Measurements of Air-kerma in Mammography X-Ray Standard Using Free-air Chamber

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Abstract: Mammography x-rays standard is required to improve the quality of mammary machine and reduce the dose for women and staff. The molybdenum target x-rays machine is used as the radiation source and free-air cylindrical chamber is designed for detecting photon. Four standard radiation qualities are established with international standard documents as references. The Correction factors including air attenuation, scattered radiation, fluorescence, wall transmission, electron loss are studied in the four radiation quality. The uncertainty in absolute measurement of air-kerma includes air volume measurement of ionization chambers, current measurement, measurement of temperature and pressure, measurement of correction factors, physical constants and orientation of the reference distance. The relative combined standard uncertainty is 0.24%.

Keywords: Metrology; Free-air Chamber; Air-kerma; Correction Factor; Degree Of Uncertainty

1 Introduction

Recent years, the incidence of breast cancer have been staying in a high rate, showing no signs of decline. According to the World Health Organization, since 2008, the incidence of global breast cancer growth rate is more than 20% per annum, mortality rate exceeds 14%. Since 2008, the annual growth rate of breast cancer around the world is more than 20%, the annual mortality rate exceeds 14%. The World Health Organization predicts that there will be more than 19 million cases of breast cancer in the world in 2025. With the promotion of awareness in public health, it has been drawing attention from women to their own health, the regular breast examination has also gained public recognition.[1] Mammography X-ray examination has a good indication of soft tissue and spatial resolution, which is the most effective and accurate method for breast cancer diagnosis.[2] As more breast examinations are needed, the quality control of breast machine becomes more and more important, so it is imperative to establish a national standard for mammography examination system.

Since 2005, National Metrology Organization around the world has established the mammography standard. In 2005, the International Bureau of Metrology (BIPM) began the study of the absolute measurement of the Air-kerma of mammography X-rays, it established a standard in 2009 and conducted an international comparison. National Institute of Standards and Technology (NIST), Physikalisch-Technische Bundesanstalt (PTB), and National Metrology Institute of Japan (NIMJ) perform the comparison with BIPM of the mammography X-ray standard respectively.[3,4] The construction of the mammography X-ray standard in China is administered by National Institute of Metrology, China (NIM). In this paper, the ionization chamber of mammography X-ray standard is introduced and the correction factors are studied.

2 Free Air Ionization Chamber

The radiation source of the mammography X-ray standard is X-ray apparatus. The photon beam is limited by aperture slot. The uniform field that satisfies recurrence and transfer of air-kerma is obtained at the reference plane. Referencing radiation quality specification recommended in IEC61267,[5] the standard radiation field is established and adjusted using appropriate filters.

The mammography X-ray standard is shown in Fig. 1, including: X-ray machine, X-ray tube conditioning system, aperture, diaphragm, filter, calibration platform, controller, laser positioning, ionization chamber and so on.

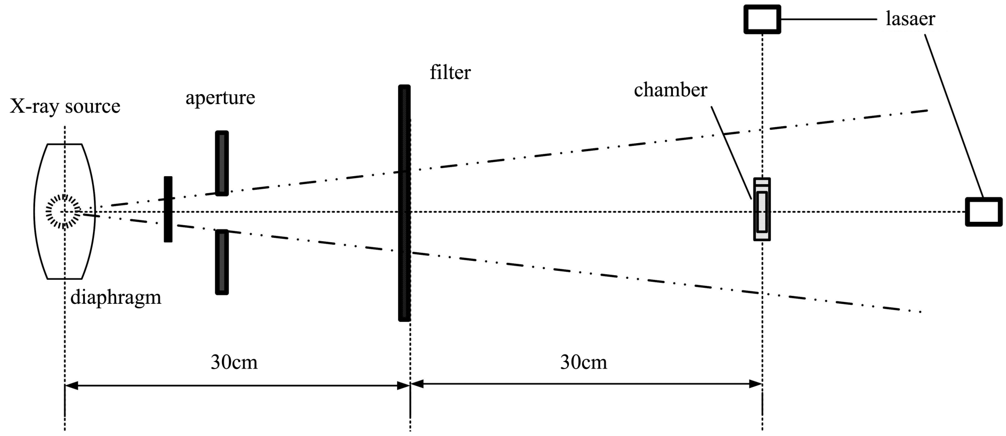

Fig. 1 The mammography X-ray standard

By definition, the air-kerma is dE_{tr} divided by dm, dE_{tr} is the sum of the initial kinetic energy of the secondary electrons released by X-ray in air which mass is dm. Thus, the air-kerma is defined by the kinetics of all secondary electrons produced. According to the mechanism of interaction between X-ray and air, the energy of photon and Compton scattering photons is transformed into the kinetic energy of secondary electrons. The secondary electrons make the air ionization, and the ionization charge can be collected by the ionization chamber, then the air-kerma is obtained. Strictly speaking, the entire range of each secondary electron needs to be fully utilized to measure all of the ionization. The secondary electrons produced by the molybdenum target X-rays have a few centimeters in the air. Suppose the air surrounding the effective air volume is also adequate and equally radiated, the effective air volume can be strictly corrected. Reference data of free air ionization chambers form BIPM and NIST[6,7], the designed cylindrical free air ionization chamber is shown in Fig 2.

According to the research status and uncertainty level of the international mammography X-ray standard, the design parameters of the air free ionization chamber in NIM are as follows: (1) The coaxial property of the aperture hole, the center axis of the high-pressure pole and the beam axis: better than 0.1mm; (2) The accuracy of positioning and repeatability of the moving collector: better than 0.01mm; (3) The symmetrical piston motion form is used to ensure that the center of the collecting area is invariable, and the parallelism of the two sides of the moving collector is perpendicular to the center axis of the high-voltage pole: better than 0.01mm; (4) The verticality of the aperture definition surface and the center axis of the high pressure pole: better than 0.01mm, (5) Distance of collecting pole center axis and high-voltage pole center axis is 25mm; (6) The center of the collection area is as small as possible behind aperture; (7) The overall height of the shield box is adjustable, the adjustment range: ±10mm; (8) The error of the high-voltage pole di-

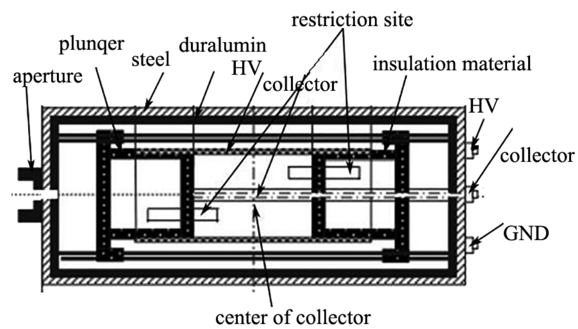

Fig. 2 Cylindrical free air ionization chamber

ameter and the diameter of the collecting pole are better than 0.01mm.

Two layer shielding material are used in the front wall of the shielding cabinet of the ionization chamber: the inner layer is 3mm hard aluminum, the outer layer is 10mm stainless steel, the hole diameter at center is 36mm; the outside is 3mm hard aluminum and 3mm stainless steel shielding; the back wall also uses 3mm hard aluminum and 3mm stainless steel, and the center hole diameter is 20mm.

3 Determination of the air-kerma rate

The air-kerma is defined as *dEtr* divided by *dm*, in which *dEtr* is the total kinetic energy of initial charged particles in a certain mass and *dm* is the mass of the material. When the defined substance is air, it is air-kerma

$$K_{air} = \frac{dE_{tr}}{dm}$$

For a free air ionization chamber standard with measuring volume V, the air-kerma rate is determined by the relation

$$K_{air} = \frac{I}{\rho_0 \cdot \frac{T_0}{(T_0 + T)} \cdot \frac{P_a}{P_0} \cdot \mathrm{V}} \cdot \frac{1}{1 - g_{\mathrm{air}}} \cdot \frac{W_{\mathrm{air}}}{e} \cdot \prod_i k_i$$

Where ρ_0 is the air density in the experimental environment, I is the ionizing current in the experimental environment, P_a is the pressure in the experimental environment, V is the volume of the free air ionization chamber, W_{air} is the ionization energy in the air, e is the electron charge, g_{air} is the fraction of the initial electron energy lost in the air through the radiation process, $\prod_i k_i$ is the product of the correction factors

$$\prod_i k_i = k_a k_s k_p k_{pol} k_{dia} k_h k_e k_{sc} k_{fl} k_{other}$$

Where k_a is the air attenuation correction factor, k_s is the saturation correction factor, k_p is the radiation through the chamber wall through the correction factor, k_{pol} is the polarity correction factor, k_{dia} is the diaphragm correction factor, k_h is the air humidity correction factor, k_e is the electron loss correction factor, k_{sc} is the correction factor of the scattered photons in the ionization chamber, k_{fl} is the correction factor of the fluorescence in the ionization chamber, and k_{other} is the other correction factors. The physical constants referred in the determination are shown in Table 1. [3]

Table 1 Physical constants used in the determination of the air-kerma rate

Constant	Value	Uncertainty(%)
p_{air}	1.2930 kg/m^3	0.01
W_{air}/e	33.97 J/C	0. 15
$1 - g_{air}$	1.0000	0. 01

4 Correction Factors

Accurate reproduction of the air-kerma using free air ionization chamber depends on accurate measurement of several physical quantities. There are uncontrollable factors affecting the accuracy of the results, so the correction factors is necessary to make the measurement results closer to the true value.

4.1 Air attenuation

When the free-air ionization chamber is used to determine air-kerma, the actual collection of ionization charges is the center of the collector. However, the reference position is the beam limiting plane of the diaphragm. As shown in Fig. 3, the aperture reference plane is the defined surface. The X-ray photon beam is attenuated by the length of the air column from the defined surface to the measurement center. For the lower energy photon, it is clear. In this case, it is necessary to introduce an air attenuation correction coefficient k_a to correct the air-kerma at the measurement point.

$$k_a = e^{\mu d}$$

Where d is the distance from the center of the collector to the aperture reference plane, and μ is the air attenuation factor.

The general methods for determining the air attenuation correction factor are, Attix total absorption

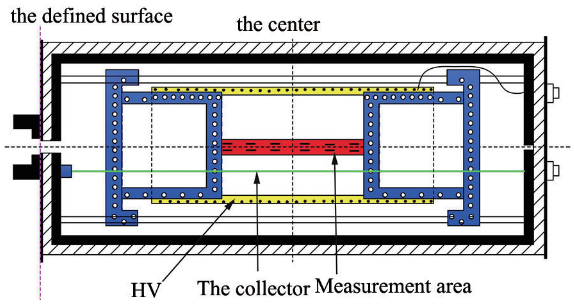

Fig. 3 Diagrammatic sketch of air attenuation

method, radiation quality spectrometry and change air process method[8]. Changing the air process method is used in this paper. Adjust the distance between the ionization chamber and the focal spot of X-ray tube to measure the air attenuation factor, which means under the condition that the X-ray photon is narrow beam, the X-ray enters the free-air ionization chamber completely, and the distance between the moving ionization chamber is d. So the ionization current of the ionization chamber can be measured at different position. In the experiment, an aperture is fixed at the proper position outside the X-ray machine, to ensure that all primary X-ray beam can enter the ionization chamber completely, but it can exert some restrictions on the scattered photon, therefore, most of the scattered photons cannot enter the ionization chamber. This satisfies the geometrical condition of narrow beam. In the narrow beam conditions, it allows the X-ray photon to enter the free air ionization chamber completely and change the ionization chamber from the X-ray tube focal spot position. The ionization chamber current are measured respectively while the changed distance is d, then

$$\ln \frac{I_1}{I_2} = -\mu d$$

According to the current value measured at different positions, both the line attenuation factor and the air attenuation correction factor are obtained. As shown in Table 2.

Table 2 Air attenuation correction factors

Radiation quality	Air attenuation correction(k_a)	Air attenuation coefficient /(cm^2/g)
Mo-25	1.039	0.002505
Mo-28	1.0374	0.002401
Mo-30	1.0349	0.002242
Mo-35	1.0326	0.002097

4.2 Recombination

There is always ion recombination in the ionization chamber, so the measured current is always less than the ideal saturated current. The ion recombination is divided into two types, initial recombination and bulk recombination. The initial recombination is the recombination at the beginning of ionization. When it is close to saturation, ionization loss caused by the initial recombination is proportional to $1/E$, E is the intensity of the electric field in ionization chamber. The bulk recombination occurs during the process of drift from the ion to the electrode at different locations in the ionization chamber. Close to saturation, the ion loss caused by the bulk recombination is proportional to $1/E^2$[9]. The relationship between the initial complex and the bulk recombination can be obtained by the ionization current of them, the initial composite is dominant when the electric field intensity is low, the bulk recombination is dominant when the electric field intensity is high[10]. When the field is near saturation, the saturation current I_s and the ionization current I_V at the collection voltage of V can be expressed as[11],

$$I_s/I_V = 1 + a/V + bI_s/V^2$$

In the method of reference[11], measure the ionization current under a plurality of excitation voltages V/n, and n is not necessarily an integer. When the I_V and $I_{V/n}$ are the correction values with the reference temperature and air pressure, the current values under different air-kerma are measured and a series of $I_V/I_{V/n} \sim I_V$ curves are made. The initial recombination and bulk recombination are obtained respectively by making a linear fit:

$$k_{init} = (a_0 - 1)/(n - 1)$$

$$k_{vol} = a_1/(n^2 - 1)$$

Thus, the saturation correction is

$$k_s = 1 + k_{init} + k_{vol} I_V$$

The results obtained by fitting the experimental data are shown in Fig. 4.

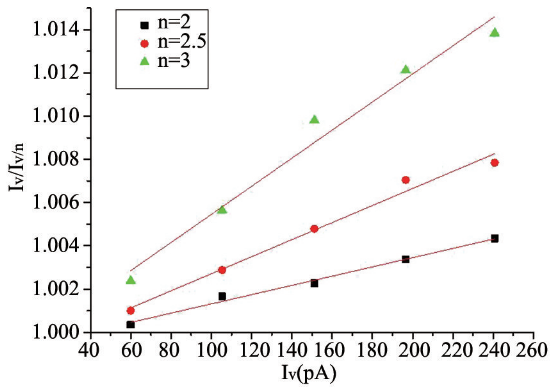

Fig. 4 Fitting results obtained with different N values

The initial recombination and bulk recombination factors were calculated from the fitting results, and then the recombination correction factor was obtained

$$k_s = 1 - 7.2 \times 10^{-4} + (7.6 \times 10^{-7}) \cdot I_V$$

Thus, the recombination correction factors under different radiation quality are figured out.

4.3 Diaphragm correction

The aperture material free air ionization chamber is cylindrical tungsten nickel-copper alloy. According to the aperture penetration analytical theory, for cylindrical aperture, the penetration of photons in the cylindrical collimated aperture wall is,

$$f = \left(\frac{2!}{\mu z} + \frac{3!}{\mu^2 z^2} + ..\right) - \frac{z^2}{h^2}\left(\frac{2!}{\mu z} + \frac{3!}{\mu^2 z^2} + ..\right) e^{[-\mu(z-h)]}$$

Where μ is the line weakening coefficient of the aperture wall material, z is the distance from the aperture to the source, and h is the length of the aperture.

In the mammography X-ray standard, there is $\frac{z^2}{h^2} \cdot e^{[-\mu(z-h)]} << 1$, and

$$k_l = \frac{1}{1+f} = 1 - \frac{2}{\mu z}$$

The line attenuation factor of the material at different effective energy can be found in the NIST database, and then the aperture of the edge of the penetration correction can be calculated.

4.4 Wall transmission

The wall transmission correction can be got by measuring the penetration of the ionization current I_p at the maximum equivalent energy conditions when the aperture was replaced with lead,

$$k_p = \frac{I - I_p}{I}$$

Where I is the measured current when there is no lead.

4.5 Polarity

The collector voltage polarity effect can be corrected by averaging the measured values of the ionization current at positive and negative polarized voltages, which is caused by the potential difference between the collector and the protective electrode. The actual measured polarity correction is,

$$k_{pol} = k_p = 1 - \frac{I_p - I_{leakage}}{I_0 - I_{leakage}} = 1.0000$$

4.6 Electron loss, Scattered radiation, Fluorescence

The free-air ionization chamber of the standard is cylindrical. A Monte Carlo simulation program is used to construct the cylindrical ionization chamber model. The correction factors are calculated by the program. The simulated photon number is 10^8, the energy range is from 5 keV to 60 keV, and the cut-off energy of photons and electrons is 1 keV and 512 keV respectively. Through the selection of the physical process in the EGS simulation program, the energy deposition of the incident photon, the scattered photon and the fluorescent photon in the collecting area and the upper and the lower walls can be obtained respectively, then the electron loss, scattering and fluorescence photon correction factor are calculated.

In summary, all the correction factors obtained by experiment and simulation are listed in Table 3.

Table 3 Correction factors for the mammography standard

Correction factors	Radiation quality			
	Mo-25	Mo-28	Mo-30	Mo-35
k_a	1.0390	1.0374	1.0349	1.0326
k_p	0.9999	0.9999	0.9999	0.9999
k_{dia}	0.9999	0.9999	0.9999	0.9999
k_{pol}	1.0000	1.0000	1.0000	1.0000
k_h	0.9980	0.9980	0.9980	0.9980
k_s	1.000348	1.000413	1.000348	1.000421
k_e	1	1	1	1
$k_{sc}\,.\,k_{fl}$	0.99356	0.9936	0.99369	0.99372
$\prod_i k_i$	1.0205	1.0166	1.01694	1.0123

5 Uncertainties

In the radiation field, the air-kerma is determined by using cylindrical free-air ionization chamber, as shown in equation. The ionization chamber is placed on the radiation field axis, the measuring rod and the laser positioner are used to determine the position. According to the formula, the uncertainty sources include free-air ionization chamber volume measurement, current measurement, temperature, barometric pressure, correction factors, reference physical constants and positioning distance. The physical quantities are independent of each other, namely

$$u_{rel}(f)=\sqrt{(u_{rel}(V))^2+u_{rel}(I))^2+u_{rel}(T))^2+u_{rel}(P))^2+u_{rel}(\prod_i k_i))^2+u_{rel}(g_{air}))^2+u_{rel}(W_{air}/e))^2+u_{rel}(\rho_{air}))^2+u_{rel}(d))^2}$$

There are two types of uncertainty assessments, one is caused by the statistical fluctuation of the measured data. According to the method of type A uncertainty, the standard deviation can be obtained from the Bessel formula, and then the relative standard uncertainty is obtained indirectly. The other is caused by the resolution of the measuring instrument itself, by type B, which can be obtained by a certificate or calibration certificate. The total uncertainty is obtained based on the physical constants uncertainty and the calculated uncertainty from the measurements of the free air ionization chamber, as shown in Table 4. The total relative uncertainty of the standard is 0.24% (k=2).

Table 4 Uncertainties associated with the standard

Values	u_{iA}(%)	u_{iB}(%)
p_{air}	-	0.01
W_{air}/e	-	0.15
$1-g_{air}$	-	0.01
V	0.04	-
I	0.02	0.01
P	0.01	0.01
T	0.04	0.04
d	0.01	0.10
$\prod_i k_i$	0.03	0.14
Relative standard uncertainty(%)	0.07	0.23
Total uncertainty(%)	0.24	

6 Conclusion

This paper introduces the cylindrical free air ionization chamber of the mammography X-ray standard established by NIM. In this paper, the correction factors that need to be considered in the determination of the air-kerma are studied. The correction factors of air attenuation, recombination, diaphragm correction, wall penetration, polarity correction, electron loss, scattering and fluorescence photon and other correction factors are determined by experiment and simulation. The relative standard uncertainty of each measurement and physical constant used in the determination is 0.24% (k=2), which satisfies the requirement of the reference quantity.

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