CALIBRATION AND MEASUREMENT OF THE X-RAY PERSONAL DOSE EQUIVALENT WITH A $H_p(10)$ IONIZATION CHAMBER

by

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The value of the personal dose equivalent at a 10 mm depth is to characterize the energy deposition of strong penetrating radiation in the human body and is derived by measurement of air kerma and application of conversion coefficients from the ISO report. However, the conversion coefficients depend strongly on the photon energy and angles of incidence for low-energy photons. In order to overcome the problem that the conversion coefficient of low energy rays changes greatly due to the small change of energy, a secondary standard ionization chamber was used to measure the personal dose equivalent directly. A matched reference field was established with 20-250 kV X-rays and correction factors with the $H_p(10)$ chamber were calculated under these radiation qualities with different angles of incidence. The results showed that the differences were almost 22.7 % of correction factors for the low energy photons at angles of incidence 0°. With the conversion coefficient recommended in ISO 4037-3-2019, the performance of the chamber response with respect to $H_p(10)$ in the energy range from 33 keV to 208 keV was within about 10 %, and in the energy range from 12 keV to 208 keV and for angles of incidence between 0° and 75° was within about 19 %.

Key words: X-ray, personal dose equivalent, H_p (10) ionization chamber, correction factor

INTRODUCTION

In the field of radiation protection, the biological effect produced by a certain absorbed dose is related to the type of radiation, irradiation conditions, radiation dose, biological species, and individual differences. Therefore, the same absorbed dose may not produce the same degree of biological effect. In order to compare the different biological effects caused by different types of radiation and express the harmful effects of radiation on the body, quality factors are introduced in radiation protection. When the absorbed dose is multiplied by these coefficients, it becomes a new physical quantity, called the dose equivalent, H [1, 2]. The dose equivalent is used to compare the biological effects caused by different types of radiation. According to ICRU 57 [3] and ICRP 74 [4], the personal dose equivalent at a 10 mm depth, $H_p(10)$ is used to express the operational quantity for individual monitoring with the strongly penetrating radiation. For occupational exposure workers, ICRP has set the recommended dose limit. The average effective dose is 20 mSv a^{-1} in a consecutive five-year period, and it is further stipulated that the effective dose in any year should not exceed 50 mSv. Occupational exposure workers usually wear personal dosimeters to monitor the dose from external exposure. Therefore, it is important for these personal dosimeters to monitor $H_p(10)$ accurately, and they need to be calibrated regularly [5].

There are three methods for determining the conventional true value of $H_p(10)$. The first method is to calculate the conversion coefficients and apply to the measured value of the air kerma with an ionization chamber. The conversion coefficient is obtained by a suitable spectrometer according to Annex B of ISO 4037-2 and calculated from the measurement of the spectral distribution of the corresponding series [6]. For monoenergetic photon radiation of energy, E, the conversion coefficients $h_{pK}(10;\ E,\ \alpha)$ from K_a to $H_p(10)$ for the slab phantom with different angles of incidence, α, are listed in ICRP 74 and ICRU 57. The second method is to measure the air kerma at each irradiation with the K_a secondary standard chamber and applying the recommended conversion coefficient. However, this method requires the radiation field to meet the requirements of matched reference fields. The last method is using a secondary ionization chamber to measure $H_p(10)$ in a slab phantom directly [7-11]. This ionization chamber has a flat energy and angle dependence and also has a great linearity of the

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dose rate. The advantage of this method is that for the ionization chamber once calibrated, spectrometric measurements are unnecessary, and no conversion coefficients are needed.

In this work, some requirements and changes to the new standard were considered. The matched reference fields were established and recommend conversion coefficients were adopted for comparison [12, 13] and correction factors were calculated with the energy from 16 keV to 208 keV. The $H_p(10)$ ionization chamber will be used to directly measure the $H_p(10)$ and it will provide calibration for more personal dosimeters in this photon energy.

THEORY AND METHODS

Correction factors

For filtered X-ray reference radiation quality, R, the conventionally true value of the personal dose equivalent on the slab phantom, $H_p(10; R, \alpha)$, at the angle of incidence, α, is given by

$$H_p(10; R, \alpha) = N_H\, k(R, \alpha) Q_{R,\alpha} k_{T,P} \quad (1)$$

where $Q_{R,\alpha}$ is charge measured by the chamber in radiation quality, R, with angle of incidence α, N_H – the calibration factor corresponding to the radiation quality N-60 and the angle of incidence $\alpha = 0°$, $k(R, \alpha)$ – the correction factor, and $k_{T,P}$ – the correction factor for temperature and pressure, is given by

$$k_{T,P} = \frac{T + 273.15}{T_0} \frac{P_0}{P} \quad (2)$$

where T [K] is the temperature of measurement, P [kPa] – the pressure, T_0 is 293.15 K, P_0 is 101.325 kPa. Furthermore, N_H is also given by the following formula

$$N_H = h_{pK}(10; N-60, 0°) \frac{K_{a,N-60}}{Q_{N-60,0°}} \quad (3)$$

where $K_{a,N-60}$ is the value of air kerma corresponding to the radiation quality N-60; $h_{pK}(10; N-60, 0°)$ – the conversion coefficient from K_a to $H_p(10)$ for the slab phantom at the reference radiation quality N-60 and the reference angle of radiation incidence $\alpha = 0°$. $Q_{N\text{-}60,0°}$ – the charge measured with correction by the chamber in radiation quality N-60 with an angle of incidence, 0°. With eqs. (1) and (2), the correction factor $k(R, \alpha)$ for the radiation quality R and the angle of incidence, α, is also given by

$$k(R, \alpha) = h_{pK}(10; R, \alpha) \frac{K_a}{Q_{R,\alpha} k_{T,P}} \frac{1}{N_H} \quad (4)$$

where $h_{pK}(10; R, \alpha)$ is the conversion coefficient from K_a to $H_p(10)$ for the slab phantom at the reference radiation quality, R, and the reference angle of radiation incidence, α, and K_a – the value of air kerma at the reference radiation quality, R.

Experimental equipment

The $H_p(10)$ ionization chamber used to measure the $H_p(10)$ directly, on a slab phantom, is shown in fig. 1. The model of the $H_p(10)$ ionization chamber is TW34035, made in PTW-Freiburg, Germany. The chamber consists of a measuring part and a backscatter part which are combined [14]. The outside dimensions of the measuring part are 300 mm 300 mm with a total thickness 31 mm. The active volume is 10 cm^3 which is covered in layers made of polymethil methacrylate (PMMA). The high voltage electrode is made of graphite with 100 mm in diameter and 40 m in thickness. The back end of the active volume of the ionization chamber is the zero potential. The backscatter part is made of PMMA with a slab of the dimensions 300 mm 300 mm 120 mm. A sketch of the $H_p(10)$ ionization chamber with the backscatter part is shown in fig. 2.

The irradiation facility in this study is based on two different X-ray units made by Yxlon. For the radiation qualities N-20 to N-60, the MG165 tube was used. For the radiation qualities N-60 to N-250, the MG325 tube was used. Both X-ray tubes have a tungsten target with a target angle of 20°. The X-ray beams were collimated by a tungsten alloy diaphragm and the beam diameter was 40 cm at 2.5 m for low energy and 60 cm at 2.5 m for medium energy. The angle control of the ionization chamber for measuring was through a rotating platform, using a stepper motor to complete the adjustment of the positive and negative direction angle. The adjustment accuracy is 0.05°. The direction of 0° is that the X-ray beam was directly incident on the plane of the ionization chamber. Starting from 0°, the clockwise rotation is defined as the positive direction, $+\alpha$. And conversely, the anti-clockwise direction is defined as a negative direction, $-\alpha$.

Measurement procedure

The reference measurement point was 2.5 m from the focal spot. The air kerma was measured by a

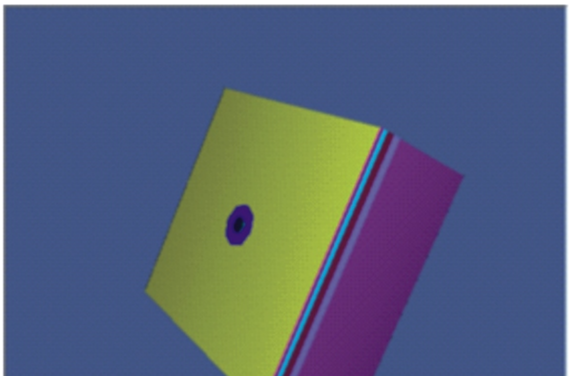

Figure 1. The simulation structure of the $H_p(10)$ ionization chamber

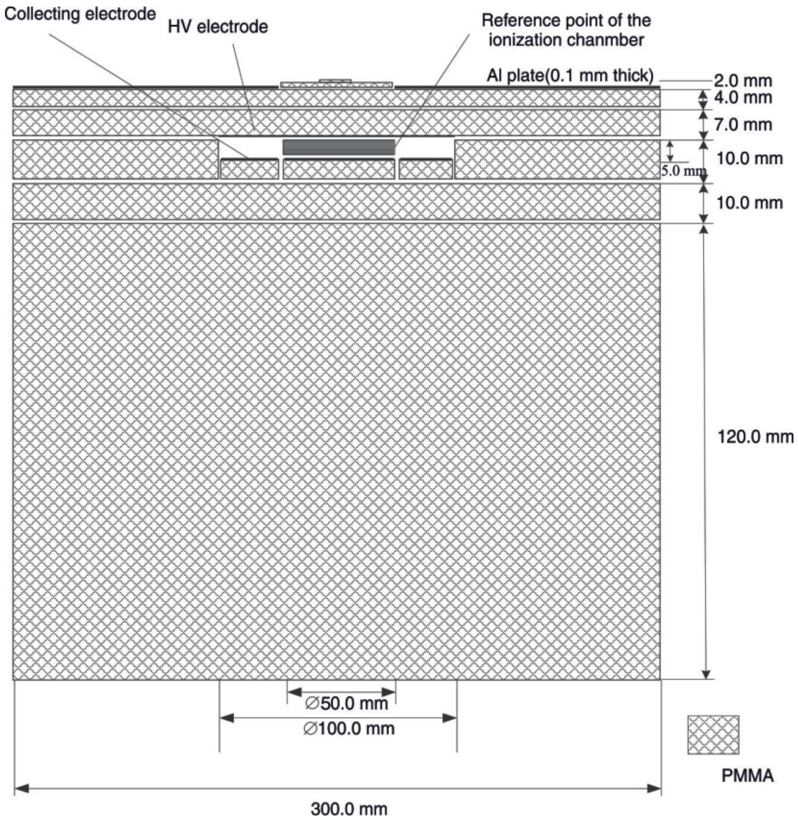

Figure 2. Sketch of the $H_p(10)$ ionization chamber with the backscatter part

parallel-plate ionization chamber for low-energy and a spherical ionization chamber for medium-energy. Two chambers were traceable to the primary standard of X-ray air kerma in the National Institute of Metrology, China (NIM). The potential voltage of the $H_p(10)$ ionization chamber was set to +400 V. The leakage current of the chamber was about 4 10^{-16} A. For radiation quality, R, and each angle of incidence, with a charge collecting time of 100 seconds were performed. The conversion coefficient $h_{pK}(10; R, \alpha)$, was taken from ISO 4037-3. The calibration factor N_H and the correction factors $k(R, \alpha)$ were valid for the reference conditions.

RESULTS AND DISCUSSION

Radiation qualities of the X-ray and energy spectra

According to ISO 4037-1-2019, the narrow spectrum series of the X-ray matched reference fields were established. The half value layer (HVL) of radiation qualities were measured with a transfer ionization chamber at 2.5 m and the characteristics were listed in tab. 1. The results of all measured HVL values met the specification requirements except for N-250. There

Table 1. Radiation qualities of the X-ray narrow series from 20 kV to 250 kV

Radiation quality	Tube voltage [kV]	Additional filter [mm]				1st HVL [mm]		
		Pb	Sn	Cu	Al	This work	ISO	$\lvert D_{HVL, abs}\rvert$
N-20	20	–	–	–	0.99	0.365 Al	0.362 Al	0.003
N-25	25	–	–	–	1.98	0.679 Al	0.677 Al	0.002
N-30	30	–	–	–	4	1.190 Al	1.17 Al	0.020
N-40	40	–	–	0.21	4	2.68 Al	2.65 Al	0.030
N-60	60	–	–	0.60	4	0.238 Cu	0.235 Cu	0.003
N-80	80	–	–	1.99	4	0.590 Cu	0.580 Cu	0.010
N-100	100	–	–	4.98	4	1.128 Cu	1.09 Cu	0.038
N-120	120	–	1.00	4.97	4	1.739 Cu	1.67 Cu	0.069
N-150	150	–	2.49	–	4	2.424 Cu	2.30 Cu	0.124
N-200	200	1.03	2.97	2.01	4	4.097 Cu	3.91 Cu	0.187
N-250	250	3.00	1.99	–	4	5.316 Cu	5.08 Cu	0.236

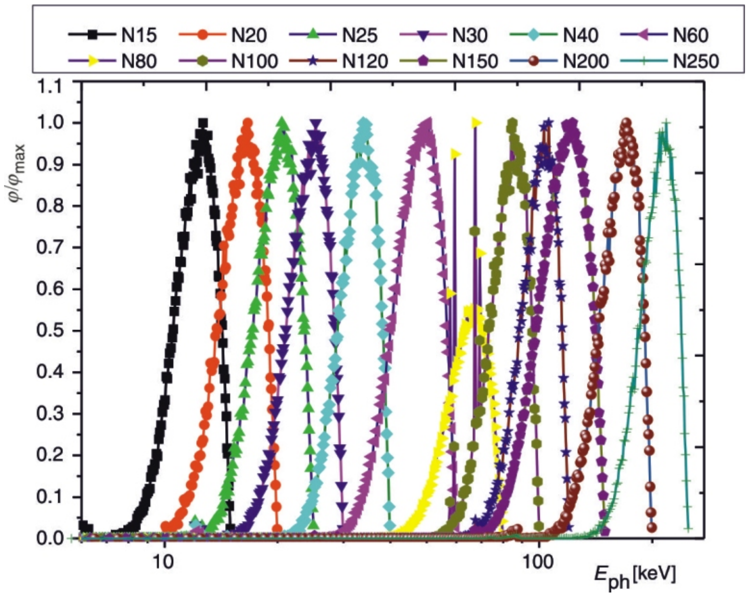

Figure 3. Normalized fluence spectra of the N-series

Table 2. Correction factors $k(\mathrm{R}, \alpha)$ for the radiation qualities of the narrow spectrum (ISO 4037-3-2019)

Radiation quality	E_{ph} [keV] according to		N_H [Sv· C^{-1}]	$k(\mathrm{R}, \alpha)$					
	This paper	ISO 4037		0°	15°	30°	45°	60°	75°
N-20	16.1	16.3	3.55	0.81	0.82	0.84	0.87	0.92	1.04
N-25	20.0	20.3		0.84	0.84	0.86	0.88	0.93	1.08
N-30	24.3	24.6		0.87	0.87	0.89	0.90	0.94	1.10
N-40	33.0	33.3		0.95	0.95	0.96	0.98	1.01	1.15
N-60	47.6	47.9		1.00	1.00	1.01	1.01	1.04	1.14
N-80	64.8	65.2		0.97	0.97	0.98	0.98	1.01	1.08
N-100	82.7	83.3		0.95	0.95	0.95	0.97	0.98	1.06
N-120	99.8	100		0.93	0.93	0.93	0.94	0.97	1.02
N-150	117.5	118		0.92	0.92	0.92	0.93	0.95	1.01
N-200	164.4	165		0.90	0.90	0.90	0.91	0.93	0.99
N-250	207.8	207		0.91	0.90	0.90	0.91	0.94	1.01

were larger than recommended values due to the influence of two factors. The one is that the probability of the *Compton Effect* increases with the increase of energy. For the measurement of high energy X-ray HVL, it is important to limit the beam and control the effect of scattered radiation. The photons irradiating the ionization chamber rods and other supports objects will cause more scattering. The greater the scattering, the larger the measured half-value layer. The other is the fact that HVL values determined using dosimetry are about 2.5 % larger than the values determined from the spectra by calculation, and the recommended HVL values are taken from Physicalisch-Technische Bundesanstalt (PTB) calculated results with the spectra [15]. The mean energy was calculated by energy spectra with the EGSnrc Monte Carlo simulation program [16]. The results of the energy spectra of the narrow spectrum series of filtered X-ray were shown in fig. 3. A good agreement for the mean energy was found between the calculated values and those given by ISO for which the maximum deviation is 1.5 % in tab. 2, respectively.

Electric field distribution of the $H_p(10)$ ionization chamber

In order to study the radiation characteristics of the chamber, it is necessary to form a region in the inner space of the ionization chamber with the condition of the charged particle equilibrium, the total energy and energy spectrum distribution of the charged particles entering the region and leaving the region are balanced. In order to ensure the uniformity of the electric field distribution, the electric field distribution between the high voltage plate and the collector plate in the ionization chamber was studied. The finite element method (FEM) was used to simulate the calculation. Electric field distribution was calculated through the ANSOFT MAXWELL 2-D software. The high voltage electrode and collector in the ionization chamber were all composed of graphite. The result of the electric field distribution of the $H_p(10)$ ionization chamber was shown in fig. 4. It showed that the potential distribution was uniform in the collection area.

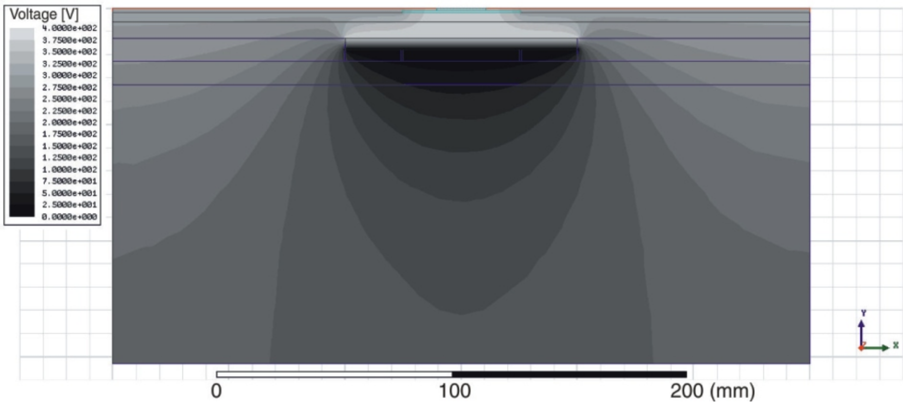

Figure 4. Electric field distribution of $H_p(10)$

Table 3. Correction factors k (R, α) for the radiation qualities of the narrow spectrum (ISO 4037-3-1999)

Radiation quality	E_{ph} [keV] according to		N_H [Sv C^{-1}]	$k(R, \alpha)$					
	This paper	ISO 4037		0°	15°	30°	45°	60°	75°
N-20	16.1	16	3.53	0.66	0.68	0.68	0.68	0.68	0.80
N-25	20.0	20		0.79	0.80	0.82	0.82	0.85	0.91
N-30	24.3	24		0.85	0.85	0.87	0.88	0.90	1.00
N-40	33.0	33		0.93	0.93	0.94	0.94	0.98	1.17
N-60	47.6	48		1.00	1.00	1.00	1.00	1.03	1.09
N-80	64.8	65		0.97	0.97	0.98	0.98	1.01	1.05
N-100	82.7	83		0.96	0.96	0.96	0.97	0.99	1.03
N-120	99.8	100		0.95	0.93	0.94	0.95	0.97	1.00
N-150	117.5	118		0.93	0.92	0.93	0.94	0.96	0.98
N-200	164.4	164		0.90	0.90	0.91	0.91	0.94	0.97
N-250	207.8	208		0.91	0.91	0.92	0.92	0.94	0.98

The results of $k(R, \alpha)$ calculated from old and new ISO 4037

The $h_{pK}(10;R,\alpha)$ was used based on old and new ISO 4037-3 recommendations. In ISO 4037-3-1999, data for the angle of incidence α = 15° and 75° are not given [17]. Therefore, the respective mean value of the $h_{pK}(10;R,\alpha)$ values given for $\alpha = 10°$ and $\alpha = 20°$ was used as the conversion coefficient for these radiation qualities. Also, the respective mean value of the $h_{pK}(10;R,\alpha)$ values given for α = 70° and α = 80° was used as the conversion coefficient. Although the ionization chamber was designed symmetrically with a combination of multiple PMMA parts, the small difference of the thickness of the PMMA and graphite layers of the chamber may lead to different measuring results. To verify and reduce this influence for each radiation quality, the correction factors $k(R,\alpha)$ were each determined at the angle $+\alpha$ and $-\alpha$, and the mean value of these two values were calculated. The calibration factor N_H and the correction factors $k(R,\alpha)$ with respect to $H_p(10)$ for the radiation qualities of the narrow spectrum are listed in tabs. 2 and 3 and figs. 5 and 6.

For filtered X radiation, the recommend conversion coefficients are listed in ISO 4307-3. Although the X-ray radiation quality established by different X-ray facilities meets the standard requirements, the spectral distributions will be a little different, especially for low energy photons [18]. Because the change of energy distribution may have a great influence on the value of the conversion coefficient, it is the best way to measure the personal dose equivalent directly with a secondary standard ionization chamber which is calibrated without considering the influence of the low-energy photon spectrum in the range of uncertainty. The measurement results were shown in tab.

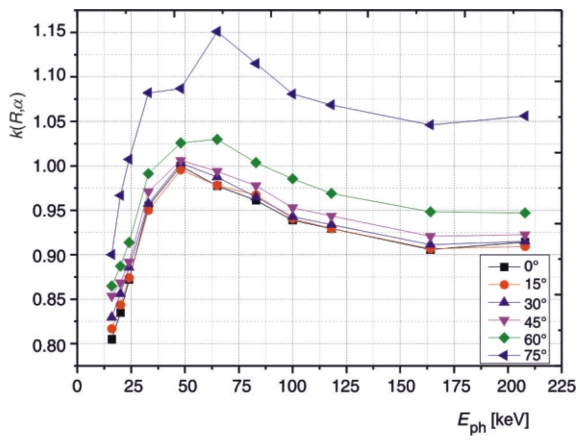

Figure 5. Correction factors $k(R,\alpha)$ for the ISO radiation qualities N-20 to N-250 at the angles of incidence, α, of 0°, 15°, 30°, 45°, 60° and 75° ($h_{pK}(10;R,\alpha)$ taken from ISO 4037-3-2019)

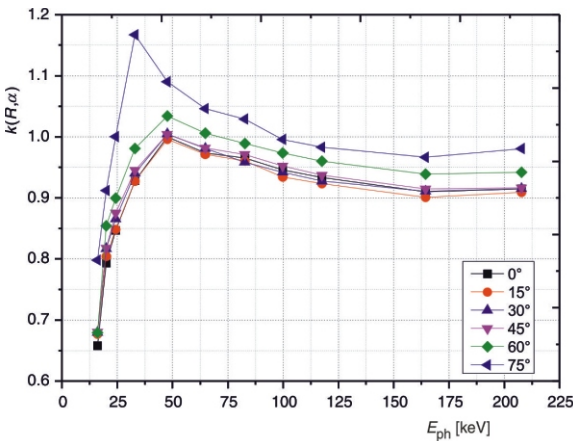

Figure 6. Correction factors $k(R,\alpha)$ for the ISO radiation qualities N-20 to N-250 at the angles of incidence, α, of 0°, 15°, 30°, 45°, 60° and 75°($h_{pK}(10;R,\alpha)$ taken from ISO 4037-3-1999)

2 and tab. 3 when different $h_{pK}(10;R,\alpha)$ were considered. In tab. 2, the ISO 4037-3-2019 recommended conversion coefficient was used. These data were obtained from the PTB measurement and calculation with the unfolding spectrum. Compared to results in tab. 2, the conversion coefficients were taken from ISO 4037-3-1999 and the results are listed in tab. 3. These conversion coefficients were obtained by averaging the spectrum distribution based on the monoenergetic data reported in ICRP 74. In tab. 4, the calculated $k(R,\alpha)$ values at angles of incidence from 0° to 75° show a mean deviation from the ISO values of no more than 5 % when the photon mean energy is more than 33 keV. When the photon mean energy is within 20 keV-33 keV, the calculated $k(R,\alpha)$ values show a mean deviation no more than 10 % except for angles of incidence 75° in N-20. In fig. 7, it is indicated that the correction factors $k(R,\alpha)$ were changed a lot especially in the low-energy photons. The deviation would be almost 35.3 % if the mean energy is less than 20 keV. If we established the matched reference fields, it is necessary to adopt a new standard to calculate the personal dose equivalent accurately especially in the low energy photon range.

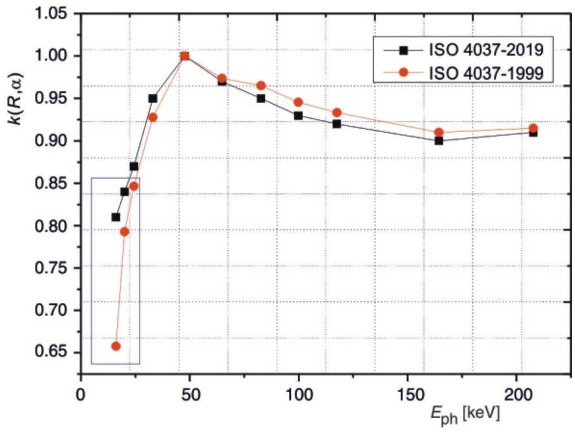

Figure 7. Comparison of correction factors $k(R,\alpha)$ for the ISO radiation qualities N-15 to N-250 at the angles of 0°, ($h_{pK}(10;R,\alpha)$ taken from ISO 4037)

The dose rate dependence for the $H_p(10)$ chamber

The dose rate dependence of the $H_p(10)$ chamber was examined by using three radiation qualities of the X-ray and changing the tube current to get different dose rates. The different values of K_a were measured by the secondary standard ionization chamber. For the very low dose rate, the response of the ionization chamber will be very weak. From fig. 8, it was indicated that the linearity of the dose rate conformed to the general law.

The uncertainty of correction factors

The maximum expanded uncertainty of the correction factors $k(R,\alpha)$ was calculated to be 5.3 % (k = 2) depending on the radiation quality and angle of the irradiation direction, which were calculated in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM) [19]. The results of the uncertainty were listed in tab. 5. The expanded standard uncertainty (k = 2) of the conventionally true values increased with the decrease of photon energy and the

Table 4. The deviation of correction factors $k(R,\alpha)$

Radiation qualities	0°	15°	30°	45°	60°	75°
N-20	22.7 %	20.6 %	23.5 %	27.9 %	35.3 %	30.0 %
N-25	6.3 %	5.0 %	4.9 %	7.3 %	9.4 %	18.7 %
N-30	2.4 %	2.4 %	2.3 %	2.3 %	4.4 %	10.0 %
N-40	2.2 %	2.2 %	2.1 %	4.3 %	3.1 %	–1.7 %
N-60	0.0 %	0.0 %	1.0 %	1.0 %	1.0 %	4.6 %
N-80	0.0 %	0.0 %	0.0 %	0.0 %	0.0 %	2.9 %
N-100	–1.0 %	–1.0 %	–1.0 %	0.0 %	–1.0 %	2.9 %
N-120	–2.1 %	0.0 %	–1.1 %	–1.1 %	0.0 %	2.0 %
N-150	–1.1 %	0.0 %	–1.1 %	–1.1 %	–1.0 %	3.1 %
N-200	–1.1 %	0.0 %	–1.1 %	0.0 %	–1.1 %	2.1 %
N-250	0.0 %	–1.1 %	–2.2 %	–1.1 %	0.0 %	3.1 %

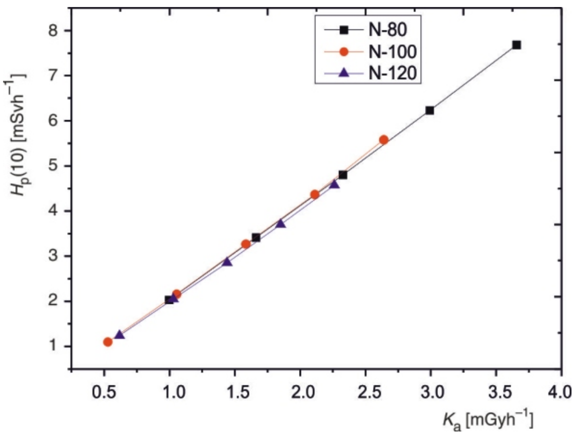

Figure 8. Dose rate dependence for the H_p(10) chamber under N-80 to N-120

Table 5. Uncertainty of the correction factors of the H^p(10) ionization chamber

Source	u_A [%]	u_B [%]
Air kerma		1.5
Current	0.5	
Temperature	0.1	0.05
Pressure	0.1	0.05
Position	0.2	0.1
h_{pK} (10;R,)		2
Long term stability		0.5
Uncertainty of the calibration factor k (R, α)	5.3 % [k = 2]	

increase of angle. In fact, the biggest influence is the uncertainty introduced by the conversion coefficient. It could be more accurate to use the spectra measured by the spectrometer in order to calculate new standard conversion coefficients and measure the true value of air kerma with the primary standard directly.

CONCLUSIONS

The X-ray personal dose equivalent was measured and calibrated. The reference radiation qualities of the X-ray from 20 kV-250 kV were established and the HVL were measured by a dosimeter. The energy spectra were simulated and the mean energy with each radiation quality was calculated with energy spectrum distribution. A H_p(10) chamber was used as a transfer secondary standard chamber. The FEM was used to simulate the electric field distribution and the result indicated that the electric field distribution was uniform. When the new standard was adopted, the performance of the chamber response with respect to H_p(10) in the energy range from 33 keV to 208 keV was within 10 %, and in the energy range from 16.1 keV to 208 keV and for angles of incidence between 0° and 75° was within 19 %. It is pointed out that the H_p(10) chamber can directly measure the conventional true value of H_p(10) in the large range of energy and dose rate after calibration. The expanded uncertainty of the correction factor k is 5.3 % (k = 2). It is convenient to measure the personal dose equivalent directly for more dosimeters calibration and no conversion coefficients are needed. Also, the calibrated H_p(10) chamber will be used directly to establish the matched reference radiation field for more secondary standard laboratories and it can quickly test the radiation field changes.

DATA AVAILABILITY

The data used to support the findings of this study are available from the corresponding author upon request.

AUTHORS' CONTRIBUTIONS

The simulated data were organized and analyzed by Y. Xu and the manuscript was also written by Y. Xu. R. Zhao executed the development of the Monte Carlo code and provided the research ideas and methods.

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КАЛИБРИСАЊЕ И МЕРЕЊЕ ЛИЧНОГ ЕКВИВАЛЕНТА ДОЗА X-ЗРАЧЕЊА Hp (10) ЈОНИЗАЦИОНОМ КОМОРОМ

Вредност личног еквивалента дозе на дубини од 10 мм карактерише депоновање енергије продорног зрачења у људско тело, а изведена је мерењем керме у ваздуху и применом коефицијената конверзије из ISO извештаја. Међутим, коефицијенти конверзије веома зависе од енергије фотона и упадних углова за фотоне ниских енергија. Да би се превазишао проблем знатне промене коефицијента конверзије нискоенергетског зрачења услед мале промене енергије, коришћена је секундарна стандардна јонизациона комора за директно мерење личног еквивалента дозе. Подударно референтно поље успостављено је са X-зрачењем од 20-250 kV, а корекциони фактори коморе Hp (10) израчунати су са овим квалитетима зрачења при различитим угловима упада. Резултати су показали да су разлике корекционих фактора биле скоро 22.7 % за фотоне ниских енергија под упадним углом од 0°. Са коефицијентом конверзије препорученим у ISO 4037-3-2019, перформанса одзива коморе у односу на Hp (10) у енергетском опсегу од 33 кеВ до 208 кеВ била је у границама око 10 %, а у енергетском опсегу од 12 keV до 208 keV и за упадне углове између 0° и 75°, била је у распону око 19 %.

Кључне речи: X-зрачење, лични еквивалент дозе, Hp (10) јонизациона комора, фактор корекције