Simulation of correction factor about electronic loss and fluorescence and scattering for W/MO X-rays

Ji Wang\textsuperscript{1,2}, Shiwei Ren\textsuperscript{1}, Jinjie Wu\textsuperscript{2}*, Siming Guo\textsuperscript{2}, Hongjie Li\textsuperscript{1}

\textsuperscript{1}Hebei University Of Science and Technology, Shijiazhuang, People’s Republic of China\textsuperscript{2}National Institute of Metrology, Beijing, People’s Republic of China

E-mail: wujj@nim.ac.cn

Abstract: The Monte–Carlo (MC) program EGSnrc was used to establish the model of low-energy radiation field and low-energy free air ionisation chamber. The electron loss correction factor and the fluorescence scattering correction factor of the molybdenum-filtered X-ray radiation of 23 \text{~} 35\text{kv} tungsten target were simulated. The results show that due to the low effective energy of the radiation and the energy is close, the influence of the electronic loss correction factor is negligible, and the fluorescence and scattering correction factors increase slightly with the increase of the effective energy.

1 Introduction

In recent years, breast cancer has developed into the first killer that seriously threatens women's health. Mammography significantly reduces the risk of early breast cancer screening in various tests and thus reduces the risk of breast cancer by 25–30\%. The improvement of inspection equipment can improve the quality of images and the ability to detect early breast cancer [1, 2]. For most people, the density of breast tissue is small, and the image resolution and contrast of molybdenum target X-ray machines are higher. For some large thickness, high density of breast tissue, to penetrate tissue high density, can shorten the 1/5 to 2/3 of irradiation time [3].

In recent years, the technology of Monte–Carlo (MC) has been gradually promoted in scientific research, especially in nuclear science and technology. D T Burns of France used EGS4 MC programme to simulate the electronic loss correction factor, scattering photon correction factor, and fluorescence photon correction factor of free air ionisation chamber. International research institutions such as BIPM, PTB, and NRC also commonly use the MC method to calculate the electron loss correction factor and the scattering fluorescence correction factor of the free air ionisation chamber. The low-energy X-rays mainly produce the photoelectric effect and the Compton effect in the air. In the ionisation chamber, a small part of the secondary electrons generated by the X-rays and the air may hit on the wall of the ionisation chamber without being collected, which will cause electrons loss [4]; The photoelectric effect and Compton scattering also produce scattered photons and fluorescent photons, which will continue to interact with air, making the measured secondary electrons larger than the theoretical value. Therefore, in the absolute measurement of air kerma, electron loss, scattered photons, and fluorescence photons must be corrected as necessary [5, 6].

2 Free air ionisation chamber

The free air ionisation chamber is a commonly used gas detector in the X-ray base standard research work. It is often used in the absolute measurement of the X-rays air kerma. National Institute of Metrology (NIM) has studied and designed a flat type free air ionisation chamber device for low-energy X-ray air kerma absolute measurement under the existing low-energy X-ray reference radiation field and molybdenum target X-ray radiation field. The purpose of this ionisation chamber design is to establish an absolute measurement standard for X-ray photon flux based on the energy range of the low-energy reference radiation field and absolute measurement the air kerma. The design of the ion chamber assembly is shown in Fig. 1. The main structure of the device includes aperture, front panel, rear panel, top cover, bottom plate, handle, high-voltage insulation mat, ionisation chamber, and the like. The outside of the ionisation chamber is surrounded by a front panel, a front panel, a top cover, a bottom panel, and a side panel, mainly for shielding the interference rays outside the ionisation chamber [7, 8].

Ionisation chamber structure parameters: aperture diameter 10 mm, collecting length 40 mm, collecting width 100 mm, effective measurement volume 3194 mm\textsuperscript{3}, air attenuation length 100 mm, upper and lower plate spacing 79.2 mm, polarisation voltage 1.6 kV.

3 Electronic loss correction factor and scattering fluorescence correction factor

Kerma is defined as the sum of the initial kinetic energy of all charged particles released by uncharged particles in a substance of mass dm divided by dm. When the defined substance is air, it is the air kerma [9].

The formula is as follows:

\[
K = \frac{dE_{\text{tr}}}{dm}
\]
When an X-ray air kerma rate $K$ is absolutely measured with a flat type free air ionisation chamber, the X-ray air kerma rate $K$ is expressed as:

$$K = \frac{I}{\rho_{\text{air}}} \times K_{\text{TP}} \times \frac{W_{\text{air}}}{c} \times \frac{1}{1 - g_{\text{air}}} \prod k_i$$

where $I$ is the current resulting from air ionisation at the collection chamber of the ionisation chamber; $\rho_{\text{air}}$ is the density of the air in the laboratory; $K_{\text{TP}}$ is the temperature and pressure correction factor for the air in the collection chamber of the ionisation chamber; $V$ is the effective volume of the collection region of the ionisation chamber; $W_{\text{air}}$ is the average energy required for each ion pair generated in the air; $g_{\text{air}}$ is the fraction of the electron initial bremsstrahlung radiation in the air; $\prod k_i$ is the correction factor to correct the measurement result. Product:

$$\prod k_i = k_a \times k_d \times k_s \times k_p \times k_{\text{dia}} \times k_{\text{pol}} \times k_{\text{sc}} \times k_{\text{fl}} \times k_{\text{other}}$$

where $k_a$ is the correction of the air attenuation from the aperture to the collector in the ionisation chamber; $k_d$ is the correction of the sudden change of the electric field between the high voltage pole and the collector stage of the ionisation chamber; $k_s$ is the correction of ion saturation in the collection region of the ionisation chamber; $k_p$ refers to the correction of the effect of air humidity on the measured ionisation current in the ionisation chamber; $k_p$ is the correction of radiation penetration through the chamber of the ionisation chamber; $k_{\text{dia}}$ is the correction of X-rays passing through the edge of the aperture; $k_{\text{pol}}$ is the ionisation chamber collection stage. Correction of the polarity effect between protection levels; $k_{\text{sc}}$ is the correction of electron loss caused by the secondary electrons not being ionised in the collection area; $k_{\text{fl}}$ is the correction of the effect of scattered photons generated in the ionisation chamber on the measurement; $k_{\text{other}}$ is the correction of the fluorescence photon generated in the ionisation chamber versus the measurement result. $k_{\text{other}}$ is other correction factors [10, 11].

When X-rays enter the ionisation chamber through the aperture, X-rays in the collection area interact with air to produce secondary electrons. Under laboratory conditions, the initial kinetic energy of secondary electrons cannot be completely converted into ionisation currents and collected. At all stages of the collection, the secondary electrons that are likely to be produced do not ionise in the collection zone. This part of the energy is lost and the collection stage does not collect all the charges. This will make the measured ionisation current value smaller. Therefore, we must use the electronic loss correction factor $k_e$ to correct this part of the deviation [12].

X-ray and air generation Compton effect and photoelectric effect will produce scattered photons and fluorescent photons. Fluorescence photons and scattered photons will interact with air to generate additional secondary electrons. The scattering fluorescence correction factor is to correct the measurement deviation caused by this part of secondary electrons. The definition of the X-ray air kerma kinetic energy shows that the initial kinetic energy of all charged particles does not include extra electrons generated by scattered photons and fluorescent photons. However, under the experimental conditions, this part of the bias is always present, which will result in large measurement results. This requires correcting the deviation using the scattering fluorescence correction factor $k_{\text{fl}}k_{\text{other}}$ [13].

## 4 Monte Carlo simulation

### 4.1 EGSnrc simulation program

EGS is a MC simulation program that simulates the transport of electrons and photons in matter. It is a theoretical analysis and simulation tool that simulate the transport laws of electrons and photons in matter [14, 15]. The photon energy generated by the low-energy X-ray radiation field is between 10 and 50 keV. This article uses X-rays with a tube voltage of 23/25/28/30/35, the additional filter of 0.06 mm molybdenum, and the number of photons is 1 billion. The photon energy will vary from 10 to 35 keV.

The EGSnrc program includes a variety of physical processes, including electron pair effects, photoelectric effects, Compton scattering, Rayleigh scattering, photoelectron angle distribution, Doppler broadening, Bremsstrahlung, and others [16] (Fig. 2).

### 4.2 Flat free air ionisation chamber geometry model

Using the EGSnrc MC Simulation software to establish a flat free air ionisation chamber model, the geometric model structure of EGSnrc is shown in Fig. 3.

The ionisation chamber structure simulated by the EGSnrc program is a flat panel type. According to the dimensions and material requirements of the design of free air ionisation chamber, the entire simulation consists of six materials, namely Fe, W, Al, PMMA, C, and air. The model is divided into 18 regions, but the areas we focus on are mainly concentrated in the two parts of the ionisation chamber upper and lower plates and the ionisation chamber collection area. In addition, in order to obtain more accurate simulation results, we need to build a shielding layer with Fe material in the ionised outdoor layer. In the simulation process, the density and cross-section data of the material are first imported using the PEGRNRC material library, then the geometric structure type is defined, the number of simulated photons is 10⁹, and the X-
ray tube voltage is set to 23/25/28/30/35 KV. The photon and electron cut-off energy settings are 1 and 512 keV, respectively. By selecting the physical process in the EGSNRC simulation program, the energy deposition of incident photons, scattered photons and fluorescent photons in the collection zone and the upper and lower walls can be obtained, respectively.

The energy deposited by the incident photons entering the ionisation chamber in the collection zone is $E_a$, and the energy deposition energy at the upper and lower walls of the ionisation chamber (outside the collection zone) is $E_e$, defined by the electronic loss factor $k_e$:

$$k_e = \frac{E_a + E_e}{E_a}$$

The scattering fluorescence correction factor $k_{sc}k_{fl}$ can be calculated by the formula:

$$k_{sc}k_{fl} = \frac{E_{sc}}{E_a + E_{sc} + E_{fl}}$$

Where, $E_{sc}$ and $E_{fl}$ are the energy deposition of scattered photons and fluorescent photons in the collection zone, respectively.

4.3 EGSnrc simulation results

Using the EGSnrc MC program to simulate the entire process of X-ray interaction with air in a flat free air ionisation chamber, and the electron loss correction factor and the fluorescence scattering correction factor in the calculation formula of the X-ray air kerma energy were obtained, as shown in Table 1.

From Fig. 4, we can see that the electronic loss correction factor is always 1.000. Theoretical analysis shows that because the effective energy of radiation is about 16 keV and the energy is low, the secondary electrons generated by X-rays in the air have lower kinetic energy and the range in air is too short, and the upper and lower plates of the ionisation chamber cannot be touched, so no electronic loss occurs. Therefore, the electronic loss correction factor is 1.000. From Fig. 5, it can be seen that the value of the scattering fluorescence correction factor is also close to 1, and it tends to increase with the increase of X-ray effective energy. This is probably because effective energy is around 16 keV, with the increase of effective energy, the probability of occurrence of Compton effect of the incident photon is relatively increased. Scattering photons and fluorescent photons pass through the ionisation chamber without interacting with the air at the collector. After that, the scattering fluorescence factor will also show a gradual increase.

4.4 Compared with other countries

At present, most of the world's international diagnostic breast radiation are Mo target Mo-filtered radiation. BIPM began to add molybdenum filter in the low-energy tungsten target radiation field in 2005 to establish seven radiations of 23–50 kV, and it began to organise in 2009. International key comparison BIPM.R/I(-1)-K7. PTB also established four tungsten-targeted molybdenum-filtered mammography radiations at 25–35 kV in the low-energy radiation field and compared it with BIPM in 2011. Now we compare the electron loss of four radiation quality and the correction factors for fluorescence scattering in all three institutions. The results are shown in Table 2.

It can be seen from the comparison that due to the lower effective energy of the radiation, the photon has a short range in the air and does not contact the upper and lower plates of the ionisation chamber without generating electron losses. Therefore, the electronic loss correction factor is 1.000. The fluorescence and scatter correction factors show the same trend and increase with the increase in energy. Due to the large collection pole width (240 mm) of the reference ionisation chamber of the PTB, the photon and air produce more of the Compton effect. Most of the scattered photons and fluorescent photons do not interact with the air in the collector to produce charged particles from the ionisation chamber. Therefore, the fluorescence and scattering correction factors of PTB differ greatly from BIPM and NIM.

| Table 1 Simulation correction factor results |
|---------------------------------------------|
| Quality | W/Mo-23 | W/Mo-25 | W/Mo-28 | W/Mo-30 | W/Mo-35 |
|---------|---------|---------|---------|---------|---------|
| effective energy/keV | 15.4 | 15.56 | 15.8 | 15.99 | 16.4 |
| $k_e$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $k_{sc}k_{fl}$ | 0.99391 | 0.99397 | 0.99412 | 0.99419 | 0.99424 |

| Table 2 Comparison of three agency correction factors |
|-----------------------------------------------|
| W/Mo-25 | W/Mo-28 | W/Mo-30 | W/Mo-35 |
|---------|---------|---------|---------|
| $k_e$ | $k_{sc}k_{fl}$ | $k_e$ | $k_{sc}k_{fl}$ | $k_e$ | $k_{sc}k_{fl}$ | $k_e$ | $k_{sc}k_{fl}$ |
| BIPM | 1 | 0.9946 | 1 | 0.9946 | 1 | 0.9946 | 1 | 0.9946 |
| PTB | 1 | 0.9910 | 1 | 0.9911 | 1 | 0.9911 | 1 | 0.9912 |
| NIM | 1 | 0.9940 | 1 | 0.9941 | 1 | 0.9942 | 1 | 0.9942 |

![Effective energy and correction factor graph](image)
5 Conclusion

Here, the electron loss correction factor and the scattering fluorescence correction factor of the tungsten target molybdenum-filtered mammogram X-ray radiation were calculated using the EGSnrc MC program. The trend of change was studied, and the electron loss was negligible at lower energy range. The fluorescence correction factor gradually increases as the X-ray energy increases. Completed the preliminary work of traceability of tungsten target molybdenum-filtered X-ray air kerma.

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7 References

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