The impact of flattening filter free (FFF) photon beams to ion recombination correction factor

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Abstract. This study aimed to evaluate ion recombination correction for ionization chamber in flattening filter free (FFF) photon beams and compare it to the flattened (with-flattening-filter) photon beams. The evaluation of ion recombination correction factor was performed for FC65-G, SNC600c, and CC13 ionization chambers. The measurements of three ionization chambers were performed using the water phantom and the Varian Trilogy linac with FFF capability. The ion recombination correction factor values for the three ionization chambers were obtained from the calculation using the simple two-voltage method and Jaffe plot curve fitting. The ion recombination correction factor value obtained from all three ionization chambers were higher for unflattened (FFF) photon beams than the flattened (WFF) photon beams with discrepancy less than 3%. The ion recombination correction value obtained from the linear Jaffe plot curve fitting had the highest discrepancy at about 7.67% when compared to the two-voltage method. On the contrary, the ion recombination correction value obtained from the Jaffe plot with quadratic and exponential quadratic curve fitting had discrepancies less than 2% when compared to the two-voltage method.

1. Introduction
Flattening-filter-free (FFF) photon beams have higher dose rates, lower scattering radiation, and lower out of field doses than flattened (with-flattening-filter) photon beams [1,2]. The dose rates can be two to four times higher than flattened (WFF) photon beams. The special consideration in the selection of dosimetry systems, including ion recombination correction factor, is needed to provide an accurate measurement due to the higher dose rate in FFF photon beams [3]. Calibration inaccuracies, including the determination of ion recombination correction, are classified as errors that could occur while using FFF photon beams [4]. The ion recombination correction factor for the ionization chamber can be affected by the higher dose rate [5]. Ion recombination correction factors in FFF photon beams were higher than in flattened (WFF) photon beams, and the discrepancies were less than 2% [2,6–8].

The ion recombination correction factor can be determined using several methods, including the two-voltage method and Jaffe plot. A simple of two-voltage method for pulsed photon beams is provided in the IAEA TRS-398 protocol which is based on the previous study [9]. The two-voltage method is used to determine ion recombination correction factors in FFF photon beams in several studies [2,6–8]. Whereas, the Jaffe plot is a curve of \( 1/Q \) with \( 1/V \), where \( Q \) is the collected charge and \( V \) is the voltage used. The Jaffe plot method is more robust measurement than the two-voltage method for the determination of ion recombination correction factors [10]. The two-voltage method can be used if there...
is a linear relation in $I/Q$ with $I/V$ curve [11]. Another study also stated that the two-voltage method caused an overestimate of the radiation beams output up to 0.7% for a $10 \times 10$ cm$^2$ field size [12]. Several previous studies compared the correction value of ion recombination factor between the two-voltage method and the Jaffe plot curve fitting in which its discrepancy was less than 2% for both methods [6–8,13]. This study aimed to evaluate ion recombination correction for ionization chamber in unflattened (FFF) photon beams and compare it to the flattened photon beams. Two-voltage and Jaffe plot method were used to evaluate the ion recombination correction factors.

2. Method

The evaluation of ion recombination correction factor was performed for FC65-G, SNC600c, and CC13 ionization chambers in flattened (WFF) and unflattened (FFF) photon beams. The measurements of three ionization chambers were performed using the water phantom and the Varian Trilogy linac with FFF capability. The voltage variations from 5 V to 500 V were used for the measurement with a depth of 10 cm, a field size of $10 \times 10$ cm$^2$ and SSD of 100 cm. The nominal dose rates used were 600 MU/min for flattened beams and 1120 MU/min for unflattened photon beams. Meanwhile, the nominal dose setting for both beams was 200 MU.

Ion recombination correction factors were calculated using two methods, namely: the two-voltage method (Equation 1) and Jaffe plot. A pair of voltages (+300 V and +100 V) was used for the two-voltage method. Equation 1 was provided in IAEA TRS-398 with $a_0$ = 1.198; $a_1$ = -0.875; $a_2$ = 0.677 for voltage ratio equal to 3. $Q_V$ was the electrometer reading (showing the collected charge) for higher voltage and $Q_L$ was for the lower one.

$$k_{s(TRS-398)} = a_0 + a_1 \left( \frac{Q_L}{Q_V} \right) + a_2 \left( \frac{Q_L}{Q_V} \right)^2$$

(1)

The determination of ion recombination correction factors using Jaffe plot curve fitting method was obtained from linear, quadratic and exponential quadratic (Equation 2) curve fitting. The model for exponential quadratic fitting was proposed by Podgorsak and Zankowski [14].

$$\frac{1}{Q(V)} = \left( \frac{1}{q_{\text{sat}}} + \frac{\alpha}{V} + \frac{\beta}{V^2} \right)e^{-\gamma V}$$

(2)

The curve fitting was conducted using MATLAB R2014a program (license number: 271828). The saturation charge ($Q_{\text{sat}}$) values obtained from linear and quadratic curve fitting were used to determine ion recombination correction ($k_s$) using Equation 5. Meanwhile, Equation 6 was used to determine ion recombination correction ($k_s$) using parameter $Q_{\text{sat}}$ from Equation 4. Whereas, $Q(V)$ was the electrometer reading (showing the collected charge) for 300 V. In addition, the absorbed dose to water at maximum depth ($D_{W,Q(\text{Zmax})}$) was obtained using Equation 7 [10]. Meanwhile, the percentage depth of dose at 10 cm depth ($PDD_{10\,cm}$) were 66.54% for flattened (WFF) photon beams and 63.65% for FFF photon beams.

$$k_s = \frac{Q_{\text{sat}}}{Q(V)}$$

(3)

$$k_s = \frac{Q_{\text{sat}}}{Q(V)e^{-\gamma V}}$$

(4)

$$D_{W,Q(\text{Zmax})} = \frac{Q(V)N_{D,W,Q}\cdot Q_{\text{pol}}\cdot k_{FP}\cdot k_{\text{pol}}\cdot k_{\text{elec}}}{PDD_{10\,cm}/100}$$

(5)
3. Results and Discussion
The saturation curves for each ionization chamber can be seen in Figure 1. The saturation area can be seen from 100 V to 500 V and corresponds to the ionization area for gas-filled detector [15]. In this ionization area, the applied voltage is considered high enough to reduce the effect of ion recombination found at the lower voltage.

The collected charge measured on the flattened (WFF) photon beams was greater than the FFF photon beams; and the same results were found in the previous study [8]. The results show that there was a possibility of the dependence on the response of ionization chambers to photon energy. The collected charge in the ionization chamber was proportional to the energy of beam [15]. Linac with FFF photon produced higher intensity of low energy photon; so that, it will provide lower average energy than flattened beams. The average energy of 6 MV photon beams from Varian linac was about 0.8 MeV for unflattened (FFF) beams and 1.3 MeV for flattened (WFF) beams [16]. Consequently, flattened beams show higher collected charges due to its higher average energy.

The ion recombination correction factor ($k_r$) was obtained using two-voltage and Jaffe plot method; and it can be seen in Table 1. The discrepancy of ion recombination correction factor between flattened (WFF) and unflattened (FFF) photon beams was shown as $Y$. Whereas, $X$ parameters show the discrepancy of ion recombination correction factor between two-voltage and Jaffe plot method. It shows that the ion recombination correction factor for unflattened (FFF) beams were higher in which its discrepancy was less than 3% and consistent with the previous studies [2,6,8]. The higher ion recombination correction factor was caused by higher dose rate as a characteristic of FFF photon beams due to higher fluence. The ion recombination correction factor was affected by dose rate, especially general recombination. The higher dose rate in FFF beams show shorter measurement time; so that, the amount of charge collected was lower and consequently obtained higher ion recombination.

Figure 1. Saturation curve for FC65-G (a), SNC600c (b) and CC13 (c) ionization chambers on flattened (WFF) and unflattened (FFF) photon beams
Table 1 The ion recombination correction factor ($k_s$), its discrepancy between flattened (WFF) and FFF beams ($Y$), its discrepancy between both methods obtained using two voltage method and Jaffe plot curve fitting ($X$), the absorbed dose to water at maximum depth ($D_{w,Q}(z_{max})$), and the time for measurement ($t$)

| Method                        | Parameters | FC65-G WFF | FC65-G FFF | SNC600c WFF | SNC600c FFF | CC13 WFF | CC13 FFF |
|-------------------------------|------------|------------|------------|-------------|-------------|----------|----------|
| Two-voltage (TVM)             |            |            |            |             |             |          |          |
|                               | $k_s$      | 1.0029     | 1.0055     | 1.0027      | 1.0053      | 1.0041   | 1.0068   |
|                               | $Y$        | 0.259      | 0.259      | 0.259       | 0.259       | 0.269    |          |
|                               | $D_{w,Q}(z_{max})$ (Gy/MU) | 0.996 | 0.998 | 0.998 | 1.005 | 0.945 | 0.950 |
|                               | $t$ (minute) | 8.17      | 7.60       | 6.13        | 6.07        | 6.40     | 5.82     |
| Linear Fitting                |            |            |            |             |             |          |          |
|                               | $k_s$      | 1.036      | 1.044      | 1.019       | 1.031       | 1.058    | 1.084    |
|                               | $X$        | 3.30       | 3.83       | 1.63        | 2.56        | 5.37     | 7.67     |
|                               | $Y$        | 0.772      | 1.18       |             |             |          |          |
|                               | $D_{w,Q}(z_{max})$ (Gy/MU) | 1.029 | 1.036 | 1.014 | 1.031 | 0.996 | 1.024 |
| Jaffe plot                    |            |            |            |             |             |          |          |
|                               | $k_s$      | 0.9998     | 1.003      | 1.0006      | 1.0019      | 1.0003   | 1.0128   |
|                               | $X$        | -0.309     | -0.249     | -0.209      | -0.338      | -0.378   | 0.596    |
|                               | $Y$        | 0.320      | 0.130      |             |             |          | 1.25     |
|                               | $D_{w,Q}(z_{max})$ (Gy/MU) | 0.993 | 0.996 | 0.995 | 1.002 | 0.941 | 0.957 |
| Quadratic Fitting             |            |            |            |             |             |          |          |
|                               | $k_s$      | 1.0003     | 1.0032     | 0.9964      | 0.9977      | 0.9969   | 1.0249   |
|                               | $X$        | -0.259     | -0.229     | -0.628      | -0.756      | -0.717   | 1.80     |
|                               | $Y$        | 0.290      | 0.130      |             |             |          | 2.81     |
|                               | $D_{w,Q}(z_{max})$ (Gy/MU) | 0.994 | 0.996 | 0.991 | 0.997 | 0.938 | 0.968 |
| Exponential Quadratic Fitting |            |            |            |             |             |          |          |
|                               | $t$ (minute) | 24.9       | 24.9       | 24.9        | 23.6        | 24.0     | 23.2     |

In addition, the highest discrepancy at about 7.67% between two voltage method and Jaffe plot was obtained from the linear curve fitting. The result was contrary to the previous study stating that the discrepancy between the linear fitting and two voltage method was less than 1% [6,7]. This difference was mainly caused by the range of voltage used for linear fitting. This study used a wider voltage range than the previous studies which laid from recombination area (<~100 V) to ionization area (saturation area). Conversely, the previous studies merely used range voltage that laid in the ionization area. However, another study investigated ion recombination correction factor for a parallel plan ionization chamber on electron beams using two-voltage method and Jaffe plot linear fitting but showed discrepancy nearby 6% between both methods [17]. On the contrary, both quadratic and quadratic exponential fitting showed discrepancies less than 2%. In addition, those discrepancies were consistent with the previous studies [8,13]. Moreover, the quadratic fitting had the least discrepancy which was less than 1%.

In addition, Table 1 shows the results of absorbed dose calculation at maximum depth ($D_{w,Q}(z_{max})$) based on IAEA TRS-398. The result showed that two-voltage method was well agreed to use during
absolute dose determination for both flattened and unflattened photon beams with deviation of < 0.5% (relative to 1 Gy/MU at maximum depth) for FC65-G and SNC600c ionization chambers. Meanwhile, the Jaffe plot method using linear fitting generally showed the largest deviation for FC65-G and SN600c ionization chambers. The Jaffe plot method using quadratic and quadratic exponential fitting also showed lower deviation value for FFF photon beams using SNC600c ionization chamber. Moreover, CC13 ionization chamber showed large deviations (relative to 1 Gy/MU at maximum depth) for all of the methods which were < 6.2%. Hence, CC13 ionization chamber used in this study is not recommended for absolute dose measurement compared to other chambers.

The time taken for measurement in Table 1 indicates the time needed for collecting data and excludes the time for device set up. As shown in Table 1, Jaffe plot method took longer time for measurement than two-voltage method. Therefore, Jaffe plot method is not efficient and practical compared to the two-voltage method.

4. Conclusion

The unflattened (FFF) photon beams had higher ion recombination correction factor than the flattened (WFF) beams in which its discrepancy was less than 3%. The highest discrepancy between two-voltage method and Jaffe plot was obtained from linear fitting, i.e. 7.67%. On the other hand, the other two fittings showed that discrepancies were less than 2% which were consistent with the previous studies. The two-voltage method, Jaffe plot quadratic and quadratic exponential methods showed good results for absolute dose measurement. However, Jaffe plot method is not as efficient and practical as the two-voltage method because it took longer time for measurement.

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