CALIBRATION OF IONIZATION CHAMBER IN MEGAVOLTAGE X-RAY FIELD OF MEDICAL LINEAR ACCELERATOR

by

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Ionization chambers were calibrated regarding absorbed dose to water in MeV X-ray fields of a medical linear accelerator, with nominal maximum energies of 6 MeV and 15 MeV. Whereas, absorbed doses to water at a depth of 10 cm below the water surface were measured using the same ionization chamber (referred to as IC-1) in two different manners (*i. e.*, applying the old beam quality correction factor k_{Q_0} from the old IAEA/TRS-398 protocol, referred to as $D_{10}^{1-\text{old}}$ and using the new one, k_Q from the updated protocol, referred to as $D_{10}^{1-\text{new}}$. The calibration factors of IC-1, $N_{D,w,Q}^{1}$ were deduced (for beam qualities Q of MeV X-ray fields with maximum energies of 6 MeV and 15 MeV). The identical procedure was applied to two other ionization chambers (IC-i, i = 2, 3) to obtain absorbed doses to water at a depth of 10 cm (referred to as $D_{10}^{i-\text{new}}$) using the new beam quality correction factor. A comparison between $D_{10}^{1-\text{new}}$ and $D_{10}^{i-\text{new}}$ was conducted to derive the calibration factors of the IC-i, $N_{D,w,Q}^{i}$. The combined standard uncertainties of $N_{D,w,Q}^{i}$ (i =1, 2, 3) were estimated within 1.22 % and 2.30 %, respectively.

Key words: absorbed dose, beam quality, nominal maximum energy

INTRODUCTION

Ionizing radiation reference fields are normally established to ensure the proper operation of ionizing radiation measuring devices (*e. g.*, ionization chambers, IC). For calibrations of IC in terms of absorbed dose to water (D_w), the ^{60}Co beam quality has been frequently used as the reference field. The IAEA released a practical protocol (known as the IAEA/TRS-398 protocol) [1] guiding to determine the value of D_w caused by teletherapy units (*i. e.*, ^{60}Co and/or Megavoltage (MeV) X-ray medical linear accelerator – LINAC). The IAEA/TRS-398 protocol can also be applied for calibrations of IC in different beam qualities (*i. e.*, symbolized as Q_0 for ^{60}Co and Q for other qualities of LINAC).

When an IC is calibrated in a ^{60}Co reference field (in terms of D_w, with a calibration factor denoted as N_{D,w,Q_0}), to be used in the measurement of D_w caused by an MeV X-ray LINAC (with a beam quality of Q), a correction factor (k_{Q,Q_0}) [1] must be applied to convert the output reading recorded by the IC in the MeV X-ray LINAC field to that in the ^{60}Co field (the reference field).

However, ^{60}Co radiotherapy units will be scarce in the future due to the inconvenience of source replacement, while LINAC will become more popular instead. Therefore, calibrating IC in ^{60}Co fields will no longer be convenient. Consequently, calibrating IC in MeV X-ray fields will soon become a crucial trend.

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The IAEA also released several publications guiding the calibration procedures for IC in radiotherapy external beams [1, 2]. It was also noticed that the values of k_{Q,Q_0} will soon be replaced by k_Q (in MeV X-ray fields) [3] in the updated IAEA/TRS-398 protocol. Those protocols may guide the calibration facilities to supply their customers with values of N_{D,w,Q_0}, and/or $N_{D,w,Q}$ (based on their available radiotherapy reference fields).

The National Physical Laboratory (NPL), a primary standard dosimetry laboratory (PSDL) in the UK, was the first laboratory to supply calibration services for IC in MeV X-ray fields [4]. This means the laboratory has been able to provide its customers with the values of $N_{D,w,Q}$.

The values of k_Q were investigated through numerical simulated and experimental data and are available [5] for various IC technical characteristics and the values of beam quality index (*i. e.*, tissue-phantom ratio, $TPR_{20/10}$, to be understood as the ratio of the absorbed doses at depths of 20 cm and 10 cm below the water surface, measured with a constant source-to- chamber distance (SCD) of 100 cm and a field size (FS) of 10 cm × 10 cm at the plane of the IC in water [1]).

The determination of D_w values (caused by different gamma and X-ray beam qualities) using IC was implemented for three different beam qualities following various practical protocols [6] including the IAEA/TRS-277 in 1987 [7]; Hospital Physicists' Association – HPA, in 1983 [8]; Nordic Association of Clinical Physics – NACP, in 1980 [9]; American Association of Physicists in Medicine – AAPM, in 1983 [10]; National Council on Radiation Protection and Measurement – NCRP, in 1981 [11]; and International Commission on Radiation Units and Measurement - ICRU, in 1973 [12]. The differences between the values of D_w determined by different protocols were noted as not significant when compared to those from the IAEA/TRS-398 protocol [1], which was considered as the reference in the comparison.

In this work, the MeV X-ray reference fields with nominal maximum energies of 6 MeV and 15 MeV (generated from the Varian TrueBeam STx LINAC) were used for calibrating three different IC in terms of D_w following the updated IAEA/TRS-398 protocol [13] for different investigated geometries. In particular, the following tasks were performed:

– the absorbed doses to water at a depth of 10 cm below the water surface, D_{10} (for different investigated geometries), were measured using the same ionization chamber, IC-1. This chamber was calibrated in a ^{60}Co radiotherapy reference field, with the calibration factor of N^1_{D,w,Q_0}. The measurements were conducted in two different manners: (i-a) by applying the old beam quality correction factor (BQCF) k_{Q,Q_0} (referred to as k_{Q_0} in this work), following the old IAEA/TRS-398 protocol, referred to as $D_{10}^{1-\text{old}}$, and (i-b) by applying the new BQCF (k_Q, as provided in the updated IAEA/TRS-398 protocol), referred to as $D_{10}^{1-\text{new}}$. The calibration factor of the IC-1, $N^1_{D,w,Q}$ (in terms of absorbed dose to water, D_w, in the MeV X-ray fields of the LINAC with a beam quality of Q) was deduced by comparing $D_{10}^{1-\text{old}}$ and $D_{10}^{1-\text{new}}$, and
– the values of D_{10} (for different investigated geometries) were also measured using two other IC (IC-i, $i = 2, 3$), applying the new BQCF of k_Q, referred to as $D_{10}^{1-\text{new}}$. A comparison between pair values of $D_{10}^{1-\text{new}}$ and $D_{10}^{i-\text{new}}$ was conducted to derive the calibration factor of IC-*i*, $N^i_{D,w,Q}$ (in terms of D_w, in the MeV X-ray fields of LINAC with the beam quality of Q). The combined standard uncertainties of $N^1_{D,w,Q}$, and $N^i_{D,w,Q}$ were estimated and presented in this work.

MATERIAL AND METHOD

Varian TrueBeam STx medical linear accelerator

The TrueBeam STx is one of the most advanced LINAC from Varian, and it is used for radiotherapy and radiosurgery. It features a 120 multileaf collimator including 32 leaf pairs each 2.5 mm thick lead at the central beamline and 28 leaf pairs each 5 mm wide lead surrounding it. This design ensures exceptional precision in target conformation and minimizes the X-ray penumbra effect. The LINAC can be used for external radiotherapy with two operational modes of X-ray beams (*i. e.*, with or without the flattening filter, FF). In this work, the LINAC was used to generate X-ray beams with nominal maximum energies of 6 MeV and 15 MeV, operated in the FF mode.

Measuring assembly and water phantom

In general, a measuring assembly consists of an IC and an electrometer. In this study, measurements were conducted using three distinct measuring assemblies. The first two were combinations of IC (FC65-G and CC13) and the DOSE1 electrometer, which were manufactured by the IBA Dosimetry company. The third was a combination of the PTW Semiflex IC (model: TM31010-004086) and the PTW Unidos (model: T10001-11831) electrometer, manufactured by PTW-Freiburg.

The IC-1 (FC65-G), IC-2 (CC13), and IC-3 (PTW-31010) are all cylindrical ionization chambers with respective active volumes of 0.65 cm^3, 0.13 cm^3, and 0.125 cm^3. The FC65-G and CC13 have inner diameters of the outer electrodes of 6.2 mm and 6.0 mm, respectively. Their inner electrode diameters are 1.0 mm. The lengths of their inner electrodes are 20.5 mm and 3.3 mm, respectively.

The PTW-31010's outer electrode has an inner diameter of 5.5 mm and the aluminum central electrode has a diameter of 1.1 mm. Its sensitive volume is 6.5 mm long.

All measuring assemblies were initially calibrated by a recognized international standard dosimetry laboratory such as PSDL or IAEA-SSDL and recalibrated annually by the Viet Nam secondary standard dosimetry laboratory (VN-SSDL), as required by a Vietnam authority organization. In this study, these three measuring assemblies were used to determine the values of D_{10}^i. Their calibration factors(N_{D,w,Q_0}^i) in the ^{60}Co reference field were available.

In this work, a water phantom (known as the Blue Phantom 2) with dimensions of 48 cm × 48 cm × 48 cm was used, accompanied by a convenient three-dimensional scanning system, to facilitate the IC positioning.

Investigated geometry, measured and derived quantity

In this work, measurements (corresponding to investigated geometries) were conducted using three assemblies to obtain the measured and derived quantities. More details can be seen in tab. 1.

In all measurements, the delivered Monitor Unit (MU) values were consistently set to 600 MU (at a rate of 100 MU per minute), achieving statistical uncertainties of less than 0.5 % for the recorded readings of the IC.

Measurement of absorbed dose to water using ionization chamber

In general, to measure a value of D_{10}^i (i = 1, 2, 3) per MU using an IC, one typically applies the practical protocol guided by the IAEA (*i. e.*, IAEA/TRS-398 [1]). The following steps were carried out:

– measuring and correcting the data from IC-*i* (to obtain the corrected value of M_c^i) by following these steps: (i-a) Converting the measured data from IC-*i*, M_u^i (at nonstandard measuring conditions), to the standard conditions of temperature and pressure by multiplying with a factor of $k_{T,P}$; (i-b) Correcting that value for other influencing factors such as the calibration factor of the electrometer, $k_{\rm elec}$; ionization chamber polarity, k_{pol}^i, and the recombination effect inside the IC, k_s^i). The corrected value of M_c^i can be calculated using eq. (1), with all correction factors derived following the guidance from [1].

$$M_c^i = M_u^i k_{T,P} k_{elec} k_{pol}^i k_s^i \tag{1}$$

– calculating the values of D_{10}^i involves correcting the value of M_c^i for beam quality. This process converts the M_c^i value, measured by IC-i in the Q beam quality field with the calibration factor of $N_{D,w,Q}$ in terms of D_w, to the reference field of Q_0 beam quality. To obtain the reference values of D_{10}^i in a reference field of Q_0 beam quality, the M_c^i value must be multiplied by a correction factor of k_{Q,Q_0}, and the calibration factor of IC-i, $N_{D,w,Q}$ in terms of D_w.
– finally, the measured data in non-reference conditions, M_u^i was converted to the value of D_{10}^i in the radiation field with the beam quality of Q under standard conditions, such as temperature, pressure, radiation reference field, *etc*. The value of D_{10}^i can be calculated using eq. (2), with the unit converted into cGy per total delivered MU to the IC.

$$D_{10}^i = (M_u^i k_{T,P} k_{elec} k_{pol}^i k_s^i)\cdot \\ \cdot(N_{D,w,Q}^i \cdot k_{Q,Q_0}^i) \tag{2}$$

Calculation of ionization chamber calibration factor in MeV X-ray reference field

Applying eq. (2) for measurements by the same IC-1 (FC65-G) in the field of Q beam quality (with the assumption that the IC-1 was calibrated in the field of Q_0 beam quality with a calibration factor of N_{D,w,Q_o}^1 accompanying with the beam correction factor of k_{Q,Q_0}^1 – *i. e.*, $k_{Q_0}^1$ in this work). That means the first bracket factor in eq. (2) is the same for measurements using the same IC in the same field of Q beam quality. For consistency with the notation in the newly updated IAEA/TRS-398 protocol [13], $N_{D,w,Q}$ and k_Q^1 were assumed to be the calibration factor and beam quality

Table 1. Investigated geometry, measured and derived quantity

Investigated geometry		Available/measured quantity				Derived quantity		
E [MeV]	Distance [100 cm]	M_C [nC/MU]	N_{D,w,Q_o} [cGy/nC]	k_{Q_0}	k_Q	N_{D,w,Q_o} [cGy/nC]		
						FC65-G	CC13	PTW 31010
6	SCD	x	x	x	x	$N_{D,w,Q}^1$ Eq. (4)	$N_{D,w,Q}^2$ Eq. (5)	$N_{D,w,Q}^3$ Eq. (5)
	SSD	x	x	x	x			
15	SCD	x	x	x	x			
	SSD	x	x	x	x			

correction factor of IC-1 in the field of Q beam quality, respectively, achieving the relationship described in eq. (3). From eq. (3), the value of $N^1_{D,w,Q}$ can be deduced as in eq. (4). Where the beam quality values of $k^1_{Q_0}$ and k^1_Q (for the IC-1) can be interpolated from tab. 6-III of [1] and tab. 16 of [13] based on the measured value of $TPR_{20/10}$.

$$N^1_{D,w,Q_o} k^1_{Q_o} = N^1_{D,w,Q} k^1_Q \quad (3)$$

$$N^1_{D,w,Q} = \frac{N^1_{D,w,Q_o} k^1_{Q_o}}{k^1_Q} \quad (4)$$

Consequently, applying eq. (2) for measurements by the IC-1 and by the IC-i ($i = 2, 3$) in the same MeV X-ray beam quality of LINAC (that means: all parameters in eq. (2) were known for the IC-1). Then, the unique unknown parameter of $N^i_{D,w,Q}$ for the IC-i could be derived as follows

$$N^i_{D,w,Q} = = \frac{(M^1_u k_{T,P} k_{elec} k^1_{pol} k^1_s) \cdot (N^1_{D,w,Q} k^1_Q)}{(M^i_u k_{T,P} k_{elec} k^i_{pol} k^i_s) \cdot k^i_Q} \quad (5)$$

RESULT AND DISCUSSION

Calibration factor of ionization chamber in MeV X-ray reference field

Table 2 shows the existing calibration factors (N^i_{D,w,Q_0} in ^{60}Co field, available from calibration certificates, performed by internationally recognized standard dosimetry laboratory) and measured values of beam quality index (*i. e.*, $TPR_{20/10}$, k_{Q_0}, and k_Q) for different IC and different MeV X-ray energies. The values of beam quality (k_{Q_0}, k_Q) decrease as the MeV X-ray LINAC energies increase.

Table 3 presents the values of $N^i_{D,w,Q}$ (the calibration factors for three different IC in various MeV X-ray beam qualities, calculated using two different methods as described in eq. (4) and eq. (5)) and for two different investigated geometries.

Table 2. Calibration factors of different ionization chambers in terms of absorbed dose to water in ^{60}Co field and measured values of beam quality index for different ionization chambers

E [MeV]	Quantity	Ionization chamber		
		FC65-G	CC13	PTW31010
	$N_{D,w,Qo}$ [cGy/nC]	4.83	26.4	30.1
6	$TPR_{20/10}$	0.6680		
	k_{Q_0}	0.9942	0.9948	0.0917
	k_Q	0.9930	0.9925	0.9920
15	$TPR_{20/10}$	0.7630		
	k_{Q_0}	0.9800	0.9788	0.9740
	k_Q	0.9730	0.9718	0.9720

E: the nominal maximum energy of MeV X-ray LINAC

From tab. 3, it can be observed that the values of $N^i_{D,w,Q}$ for the same IC show negligible differences, even across two different beam qualities of the MeV X-ray LINAC, with the largest difference being approximately 0.7 %. This reveals that the energy responses of IC are identical in a wide range of spectrum-averaged energies of MeV X-ray LINAC.

Combined standard uncertainty of ionization chamber calibration factor

Table 4 shows the uncertainty budgets and the combined standard uncertainties of $N^i_{D,w,Q}$ values calculated using two different methods, *i. e.*, following eqs. (4) and (5). The uncertainty budget values were taken as the largest values ever encountered. The maximum combined standard uncertainty of $N^i_{D,w,Q}$ was estimated to be as less than 2.30 %, which is considered acceptable.

CONCLUSION

The MeV X-ray reference fields of a Varian TrueBeam STx medical linear accelerator (with the maximum X-ray energies of 6 MeV and 15 MeV) were used to calibrate different radiotherapy ionization chambers in different MeV X-ray beam qualities following the IAEA updated practical protocol known as the updated IAEA/TRS-398 [13]. The different ionization chamber calibration factors in terms of ab-

Table 3. Calibration factors of different ionization chambers in terms of absorbed dose to water for various MeV X-ray beam qualities, calculated based on two distinct models, *i. e.*, eqs. (4) and (5)

Investigated geometry			Calculated calibration factor in MeV X-ray [cGy/nC]		
E [MeV]	SSD [cm]	SCD [cm]	FC65-G ($N^1_{D,w,Q}$)	CC13 ($N^2_{D,w,Q}$)	PTW 31010 ($N^3_{D,w,Q}$)
			Eq. (4)	Eq. (5)	Eq. (5)
6	100		4.83	26.4	30.2
		100	4.83	26.4	30.1
15	100		4.86	26.6	30.3
		100	4.86	26.6	30.3

E: the nominal maximum energy of MeV X-ray LINAC

Table 4. The combined standard uncertainty of ionization chamber calibration factor in MeV X-ray reference fields with different beam qualities, calculated based on two different models, *i. e*., eqs. (4) and (5)

Quantity	$N^1_{D,w,Q}$	$N^i_{D,w,Q}$
Model	eq. (5)	eq. (6)
Influenced quantity	Uncertainty budget is taken into account [%]*	
N_{D,w,Q_o}	1.00	
k_{Q_0}	0.50	
k_Q	0.50	
M_u		0.50
$k_{T,P}$		0.10
k_{elec}		0.20
k_{pol}		0.70
k_s		1.00
$N^1_{D,w,Q}$		1.66
Combined standard uncertainty	1.22	2.30

*the value was estimated based on the maximum standard uncertainty ever encountered

sorbed dose to water, $N_{D,w,Q}$ (for different MeV X-ray beam qualities) were obtained with negligible differences between calculation models and varying distance geometries. The combined standard uncertainty of $N_{D,w,Q}$ was also estimated as low as less than 2.30 % (with the uncertainty budgets being taken as the ever-encountered maximum ones).

AUTHOR'S CONTRIBUTIONS

N-T. Le designed, supervised, performed measurements, analyzed the data, and wrote the manuscript; H-L. Pham, T-P-H. Hoang, J. Sunjun, D-L. Bui, T-A. Le, H-Q. Nguyen, D-K. Pham, V-C. Phan, and Q-T. Pham performed measurements and collected and analyzed the data. T-K. Nguyen, V-L. Bui, T-D. Phan, and H-N. Tran, analyzed the data, and reviewed and edited the manuscript.

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КАЛИБРАЦИЈА ЈОНИЗАЦИОНЕ КОМОРЕ У МЕГАНАПОНСКОМ РЕНДГЕНСКОМ ПОЉУ МЕДИЦИНСКОГ ЛИНЕАРНОГ АКЦЕЛЕРАТОРА

Јонизационе коморе калибрисане су у погледу апсорбоване дозе у води у меганапонским рендгенским пољима медицинског линеарног акцелератора са номиналним максималним енергијама од 6 MeV и 15 MeV. Док су апсорбоване дозе у води на дубини од 10 cm испод површине воде мерене коришћењем исте јонизационе коморе IC-1 на два различита начина: применом старог фактора корекције квалитета снопа k_{Q_0} из старог IAEA/TRS-398 протокола, који је означен са D_{10}^{1-old}, и коришћењем новог фактора k_Q из ажурираног протокола, који је означен са D_{10}^{1-new}. Одређени су калибрациони фактори IC-1, $N_{D,w,Q}^{1}$ за квалитет снопа Q меганапонских рендгенских поља са максималним енергијама од 6 MeV и 15 MeV. Идентицан поступак примењен је на две друге јонизационе коморе (IC-i, $i = 2, 3$) да би се добиле апсорбоване дозе у води на дубини од 10 cm означене са D_{10}^{i-new}, коришћењем новог фактора корекције квалитета снопа. Поређење између D_{10}^{1-new} и D_{10}^{i-new} спроведено је да би се извели фактори калибрације IC-i, $N_{D,w,Q}^{i}$. Комбиноване стандардне несигурности $N_{D,w,Q}^{i}$ (i = 1 и 2, 3) процењене су на 1.22 % и 2.30 %, респективно.

Кључне речи: айсорбована доза, квалишеш снойа, номинална максимална енерīија