原著

Effect of Electron Beam Energies on the Calibration Factor in Cross-Calibration With and Without an External Monitor Chamber

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Abstract : The purpose of this study was to investigate the effect and address the suitable electron energy in cross-calibration with or without an external monitor chamber. First, using the two linear accelerators, the calibration factor ($N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$) and absorbed dose to water calibration factor ($N_{\mathrm{D,w}}$) values are compared with or without an external monitor chamber using cross-calibration in standard dosimetry 12. Next, the $N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$ uses five different energies (12, 15, 16, 18, and 20 MeV) for its cross-calibration. Then, 6 MeV electron absorbed dose at depth of the dose maximum (D ($d_{\max}$)) is calculated. We compared to D ($d_{\max}$) for the calibration factor ($N_{\mathrm{D,w}}$ (Co)) given by ^{60}Co gamma radiation. The $N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$ is almost equal in both using and not using an external monitor chamber, the difference value of $N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$ was only 0.01%. Between both D ($d_{\max}$) using calibration factors $N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$ and $N_{\mathrm{D,w}}$ (Co) is a significant difference ($P < 0.001$). Moreover, there is also a significant difference between D ($d_{\max}$) using calibration factor obtained from 20 MeV and each 12 MeV, 15 MeV ($P < 0.05$). These results demonstrate that there is no significant change with or without the external monitor chamber. Furthermore, the electron energy most suitable for obtaining calibration factors $N^{\mathrm{field}}_{\mathrm{D,w,Q_{cross}}}$ in cross-calibration is found to be 20 MeV, and the absorbed dose is almost the same value at 12, 15, 16, and 18 MeV

Keyword : cross-calibration, electron beam dosimetry, electron beam energy, external monitor chamber

1. Introduction

In September 2012, the Japan Society of Medical Physics (JSMP) Task Group published a standard dosimetry of the absorbed dose in external beam radiotherapy (Standard Dosimetry 12) as a new high-energy photon and electron dosimetry protocol [1]. In this protocol, the electron beam quality was specified by the depth of the 50% adsorbed dose in water, R_{50}. This was in accordance with international measurement methods such as the IAEA's Technical Report Series (TRS)-398 and AAPM's TG-51 [2-3]. Further, in Standard Dosimetry 12, the absorbed dose to water calibration factor ($N_{\mathrm{D,w}}$) was calibrated for ^{60}Co gamma radiation, measured with the water absorbed dose at calibration depth using an ion chamber. Thus, the water absorbed dose at the depth of the dose maximum (D ($d_{\max}$)) is obtained. In the electron field, the cross-calibration of a plane-parallel chamber is used in electron beams with a reference cylindrical chamber calibrated for ^{60}Co gamma radiation. Moreover, additional steps such as cross-calibration help to determine the absorbed dose to water using the plane-parallel chamber in a manner that is more reliable than that when directly calibrating for ^{60}Co. This is primarily because while determining the beam quality correction factor ($k_{\mathrm{Q,Q_0}}$)), problems associated with the wall correction factor (P_{wall}) collection for the plane-parallel chamber in ^{60}Co are avoided. Therefore, Standard Dosimetry 12 is the recommended cross-calibration to be used in individual facilities [1]. Similarly, TRS-398 has also been recommended for cross-calibration in the electron field [2].

In cross-calibration of the electron beam, the highest energy available for low electron energies increases the effect of the cavity correction factor (P_{cav}) for

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cylindrical chambers [4-8]. Cross-calibration can be used for the highest-energy electron beam (Q_{cross}) in user beams. Furthermore, the recommended highest-energy electron beam available for use is the half-value depth of the water absorbed dose (R_{50}) > 7 g cm^{-2} (the mean energy at the phantom surface in MeV (E_0) ≧ 16 MeV). This is because the dose gradient near the calibration depth can be diminished using this high-energy electron beam. At the location of this study, only one linear accelerator equipped with electron-beam energy over 16 MeV was available. Thus, locating both a reference dosimeter and an external monitor chamber for accelerator output correction was also recommended. In this case, two sets were needed for the chamber and electrometer. Not only was this highly expensive, but many facilities also did not have two sets. Therefore, such cross-calibration could not be performed.

The purpose of this study is to investigate the relevant effects and obtain the suitable electron energy for cross-calibration with or without an external monitor chamber.

2. Materials and Methods

In this study, absolute dose measurements were performed using a RAMTEC Smart electrometer (TOYO MEDIC Co., Ltd.) with a 0.6 cm^3 farmer-type ion chamber PTW30013 (PTW-Freiburg, S/N 4013) and MAX-4000 (Standard Imaging, Inc.) with PTW30013 (S/N 4006) as an external ion chamber. A field chamber was created using a plane-parallel chamber NACP02 (IBA Dosimetry) and electrometer with RAMTEC Smart. Four linear accelerators, a Varian Clinac® iX (12 MeV and 15 MeV electron beam), a Varian Clinac® 21EX (12 MeV), a Varian Trilogy® (16 MeV and 20 MeV), and a Novalis® Tx (18 MeV, BRAINLAB) were used at the irradiation units in our department. These were performed in a water phantom (WP1D; IBA Dosimetry), for the immobilization of the external ion chamber (Fig. 1 (a)).

In terms of the absorbed dose to water at the cross-calibration quality Q_{cross}, the calibration factor for the chamber under calibration is given by

$$N^{field}_{D,w,Q_{cross}} = \frac{M^{ref}_{Q_{cross}} N^{ref}_{D,W,Q_0} k^{ref}_{Q_{cross}Q_0}}{M^{field}_{Q_{cross}}}, \quad (1)$$

where

$M^{ref}_{Q_{cross}}$ denotes the cross-calibration measurement value of the reference monitor chamber,

$M^{field}_{Q_{cross}}$ denotes the cross-calibration measurement value of the field monitor chamber,

N^{ref}_{D,W,Q_0} denotes absorbed dose to water calibration factor of the reference beam quality in the reference monitor chamber, and

$k^{ref}_{Q_{cross}Q_0}$ denotes the beam quality conversion factor of Q_{cross} for the reference chamber.

In practice, to minimize the effect of any variation in the accelerator output, the readings $M^{ref}_{Q_{cross}}$ and $M^{field}_{Q_{cross}}$ should be the averages $\overline{M^{ref}_{Q_{cross}} / M^{em(ref)}_{Q_{cross}}}$ and $\overline{M^{field}_{Q_{cross}} / M^{em(ref)}_{Q_{cross}}}$, respectively, measured relative to an external monitor.

The cross-calibrated chamber with calibration factor $N^{field}_{D,w,Q_{cross}}$ can subsequently be used for the determination of the absorbed dose $D_{w,Q}$ in a user beam of quality Q through the following equation:

$$D_{w,Q} = M^{field}_{Q} N^{field}_{D,w,Q_{cross}} k_{Q,Q_{cross}}, \quad (2)$$

where, $k_{Q,Q_{cross}}$ denotes the cross-calibration quality Q_{cross} [1].

2.1 Examining the Effects of an External Monitor Chamber

The effects of using (or not using) the external monitor chamber were investigated to acquire the cross-calibrated chamber with calibration factor $N^{field}_{D,w,Q_{cross}}$ for 12 MeV in Clinac® 21EX and 15 MeV in Clinac® iX by applying cross-calibration. The reference chamber $N_{D,w}$ = 5.37E-2 Gy/nc) was located inside the water phantom, with the reference point positioned 0.5 rcyl deeper than the point of interest (12 MeV:3.01 g cm^{-2}, 15 MeV:3.74 g cm^{-2}). Although the external monitor is laterally displaced in TRS-398, oblique detections were located using the external monitor chamber. Moreover, it was reduced owing to the influence of touching by replacing the field chamber with the reference chamber. The external monitor chamber was displaced by over 5 cm from the reference chamber and had a depth of 3.5 g cm^{-2} (Fig. 1 (b), (c) and (d)). The temperature of the water in the phantom was adjusted within the range of ± 1° at room temperature. The operating voltages for the reference chamber, the external chamber, and the field chamber were set to -400 V, -300 V, and -200 V, respectively. The electrometer was warmed up and 500 monitor unit (MU) pre-irradiation was performed. Following this, measurements were taken using the standard applicator of size 15×15 cm^2 and a source-to-surface distance of 100 cm. The averages of five measurements were determined using 200 MU irradiation in 12 and 15 MeV electron beams. The $M^{ref}_{Q_{cross}}$ value of the reference chamber was obtained, following which the average values were added to the temperature-pressure correction factor (k_{TP}), ion-recombination correction factor (k_s), and polarity effect factor (k_{pol}). Then, the $M^{field}_{Q_{cross}}$ value of the field chamber (NACP02: S/N 13603) of the reference point was also measured. The center of the inner surface of the entrance window served as the reference point for plane-parallel chambers. At the same time, adjustment of slight water level change to the difference of cubic volume two chambers and chamber sleeve were performed. In particular, attention was paid to the precision of the geometric arrangement. The $M^{field}_{Q_{cross}}$ value of the field chamber was obtained as an average value using the same method as in the reference chamber. All these measurements were performed using a coefficient of variation (CV) value of 0.05%. $N^{field}_{D,w,Q_{cross}}$ is given by equation 1. Considering the case in which the external monitor chamber is not used, $N^{field}_{D,w,Q_{cross}}$ was calculated using $M^{em(ref)}_{Q_{cross}} / M^{em(field)}_{Q_{cross}} = 1$.

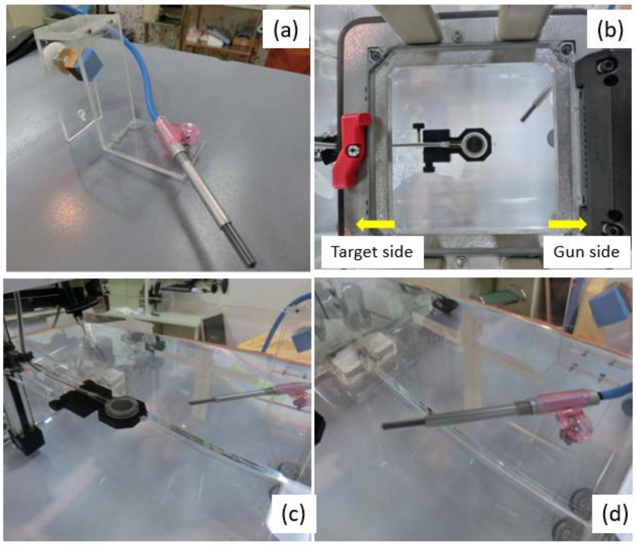

Fig. 1. Original chamber holder was showed (a). The geometry of field chamber and external monitor chamber for an overhead view (b) and an oblique view (c), (d).

These experiments were repeated six times each week. Subsequently, the average values of $N^{field}_{D,w,Q_{cross}}$ in the cases with and without the external monitor chamber were compared.

2.2 Comparison of Absorbed Dose for Different Cross-calibration Energies

2.2.1 Calculation of $N^{field}_{D,w,Q_{cross}}$ for Different Cross-Calibration Energies

Three different plane-parallel chambers were used as field chambers: NACP02-1:S/N 13603 $N_{D,w}$ = 0.1678 Gy/nc, NACP02-2:S/N 12406 $N_{D,w}$ = 0.1616 Gy/nc, and NACP02-3:S/N 11202 $N_{D,w}$ = 0.1562 Gy/nc. $N^{field}_{D,w,Q_{cross}}$ was applied to change the electron-beam energies. Table 1 shows R_{50}, E_0, and the calibration depth (d_c) of the measured electron-beam energies,

Table 1. Characteristics of clinical electron beams from each linear accelerators.

Energy (MeV)	12	15	16	18	20
R_{50} (g cm^{-2})	4.87	6.15	6.61	7.62	8.30
E_0 (MeV)	11.4	14.3	15.4	17.8	19.3
Calibration depth (g cm^{-2})	2.86	3.59	3.87	4.50	4.88

Table 2. The average value of $N^{field}_{D,w,Q_{corss}}$ with or without external chamber in two linear accelerators.

Machine (Energy)	External chamber	$N^{field}_{D,w,Qcross}$	Difference (%)
Clinac® 21EX (12 MeV)	With	0.1516 ± 0.0008	-0.04
	Without	0.1517 ± 0.0004	
Clinac® iX (15 MeV)	With	0.1501 ± 0.0004	0.01
	without	0.1501 ± 0.0003	

respectively. The measurement value (M, k_s, k_{pol}) was determined using the same method in the reference chamber and the three field chambers. It was observed that the mean calibration factor ($N^{field}_{D,w,Q_{cross}}$) using the measured cross-calibration of each energy is thrice another day.

2.2.2 Examining Absorbed Dose at the Depth of the Dose Maximum for Each $N^{field}_{D,w,Q_{cross}}$ Value

Using $N^{field}_{D,w,Q_{cross}}$ of each electron energy value for cross-calibration as described above, the 6 MeV electron D (d_{max}) was obtained in Clinac® iX via equation 2. Additionally, 200 MU of irradiation was obtained. A standard applicator of size 10 × 10 cm^2 was used to obtain the measurements. The D (d_{max}) value of each of the three field chambers and their average value were calculated. This was compared to the calculated absorbed dose using water calibration factor ($N_{D,w}$ (Co)) given by the ^{60}Co-γ ray. In this case, D (d_{max}) obtained a new high-energy electron dosimetry protocol in 2012 (Standard Dosimetry 12).

2.3 Statistical Analysis

All the analyses were conducted using R version 3.6.1 (R Core Team (2019)). Two-way factorial analysis of variance was used as the comparison test for statistical analysis difference among the group means. The pairwise t-test was used for multiple comparisons of multiple groups, and Bonferroni's P value adjustment method was applied.

3. Results

3.1 Effects of Using or not Using the External Monitor Chamber

The average $N^{field}_{D,w,Q_{cross}}$ value was measured six times with and without the external monitor chamber, as listed in Table 2. In Clinac® iX, this value was 0.1501 ± 0.0004 with the external monitor chamber and 0.1501 ± 0.0003 without the external monitor chamber at 15 MeV. The average $N^{field}_{D,w,Q_{cross}}$ value was moderate and almost equal with and without the external monitor chamber, with a difference of only 0.01% between the two cases. The Clinac® 21EX (12 MeV) values were slightly higher than those in Clinac® iX, with an $N^{field}_{D,w,Q_{cross}}$ difference value of -0.04%. Consequently, all $N^{field}_{D,w,Q_{cross}}$ were calculated without the external monitor chamber using the equation $M^{em(ref)}_{Q_{cross}} / M^{em(field)}_{Q_{cross}} = 1$.

3.2.1 Calculation of $N^{field}_{D,w,Q_{cross}}$ for Different Cross-Calibration Energies

As Fig. 2 shows, $N^{field}_{D,w,Q_{cross}}$ decreased as R_{50} increased, despite differences in the sensitivity of each of the three plane-parallel chambers. Thus, the slopes of approximate expression for $N^{field}_{D,w,Q_{cross}}$ values in the three chambers were obtained as -0.0013 (R^2 = 0.9865) for NACP02-1, -0.0013 (R^2 = 0.9884) for NACP02-2, and -0.0011 (R^2 = 0.9962) for NACP02-3. The same result was obtained when the NACP-02 chamber was used as a field chamber.

3.2.2 Examining Absorbed Dose at the Depth of the Dose Maximum for Each $N^{field}_{D,w,Q_{cross}}$ Value

Using $N^{\text{field}}_{\text{D,w,Q}_{\text{cross}}}$ for each energy value obtained in Subsection 2-2-1, the 6 MeV electron D (d_{max}) was calculated in Clinac® iX. As Fig. 3 shows, D (d_{max}) was obtained as 1.984 ± 0.005 Gy for $N_{\text{D,w}}$ (Co), 1.965 ± 0.004 Gy for 12 MeV ($N^{\text{field}}_{\text{D,w,Q}_c}$) (12)), 1.965 ± 0.002 Gy for 15 MeV ($N^{\text{field}}_{\text{D,w,Q}_c}$ (15)), 1.961 ± 0.005 Gy for 16 MeV ($N^{\text{field}}_{\text{D,w,Q}_c}$ (16)), 1.958 ± 0.004 Gy for 18 MeV ($N^{\text{field}}_{\text{D,w,Q}_c}$ (18)), and 1.954 ± 0.002 Gy for 20 MeV ($N^{\text{field}}_{\text{D,w,Q}_c}$ (20)). It was observed that the absorbed dose under cross-calibration was 0.94% for $N^{\text{field}}_{\text{D,w,Q}_c}$ (12), 0.95% for $N^{\text{field}}_{\text{D,w,Q}_c}$ (15), 1.17% for $N^{\text{field}}_{\text{D,w,Q}_c}$ (16), 1.31% for $N^{\text{field}}_{\text{D,w,Q}_c}$ (18), and 1.52% for $N^{\text{field}}_{\text{D,w,Q}_c}$ (20), a significant decrease in comparison with that under Standard Dosimetry 12. For the absorbed dose, the two-way analysis of variance (ANOVA) showed a statistical difference in the calibration factor (d.f. = 5, 10, F = 35.24, $P < 0.0001$), but between chambers (d.f. = 2, 10, F = 2.75, P = 0.11). Therefore, any calibration factor group that had a significant difference and performed multiple comparisons was

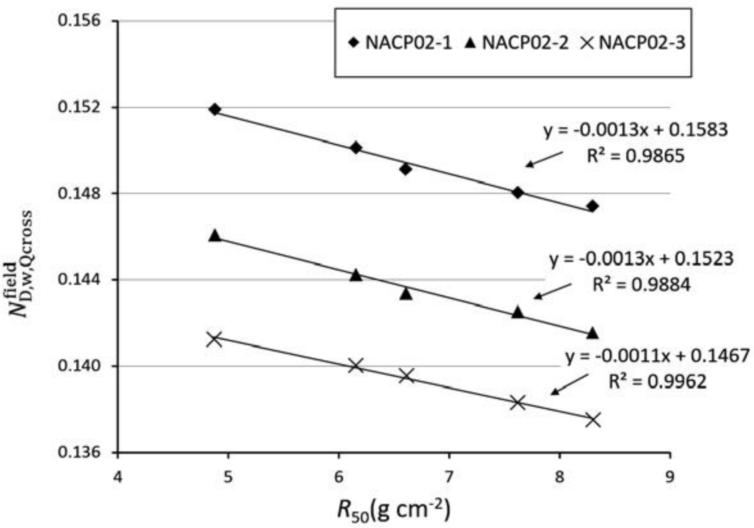

Fig. 2. $N^{\text{field}}_{\text{D,w,Q}_{\text{corss}}}$ values of three plane-parallel chambers for each R_{50}.

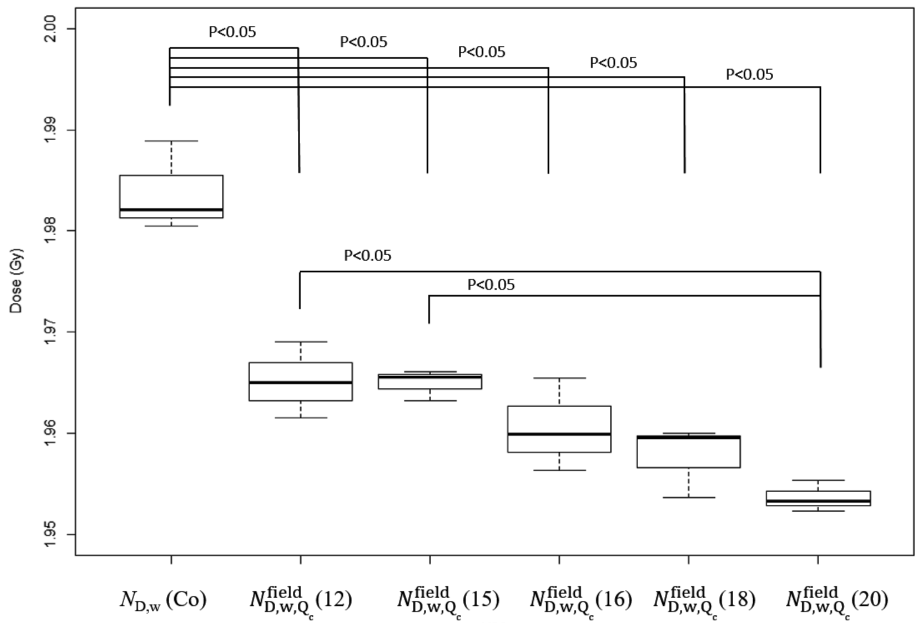

Fig. 3. The water absorbed dose at depth of the dose maximum of 6 MeV electron beam calculated using each $N_{\text{D,w}}$ in Clinac® iX.

considered (the pairwise t-test). It can be noted the absorbed dose for each $N_{D,w,Q_{cross}}^{field}$ differed significantly from that for $N_{D,w}$ (Co) ($p < 0.001$). For example, the absorbed dose for N_{D,w,Q_c}^{field} (20) was 0.59% and 0.57% lower than the absorbed dose N_{D,w,Q_c}^{field} (12) and N_{D,w,Q_c}^{field} (15), respectively, demonstrating a significant difference ($P < 0.05$).

4. Discussions

In this work, the effect of using or not using the external monitor chamber as well as the absorbed doses for different electron energies in cross-calibration were obtained. Standard Dosimetry 12 and TRS-398 show that the external monitor chamber was positioned to minimize the effect of any variation in the accelerator output [1-2]. Here, it was observed that the average values of $N_{D,w,Q_{cross}}^{field}$ showed no difference with or without the external monitor chamber in the two devices (Table 2). Therefore, the external monitor chamber is not required when the CV is maintained at 0.05%. If the external monitor chamber is not precisely positioned, there is a high possibility that it will reflect its position deficiency rather than correcting the output variation of the device. In addition, the positioning of the external monitor chamber requires a two-dosimeter system, which is unavailable in many facilities, particularly small ones. Considering these factors, it is suggested that the external monitor chamber is not positioned. While this study only considers two devices in specific facilities, it is important that other devices and other facilities are studied in the future. In the facilities used herein, before performing cross-calibration, it was observed that the CV was identified as 0.05% for measuring any $N_{D,w,Q_{cross}}^{field}$.

To obtain the suitable electron energy, the same three types of plane-parallel chambers were utilized. D (d_{max}) for $N_{D,w}$ (Co) in Standard Dosimetry 12 was compared to $N_{D,w,Q_{cross}}^{field}$ for each electron energy value (12, 15, 16, 18, and 20 MeV) under cross-calibration. In the case of cross-calibration, D (d_{max}) for $N_{D,w,Q_{cross}}^{field}$ was between -0.94 to -1.52%, which is smaller than that of $N_{D,w}$ (Co). By using the electron-beam quality, it appeared that P_{wall}, which is a beam-quality correction factor (k_{Q,Q_0}) of the reference ionization chamber based on the ^{60}Co-γ ray beam quality, was removed. This appears to reflect the improved uncertainty of the absorbed dose. For each energy value, the obtained results show a significant difference in the absorbed dose for different calibration factors in multiple group verifications. In multiple comparisons, a significant difference was observed between $N_{D,w}$ (Co) and each $N_{D,w,Q_{cross}}^{field}$ ($p < 0.001$). In terms of the electron-beam energies, a significant difference was observed between the D (d_{max}) value for N_{D,w,Q_c}^{field} (20) and that for N_{D,w,Q_c}^{field} (12) ($p < 0.05$) and N_{D,w,Q_c}^{field} (15) ($p < 0.05$) (Fig. 3). However, D (d_{max}) was almost identical when using N_{D,w,Q_c}^{field} (12), N_{D,w,Q_c}^{field} (15), N_{D,w,Q_c}^{field} (16), and N_{D,w,Q_c}^{field} (18) ($p > 0.05$). For D (d_{max}) of N_{D,w,Q_c}^{field} (18), no significant difference was observed at the energy value recommended in Standard Dosimetry 12 and TRS-398 (E_0 = 17.75 MeV) and at unrecommended values (12, 15, and 16 MeV). These observations indicate that cross-calibration should have been performed using an electron-beam energy of 20 MeV in facilities where an electron-beam energy of 20 MeV (E_0 = 19.4 MeV) is enabled for linear accelerators. However, linear accelerators are not equipped for the electron-beam energy of 20 MeV (E_0 = 19.4 MeV) despite $R_{50} > 7$ g cm^{-2} ($E_0 \geqq 16$ MeV) being recommended in Standard Dosimetry 12 and TRS-398. Maximum electron energy should be used in our facilities during cross-calibration, because the uncertainty appeared to be less than that using $N_{D,w}$ (Co) as a dosimeter. Linear accelerators that operate clinically in Japan are equipped for maximum electron-beam energy of 12 MeV or 15 MeV. It is worth noting that the facilities used herein did not have two sets of dosimeters and no equipped recommended energy will proceed utilization for cross-calibration of electron beams. However, in this study, only NACP-02 was used as the field chamber; in the future, it will be necessary to consider using other plane-parallel chambers.

5. Conclusions

In this study, it was found that the obtained $N^{\text{field}}_{D,w,Q_{\text{cross}}}$ values did not differ significantly with or without an external monitor chamber. The suitable electron energy to obtain calibration factors $N^{\text{field}}_{D,w,Q_{\text{cross}}}$ in cross-calibration was obtained as 20 MeV. It was observed that the absorbed dose was almost the same value at 12 MeV, 15 MeV, 16 MeV, and 18 MeV. Notably, it was found that in facilities not equipped for the electron-beam energy of 20 MeV, the cross-calibration in the electron beam cannot use the external monitor chamber; however, it can use the maximum electron-beam energy.

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Compliance with ethical standards

Conflict of interest

All authors declare that there is no conflict of interest.

Ethical standards

This article does not contain any studies performed with human or animal participants.

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