Journal of the Korean Physical Society (2023) 83:226–232
https://doi.org/10.1007/s40042-023-00866-y

Online ISSN 1976-8524
Print ISSN 0374-4884

ORIGINAL PAPER - CROSS-DISCIPLINARY PHYSICS AND RELATED AREAS OF SCIENCE AND TECHNOLOGY

Preliminary study on dose conversion parameters for absorbed dose to water in kV X-ray beams

Yunho Kim[1] · Chul-Young Yi[1] · In Jung Kim[1,2] · Jong In Park[1]

Received: 23 March 2023 / Revised: 8 June 2023 / Accepted: 9 June 2023 / Published online: 29 June 2023

Abstract
Although accurate X-ray dosimetry standards are crucial for certain medical and industrial applications, insufficient research attention has been given to the standards concerning the absorbed dose to water for kV X-rays. To determine the absorbed dose to water based on measurement standards for the air kerma, it is necessary to evaluate the dose conversion factor from the air kerma to the absorbed dose to water. This factor can be derived from the dose conversion parameter, obtained through theoretical calculations such as Monte Carlo (MC) simulations, and the response ratio of the ion chamber in water and air, obtained through measurements. In this study, the dose conversion parameters were preliminarily evaluated for kilovolt X-ray beams using MC simulations. The modeling of the X-ray tube at the Korea Research Institute of Standards and Science (KRISS) was optimized to reproduce the beam qualities of the reference kilovolt X-ray beams recommended by the Consultative Committee for Ionizing Radiation (CCRI) using the Electron Gamma Shower MC code from the National Research Council Canada. The spectral distributions of the reproduced X-ray beams were used to calculate the dose conversion parameters in MC simulations. To obtain the dose conversion parameter, the air kerma and absorbed dose to water at the reference positions were calculated, and responses of an ion chamber in the air and in a water phantom were calculated, as well. The evaluated dose conversion parameters were found to be in the range of 1.0355–1.0961 for the KRISS reference X-ray beams of 100–250 kV. These results were agreed within 1% of those of other research groups. To understand the sensitivity of the obtained conversion parameters, case studies were performed under different conditions, such as different X-ray beam qualities and geometric specifications of the ion chamber. A maximum difference of 0.56% was found in the case studies.

Keywords Dosimetry · Standard · Absorbed dose to water · Air kerma · Monte Carlo

1 Introduction

Radiation dosimetry for X-rays in the kilovolt region has been studied for the sakes of radiation protection and applications in industry and medicine. Accordingly, dosimetry standards are essential for precise dosimetry. At present, most countries have established the measurement standards of air kerma for kV X-rays and disseminated these standards for radiation protection purpose. However, absorbed dose-to-water standards for kV X-rays, which are useful, especially in medical applications such as radiation diagnosis and therapy in the kV range, have not been widely established. These are being studied by only a couple of national measurement institutes (NMIs) [1, 2].

Several technical protocols and reports, such as the International Atomic Energy Agency Technical Report Series No. 398 [3], and the American Association of Physicists in Medicine (AAPM) TG-61 [4], have already suggested procedures for measuring the absorbed dose of the water of kV X-rays. However, to ensure the precise and reliable measurement of the absorbed dose to the water of kV X-rays, it is essential to establish and disseminate measurement standards to the public.

The absorbed dose of water D_w is defined as follows [5]:

✉ Yunho Kim
yhkim24@kriss.re.kr

1 Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea

2 University of Science and Technology, Daejeon 34113, Republic of Korea

$$D_w = \frac{d\bar{\varepsilon}}{d\,m_w} \quad (1)$$

where $d\bar{\varepsilon}$ is the mean energy imparted by the ionizing radiation to the water of mass dm_w. The imparted energy ε is the sum of all energy deposition in the volume [5].

The absorbed dose of water can be measured absolutely or directly using the water or graphite calorimeters. These types of calorimeters are being adopted as primary dosimetry standards for therapeutic high-energy photons and electrons in many countries [6–9]. These calorimeters are typically operated under a dose rate of a few Gy/min, similar to the conditions of radiation therapy. However, because kV X-ray beams have much lower energy and dose rate than therapeutic high-energy beams, these calorimeters are not suitable for kV X-rays.

Two methods can be adopted to establish measurement standards for the absorbed dose of water in kV X-ray beams: (a) developing a calorimeter applicable to kV X-rays and (b) using ionometry with a theoretical approach. NMIs studying the absorbed dose to water standards for kV X-rays have also introduced water calorimeters optimized for the measurement conditions of kV X-rays and ionometry based on the developed air kerma standards [10, 11].

At the Korea Research Institute of Standards and Science (KRISS), measurement standards for the absorbed dose to water in kV X-ray fields are being studied using air-kerma-based measurements and a theoretical approach adopting Monte Carlo (MC) techniques. By adopting the dose conversion factor from the air kerma to the absorbed dose to water, measurement standards for the absorbed dose to the water of kV X-rays can be established.

The absorbed dose of water D_w and dose conversion factor $C_{w,a}$ can be expressed as follows:

$$D_w = K_{air,FAC} k_{rn} C_{w,a} \quad (2)$$

$$C_{w,a} = \left(\frac{Q_w}{Q_{air}}\right)_{meas.} \left(\frac{D_w/D_{cav,w}}{K_{air}/D_{cav,air}}\right)_{MC} = \left(\frac{Q_w}{Q_{air}}\right)_{meas.} C_{MC} \quad (3)$$

where $K_{air,FAC}$ is the reference air kerma measured according to the free air chamber primary standard of KRISS [10, 11], k_{rn} is a correction factor for radial non-uniformity, and Q_w and Q_{air} are the measured charge values from an ion chamber positioned at the reference depth of 2 g/cm^2 in a water phantom and in free air, respectively. $D_{cav,w}$ and $D_{cav,air}$ are the absorbed doses to the cavity of an ion chamber positioned in the same ways as in the measurement conditions. C_{MC} denotes a conversion parameter obtained from MC simulations. The subscripts "meas." and "MC" denote results obtained from measurements and Monte Carlo simulations, respectively. This formalism is similar to those in the published protocols [3, 4]. However, more precise measurements of the absorbed dose to water can be achieved using the presented dose conversion factor, which combines measurement- and MC-based approaches, compared to those obtained using the purely theoretical approaches of other protocols based on mass energy absorption coefficient.

In this article, we detail preliminary studies on the dose conversion parameters C_{MC} to be adopted in measurement standards for absorbed dose to water in kV X-rays, especially in the medium-energy region. For the MC simulations, the Electron Gamma Shower toolkits from the National Research Council Canada (EGSnrc) code [12] were utilized. To evaluate the conversion parameters C_{MC}, an X-ray tube was modeled to reproduce the KRISS reference X-ray beams. Furthermore, the reference X-ray beams recommended by the Consultative Committee for Ionizing Radiation (CCRI) were reproduced through optimized X-ray tube modeling. Based on the reproduced reference X-ray beams, the air kerma and absorbed dose to water at the reference position, as well as the responses of an ion chamber, were also calculated. Section 2 introduces the Monte Carlo simulation methods for obtaining the conversion factors from the air kerma to the absorbed dose to water of the kV X-rays. Section 3 presents the results of the evaluated conversion parameters obtained through MC simulations for the reference kV X-ray beams. Finally, Sect. 4 summarizes our work.

2 Method

2.1 Medium-energy X-ray tube modeling

The Beamnrc code in the EGSnrc package was applied to model an X-ray tube to reproduce the measured beam qualities of the KRISS reference X-ray beams in the medium energy region. Components of the X-ray tube, such as the anode and window, were defined based on the vendor's information. By generating electrons incident on the anode with a focal spot size of 5.5 mm, the four reference beam qualities (100, 135, 180, and 250 kV) recommended by CCRI were simulated. Figure 1 presents a schematic of the X-ray tube model, which includes the following components:

- Anode: a tungsten target with a 20° angle, embedded on a copper block.
- X-ray tube window: a 3-mm-thick beryllium window with a diameter of 43 mm.
- X-ray tube body: a copper block to prevent X-ray leakage.
- Additional filter: additional filtration for generating the reference beam qualities.
- Collimators: tungsten blocks used to generate the reference field with a diameter of approximately 10 cm at the reference distance of 1 m.

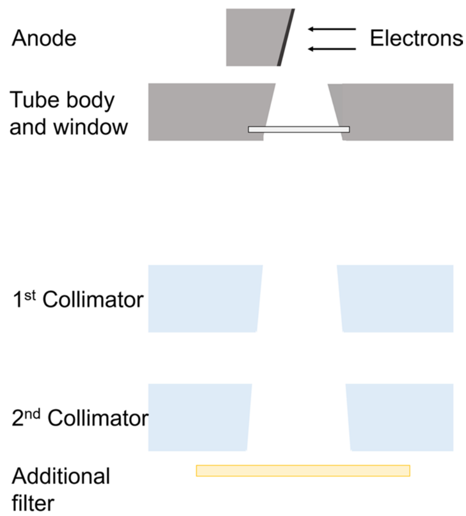

Fig. 1 Schematic of geometry used in X-ray tube simulations (not to scale)

The cutoff energy of both photons (PCUT) and electrons (ECUT) was set to 1 keV. In addition, the threshold energy for both photons (AP) and electrons (AE) was defined as 1 keV. All components in the X-ray tube modeling were defined according to the electron stopping power recommended by the International Commission on Radiation Unit and Measurement (ICRU) report No. 37 [13]. The XCOM library [14] was applied to transport the photons. Spectral distributions of the simulated beams at a distance of 1 m were calculated for the four beam qualities.

The obtained spectral distributions were used to reproduce the measured half-value layer (HVL) values; the HVL is one of the beam quality parameters used for kV X-rays. The HVL values in the simulations were determined by comparing the attenuated air kerma ratios for aluminum or copper with different thicknesses. Air kerma was estimated using the air kerma approximation method [5] based on the mass energy absorption coefficient from the NIST database [15]. The X-ray tube model underwent multiple iterative adjustment in the geometric specifications of the defined components until the deviation of the HVL from the measured value was reduced to less than 2%.

2.2 Evaluation of the dose conversion parameter C_{MC}

The values of the conversion parameter from MC, $C_{MC} = \left(\frac{D_w/D_{cav,w}}{K_{air}/D_{cav,air}}\right)_{MC}$, for the CCRI-recommended reference beams at KRISS were calculated. The user codes of egs_kerma, cavity, and egs_chamber in the EGSnrc package were utilized to evaluate the air kerma K_{air}, absorbed dose to water D_w at a water depth of 2 g/cm^2, and chamber responses $D_{cav,w}$ and $D_{cav,air}$. The XCOM library with a renormalized cross section for air and water and ESTAR [16] data adopting recommendations from ICRU report 90 [5] were applied for the transportation of photons and electrons, respectively. The threshold and cutoff energies were defined as 1 keV for both photons and electrons, as described in Sect. 2.1. Simulated X-rays were isotropically emitted and collimated to achieve a field size with a diameter of 100 mm at the reference distance of 1 m.

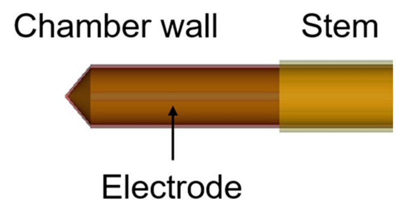

Fig. 2 Simulated PTW 30013 ion chamber in EGSnrc

The scoring cell for calculating the air kerma and absorbed dose to water was defined with a diameter of 10 mm and a thickness of 1 mm. The dimensions of the water phantom in the calculations for the absorbed dose of water were defined as 300 mm × 300 mm × 300 mm.

To evaluate the chamber responses of $D_{cav,w}$ and $D_{cav,air}$, an ion chamber (Model 30,013, Physikalisch-Technische Werkstätten (PTW), Germany) was modeled according to the vendor's information, as presented in Fig. 2. The PTW 30013 chamber has a wall made of 0.335-mm-thick poly methyl methacrylate (PMMA) and 0.09-mm-thick-graphite, and its nominal sensitive volume is 0.6 cm^3. An electrode of the chamber is made of aluminum and its diameter is 1.15 mm. The absorbed dose to the cavity of the ion chamber was calculated for four types of reference X-ray beams. $D_{cav,w}$ was calculated for the ion chamber positioned at a depth of 2 g/cm^2 in the water phantom and a distance of 1 m from X-ray target, and $D_{cav,air}$ was calculated for that positioned at the reference distance of 1 m in free air. To verify the reliability of the MC simulations used in this study, the obtained dose conversion parameters for the reference X-ray beams were compared to the results published by other research groups. The other research groups have evaluated the dose conversion parameters or equivalent values with the different approaches from the present study, the details are presented with the comparison results in Sect. 3.2.

2.3 Sensitivity studies on the dose conversion parameters based on MC simulations

To study the sensitivity of the conversion parameter C_{MC} obtained from MC calculations, the trends of C_{MC} were analyzed by assuming different parameters. The components expected to have significant effects on the simulation results are the incident energy spectra of X-rays and geometric specifications of the ion chamber, such as wall thickness and collecting electrode dimensions. As the cross section of radiation can be expressed as a function of energy as well-known, different energy spectra induce changes in the calculations of absorbed dose to water, air kerma, and absorbed dose in the cavity of the ion chamber. In addition, secondary charged particles depositing their energy in the cavity are generated from interactions in the chamber wall and transportation of the generated charged particles might be disturbed by collecting electrode of the chamber. Therefore, the influence of energy spectra and geometric specifications of the ion chamber on C_{MC} were studied in the present study.

To understand the dependence of the MC calculations on the incident energy spectra of X-rays, different energy spectra assumed as the HVL values deviating by approximately 5% from the measurements were produced for the reference X-ray beams. The assumed energy spectra were obtained using the X-ray spectrum calculator SpekCalc [17–19]. These energy spectra were used to calculate C_{MC}, and the calculations were performed until the statistical uncertainties were no greater than 0.15%. The results from different energy spectra were compared with the results for the corresponding KRISS reference beam qualities given in Sect. 2.2.

To determine the effect of the chamber wall, a PMMA thickness increased by 5% and a nominal thickness of graphite in the chamber wall were modeled. Using the assumed geometry of the ion chamber, the absorbed dose to the cavity was calculated for the chamber in the air and in the water phantom. Additionally, the ion chamber with a collecting electrode with a diameter reduced by 5% was modeled and used to study the influence of the reduced electrode size. The conversion parameter C_{MC} calculated with the assumed chamber geometry was also compared to the values specified in Sect. 2.2.

3 Results and discussion

3.1 Medium-energy X-ray tube modeling

The energy spectra of the CCRI-recommended X-ray beams were obtained by iteratively adjusting until a difference of the HVL value differences between the simulation and measurements were less than 2%. The statistical uncertainty of the calculated total fluence was less than 0.1% for each beam. From the obtained spectral distributions, the attenuated air kerma for aluminum or copper with different thicknesses was calculated using the mass energy absorption coefficients. The calculated trends of the attenuation were then analyzed to estimate the HVL values by interpolation.

Table 1 Beam qualities of the reference kV X-ray beams from measurements and simulations

Tube potential (kV)	Half-value layer (mm Al/mm Cu)*		
	Measurements	Simulations	Difference (%)
100	4.025	4.030	0.12
135	0.497	0.501	0.80
180	1.004	1.021	1.69
250	2.535	2.533	−0.08

*The HVL of the 100 kV X-ray beam is presented in mm Al
The values of the other beams are presented in mm Cu

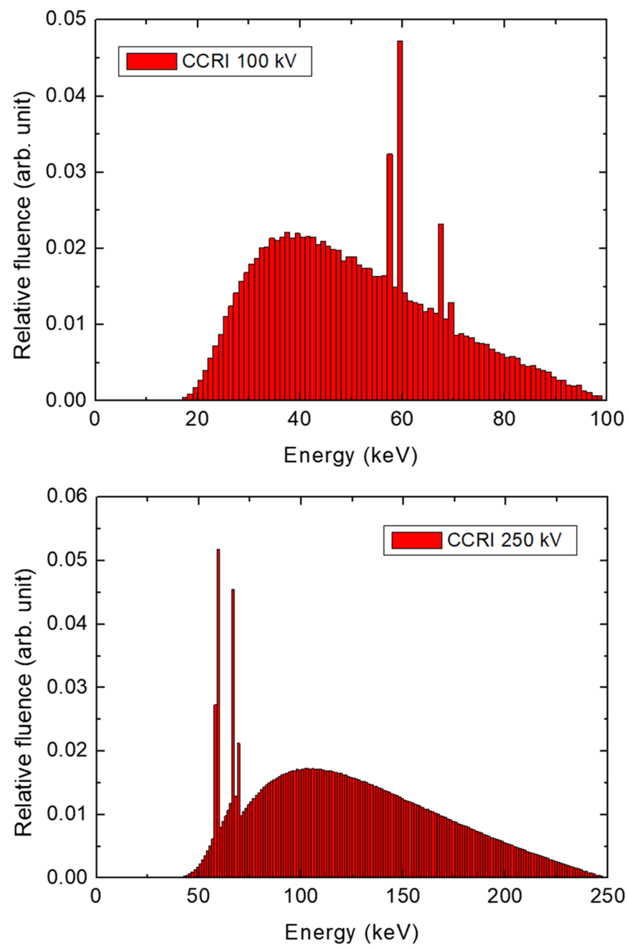

Fig. 3 Energy spectra of incident X-rays at tube potentials of 100 kV (top) and 250 kV (bottom)

As a result, the final HVLs showed a maximum difference of 1.69% from the measurements for the 180 kV beam, while the differences for the other beams were less than 1%. The detailed results of the HVL estimation are presented in Table 1. Figure 3 shows the energy spectra of the X-ray beams at tube potentials of 100 kV and 250 kV.

Based on the well-reproduced HVL estimations in the simulations, the obtained energy spectra of the X-ray beams were found to be suitable to evaluate the dose conversion parameters for the KRISS reference X-ray beams.

3.2 Evaluation of the dose conversion parameter C_{MC}

Based on EGSnrc MC simulations, the values of C_{MC} were obtained for the KRISS reference X-ray beams. The statistical uncertainties of the calculations for K_{air} and D_w were less than 0.02% and less than 0.06%, respectively. In addition, the statistical uncertainties of the absorbed dose to cavity were less than 0.06% for $D_{cav,air}$ and less than 0.08% for $D_{cav,w}$. Consequently, the calculated C_{MC} showed statistical uncertainties of less than 0.12%.

The calculated results were compared to the conversion parameters and C_{MC}-equivalent values from other studies based on the following relationship:

$$k_{rn}\left(\frac{D_w/D_{cav,w}}{K_{air}/D_{cav,air}}\right)_{MC} = \frac{N_{D_w}}{N_{K_a}} = P_{Q,cham}P_{sheath}\left[\left(\frac{\overline{\mu}_{en}}{\rho}\right)^w_{air}\right]_{water} \quad (4)$$

where N_{D_w} and N_{K_a} are calibration coefficients of the ion chamber for the absorbed dose to water and air kerma, respectively. $P_{Q,cham}$ is an overall correction factor for the ion chamber, P_{sheath} is a correction factor for the waterproofing sleeve, and $\left[\left(\frac{\overline{\mu}_{en}}{\rho}\right)^w_{air}\right]_{water}$ is the water-to-air ratio of the mean mass energy-absorption coefficients at the reference point in water [4]. When comparing $C_{MC} = \left(\frac{D_w/D_{cav,w}}{K_{air}/D_{cav,air}}\right)_{MC}$ with the equivalent values, a radial non-uniformity correction factor of k_{rn} was assumed to be 1.

The compared conversion parameters C_{MC} and C_{MC}-equivalent values from the other studies were obtained based on the approaches as follows: (1) calculations of C_{MC} using PENELOPE code [20] presented by BIPM [21], (2) approaches based on the correction factors for the ion chamber and for sleeve effect, and mass energy absorption coefficients published in the AAPM TG-61 report [4], and (3) measurement of calibration coefficients of the PTW 30013 ion chamber conducted by supplementary comparison (SC) of the primary standards based on the calorimetry for absorbed dose to water in the medium-energy X-ray range (EURAMET.RI(I)-S13) [22]. Table 2 and Fig. 4 present the simulation results and a comparison to the results of other studies.

The calculated C_{MC} values of the present study showed a maximum difference of less than 1% for the 250 kV X-ray beam compared to the equivalent parameters published in the other studies. The conversion parameter obtained in the present study at 250 kV showed the lowest value in the comparison, but the calculated values for the other three beams were positioned among the results of the other studies. Although the details of the evaluation methods differed, because an agreement within 1% was obtained, we conclude that the simulation results obtained in the present study are suitable for application to the dose conversion factor $C_{w,a}$.

Although a good agreement of C_{MC} compared to the corresponding values in the other studies was found, uncertainty analysis should be performed with thorough studies on the sensitivity of the obtained dose conversion parameters. The uncertainty evaluation is not finalized in the present study. Partial sensitivity studies for the dose conversion were performed as described in Sect. 3.3.

Table 2 Conversion parameter C_{MC} and the C_{MC}-equivalent values for the reference X-ray beams

Tube potential (kV)	Present study	BIPM	AAPM TG-61[1]	EURAMET. RI(I)-S13[2]
100	1.0355	1.0405	1.043	1.0282
135	1.0699	1.0717	1.071	1.0680
180	1.0811	1.0887	1.087	1.0745
250	1.0961	1.1064	1.102	1.1041

[1]From the AAPM TG-61, the correction factors for the PTW 30010 model were applied considering that the 30,010 and 30,013 models have the same geometric specifications

[2]Weighted mean values from the supplementary comparison project for absorbed dose to water in kV X-rays conducted by the European Association of National Metrology Institutes

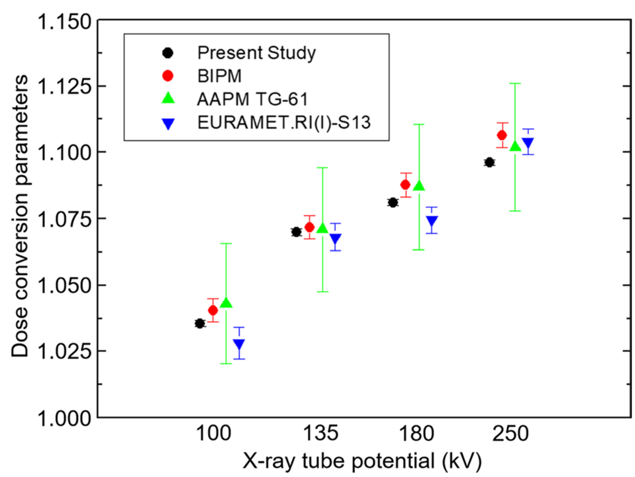

Fig. 4 Comparison of dose conversion parameter in the present study to the equivalent values from the other studies, based on Eq. (4). The uncertainty bars in figure represent the stated standard uncertainties (black-filled circles: present study, red-filled circles: D. Burns et. al. [21], green-filled triangles: AAPM TG-61 report [4], and blue-filled inverted triangles: EURAMET.RI(I)-S13 [22]). Uncertainty bars of the results from the present study mean the calculated statistical uncertainties

3.3 Sensitivity studies on the dose conversion parameters based on MC simulations

The sensitivity of the dose conversion parameters was studied by assuming different MC parameters. The assumed parameters were different energy spectra of the incident X-rays and different geometric specifications of the chamber. Calculations of C_{MC} using the two assumed conditions in MC simulations showed a maximum statistical uncertainty of the calculations less than 0.16%.

For the different energy spectra of the incident X-rays, the MC conversion parameters at the four reference X-ray beam qualities were calculated by defining the energy distribution of the X-ray with the HVL differed as ± 5%. The MC conversion parameters calculated with the different energy spectra differed by 0.53% compared to those at KRISS reference beam qualities. The trend of the conversion parameters C_{MC} at various energy spectra indicated an increase as the assumed HVL thickness increased. When a deviation of 5% in the HVL thickness was assumed, which is much larger than the precision in the measurement of HVL, the resulting uncertainty due to the energy spectra of the incident X-rays is expected to be much smaller than 0.53%. The details are shown in Fig. 5.

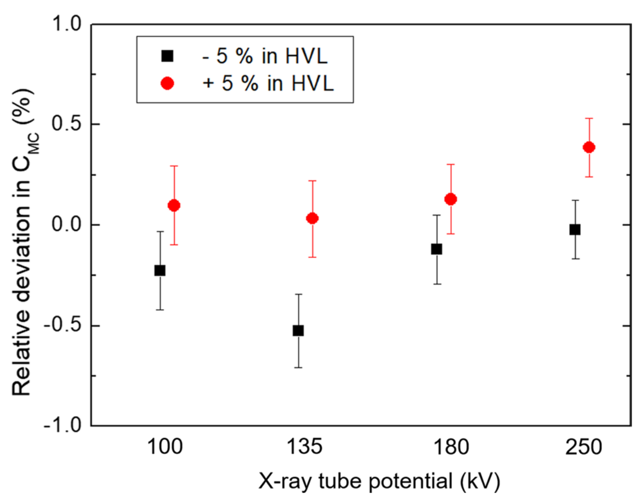

Fig. 5 Influence of incident X-ray energy spectra on the dose conversion parameters. Black-filled boxes: assumed as –5% deviation in the HVL; red-filled circles: assumed as + 5% deviation in the HVL. Uncertainty bars represent the statistical uncertainties from calculations

The influence of the geometric specifications of the ion chamber was analyzed. The calculations with the assumed diameter of the collecting electrode of the ion chamber showed a difference of over 1% in the absorbed dose to the cavity. However, the change in the conversion parameters C_{MC} was less than 0.33%. For the assumed wall thicknesses of the ion chamber, the calculated absorbed dose to the cavity also showed a difference of over 1%. However, the maximum change in the conversion parameters C_{MC} was 0.23%, similar to the case with the assumed electrode diameter. The results are summarized in Table 3.

When the manufacturing tolerance in the dimensions of the ion chamber is less than 5%, the influence of the chamber geometry on C_{MC} values was expected to be less than 0.56%, which is the maximum change incorporating the two assumed geometric conditions.

In addition to the sensitivity evaluation performed in the present study, it is needed to consider the other terms contributing to the uncertainty of the dose conversion parameter such as chamber positioning, the cross-section data, electron transportation parameters and the algorithm used for radiation transportation in the simulation. Uncertainty arising from the water-to-air ratio of the mass-energy absorption coefficients at the reference depth in water, corresponding to the ratio of absorbed dose to water and air, could be estimated to be 0.3% based on the previous publications [21–23]. However, for the electron transportation parameters in EGSnrc and trends of the depth-dose curve in the water phantom, additional studies might be necessary. These additional studies for uncertainty evaluation will be performed as future work.

4 Conclusion

This section summarizes the preliminary study on dose conversion factors from the air kerma to the absorbed dose to water for the reference kV X-ray beams of the KRISS. Detailed MC studies involving beam optimization and modeling of the ion chamber were performed to evaluate the

Table 3 Changes in C_{MC} due to the assumed chamber geometry

Tube potential (kV)	C_{MC} with the assumed electrode diameter		C_{MC} with the assumed wall thickness	
	Results	Difference (%)	Results	Difference (%)
100	1.0331	−0.24	1.0352	−0.04
135	1.0664	−0.33	1.0674	−0.23
180	1.0824	+0.12	1.0791	−0.19
250	1.0982	+0.19	1.0944	−0.15

dose conversion parameters, which can be adopted to establish measurement standards for the absorbed dose to water in kV X-rays.

In the simulations, the X-ray tube model was optimized to reproduce the energy spectra of the reference X-ray beams at KRISS to verify that the HVL values are consistent with the measurements. The reproduced energy spectra showed HVL differences of less than 2% compared to measurements and were used to evaluate the dose conversion parameters C_{MC} and its sensitivity.

Using the four optimized reference X-ray beams, the conversion parameters were calculated by applying the XCOM library with a renormalized cross section for air and water and ESTAR data, adopting recommendations from the ICRU report 90. The calculated conversion parameters agreed well within 1% with those of other studies, indicating their suitability for determining the dose conversion factor $C_{w,a}$. If the determined dose conversion parameters are adopted, the absorbed dose to water based on the air kerma standards at the KRISS is expected to be consistent with that of other NMIs within the uncertainties of approximately 2%.

To evaluate the sensitivity of the dose conversion parameters obtained from MC simulations, various case studies were conducted using different energy spectra of the X-rays and assumed chamber dimensions for the collecting electrode and the wall thickness. The maximum difference observed among different energy spectra was found to be 0.53%. Furthermore, the maximum discrepancy resulting from the assumed chamber geometry was found to be 0.56%. For most cases, discrepancies were less than 0.3% in terms of the influences of the energy spectra and chamber geometry. These observed discrepancies will be taken into account for the uncertainty evaluation. As only two components in simulations affecting the dose conversion parameters were considered, additional terms contributing to the uncertainty such as the electron transport parameters in EGSnrc code and trends of the depth-dose curve in water should be conducted to evaluate the uncertainty in future work.

In addition to obtaining dose conversion parameters for the commercial ion chamber in the present study, we also plan to determine these parameters for a new ion chamber to be developed. This new ion chamber is expected to provide greater accuracy compared to existing commercial ones. Therefore, by using the new ion chamber and adopting the evaluation technique developed in the present study, a more accurate and precise evaluation of the dose conversion factor will be achieved, resulting in precise measurement standards for the absorbed dose to water in kV X-ray beams.

Acknowledgements This work was supported by the Korea Research Institute of Standards and Science, Rep. of Korea under the project "Development of measurement standards and techniques for medical ionizing radiation," [23011069].

References

1. D.T. Burns, C. Kessler, B. Rapp, Metrologia **57**, 06008 (2020)
2. D.T. Burns et al., Metrologia **55**, 06006 (2018)
3. IAEA, *Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to water*, Technical Report TRS-398 (IAEA, Vienna, 2000)
4. C.-M. Ma et. al., Med. Phys. **28**(6), 868–893 (2001)
5. S.M. Seltzer et al., J. ICRU **14**, 1–110 (2014)
6. I.J. Kim et al., Nucl. Eng. Technol. **49**, 810–816 (2017)
7. KRISS, *Development of measurement standards for ionizing radiation,* report IR-2017-051 (KRISS, 2017)
8. S.R. Domen, J. Res. Natl. Inst. Stand. Technol. **99**, 121–141 (1994)
9. ARPANSA, *The Australian primary standard for absorbed dose to water*, Technical Report Series No. 166 (2016)
10. D.T. Burns et al., Metrologia **59**, 06009 (2022)
11. D.T. Burns et al., Metrologia **59**, 06011 (2022)
12. I. Kawrakow et. al., *The EGSnrc Code System: Monte Carlo Simulation of Electron and Photon Transport*, Technical Report PIRS-701, (2015)
13. M.J. Berger et al., J. ICRU **19**, 2 (1984)
14. M.J. Berger et. al., *XCOM: Photon Cross Sections Database*, NBSIR87-3597 (1987, last update at Nov. 2010)
15. J.H. Hubbell, S.M. Seltzer, *Table of X-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest*, NISTIR 5632 (NIST, 1995)
16. M.J. Berger, *ESTAR PSTAR ASTAR, Stopping Power and Range of electrons, Protons, Alpha* (NEA, 1995)
17. G. Poludniowski, M. Evans, Med. Phys. **34**(6), 2164–2174 (2007)
18. G. Poludniowski, Med. Phys. **34**(6), 2175–2186 (2007)
19. G. Poludniowski et al., Phys. Med. Biol. **54**(19), 433–438 (2009)
20. F. Salvat et al., *PENELOPE-2008: A Code System for Monte Carlo Simulation of Electron and Photon Transport* (Nuclear Energy Agency, 2009)
21. D.T. Burns, C. Kessler, P. Roger, *New BIPM absorbed-dose standard for medium-energy x-rays*, report for Consultative Committee for Ionizing Radiation CCRI(I)/17-06 Bureau International Poids et Mesures (BIPM, 2017)
22. L. Büermann et al., Metrologia **53**, 06007 (2016)
23. P. Andreo, D.B. Burns, F. Salvat, Phys. Med. Biol. **57**, 2117 (2012)