The Comparison of Measurement Methods for Air-Kerma Rate in Narrow-Spectrum Series

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Abstract: The air-kerma is one of the most important physical quantities in ionizing radiation dosimetry. The measurement of air-kerma rate in narrow-spectrum series is the basis to determine the radiation dose at protection level. In this article, the absolute measurement method is used to derive the standard air-kerma rate of the ISO 4037 narrow-spectrum series that ranges from 60 kV to 150 kV by a primary standard ionization chamber, it is used in direct comparison for air kerma. The indirect method is used to obtain the air-kerma rate by a secondary standard transfer ionization chamber named A5 chamber with calibration factors of the corresponding reference qualities. The results are very similar comparing between absolute and indirect methods for air-kerma rate, all the differences are within ±3.3%.

Key words: Air-Kerma Rate; Narrow-Spectrum Series; Absolute Measurement; Indirect Measurement

1 Introduction

It has been 123 years since Wilhelm Conrad Roentgen discovered invisible and penetrating radiation named as x-ray. In order to highlight his outstanding contribution, it is also named as 'Roentgen Radiation'[1]. X-ray has used in various fields including medical radiotherapy, industrial application, scientific research, environmental protection and so on. X-ray brings value to people´s life, however, it also has adverse radiation effect on human health. Especially after the accident at the Fukushima nuclear power plant in Japan, radiation protection has become the focus for industrial and civil safety. People are increasingly eager to know the radiation dose in their living environment[2]. The range of air-kerma rate at protection level is between 1×105Gy/h and 10Gy/h. X and γ reference radiation for calibrating protective dosimeters are recommended in the standard ISO 4037-1[3]. According to statistics, there are tens of thousands of radiation protection instruments in China, and thousands of instruments can be produced each year. Based on the safety requirement, hundreds of radiation protection monitoring stations are checking the environmental radiation dose rate constantly. To ensure the accuracy of measured values from radiation detectors, it is essential to establish and maintain a complete radiation protection system. The X-ray qualities of narrow-spectrum series in the standard ISO 4037-1 are mainly used for the calibration of radiation protection instruments. In this article, it demonstrates two ways to calculate the air-kerma rate and provides the objective results.

2 Absolute Measurement for Air-Kerma Rate

Air kerma plays a very important role in the practical calibration of reference photon radiation fields and radiation instruments. It is defined as the quotient of the sum of initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation, such as photons and neutrons, in a sample of air divided by the mass of the air. X-ray is one of the uncharged ionizing radiations, the energy is transferred into the air with a two-step procedure. First of all, the energy of X-ray is transferred to charged particles in the air by photon interactions, such as photoelectric effect, compton scattering and pair production[4]. Secondly, these secondary charged particles transfer their energy to the air through atomic excitation and ionization, which produce lots of ion pairs. The air kerma can be derived by using the free-air ionization chamber to collect the ionized charge, the structure diagram is shown in Fig.1.

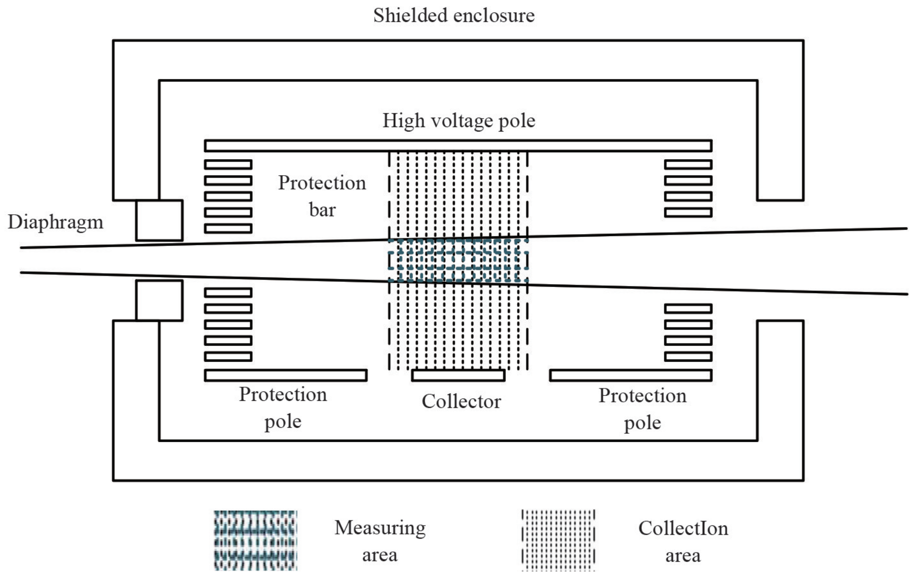

Fig. 1 Structure Diagram of Free-Air Ionization Chamber

The free-air ionization chamber is made up of high voltage pole, protection pole, protection bar, collector, diaphragm, shielded enclosure and so on. The incident X-rays interact with the air in the free volume of the free-air ionization chamber to produce secondary electrons, which ionize the air to produce electron ion pair that consists of an electron and a positive ion. In the absence of the electric field, electron ion pairs diffuse freely into the surrounding area. In this process, electrons and positive ions can recombine to form neutral molecules. If DC high-voltage V is applied between the collector and the high voltage pole of the ionization chamber, the electric field is formed between the two poles. Under the action of the electric field, electrons and positive ions will shift to positive and negative poles, respectively. As the polarization voltage V gradually increases, the ionization chamber will move from the recombination zone into the saturation zone. The working area of the free air ionization chamber for the absolute measurement of air-kerma is the saturation zone. In the saturation region, the appropriate polarization voltage is selected so that the electron ion pair is hardly recombined again and is completely collected by the ionization chamber to form the ionization current, which is measured by the micro-current measurement system. In order to determine the air-kerma rate for a free-air ionization chamber, its parameters should be known in detail, which is shown in Table 1. The reference radiation qualities of narrow-spectrum series in the range from 60 kV to 150 kV in the standard ISO 4037-1 have been established, the results of which are shown in Table 2.

Table 1 The Parameters of Free-Air Ionization Chamber

Aperture Diameter / cm	1.0002
Collecting Length / cm	10.052
Electrode Separation / cm	20.9
Collector Width / cm	28
Measuring Volume / cm^3	7.8980
Attenuation Length / cm	36.59
Polarizing Voltage / V	4000

The aperture diameter can limit theamount of X-rays that enter the ionization chamber. The measuring volume is calculated by the values of aperture diameter and collecting length, which can be equivalent to a cylindrical shape. The attenuation length is used to calculate the air attenuation k_a, which is one of the most important correction factors for determining the air-kerma rate. The free-air ionization chamber needs to be added by 4000V polarizing voltage to provide enough electric field that shifting electrons and positive ions to positive and negative poles, respectively.

Table 2 The Results of ISO 4037 Narrow-Spectrum Series

Mean Energy E/keV	Tube Potential kV	Additional Filtration / mm				1st HVL mm Cu	2nd HVL mm Cu
		Pb	Sn	Cu	Al		
47.6	60	-	-	0.601	3.958	0.232	0.266
64.7	80	-	-	1.987	3.9	0.586	0.634
82.9	100	-	-	4.981	3.9	1.128	1.190
99.8	120	-	0.997	4.973	3.939	1.739	1.808
117.8	150	-	2.493	-	3.952	2.424	2.545

Using free-air ionization chamber determines the air-kerma rate by the relation

$$\dot{K} = \frac{I}{\rho_{air} V} \frac{W_{air}}{e} \frac{1}{1-g_{air}} \prod_i k_i \qquad (1)$$

where K is the air-kerma rate at the distance of 1m from the x-ray focal spot, I is the ionization current measured by the micro-current measurement system, ρ_{air} is the density of air in the experiment, which is calculated by formula (2), V is the measurement volume of the free-air ionization chamber, W_{air} is the mean energy which is used to produce an ion pair in air for an electron, g_{air} is the share of the initial electron energy lost by bremsstrahlung radiation in air and $\prod k_i$ is the product of all correction factors, such as k_a, k_{sc}, k_{fl}, k_e, k_s, k_{dia}, k_p, k_d, k_{pol} and k_h.

$$\rho_{air} = \rho_0 \frac{T_0}{(T_0 + T)} \frac{P_{air}}{P_0} \qquad (2)$$

where ρ_0 is the density of air under reference conditions (T_0 = 273.15 K, P_0 = 101.325 kPa), T is the experimental temperature, the unitis Celsius, and P_{air} is experimental pressure of the air. The values of W_{air} /e, 1- g_{air} and ρ_0 are given in Table 3.

Internationally, there are usually two methods for the comparison of air kerma, one is to use the standard ionization chamber to directly participate in the alignment, such as BIPM RI(I)-K2, the other is to use the transfer ionization chamber to participate in comparison, such as EUROMET.RI(I)-S3[5,6]. Absolute measurement of air kerma rate is a direct measurement that depends on other physical quantities. Consequently, the measurement process needs to be corrected to ensure the accuracy of the reference value. The correction factors are calculated by the free-air ionization chamber at the radiation qualities of narrow-spectrum series in the range from 60 kV to 150 kV using the NIM standard, the results are given in Table 4. From these values, the air-kerma rate calculated by absolute measurement using the free-air ionization chamber can be determined by the relation (1), the values are also shown in Table 4.

Table 3 Values Used in the Determination of the Air-Kerma Rate

W_{air}/e	33.97 J/C
$1-g_{air}$	1
ρ_0	1.293 kg/m^3

Table 4 Correction Factors and Air-kerma Rates of the Narrow-Spectrum Series

Radiation Quality	60 kV	80 kV	100 kV	120 kV	150 kV
Air Attenuation k_a	1.0092	1.0080	1.0073	1.0069	1.0065
k_{sc} k_{fl}	1.0000	0.9943	0.9945	0.9960	0.9964
Electron Loss k_e	1.0000	1.0000	1.0017	1.0044	1.0061
Ion Recombination k_s	1.0011	1.0008	1.0008	1.0008	1.0008
Field Distortion k_{dia}	0.9998	0.9996	0.9998	0.9997	0.9996
Wall Transmission k_p	1.0000	1.0000	1.0000	1.0000	1.0000
Field Distortion k_d	1.0000	1.0000	1.0000	1.0000	1.0000
Humidity k_h	0.9980	0.9980	0.9980	0.9980	0.9980
$\prod k_i$	1.0081	1.0006	1.0021	1.0058	1.0074
Air-kerma Rate $\dot{K}$ (mGy/s)	0.0209	0.0139	0.0062	0.0063	0.0235

3 Indirect Measurement for Air-Kerma Rate

Theindirect measurement for air-kerma rate is using a transfer chamber with calibration coefficient measures the ionization current at the reference distance instead of standard ionization chamber . In this article, the exradin ionization chamber A5 is selected to serve as the transfer chamber for determining the air-kerma rate. The National Institute of Metrology (NIM), China, has been made an indirect comparison of the air-kerma standards with the Bureau International des Poids et Mesures (BIPM) in the X-ray range from 100 kV to 250 kV of the CCRI comparison qualities[3]. The calibration coefficients can be obtained under the CCRI comparison qualities that cover the range from 100 kV to 250 kV by the relation (3), the results are presented in Table 5 and derive the response as a function of photon energy of exradin ionization chamber A5, it is shown in Fig.2.

$$N_K = \frac{\dot{K}}{I} \tag{3}$$

Table 5 Calibration Coefficients of the Exradin Ionization Chamber A5 Under CCRI Radiation

Radiation Quality	1st HVL (mm Cu)	Calibration Coefficient
CCRI-100	0.232	1.0517
CCRI-135	0.586	0.9998
CCRI-180	1.128	0.9962
CCRI-250	1.739	1.0057

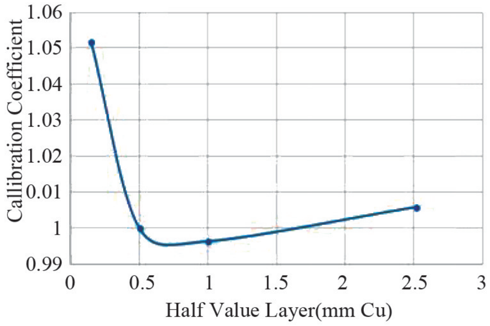

Fig. 2 Energy Dependence of Exradin Ionization Chamber A5

By interpolation, the calibration coefficients under the narrow-spectrum series that cover the range from 60 kV to 150 kV can be derived, the results are shown in Table 6. The air-kerma rate calculated by indirect measurement using the transfer chamber (exradin ionization chamber A5) can be determined by the relation (4), the values are given in Table 6 as well. All the differences are within

$$\dot{K}_n = N_{k,n} I \tag{4}$$

Where $\dot{K}_n$ is the air-kerma rate under the narrow-spectrum series, $N_{k,n}$ is the calibration coefficient under the narrow-spectrum series.

The results of air-kerma ratecalculated by absolute measurement and indirect measurement are derived, the differences are all within ±3.3% given in Table 7.

Table 6 Calibration Coefficients of Exradin Ionization Chamber A5 and Air-kerma Rates of the Narrow-Spectrum Series

Radiation quality	60 kV	80 kV	100 kV	120 kV	150 kV
Calibration coefficient $N_{k,n}$ (Gy/μC)	0.3088	0.2968	0.2961	0.2973	0.2986
Air-kerma rate $\dot{K}_n$ (mGy/s)	0.0216	0.0139	0.0061	0.0062	0.0236

Table 7 The Difference of Air-kerma Rate by Absolute Measurement and Indirect Measurement of the Narrow-Spectrum Series

Radiation Quality	60 kV	80 kV	100 kV	120 kV	150 kV
Air-kerma Rate By Absolute Measurement $\dot{K}$ (mGy/s)	0.0209	0.0139	0.0062	0.0063	0.0235
Air-Kerma Rate By Indirect Measurement $\dot{K}_n$ (mGy/s)	0.0216	0.0139	0.0061	0.0062	0.0236
Difference of Air-Kerma Rate	3.3%	0	-1.6%	1.6%	0.4%

4 Conclusion

In this article, two methods are introduced to determine the air-kerma rate for five radiation qualities of the ISO 4037 narrow-spectrum series in the range from 60 kV to 150 kV. The first method is an absolute measurement method, which uses a free-air ionization chamber to measure the ionization current under the reference point, the correction factors for the accuracy of air-kerma rate are measured through experimental and theoretical calculations, then, the results of air-kerma rate can be obtained. The other method for air-kerma rate is an indirect method, which uses a transfer ionization chamber with calibration coefficient to detect the ionization current at the reference point, the product of calibration coefficient and ionization current is the value of the air-kerma rate. By comparing the values measured by absolute way with the results measured by indirect way, the differences are all within ± 3.3%, which is not good enough for primary values. Next, what should be done is to find out the reason that affects the difference and make it as small as possible. The absolute method for air-kerma rate of all narrow-spectrum series will be researched, consequently, combining with the radiation qualities included the low air-kerma rate series, Cs and Co reference radiation qualities, environmental dosimeters can be calibrated.

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