the measurement area. Primary and secondary photons generate charged particles at collecting volume. However, for the kerma definition, charged particles which are generated from secondary is not included. So, the measurement should be corrected [1-3]. On the other hand, some charged particles which are generated by photons are kicked off to outside measurement region. These phenomena affect to the measurement results. As these phenomena, the correction factors for photon-transmission at the diaphragm edge ($k_{dtr}$), photon scattering at the diaphragm edge($k_{dsc}$), photon scattering ($k_{sc}$), and electrons loss ($k_{e}$) are introduced.

The correction factors can be evaluated by Monte Carlo method or estimated by an empirical equation. However, the empirical estimation is not suitable for the primary standard laboratory because of making a large uncertainty. Thus, the Monte Carlo simulation method was conducted in this research. The EGS5 Monte Carlo simulation was used to determine the correction factors for low-energy and medium-energy x-rays free-air ionization chambers installed at Office of Atoms for Peace (OAP).
Subsequently, the calculation results were applied for W/Mo spectrum for low energy x-rays chamber. The determination of the correction factors by two different methods (spectrum weighting and effective energy) was obtained.

![Diagram of Diaphragm](image)

**Figure 1.** The situation of transmission photons (the orange line), photon scatter at inner surface of the diaphragm (the blue line) and normal photon enters to the measurement volume (the green line).

### 2. Definitions and calculation

The correction factor for photon transmission through edge of the diaphragm \( k_{dtr} \) is defined by energy transfer to air and deposited in the measurement volume without any interaction \( (E_p) \) and energy transferred by transmission photon \( (E_{dtr}) \) [2]. The correction can be expressed as

\[
k_{dtr} = \frac{E_p}{E_p + E_{dtr}}
\]

(1)

Moreover, the scattering photons that scatter to the inner diaphragm surface and also deposit at the volume. Therefore, the correction factor can be shown as

\[
k_{dsc} = \frac{E_p + E_{dtr}}{E_p + E_{dtr} + E_{dsc}}
\]

(2)

where \( k_{dsc} \) is correction factor for diaphragm scattering and \( E_{dsc} \) is energy transferred to air by photon that scattered at the inner surface. The figure 1 shows photon situation transmission through the edge (orange line) and the scattering photon at the inner diaphragm surface (blue line).

Meanwhile, the charged particles at collecting volume are produced by the interaction of photons with the medium. There are two types of photons; primary photons and secondary photons that interact and generate the charged particles into the region. Nonetheless, the secondary photons are not included of Kerma. Thus, the correction is given by

\[
k_{sc} = \frac{E_p}{E_p + E_{sc}}
\]

(3)

where \( k_{sc} \) is correction factor for photon scattering, \( E_p \) is energy deposited by primary photons without any interaction and \( E_{sc} \) is the energy deposited by charged particles from scattered photons in the measurement region.

When electrons transfer the energy by the primary or secondary photons and their energy is larger than mean deposited, it can escape to the outside of measurement volume. The electrons must be compensated for measurement results correction. Figure 1 shows diagram of low-energy and medium-energy free air ionization. Figure 2 shows cross section view of the chamber, (a) for the low-energy free air ionization chamber, (b) the medium-energy free air ionization chamber. The \( k_e \) is expressed by
where $E_p$ is the energy deposited from electrons generated by primary photons in collecting volume and $E_{loss}$ is the energy from the electrons can escape to electrode or nearby region.

For this research, the correction factors were calculated by EGS5 code for a mono-energetic photon with two sizes of the chamber. The small size chamber was used for low-energy x-rays and large size chamber was used for medium-energy x-rays. The chambers were made from 8.0 g.cm$^{-3}$ stainless steel with a tungsten alloy diaphragm (density is 17.0 g.cm$^{-3}$ and components are 89% tungsten, 7% nickel and 4% copper) without aluminum guard bar.

\begin{equation}
    k_e = \frac{E_p + E_{loss}}{E_p},
\end{equation}

For calculation, X-ray source was assumed as a point source with mono-energy from 2 keV to 60 keV with 2 keV steps and 10 keV to 320 keV with 10 keV steps for low energy x-rays and medium energy x-rays, respectively. The chamber was located at 600 mm and 1200 mm from the point source of x-rays for low-energy and medium energy x-ray respectively. The Intel Core i7 3.38 Hz with 10$^8$ to 10$^9$ histories was used for Monte Carlo simulation. The calculation time was around 500-1000 hours for each condition. Finally, the calculation results were applied to W/Mo mammography to investigate the correction factors. Because these corrections are first calculated for monoenergetic values. Thus, the monoenergetic results are then applied to evaluate the spectrum values of $k_e$, $k_{sc}$, $k_{dtr}$, and $k_{dsc}$ by equation [4].

\begin{align}
    k_e &= \frac{\sum \Phi(E)(E_p(E) + E_{loss}(E))}{\sum \Phi(E)E_p(E)} \\
    k_{sc} &= \frac{\sum \Phi(E)(E_p(E) + E_{sc}(E))}{\sum \Phi(E)E_p(E)} \\
    k_{dtr} &= \frac{\sum \Phi(E)(E_p(E) + E_{dtr}(E))}{\sum \Phi(E)E_p(E)}
\end{align}
where $\Phi(E)$ is spectral weighting, investigated with the spectrum measurement. The correction factors are calculated by two methods: spectral weighting and effective energy.

Figure 3. The electron loss and photon scattering correction factors (a) the photon scattering correction factor for low energy x-rays (b) the electron loss correction factor for low energy x-rays (c) the photon scattering correction factor for medium energy x-rays and (d) the electron loss correction factor for medium energy x-rays.

3. Result and discussion

For low energy x-rays free-air ionization chamber, the electron-loss and photon-scattering correction factor is shown in figure 3 (a)-(b), respectively. For medium energy x-rays free-air ionization chamber, the electron-loss and photon-scattering correction factor is shown in figure 3 (c)-(d), respectively. The photon scattering correction factor also consider fluorescence effect in the Monte Carlo code and should be below 1 as shows equation (3). The photon-scattering correction factor increases with increasing the energy of X-rays. Figure 3 (a) shows large scattering in the photon energy below 20 keV due to the probability of a high photoelectric interaction effect. However, with this increasing in photon energy, the effect of scattering is reduced and the correction approach to 1. For example, in the small-sized chamber, the correction factor for scattered photon is 0.9955 for 60 keV x-rays. For the large-sized chamber, the correction factor for scattered photon is 0.9945 for 320 keV x-rays.
The calculated electron loss correction factor for is shown in figure 3 (b) for small-sized and 3 (d) for large-sized chamber. If photon energies are not greater than 50 keV, the electron which generated by ionizing from photons cannot escape from the collecting region. Whereas the photon energies are greater than 50 keV, the electron can escape to electrode or nearby region due to the high probability of photoelectric effect as shown in figure 3 (b) and 3 (d). For large-sized chamber, The correction increase slightly between 110 keV and 180 keV and decreasing until 240 keV due to photoelectric effect. In the case of photon energies are greater than 240 keV, the electrons are high probability interaction due to Compton effect [3]. Although the interaction of Compton effect cross-section is slowly changing, the energy of electron from this effect increases dramatically with increasing of photon energy. Thus, the probability of escaped electrons to the electrode is high which caused to high electron-loss correction factor.

Figure 4. The correction factor for photon scattering with inner surface of the diaphragm (blue line) and photon transmission (orange line) (a) small-sized chamber and (b) large-sized chamber.

The photon-scattering correction factor with inner surface of the diaphragm (blue line) and photon-transmission correction factor (orange line) are shown in figure 4 (a) for low energy x-rays chamber and figure 4 (b) for medium energy x-rays chamber. The diaphragm used at OAP is 10 mm diameter aperture and made from tungsten alloy. The diaphragm-scattering and photon-transmission correction factors for low and medium energy x-rays decrease moderately and approach to the same value. The diaphragm-scattering and photon-transmission correction factors decrease with an increasing of the photon energy. The diaphragm-scattering correction factors (blue line) are shown in the figure 4 (a) for small-sized chamber and figure 4 (b) for large-sized chamber. For the large-sized chamber, the diaphragm-scattering correction factor is a little bit drop down at photon energy around 50-70 keV due to the tungsten K-edge absorption [1,5]. Thus, the value of \( k_{dsc} \) is clearly decreasing between those ranges. However, the K-edge tungsten contribution characteristic from the diaphragm does not affect the correction factor.

| Beam quality (kV) | HVL (mm) | Effective energy (keV) | \( k_{isc} \) spectrum | \( k_{isc} \) eff. |
|------------------|----------|------------------------|------------------------|------------------|
| 25               | 0.333    | 15.27                  | 0.9977                 | 0.9970           |
| 28               | 0.345    | 15.57                  | 0.9975                 | 0.9971           |
| 30               | 0.354    | 15.78                  | 0.9975                 | 0.9971           |
| 35               | 0.375    | 16.23                  | 0.9973                 | 0.9972           |

The correction factors were applied to W/Mo mammography and then calculated the specific correction for the beam qualities of 25, 28, 30 and 35 kV. Table 1 shows the values of correction factor \( k_{isc} \) correction factor in the small-sized chamber, whilst the correction factor for \( k_{isc}, k_{dtr}, \) and \( k_{dsc} \) for low
energy x-rays approach to 1 which already described in previous paragraph. So, the calculated results are not shown in the table 1. The correction $k_{sc}$ was obtained by weighted energy spectral and effective energy of the beam quality as shows in figure 3 (a). The effective energy can be calculated via HVL measurement and NIST material data investigation.

4. Conclusion
The correction factors were determined by Monte Carlo simulation method for photon-scattering, electron-loss and contributions of transmitted photons through the diaphragm edge and scattered the inner surface diaphragm. For this study, the calculation results were in the energy range of 2 - 60 keV for small-sized chamber and 10 - 320 keV for large-sized chamber. The correction factors were applied to W/Mo mammography beam qualities and calculated using the weighing spectrum and effective energy method. The correction factor from two different methods has no significant difference. The photon-scattering correction factor was the largest correction for low-energy x-rays standard (around 25%) as shown in table 1 while, the other correction factors were very close to 1. The overall uncertainty was 0.03% at $k=1$.

References
[1] Kurosawa T, Tanaka N and Saito N 2011 Radiat. Prot. Dosim. 146 195–7
[2] Burns D T and Kessler C 2009 Phys. Med. Biol. 54 2737–45
[3] Huang T T, Chu C H and Lin Y C 2017 Radiat. Phys. Chem. 140 38–42
[4] Lye J, Butler D and Webb D 2009 Metrologia 47 11–20
[5] Mohammadi S M and Tavakoli-Anbaran H 2018 Appl. Radiat. Isot. 132 178–80