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Use of Cylindrical Chambers as Substitutes for Parallel-Plate Chambers in Low-Energy Electron Dosimetry

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Current dosimetry protocols recommend the use of parallel-plate chambers in electron dosimetry because the electron fluence perturbation can be effectively minimized. However, substitutable methods to calibrate and measure the electron output and energy with the widely used cylindrical chamber should be developed in case a parallel-plate chamber is unavailable. In this study, we measured the correction factors and absolute dose-to-water of electrons with energies of 4, 6, 9, 12, 16, and 20 MeV using Farmer-type and Roos chambers by varying the dose rates according to the AAPM TG-51 protocol. The ion recombination factor and absolute dose were found to be varied across the chamber types, energy, and dose rate, and these phenomena were remarkable at a low energy (4 MeV), which was in good agreement with literature. While the ion recombination factor showed a difference across chamber types of less than 0.4%, the absolute dose differences between them were largest at 4 MeV at approximately 1.5%. We therefore found that the absolute dose with respect to the dose rate was strongly influenced by ion-collection efficiency. Although more rigorous validation with other types of chambers and protocols should be performed, the outcome of the study shows the feasibility of replacing the parallel-plate chamber with the cylindrical chamber in electron dosimetry.

Keywords: Electron dosimetry, AAPM TG-51, Parallel plate chamber, Farmer chamber

Introduction

The various international dosimetry protocols have recommended the use of parallel plate ionization chamber in electron beam calibration, and especially in case of low energy electron (R_{50}<4 g/cm^2 or <10 MeV).[1-4] This is mainly because the replacement correction factor was not well defined in cylindrical chamber, although several previous studies have reported about these issues but still controversial.[5-7] In electron dosimetry with parallel plate chamber, the replacement correction factor can be taken as unity due to the design of the parallel plate chamber consisting of thin-foiled entrance window and the air-filled cavity, which could effectively minimize the electron fluence perturbations.[8,9]

However, there should be another substitute method to measure electron beam output and energy in case of unavailability of parallel plate chamber, or for the convenience of experimental set-up. This interchangeable approach could be done with widely-used cylindrical chamber, such as Farmer-type or thimble chamber, their cross calibration of course should be pre-verified. A previous study has verified the temporal use of cylindrical chamber in the measurement of 6 MeV electron beam with International Atomic Energy Agency (IAEA), Technical Reports Series No. 398 (TRS-398) protocols, but those with American Association of Physicists in Medicine (AAPM) Task Group (TG)-51 protocol was not reported yet.[10)]

In this study, we measured the electron beams of six energies (4, 6, 9, 12, 16, and 20 MeV) according to AAPM TG-51 protocols with Farmer-type (TN 30013, PTW-Freiburg, Freiburg, Germany) and Roos chamber (TN 34001, PTW-Freiburg, Freiburg, Germany). By varying the dose rate, the impact of dose rate on electron dosimetry was rigorously investigated to validate its clinical appropriateness.

Materials and Methods

1. Experimental setup

Electron beams of six energies (4, 6, 9, 12, 16, and 20 MeV) were measured with a linear accelerator (Trilogy, Varian Medical Systems, Palo Alto, CA). Small one dimensional water phantom (WP1D Phantom, IBA Dosimetry, Schwarzenbruck, Germany) of 42×36×36 cm^3 was setup, and source-to-surface distance (SSD) was set to 100 cm. The 10×10 cone was used in accordance with an initial beam modeling.

Two types of ion chambers, 0.6 cc Farmer chamber and 0.35 cc Roos chamber were used in this study as shown in Fig. 1. Their corresponding absorbed dose to water calibration factor ($N_{D,w}^{^{60}Co}$) were provided by the secondary standards dosimetry laboratories (SSDL) within an year. An UNIDOS-E electrometer (PTW-Freiburg, Freiburg, Germany) was used to read collected charge for each measurement.

2. Electron beam calibration and measurement

All measurements in this study were performed according to AAPM TG-51 protocols as following Eq. (1)

$$D_W^Q = Mk_Q N_{D,w}^{^{60}Co} \quad (1)$$

Where, M and k_Q denote fully corrected reading, and chamber-specific beam quality correction factor, respectively. The fully corrected reading M was acquired by multiplication of M_{raw} with ion recombination factors (P_{ion}), polarization correction factor (P_{pol}), electrometer correction factor (P_{elec}), and corrections for standard environmental conditions (P_{TP}). All collection factors were obtained at reference depth P_{ion}=0.6 R_{50}−0.1 (cm) with respect to each energy regardless of chamber type.

The P_{ion} were measured by varying dose rate with 100, 300, 600, and 1000 MU/min according to the Eq. (2), where V_H be the normal operating voltage and V_L be the bias reduced by the factor 2, and M_{raw}* be the chamber reading for each bias. P_{pol} was measured with reference dose-rate (1,000 MU/min) where the reference dosimetry was being

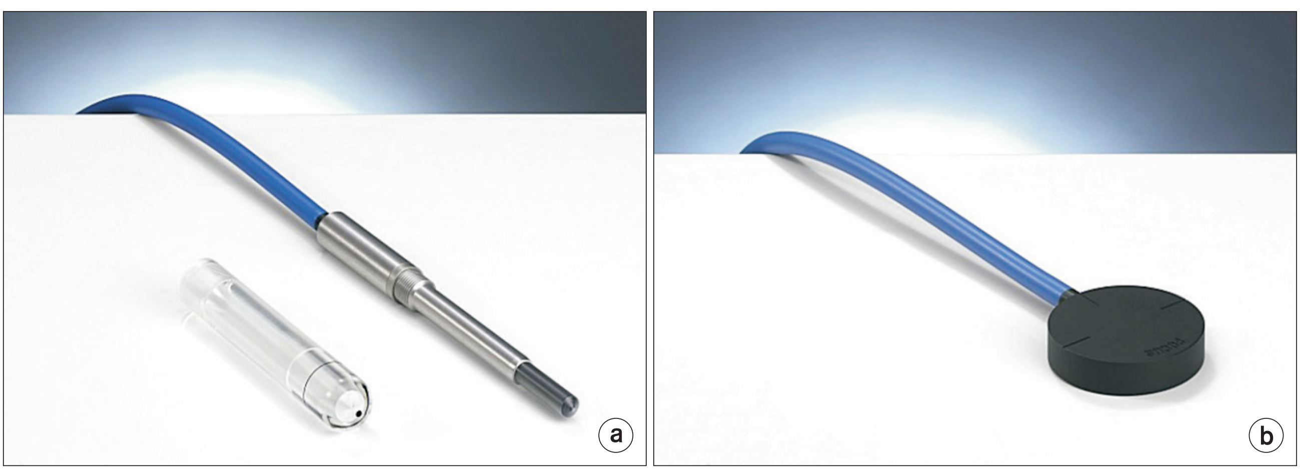

Fig. 1. Used ion chambers (a) Farmer-type chamber, and (b) Roos chamber.

performed.[1)]

$$P_{ion}(V_H) = \frac{1 - V_H / V_L}{M^H_{raw} / M^L_{raw} - V_H / V_L} \quad (2)$$

Beam quality conversion factor (k_Q) was provided by Eq. (3), and acquired by chamber-specific manner.

$$k_Q = P^Q_{gr} k_{R_{50}} \quad (3)$$

where, P^Q_{gr} and $k_{R_{50}}$ indicates gradient correction factor for cylindrical chamber and beam quality-dependent absolute dose calibration factor specified by R_{50}, respectively. The gradient correction factor for parallel-plate chamber is not necessary, and for cylindrical chamber, P^Q_{gr} was presented by a function of the radius of the chamber cavity, r_{cav}, as following Eq. (4).

$$P^Q_{gr} = \frac{M_{raw}(d_{ref} + 0.5 r_{cav})}{M_{raw}(d_{ref})} \quad (4)$$

$k_{R_{50}}$ was presented by the product of photon-electron conversion factor (k_{ecal}) and electron beam quality conversion factor ($k'_{R_{50}}$). k_{ecal} was chamber-specific, and 0.896 for Farmber chamber, and 0.901 for Roos chamber in this study. $k'_{R_{50}}$ was also provided according to the chamber-type and beam quality (R_{50}) as shown in Eq. (5) and (6).

$$k'_{R_{50}}(cyl) = 0.9905 + 0.0710 e^{(-R_{50}/3.67)} \quad (5)$$

$$k'_{R_{50}}(pp) = 1.2239 - 0.145 (R_{50})^{0.214} \quad (6)$$

After all calibration and conversion factors were obtained, the measured dose was normalized by reference percent depth dose (PDD) at d_{ref} to present the absolute dose at d_{max}. The absolute differences in P_{ion} and absolute dose were calculated, and their relationships were observed.

Results

1. Ion recombination factor

Ion recombination factor according to the six electron energies and chamber types were provided in Table 1, and also the P_{ion} differences between chambers were presented in Fig. 2(a) by 100 folds numerical value. The largest magnitude of P_{ion} differences across two chambers were at 4, and 16 MeV showing less than 0.004. P_{ion} difference (×100) according to the energy in certain dose rate were −0.043, −0.035, −0.23, and −0.026, for 100, 300, 600, and 1,000 MU/min respectively. The closest differences in P_{ion} across two chambers was acquired where the reference dosimetry was being performed (1,000 MU/min).

2. Absolute dose to water

The absolute dose with respect to each dose rate and energies were presented in Table 1, and dose difference across two chambers were provided in Fig. 2(b). The largest dose differences across two chambers were definitely observed at 4 MeV showing −1.497, 0.577, −0.336, −0.724,

Table 1. Numerical values for ion recombination factor (P_{ion}), and dose according to the chamber-type, energy, and dose rate.

Dose rate	Ion recombination factor (P_{ion})						Dose (cGy)					
	4 MeV	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV	4 MeV	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV
Farmer chamber												
100 MU/min	1.006	1.012	1.009	1.009	1.008	1.010	100.355	100.080	99.676	99.735	99.661	99.072
300 MU/min	1.008	1.012	1.010	1.010	1.008	1.011	100.748	100.156	99.776	99.910	99.635	99.277
600 MU/min	1.007	1.011	1.010	1.010	1.008	1.010	100.799	100.154	99.875	100.032	99.709	99.174
1,000 MU/min	1.009	1.011	1.011	1.010	1.010	1.011	101.219	100.302	100.176	100.104	100.078	99.325
Roos chamber												
100 MU/min	1.008	1.011	1.009	1.010	1.008	1.010	101.852	99.620	100.012	100.459	100.039	98.962
300 MU/min	1.009	1.010	1.009	1.011	1.009	1.011	102.060	99.579	100.012	100.539	100.196	99.283
600 MU/min	1.011	1.012	1.011	1.011	1.012	1.013	102.434	100.064	100.450	100.697	100.703	99.565
1,000 MU/min	1.009	1.012	1.010	1.009	1.011	1.012	102.222	100.064	100.327	100.496	100.623	99.441

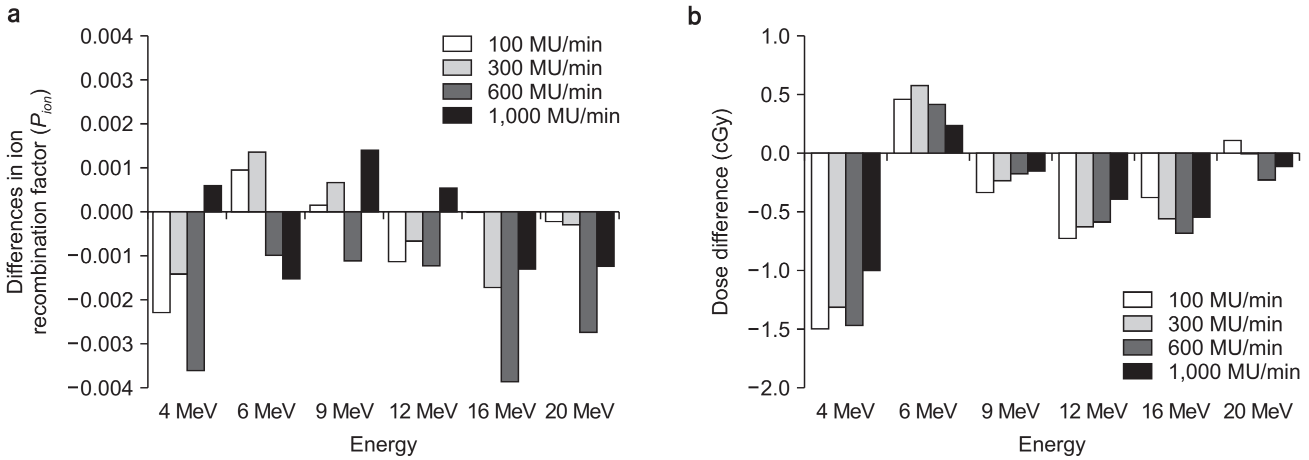

Fig. 2. Differences in (a) ion recombination factors (P_{ion}), and (b) dose across two different chamber types.

−0.681, and −0.229 for 4, 6, 9, 12, 16, and 20 MeV. Absolute dose difference according to the energy in certain dose rate were −0.394, −0.361, −0.454, and −0.328, for 100, 300, 600, and 1,000 MU/min respectively. Although absolute dose difference in 4 MeV was relatively higher than those of energies equal or greater than 6 MeV, those with 1,000 MU/min were less than 1% while larger than 1.3% in other dose rate.

By closely examining Eq (1). and other correction factors, the absolute dose to water could be determined by multiplication of the raw reading, P_{ion}, P_{pol}, P_{TP}, P_{elec}, k_Q, and $N_{D,w}^{^{60}Co}$. Among them, the dose-rate dependent variables were raw reading and P_{ion}, while other factors cannot influence the absolute dose to water by varying dose rate. Fig. 3 showed the impact of dose rate on the measurement of P_{ion}, raw reading, and absolute dose across chambers. It can be showed that an almost linear patterns on absolute dose with respect to dose rate were mainly influenced by the collected charge not by P_{ion} for both chambers.

Discussion

This study investigated the electron reference dosimetry with Farmer-type and Roos chamber, and the impact of dose rate on dosimetric parameters. Including AAPM TG-51 and IAEA TRS-398 protocols, various studies have been made to verify the appropriateness of chamber types in electron dosimetry. Although other literatures have still argued about them, it is noticeable that they commonly recommended using parallel plate chamber in low electron energies rather than cylindrical chamber.[5,6,8,11) All acceptance with recommendations has been made, but substitutable methods should be prepared in case of unavailability of parallel plate chamber, such as with widely-used cylindrical chamber.

The variations on ion recombination factor could reflect different extent of incomplete ion collection, and this discrepancy was dominant in 4 MeV as shown in Fig. 2(a). However, P_{ion} difference on 4 MeV with 1,000 MU/min was relatively small, thus the dose difference could be minimized less than 1% by the selection of dose rate on calibration circumstances (1,000 MU/min). The dose difference across chambers were higher especially in 4 MeV as shown in Fig. 2(b). The dose difference between two chambers were −1.32, 0.42, −0.22, −0.58, −0.54, and −0.06 cGy on averages, and −1.50, 0.58, −0.34, −0.72, −0.68, and −0.22 on maximum magnitude. The relatively large dose difference on 4 MeV across chamber types was shown, and this is mainly because of the appreciable perturbation in cylindrical chambers. Also necessities to extrapolate the beam quality factors in the energy range of R_{50} less than 2 cm (<6 MeV) could boost the dose difference relatively high. Because the other correction factors were acquired with fixed dose rate, the dose difference according to dose rate were only influenced by P_{ion} and ion collection efficiency with respect to the different dose rate. These verification results could suggest that the reference electron dosimetry in 4 MeV even with Farmer chamber

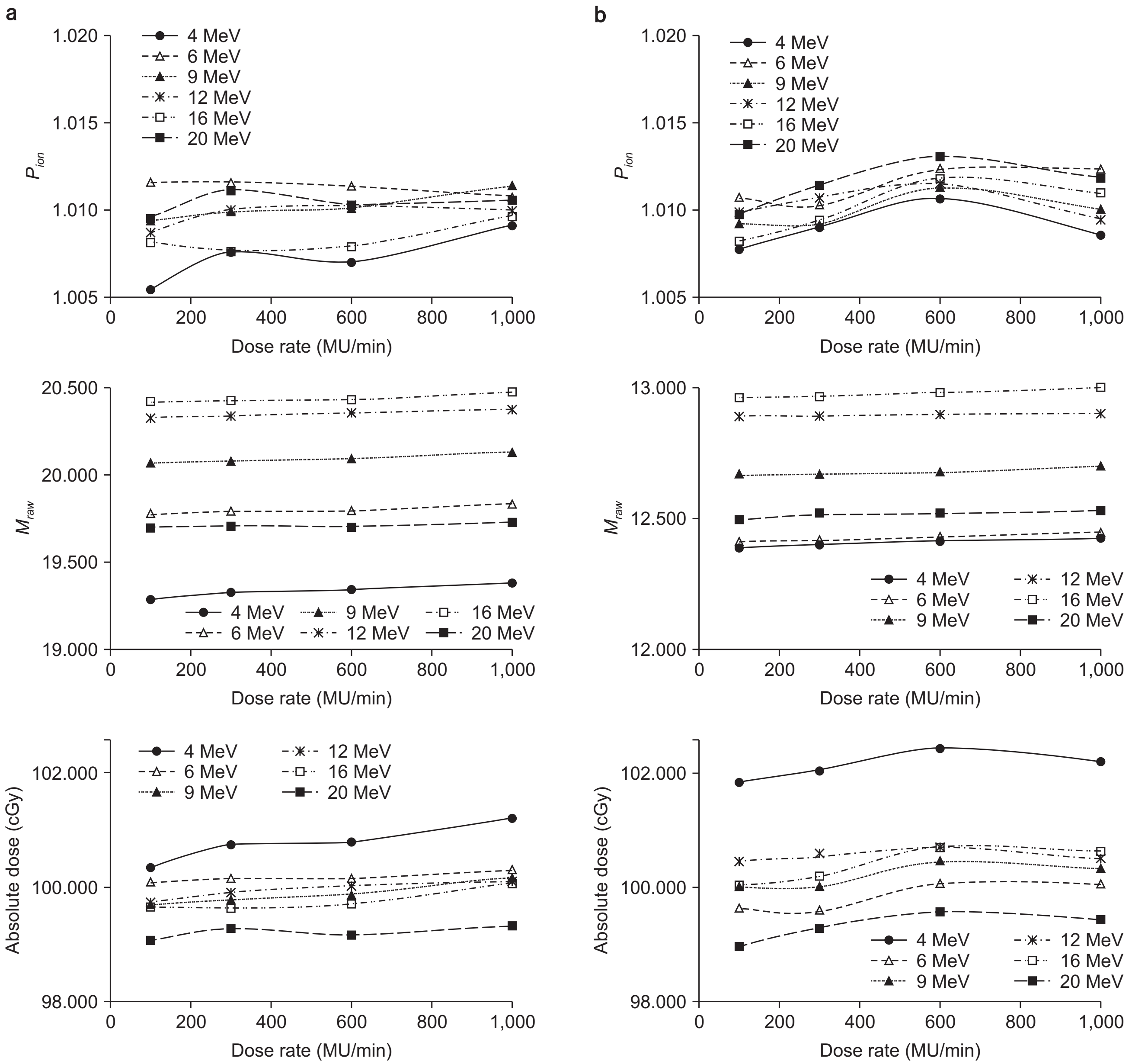

Fig. 3. The impact of dose rate on dosimetric parameters with an order of ion recombination factor (P_{ion}), collected charge, and the absolute dose. Measurements with (a) Farmer-type chamber, and (b) Roos chamber.

can be reached less than 1% difference with Roos chamber when the user measured the beam with dose-rate where the reference dosimetry were being performed.

Ion collection efficiency was strongly influenced by the dose rate of the pulsed beam, which can be determined by both dose per pulse and pulse repetition frequency.[12] Lang et al.[12] investigated the impacts of dose per pulse in ion collection efficiency, and reported that the ion collection efficiency could be decreased by 6% at the maximum dose rate. Takei et al.[13] reported that influences of pulse repetition frequency in ion collection, and they claimed that there were decreases in the collected charge within 1% for electron dosimetry. By summarizing the previous studies, the ion collection efficiency can be influenced by the dose rate of the pulsed beam. As shown in Fig. 3, the graphs on middle row could present the linear pattern of collected charge by increasing the dose rate, which is consistent with the previous literatures. However, ion recombination factor (P_{ion}) had no statistical founding with dose rate regardless of energy and chamber type. It can be interpreted that the different types of chamber could influence the P_{ion} less than only 0.4%.

Although we concluded that the usage of Farmer chamber in electron dosimetry could provide output difference less than 1% with dose-rate for reference dosimetry, this does not mean Farmer chamber could replace the parallel-plate chamber directly. For more accurate output measurement with Farmer chamber, the cross calibration between two chambers should be made in each clinic one by one. This can be regarded as our limitation of our study, and measurements with other combinations of parallel plate chambers should be preceded to generalize the use of cross factor such as Markus chamber, Advanced-Markus, and others.

Also, there exists the necessity of more rigorous and wide experiments with IAEA TRS-398. While other feasibility studies of using cylindrical chamber in low energy electron dosimetry has been made infrequently, we believe that the combination and comparison between AAPM TG-51 and IAEA TRS-398 protocols with Monte Carlo based simulations could effectively support the use of cylindrical chamber in electron beam dosimetry and thereby boost the convenience of the radiation quality assurance routine.[10)] Nonetheless, our study results showed a possibility to use cylindrical chamber in low energy dosimetry with a medium dose rate.

Conclusion

We observed the close relationship between ion collection efficiency and absolute dose regardless of chamber type suggesting the proper selection of the dose rate could influence on electron dosimetry. The study results could suggest that the cylindrical chamber can be used in electron dosimetry with dose rate for reference dosimetry as a substitute of parallel plate chamber.

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Conflicts of Interest

The authors have nothing to disclose.

Availability of Data and Materials

All relevant data are within the paper and its Supporting Information files.

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