



Research on the absolute measurement of air kerma in superficial X-ray radiotherapy

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Abstract

Scar formation results from nonregenerative healing after tissue injury. Complications may occur if the scar grows beyond a certain threshold. Superficial X-ray radiotherapy offers significant advantages as an adjuvant method for surgical treatment of scars. Following the widespread application of the superficial X-ray radiotherapy system SRT-100, accurate dose measurements are key to the implementation of superficial X-ray radiotherapy. In this study, the absorbed dose measured in superficial X-ray radiotherapy was traced to the primary standard based on air kerma. According to this principle, based on the technical parameters of the SRT-100 system, this study establishes the corresponding reference radiation qualities by relying on an industrial X-ray tube and uses a free-air ionization chamber to obtain the corresponding correction factors through experiments and simulations to realize absolute air kerma measurements and uncertainty evaluations. In this context, air kerma calibration and associated uncertainty evaluations were performed for the parallel-plate transfer ionization chambers PTW23342 and PTW23344. The results show that the mean energies of the fluence spectra simulated at the X-ray tube voltages of 50, 70, and 100 kV were 26.2, 34.1, and 44.7 keV, respectively. The measured results of the first half-value layer at the three tube voltages were 0.538, 1.146, and 2.190 mmAl. The air kerma of three radiation qualities were 1.487, 1.436, and 1.268 mGy/s. The expanded measurement uncertainty of air kerma by the free-air ionization chamber was 0.94% ($k = 2$), and the expanded uncertainties of the calibration factor in the two transfer ionization chambers were 1.00% ($k = 2$) and 0.96% ($k = 2$).

Keywords Superficial X-ray radiotherapy · Air kerma · Correction factor · Absolute measurement · Uncertainty

1 Introduction

Scars are the result of abnormal repair after skin injury; they affect the appearance of the skin and the mental health of patients [1]. Following rapid economic developments, an increasing number of patients with scars have undergone treatments for abnormal scars. Surgical resection is a traditional, direct, and effective abnormal scar treatment.

However, there are potential dangers after scar resection surgery, such as the formation of new scars, pigmentation, and skin asymmetry [2–4]. After years of clinical practice, clinicians have recognized the efficacy of resection combined with radiotherapy as the preferred treatment for recurrent scars [5–9]. The radiotherapy methods for scars include electron-beam therapy, superficial X-ray therapy, and brachytherapy [10]. The advantages of superficial X-ray radiotherapy over other radiotherapy modalities include a lower radiation energy and a more superficial dose to the skin. This is because the transient high-dose area is mainly concentrated on the skin surface, with minor effects on deeper tissues and organs; furthermore, the requirements for radiation protection are relatively simple [11]. Superficial X-ray therapy is extensively used in postoperative radiotherapy for scars because of its simple operation, low cost, and capacity to achieve significant postoperative recovery [12, 13]. Several domestic institutions have introduced superficial X-ray

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radiotherapy systems. However, inappropriate doses can lead to unsatisfactory therapeutic effects [14]. Research has shown that the total radiation dose of radiotherapy should range from 15 to 20 Gy to maintain a low-incidence scarring rate without affecting the efficacy of radiotherapy [15, 16].

A prerequisite for effective radiotherapy is the accurate measurement of the absorbed dose in normal and diseased tissues. The detectors and measurement methods usually refer to the TG 61 of the American Association of Physicists in Medicine, the Institute of Physics and Engineering in Medicine and Biology code in the UK, and the TRS 398 of the International Atomic Energy Agency [17–19]. These reports indicate that the absorbed dose of low-energy X-rays can be traced to the air kerma. The parallel-plate ionization chamber and the corresponding phantom were used to measure the absorbed dose to water using the ionization method, and relevant conversion factors were multiplied to obtain the traceability of the absorbed dose to water [20]. To ensure the accuracy of the measured dose based on the technical parameters of the X-ray radiotherapy system SRT-100, an industrial X-ray tube was used to establish the X-ray reference radiation qualities. A free-air ionization chamber (FAC) was used to complete the absolute measurement of air kerma under the corresponding radiation qualities. Parallel-plate transfer ionization chambers were calibrated, and the results were compared with international comparison results to verify the accuracy of the absolute air kerma measurements in superficial X-ray radiotherapy.

2 Experimental principles and methods

2.1 X-ray radiation device

X-ray radiation devices consist of an X-ray system, a beam-limiting diaphragm, an additional filtration system, guide rails, a positioning system, and a microcurrent measurement system [21]. The X-ray tube model was MG165 equipped with a tungsten target, and the target angle was 20°. Inherent filtration was achieved with the use of beryllium (thickness of 0.8 mm). A high-voltage generator with a tube voltage of 7.5–160 kV was used. Different reference radiation qualities can be established by adjusting the tube voltage and enhancing filtration by using a filter element with an increased thickness. A beam-limiting diaphragm was used to confine and collimate X-rays. It had an inner diameter of 7 mm, an outer diameter of 6 cm, and a thickness of 4 mm. The material was composed of 93% pure tungsten and 7% pure Ni–Fe. A uniform radiation field was formed at the reference plane to satisfy the measurement and calibration requirements of the air kerma. The principle of the microcurrent measurement system is based on the high-gain negative feedback method; this system consists of an

external capacitor, a Keithley electrometer (model 6517), a thermometer, a barometer, and the LabVIEW software program, which is used to achieve automatic control and acquisition functions. The microcurrent measurement system can measure the ionization charge with temperature and pressure corrections in real time.

2.2 FAC

The FAC can measure X-rays in the range of 8–100 kV. It serves as the core of the low-energy primary standard of air kerma and can achieve absolute air kerma measurements [22]. The design parameters of the FAC are listed in Table 1. The National Institute of Metrology in China used the FAC in a 2018 international key comparison effort and realized international equivalence [23]. The parallel X-ray beam generated by the X-ray tube enters the FAC through the front diaphragm such that the central axis of the X-ray beam is parallel and equidistant from the upper and lower electrodes. The X-ray beam leaves the FAC through the back hole. The ionization chamber was designed to measure the photon energy in the range of 8–100 keV. The design parameters of FAC are listed in Table 1.

2.3 Monte Carlo simulation software

A Monte Carlo simulation software program is typically used to simulate parameters that cannot be obtained directly or are difficult to obtain in the experiment; these parameters are used as a guide and constitute the basis for actual measurements. These include correction factors for electron loss, fluorescence scattering, and diaphragm transmission. In this study, a Monte Carlo simulation was used to obtain the correction factors. The electron gamma shower (EGSnrc) software program, developed by the National Research Council Canada, is typically used for Monte Carlo simulations in radiation dosimetry. Kawrakow [24] quantitatively analyzed the problems associated with EGS4, which made it difficult to simulate accurately the response of the ionization chamber, and proved that EGSnrc addressed these

Table 1 Design parameters of the free-air ionization chamber (FAC)

Program	Parameter
Aperture diameter (mm)	10.022
Air path length (mm)	100
Collecting length (mm)	40.497
Collecting width (mm)	100
Electrode separation (mm)	79.2
Air attenuation length (mm)	100
Measuring volume (mm ³)	3194.6
Polarizing voltage (V)	+1600

problems and improved the accuracy of the charged particle transport and atomic scattering cross section. Fu et al. [25] conducted cone-beam computer tomography simulation research based on the EGSnrc software program and verified the accuracy of the developed system. The spectral results obtained using this program showed good consistency with those obtained from the Spektr software program (a computational tool for X-ray spectrum modeling and analysis); the maximum difference was 3.0%, and the mean difference was lower than 2.0%. The DOSXYZnrc program was used to construct the FAC model. Combined with the egs-view visualization program, associated parameters were set, such as the cavity area, exit particle type and angle, medium, and density correction file. The BEAMnrc software program was used to simulate the fluence spectra of X-ray radiation. By selecting the appropriate simulation particle number, density correction file, incident particle source type and energy, cutoff energy of photons and electrons, interaction between particles, and variance reduction technology, a phase-space file with the suffix phsp was obtained. The BEAMdp software program was used in combination with the BEAMnrc program, and the generated phase-space file was opened in BEAMdp. According to the maximum and minimum energies of the particle source, the corresponding fluence spectral data were generated, including the number of particles and the uncertainty of different energies, and used to realize the calculation and data visualization of the X-ray fluence spectrum. The C++ application egs-fac implemented the transport of the particles in the FAC and calculated the associated correction factors in a self-consistent manner. The correction factors for electron loss, photon scatter, and fluorescence of low-energy and medium-energy free-air chambers were calculated by Burns [26] using the EGSnrc software program. The results were compared with those of the EGS4 software program and the PENELOPE code. Simultaneously, an uncertainty analysis was conducted, providing new values for the correction factors of the Bureau International des Poids et Mesures (BIPM) standards. This software program simulates and calculates the correction factors under the conditions of no vacuum tube, vacuum tube, and air. An FAC ionization chamber was used in this study. Therefore, correction factors without a vacuum tube were selected, namely diaphragm edge penetration, electron loss, scattering, and fluorescence photon correction factors.

2.4 Absolute air kerma X-ray measurements

The FAC operates as follows. Continuous X-rays are produced by the X-ray tube after the electron hits the target and enters the FAC through an enhanced filter and a beam-limiting diaphragm. Positive and negative ions are produced by the interaction between the X-rays and air in the cavity; these ions then move to the collecting plate under the effect of the electric field

applied between the electrode plates. The resulting ionization current was measured using a microcurrent measurement system. The air pressure and temperature in the surrounding area must be immediately monitored and corrected for the ionization current measured by the FAC. The air kerma rate was measured using an FAC according to its definition. The modified equation for the air density is given by Eq. (1).

$$\rho = \rho_0 \cdot \frac{273.15}{273.15 + T_a} \cdot \frac{P_a}{101.325} \quad (1)$$

where ρ_0 is the air density at 273.15 K and 101.325 kPa, and T_a and P_a are the air temperature and pressure during the measurements, respectively.

The air kerma rate was measured by an FAC according to its definition, and the value [27, 28] was calculated using Eq. (2).

$$\dot{K} = \frac{I}{\rho \cdot V} \cdot \frac{W_{\text{air}}}{e} \cdot \frac{1}{1 - g} \cdot \prod_i k_i \quad (2)$$

where V is the effective measurement volume of the FAC, I is the ionization current measured by the chamber, and $\frac{W_{\text{air}}}{e}$ is the mean energy that produces a pair of positive and negative ions in the air. Moreover, g is the fraction of charged particles lost in the air owing to Bremsstrahlung radiation, and $\prod_i k_i$ is the product of the correction factors. The physical constants used for the absolute measurement of air kerma rate in the X-rays are listed in Table 2.

Several correction factors affect the design and operation of FAC. These factors were obtained from experimental measurements, Monte Carlo simulations, and recommendations. The correction factors obtained from the experimental measurements are the following: air attenuation correction factor k_a , ion recombination loss correction factor k_s , wall transmission correction factor k_p , polarity correction factor k_{pol} , and electric field distortion correction factor k_d . Monte Carlo simulations provide correction factors such as the diaphragm transmission correction factor k_{dia} , the product of the scattering correction factor and fluorescence correction factor $k_{\text{sc}}k_{\text{fl}}$, and the electron loss correction factor k_e . Additionally, the product of the initial ion correction factor, the ionization work correction factor $k_{\text{ii}}k_w$, and the humidity correction factor k_h are from the recommendations.

Air attenuation correction factor In the absolute air kerma measurements, the ionization charge was collected in the collection plate of the FAC. The actual measurement

Table 2 FAC design parameters

Constant	Value
ρ (kg/m ³)	1.293
$\frac{W_{\text{air}}}{e}$ (J/C)	33.97
$1 - g$	1.0000

position was the geometric center of the front diaphragm hole in the FAC. An air gap exists between the collection plate and the diaphragm of the FAC, where the X-ray energy is attenuated. Several methods are used to obtain the air attenuation correction factor k_a using the vacuum, moving distance, and Monte Carlo methods. In this study, the moving distance method was used to obtain k_a [29]. Equations (3) and (4) are used for calculating k_a .

$$k_a = e^{\frac{\mu}{\rho} \cdot d \cdot \rho_{20^\circ\text{C}}} \quad (3)$$

$$\frac{\mu}{\rho} = \frac{\ln \frac{I_1}{I_2}}{d \cdot \rho} \quad (4)$$

where $\frac{\mu}{\rho}$ denotes the mass attenuation coefficient, d is an attenuation length of 10 cm, $\rho_{20^\circ\text{C}}$ is the air density at the temperature 20°C , and I_1 and I_2 are the ionization currents measured before and after the attenuation through the air distance, respectively.

Ion recombination loss correction factor To eliminate the inaccuracy of the experimental results caused by ion recombination during the measurement process, which yields a smaller measured ionization current than the true value, an ion recombination loss correction factor k_s is introduced. Ion recombination includes initial and volume recombinations [30]. In this study, the method recommended by BIPM was used to measure k_s [31], implemented by measuring the ionization currents at different tube voltages and currents. Equations (5) and (6) are used for calculations.

$$k_{\text{init}} = \frac{a_0 - 1}{n - 1} \quad (5)$$

$$k_{\text{vol}} = \frac{a_1}{n^2 - 1} \quad (6)$$

where k_{init} is the value of the initial recombination, k_{vol} is the volume recombination value, and n is the ratio of the polarizing voltage of +1600 V to the tube voltage of the ionization chamber in the area of the plateau with values of 2.5, 3, and 4 for the tube voltages of +640, +533, and +400 V, respectively. Additionally, a_0 is the intercept of the linear fitting equation, and a_1 is the slope of the fitting equation. Thus, k_s can be expressed by Eq. (7).

$$k_s = 1 + k_{\text{init}} + k_{\text{vol}} \cdot I_v \quad (7)$$

where I_v is the ionization current at +1600 V.

Wall-transmission correction factor Some high-energy X-rays enter the ionization chamber from the non-diaphragm hole, resulting in a higher current [32]. To correct the measurements, a wall transmission correction

factor k_p must be introduced. The incident diaphragm hole of the FAC was sealed with a lead plug to prevent radiation from entering the incident diaphragm hole. The equation used to measure the k_p is given by Eq. (8).

$$k_p = 1 - \frac{I_1 - I_{\text{leak}}}{I_2 - I_{\text{leak}}} \quad (8)$$

where I_1 and I_2 are the ionization currents with and without a lead plug, respectively, and I_{leak} is the leakage current in the system.

Electric field distortion correction factor To correct for the electric field distortion, k_d was introduced. Several factors can cause electric field distortions in the ionization chamber. The collecting plate is not coplanar with the high-voltage plate; scattered photons in the environment enter the ionization chamber through an outer Pb shielding box, and the structure of the voltage divider strips is inconsistent [33]. In the design and processing of the ionization chamber, the maximum possible reduction of the electric field distortion was considered. It is a specific measurement that adds multiple voltage divider strips between the high-voltage plate and the collecting plate so that the electric field of the ionization chamber can be distributed as evenly as possible. When the distance between the collecting plate and the voltage divider strips and that between the voltage divider strips are sufficiently large, the electric field distortion caused by this factor can be ignored [34]. The electric field distortion correction factor k_d was equal to 1.0000.

Initial ion correction factor and ionization work correction factor These two correction factors were introduced for the first time in the ICRU Report 90 [35] as $k_{\text{ii}}k_w$, a value related to the energy of the X-rays. Because $k_{\text{ii}}k_w$ increases rapidly at electron energies below 10 keV, FAC requires charged ion balance. Meanwhile, $k_{\text{ii}}k_w$ is defined for the incident charged particles released by ionizing radiation and does not include the charges of the initially charged particles. The value of $k_{\text{ii}}k_w$ is given in the ICRU Report 90 for monoenergetic photon beams in the energy range of 1–400 keV. For photon energies greater than 300 keV, the product is one. For energies less than 300 keV, the value was calculated using the fluence spectrum. To obtain the value of $k_{\text{ii}}k_w$ for the continuous fluence spectrum, the value of $k_{\text{ii}}k_w$ for different radiation qualities can be obtained based on simulated fluence spectra.

Polarity correction factor Ideally, the polarity of the bias applied to the ionization chamber should not affect the measurements. To correct for this effect, the measurements with positive and negative polarities were processed using Eq. (9), as follows:

$$k_{\text{pol}} = \frac{I_+ - I_{\text{leak}} + I_- - I_{\text{leak}}}{2I_+} \quad (9)$$

where I_+ and I_- are ionization currents at the polarizing voltages +1600 V and -1600 V.

Diaphragm transmission correction factor When an X-ray beam passes through a diaphragm, photons that pass through or are scattered by the diaphragm enter the FAC, causing additional effects on the air kerma measurements. This study used a tungsten alloy diaphragm to limit the X-ray beam and reduce the effect of scattering on the measurements. Currently, the correction factor k_{dia} is typically obtained by using Monte Carlo simulations. In this study, the EGSnrc program was used to simulate k_{dia} . First, the structural model of the FAC needed to be established; based on the model, E_g denoted the photon energy into the collection area, and E_{dia} was the deposited energy into the collection area through the hole in the diaphragm. Equation (10) is used to calculate k_{dia} .

$$k_{\text{dia}} = \frac{E_g - E_{\text{dia}}}{E_g} \quad (10)$$

Electron loss correction factor If the energy of the incident primary photon is sufficiently high, the charges generated by ionization in the ionization chamber cannot be completely collected, as expected, as a part of them directly hits the upper and lower collection plates. This part of the electron energy includes the electron energy deposited in the plates and the penetrated plates [36]. Equation (11) is used to calculate k_e .

$$k_e = \frac{E_e - E_a}{E_e} \quad (11)$$

where E_e is the deposited energy in the upper and lower collection plates, and E_a is the sum of the deposited energy in the collection volume.

Scattering and fluorescence correction factors Two correction factors are introduced to reduce the influence of additional electrons generated by scattered and fluorescent photons in the ionization chamber on the measurements [37]. Based on Eq. (12), the product of the scattering and fluorescence correction factors was simulated using the EGSnrc software.

$$k_{\text{sc}}k_{\text{fl}} = \frac{E_a}{E_a + E_{\text{sc}} + E_{\text{fl}}} \quad (12)$$

where E_{sc} is the deposited energy of the scattered photons in the collection volume of the ionization chamber, and E_{fl} is the deposited energy of fluorescent photons in the collection volume.

Humidity correction factor Humidity in the environment changes the ionization current and affects the air kerma. In this study, the humidity correction factor k_h was 0.9980, as recommended by the BIPM [38].

3 Results and discussion

3.1 Fluence spectrum simulated by Monte Carlo

Based on the technical parameters of the SRT-100, the tube voltages were set to 50, 70, and 100 kV. The corresponding enhanced filtrations were 0.419, 0.751, and 1.137 mmAl, and the purity was greater than 99.99%. Monoenergetic electrons were selected as incident particles. The cutoff energies of the electron and proton were set at 0.512 and 0.001 MeV, respectively. The ionization chamber was placed 1 m from the focal spot of the X-ray tube, and the number of simulated particles was 10^8 . Three radiation qualities were simulated using the BEAMnrc program, and a model of the X-ray tube and fluence spectra were simulated. The results are presented in Fig. 1; as shown, all the results of every fluence spectrum are normalized according to the maximum fluence data.

Figure 1a shows the simulation model of the X-ray machine established using the BEAMnrc program, including the target material, additional filtration, diaphragm, and other parameter settings. Figure 1b shows the fluence spectra of three superficial X-ray radiotherapy radiation qualities simulated at 50, 70, and 100 kV. Based on the established X-ray tube model, we selected the density correction database, chose whether to open the relevant particle reactions, and obtained a phase-space file. The phase-space file was opened in the BEAMdp software program and set to generate 200 spectral energy datasets with a minimum particle energy of 0.001 MeV. According to the fluence spectra datasets, the mean energies of the fluence spectra simulated at 50, 70, and 100 kV were 26.2, 34.1, and 44.7 keV, respectively.

3.2 HVL measurements

The half-value layer (HVL) can be used to characterize the X-ray radiation quality, which is divided into the first HVL (1st HVL) and the second HVL (2nd HVL) [39]. The 1st HVL is defined as the thickness of the absorber required when the air kerma rate is reduced to 0.5 times the air kerma rate value in the case in which no absorber is used; the 2nd HVL is defined as the absorber thickness required when the air kerma rate is reduced to 0.25. The homogeneity coefficient (h) is the ratio of the 1st and the 2nd HVLs. A model diagram of the experimental setup for measuring HVL is shown in Fig. 2.

According to the measurement method for the HVL in [40], the Farmer chamber PTW30013 was used to measure the ionization current at a distance of 1 m from the focal spot of the X-ray tube, and the absorber was placed

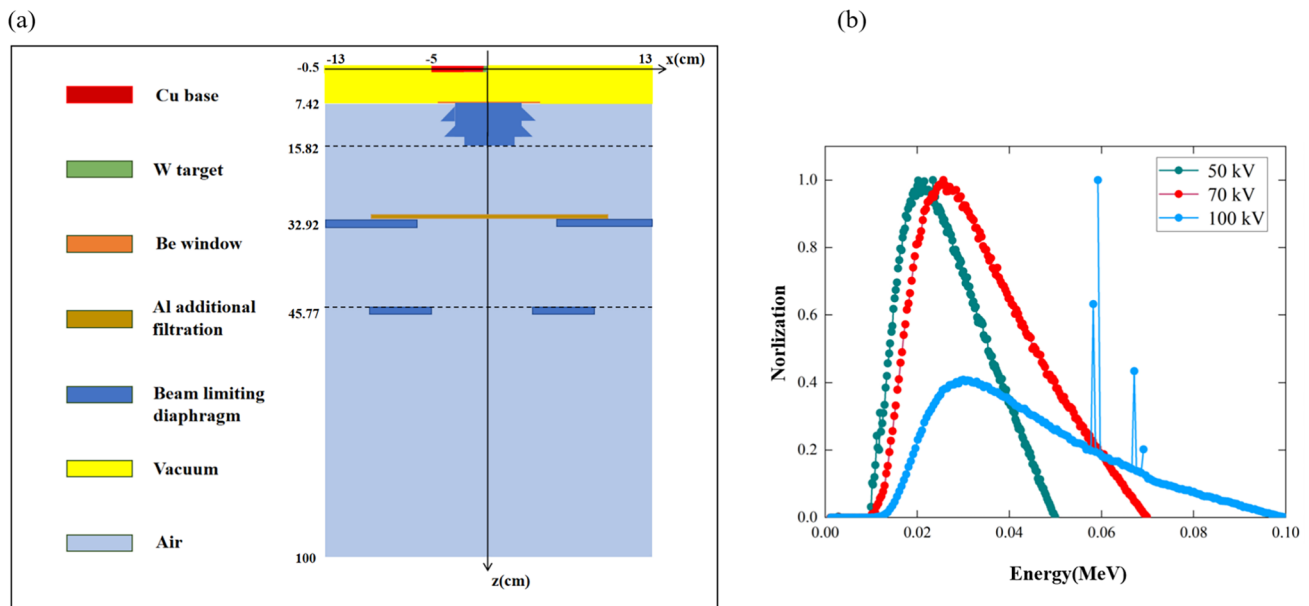
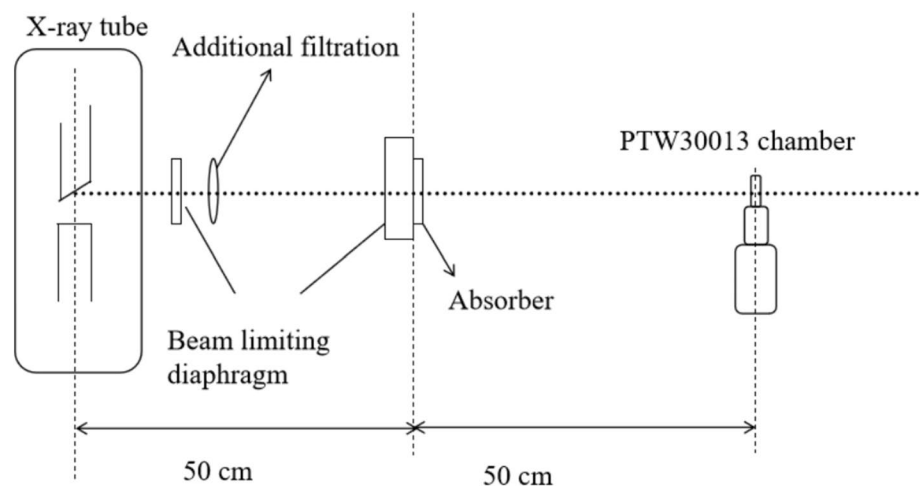


Fig. 1 (Color online) **a** Model of the X-ray tube, and **b** simulated fluence spectra of three radiation qualities

Fig. 2 Model diagram of the experimental device used to measure the half-value layer (HVL) values



at a distance of 0.5 m. Based on the ionization current measured for different absorber thicknesses, the attenuation curve was fitted to estimate the 1st and 2nd HVLs. Figure 3 shows the attenuation curves of the three radiation qualities of superficial X-ray radiotherapy in the chamber PTW30013, where the vertical coordinates were normalized according to the maximum ionization current. Table 3 lists the measurements for the 1st and 2nd HVLs and h .

3.3 Absolute air kerma measurements

According to the principle of FAC air kerma measurements, the chamber was fixed at a distance of 1 m from the focal spot of the X-ray tube using a laser and a measuring rod positioning device under established reference radiation

quality conditions. The effective measurement center axis of the ionization chamber and the X-ray beam center axis were on the same horizontal line. The FAC was connected to a microcurrent measurement system, and the ionization current was measured using the high-gain negative feedback method. The air kerma rate was measured at a position 1 m from the X-ray focal spot using the FAC by measuring and simulating the relevant correction factors and combining them with the FAC.

The ion recombination loss correction factor k_s was measured at different tube voltages and currents. Five tube currents were set at each tube voltage for each radiation quality, and three tube voltages were simultaneously set at the same time to obtain 15 corresponding ionization currents. The ionization currents for the different tube currents at each

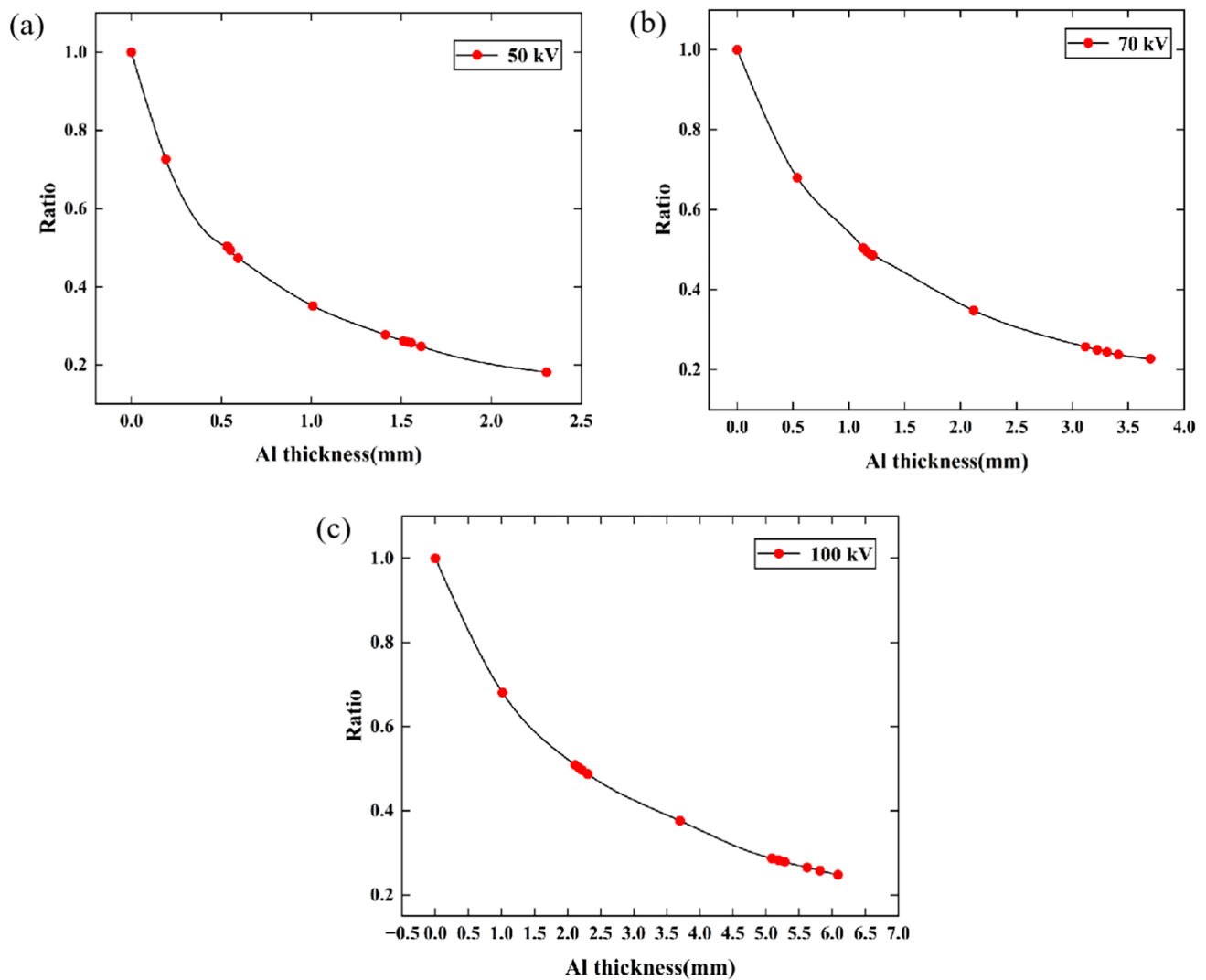


Fig. 3 (Color online) Attenuation curves of HVL measurements

Table 3 Measurements of the 1st half-value layer (HVL), 2nd HVL, and h

Tube voltage (kV)	Additional filtration Al (mm)	1 st HVL (mmAl)	2 nd HVL (mmAl)	h
50	0.419	0.538	1.055	0.51
70	0.751	1.146	2.077	0.55
100	1.137	2.190	3.833	0.57

tube voltage were processed with an ionization current at a polarizing voltage of +1600 V to obtain the k_s fitting curves. The fitting curves of k_s for three radiation qualities are shown in Fig. 4, and the values of k_{init} and k_{vol} are listed in Table 4.

Table 4 lists the initial and volume recombination values for the three radiation qualities at different tube voltages. The values were calculated from the ionization current at

different tube currents and voltages. The average initial and volume recombination values were calculated. According to Eq. 7, the k_s values at 50, 70, and 100 kV were 1.0009, 1.0011, and 1.0007, respectively.

$k_{\text{ii}}k_{\text{w}}$ was introduced as a correction factor for air kerma for the first time in the ICRU Report 90. The value of $k_{\text{ii}}k_{\text{w}}$ of monoenergetic photons (energy range of 1–400 keV) is recommended, and $k_{\text{ii}}k_{\text{w}}$ of the radiation qualities in superficial X-ray radiotherapy cannot be obtained directly. In this study, fluence spectra datasets simulated by the EGSnrc software were used to calculate the products $k_{\text{ii}}k_{\text{w}}$ of the radiation qualities. Based on the $k_{\text{ii}}k_{\text{w}}$ values of the different monoenergetic photons, the original software program was used to interpolate the products $k_{\text{ii}}k_{\text{w}}$ at each energy level in the fluence spectra. Based on the simulated data, the product outcomes $k_{\text{ii}}k_{\text{w}}$ of the fluence spectra were calculated at the three radiation qualities using

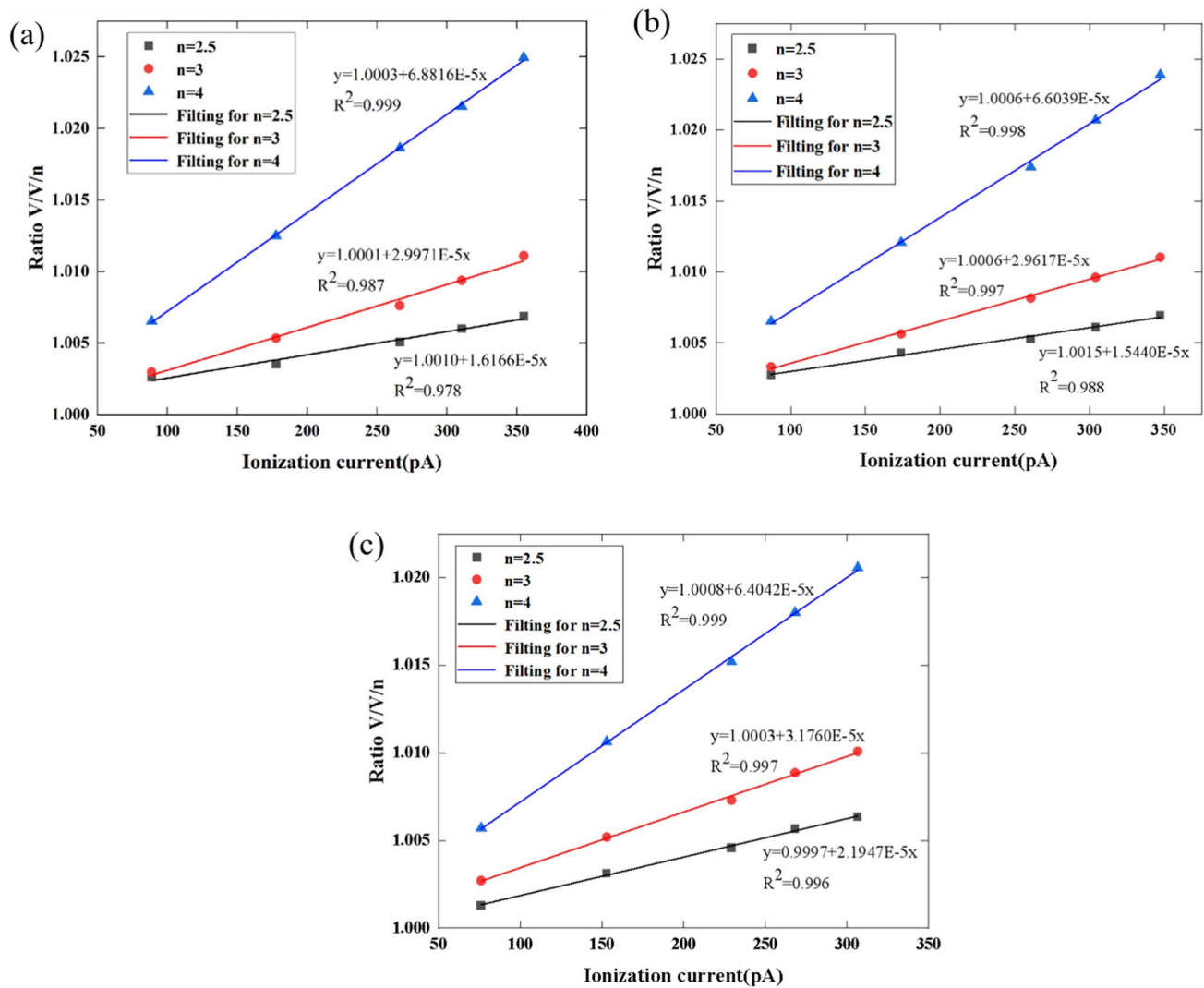


Fig. 4 (Color online) Fitting curves of k_s for three radiation qualities: **a** 50 kV, **b** 70 kV, and **c** 100 kV (curves in blue, red, and black colors in the three subplots denote the variations of k_s as functions of

the ionization current at operating voltages of + 400 V, + 533 V, and + 640 V, respectively

Table 4 Calculated averages of initial recombination and volume recombination

Radiation quality	Parameter			
	a_0	a_1	k_{init}	k_{vol}
50 kV	1.0005	3.83×10^{-5}	2.72×10^{-4}	3.80×10^{-6}
70 kV	1.0009	3.70×10^{-5}	5.00×10^{-4}	3.68×10^{-6}
100 kV	1.0003	3.92×10^{-5}	7.22×10^{-5}	4.14×10^{-6}

different interpolation methods, including linear, cubic spline, cubic B-spline, and Akima spline interpolation, as shown in Table 5; the final results were the average results.

Table 5 Values of $k_{\text{ii}}k_{\text{w}}$ of fluence spectra obtained using different interpolation methods

Radiation quality	50 kV	70 kV	100 kV
Linear	0.99786	0.99795	0.99792
Cubic spline	0.99790	0.99797	0.99793
Cubic B-splines	0.99788	0.99798	0.99794
Akima spline	0.99790	0.99797	0.99793
Average	0.9979	0.9980	0.9979

The correction factors for the superficial X-ray radiation qualities are summarized in Table 6, and the results for the air kerma rate are summarized in Table 7.

Table 6 Correction factors of the three radiation qualities studied herein

Radiation quality	50 kV	70 kV	100 kV
k_a	1.0181	1.0079	1.0051
k_s	1.0009	1.0011	1.0007
k_p	1.0009	1.0000	0.9946
k_{pol}	1.0004	1.0004	1.0004
$k_{sck_{ri}}$	0.9952	0.9947	0.9956
k_e	1.0000	1.0002	1.0045
k_{dia}	0.9999	0.9999	0.9981
k_h	0.9980	0.9980	0.9980
k_d	1.0000	1.0000	1.0000
$k_{ii}k_w$	0.9979	0.9980	0.9979
$\prod_i k_i$	1.0102	1.0002	0.9948

Table 7 Absolute air kerma measurements

Radiation quality	50 kV	70 kV	100 kV
Air density (kg/m ³)	1.293	1.293	1.293
W_{air}/e (J/C)	33.97	33.97	33.97
$1 - g$	1.0000	1.0000	1.0000
$\prod_i k_i$	1.0102	1.0002	0.9948
Volume (mm ³)	3.194	3.194	3.194
Ionization current (pA)	178.9	174.5	154.9
$\dot{K}$ (mGy/s)	1.487	1.436	1.268

3.4 Calibration of transfer ionization chambers

To verify the accuracy of the measured air kerma rate, the transfer chamber was calibrated, and the results were compared with international comparison results. The calibration factor is the ratio between the measured value corrected by the temperature and pressure using the transfer ionization chamber. The standard values were measured using the same reference radiation field. Equation (13), which is used to calculate the calibration factor, is given by

$$N_K = \frac{\dot{K}}{I_{tr}} \quad (13)$$

where $\dot{K}$ is the standard air kerma rate, and I_{tr} is the measured ionization current (corrected to 293.15 K and 101.325 kPa) by a transfer ionization chamber.

Considering the fluence of multiple electron scattering and recombination loss, the parallel-plate ionization chamber can reduce the fluence for the measurements of radiation quality at the low-energy X-ray superficial radiotherapy level because of its special structure. Two parallel-plate transfer chambers, namely PTW23342 (0.02 cm³) and PTW23344 (0.2 cm³), were used for the calibration. The

effective measurement centers were the geometric centers of the front surfaces of the chambers. During the calibration of the transfer ionization chambers, the ionization current was measured using a connected microcurrent measurement system. It is necessary to focus on the changes in temperature and humidity in the measurement environment. Two transfer ionization chambers were placed in the radiation field, and the reference point of the transfer ionization chambers coincided with the measurement point of the air kerma measured using FAC to implement the subsequent calibration. The effective measurement volumes of the two transfer ionization chambers were low, particularly when the magnitude was approximately 1 pA when PTW23342 was used. When the external environment changes, such as the leakage current, the leakage current changes by 1 fA (ionization current is approximately 1 pA), which leads to an effect of 0.1%. It is necessary to measure the ionization current several times, estimate the average value to reduce uncertainty, and then obtain the calibration factor of the transfer chamber in superficial X-ray radiotherapy radiation qualities. The ionization current was measured under the same conditions as the five CCRI radiation qualities (10–50 kV) using two transfer chambers. In this study, FAC was used to measure the radiation quality of the CCRI air kerma rate (10–50 kV), and the $k_{ii}k_w$ values were considered to obtain the calibration factors. The calibration factors of five CCRI radiation qualities (10–50 kV) and three radiation qualities in superficial X-ray radiotherapy are plotted in Fig. 5.

The black points in Fig. 5 correspond (from left to right) to 10 kV, 30 kV, 25 kV, 50 kVb, and 50 kVa for the CCRI series, and the red points correspond to 50, 70, and 100 kV for superficial X-ray radiotherapy. According to the measurements, the calibration factors changed for different radiation qualities as a function of X-ray energy. Figure 5 shows the calibration factor curves for the two transfer ionization chambers. There was a significant decrease when the X-ray energy was low, and it changed smoothly at increasing energies. This was consistent with the energy response of the ionization chamber design. Meanwhile, the calibration factors of the two transfer ionization chambers (namely PTW23342 and PTW23344) for the three radiation qualities in superficial X-ray radiotherapy were in good agreement with those of the CCRI radiation qualities. These results are traceable and equivalent to the international results for low-energy X-ray air. The accuracy of the measurement method for the air kerma rate of radiation qualities in superficial X-ray radiotherapy was verified indirectly.

3.5 Uncertainty analysis

The FAC measurements and transfer ionization chambers should consider the influence of uncertainty. The measurement uncertainty method was based on the GUM method.

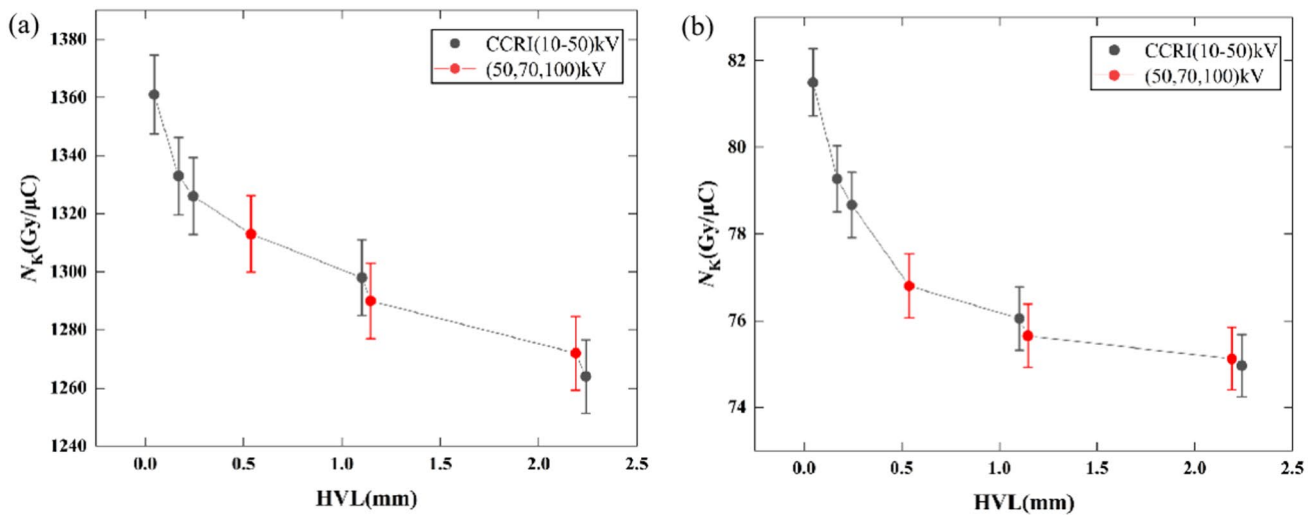


Fig. 5 (Color online) Calibration results of transfer chambers **a** PTW23342 and **b** PTW23344

Table 8 Uncertainties of correction factors for air kerma rate using the FAC

Correction factor	$u_{iA}(\%)$	$u_{iB}(\%)$
k_a	-	0.20
k_s	0.05	0.02
k_p	0.01	0.05
k_{pol}	0.01	0.05
$k_{sc}k_{fl}$	-	0.15
k_e	-	0.02
k_{dia}	-	0.01
k_h	-	0.03
k_d	-	0.10
$k_{ii}k_w$	-	0.09
$\prod_i k_i$	0.05	0.30

This includes uncertainties of Types A and B. The Type A uncertainty was derived from experimental deviations. The Type B uncertainty was evaluated using all the relevant information on the possible variability of the measured quantities [41]. According to the air kerma rate equation, the sources of uncertainty include the volume of the ionization chamber, ionization current, temperature, pressure, ionization current correction factors, and physical constants. For example, the ionization current was measured 10 times repeatedly, and the average value was estimated and used as the final value. The Type A uncertainty of the ionization current originates from the experimental deviation of the 10 measurements. After the analysis, the uncertainties of the associated correction factors measured for FAC are listed in Table 8, and the uncertainties of the air kerma values are listed in Table 9. The calibration factors measured for the transfer chambers are listed in Table 10.

Table 9 Uncertainties of air kerma rate using the FAC

Symbol	$u_{iA}(\%)$	$u_{iB}(\%)$
ρ_{air}	-	0.01
W_{air}/e	-	0.35
$1 - g_{air}$	-	0.01
I	0.01	0.01
Position	-	0.08
V	0.01	0.01
T	-	0.04
P	-	0.01
$\prod_i k_i$	0.05	0.30
$\dot{K}$	0.05	0.47

Table 10 Uncertainties of calibration factors for transfer chambers

Symbol	PTW23342		PTW23344	
	$u_{iA}(\%)$	$u_{iB}(\%)$	$u_{iA}(\%)$	$u_{iB}(\%)$
$\dot{K}$	0.05	0.47	0.05	0.47
I	0.12	0.01	0.03	0.01
T	0.01	0.04	0.01	0.04
P	0.01	0.01	0.01	0.01
Position	0.01	0.10	0.01	0.10
N_K	0.13	0.48	0.06	0.48

Table 9 shows the results when the FAC was used to measure the air kerma rate; uncertainties were obtained from the correction factors and mean ionization energy W_{air}/e . The combined relative uncertainty was 0.47%. Two transfer chambers (PTW23342 and PTW23344) were used for the calibration. Compared with PTW23344, the effective measurement volume of PTW23342 and the measured ionization current were smaller; therefore, the uncertainty

of its ionization current was higher. Table 10 shows that the resulting uncertainties in the calibration factors are primarily derived from the air kerma rate and ionization current. The combined relative uncertainties of the calibration factors were 0.50% and 0.48%, respectively. The expanded uncertainties for the calibration factors of the two transfer chambers were 1.00% ($k = 2$) and 0.96% ($k = 2$).

4 Conclusion

In this study, the absolute measurements and uncertainty evaluations of air kerma under three radiation qualities in a superficial X-ray radiotherapy series were completed using an FAC. Twoparallel-plate transfer ionization chambers were calibrated to obtain calibration factors and their uncertainties. Three radiation qualities were established based on the technical parameters of the SRT-100. The first HVLs measured were 0.538, 1.146, and 2.190 mmAl. A model of the FAC was constructed using the EGSnc software program, and the particle fluence spectrum, mean energy, and corresponding correction factors of the fluence spectrum were simulated. Based on the experiments and simulations, correction factors of the air kerma rate were obtained, and the absolute measurements of the air kerma rate of the various radiation qualities were obtained in superficial X-ray radiotherapy. The air kerma rates were 1.487, 1.436, and 1.268 mGy/s with an expanded uncertainty of 0.94% ($k = 2$). Meanwhile, the radiation quality calibration of the two transfer ionization chambers was completed, and the expanded uncertainties of the calibration factors of the ionization chambers were 1.00% ($k = 2$) and 0.96% ($k = 2$). This research provides the basis for measurements of radiation qualities of the absorbed dose to water in superficial X-ray radiotherapy, greatly reducing measurement uncertainty and laying the foundation for the measurements of the absorbed dose.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Jun-Xia Bao, Rui Zhao, and Xiao Zhang. The first draft of the manuscript was written by Jun-Xia Bao and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability The data that support the findings of this study are openly available in Science Data Bank at <https://cstr.cn/31253.11.sciencedb.j00186.01041> and <https://www.doi.org/10.57760/sciencedb.j00186.01041>.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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