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Ion recombination corrections factor in flattening filter-free and conventional photon radiation

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[Abstract]

Objective: To investigate the relationships between p_{ion} and different parameters includes calculation methods, choices of bias voltage, beam energies, dose rate, depth, different type of chamber and electrometers.

Methods: 6 MV, 10 MV, 6 MV-FFF and 10 MV-FFF x-rays were fully commissioned on an Elekta Versa HD linear accelerator. First part of this work is to investigate methods to calculate the p_{ion} values. The p_{ion} values for beams were measured at source-to-surface distances (SSD) of 100 cm in a water tank phantom at a depth of 5.2 cm for 6 MV and 6 MV-FFF beams and 10.2 cm for 10 MV and 10 MV-FFF beams in a 10 * 10 cm² field. The results are calculated by ‘two-voltage’ method and with 1/V versus 1/Q curves (‘Jaffé-plots’ method) in different energies and different bias voltage pairs to find suitable bias voltage pairs for p_{ion} calculation. Second part, this work discusses the relationships between p_{ion} and factors of dose rate, energy, types of chamber and electrometer. At last, this paper discussed the relationships of p_{ion} and

depth in water phantom and if we need to introduce ion recombination correction factor in percentage depth dose curve measurements.

Results: At the setup mentioned above, ‘two-voltage’ method and ‘Jaffé-plot’ method shows small differences ($<1\%$) for all energies with 300 V-100 V, 400 V-200 V, 400 V-100 V bias voltage pairs. All results for different chambers and vendors for all energies were within 2% from the unity ($1 \leq p_{ion} < 1.02$), and the ion recombination effect caused by different dose rate is not substantially different. The factor changes more than 2% in different depth for 10 MV-FFF beams.

Conclusion: We recommended a thoroughly p_{ion} measurement in commissioning and quality assurance procedure.

Key words: Ionization recombination correction, Versa HD, Percentage depth dose, Two-voltage method

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1. Introduction:

Flattening Filter-Free (FFF) X-ray beam has been used in clinical practice for some recently produced linear accelerators. Elekta Versa HDTM, which has traditional flattened beams, but also offers FFF photon beams up to 1400 MU/minutes for 6 MV

X-rays and 2200 MU/minutes for 10 MV x-rays. FFF high dose rate x-ray beams delivery technique has obvious advantages in organ motion management. For example, with FFF beams, large MUs can be delivered in short beam-on time within a single breath-hold or gated portion of a breathing cycle. This technique improves patients comfort and dose delivery accuracy and it becomes necessary for SBRT/SRS treatments now.^[1]

When commissioning Linear accelerator, ionization chamber has always been used when calibration absolute dose and collecting PDD curve and profile. According to TG-51 report the fully corrected charge reading from an ion chamber, M , is given by

$$M = P_{ion} * P_{TP} * P_{elec} * P_{pol} * M_{raw} \quad (1)$$

Where p_{ion} corrects for ion recombination effect. According to Attix, ion recombination effect consists of two parts, initial recombination occurs when the positive and negative ions formed in the same charged-particle track encounter and recombine, therefore it is independent of dose or dose rate and general recombination occurs when ions from different tracks meet each other and recombine on their way to the collecting electrodes and it is dose-rate-dependent. Ionization chamber's reading is minified by ion recombination effect by collecting less charge in the chamber no matter by initial recombination or general recombination.^[2] Therefore, reading of ionization chamber need to be corrects by p_{ion} and also other factor. In this study, we mainly focus on discussing p_{ion} value.

‘Two-voltage’ method

TG-51 published in 1999 suggests that p_{ion} is a function of dose rate and it should

be less than 1.05 and for measuring p_{ion} . TG-51 suggest a ‘two-voltage’ method when determining the corrected charge reading. For pulsed or pulsed-swept beams

$$\text{with } p_{ion} < 1.05, P_{ion} = \frac{1 - V_H / V_L}{M_{raw}^H / M_{raw}^L - V_H / V_L} \quad (2)$$

Although the exact equations for pulsed or pulsed-swept beams are nonlinear, this equation gives 0.2% differences when the voltage ratio to 2 and 0.3% when the bias-voltage ratio to 3 according to TG-51 report. [3]

Since TG-51 was written in 1999 and the accelerator’s ability of giving high dose rate beams increases since then, so it is essential for us to re-evaluate the validation of TG-51 recommended ‘two-voltage’ method in measuring p_{ion} factors. Furthermore, if p_{ion} changes significantly in different position in radiation field and under different setup condition. We may need to re-evaluate our method of collecting PDD and profile when commissioning accelerator.

‘Jaffé-plot’ method

Stephen F.Kry and etc. and Attix introduced a method called Jaffé-plot.[4] They assume that the relationship between one over the voltage bias adding to ion-chamber ($1/V$) and one over the charge reading ($1/Q$) are linear. They assume that it is a better method for p_{ion} calculation. In this case, we want to evaluate the accuracy of TG-51 recommended ‘two-voltage’ method by comparing it with ‘Jaffe-plot’ method in different set-ups.

The present work gives a partial discussion of the photon ionization recombination effect, this work aims at giving a thorough analysis of this effect.

89

90 **2. Methods and materials:**

91 The purpose of this work is to investigate the relationships between p_{ion} and different
92 parameters (calculation methods, bias voltage, beam energy, dose rate, depth, different
93 type of chamber and electrometers). We separate our experiments in 3 parts which are:

94 1. Verify the validity of the TG-51 ‘two-voltage’ method using ‘Jaffé-plot’ method and
95 find the suitable bias voltage for p_{ion} measurement.

96 2. Discuss the relationships between p_{ion} and factors of dose rate, types of chamber
97 and electrometer.

98 3. Discuss the relationships between p_{ion} and depth in phantom.

99

100 Four kinds of chambers are used in this study. FC65-G from Scanditronix–Wellhofer,
101 the plane-parallel Roos (type 34001) chamber from PTW, CC13 and Razor diode
102 (formerly known as CC01) chamber from IBA were used in this study. The FC65-G
103 chamber is a vented cylindrical Farmer-type ionization chamber with a volume of 0.65
104 cm³, IBA CC13 chamber is an ionization chamber with active volume of 0.13 cm³
105 and IBA Razor diode is a diode with active volume of 0.13 cm³. Three kinds of
106 electrometers are used in this study. IBA Dose2 electrometer is a Dual-Channel
107 reference class Electrometer, PTW Unidose electrometer is also a reference class
108 electrometer and standard imaging CDX-2000B electrometer are all used in this study
109 to compare the differences between chambers and electrometers.

110

Measurements were carried out on an Elekta Versa HD linear accelerator using photon energies: 6 MV, 10 MV, 6 MV FFF and 10 MV FFF (TPR20/10=0.686, 0.738, 0.679 and 0.726, respectively).

3. Theory:

According to Attix, ionization recombination effect consists of two parts, which is initial recombination and general recombination [2], for initial recombination effect, Boag(1966,1986) [5] introduced Jaffé-Zanstra theory [6] for calculate it mathematically, which is the theoretical basis of ‘Jaffé-plot’ method.

Jeffre-Zanstra theory predicts that:

$$\frac{1}{Q_1} = \frac{1}{Q} + \frac{c}{V} \quad (3)$$

Where c is a constant of the chamber and is independent of p_{ion} calculation and V is the applied bias voltage on chamber.

The reason behind this is that collection efficiency f in short pulses can be written as:

$$f = \frac{1}{u} \ln(1+u) \quad (4)$$

Where

$$u = \frac{\alpha / e}{k_1 + k_2} \cdot \frac{\rho d^2}{V} \quad (5)$$

in which ρ is the initial charge density created per pulse, d is the electrode spacing,

for cylindrical or spherical chambers d is to be replaced by $(a-b)K$, V is the voltage

applied on chamber, $\frac{\alpha / e}{k_1 + k_2}$ is a constant based on chambers. Define $\gamma = f \cdot u$, we can

rewrite equation (4) as :

$$f = \frac{\gamma}{e^{\gamma} - 1} \quad (6)$$

Then we can simplify equation (6) in chambers we used by Taylor expansion as an approximation as:

$$f = \frac{1}{1 + 0.5\gamma} \quad (7)$$

Then it can be written as equation (1) as in the experiment set-up, f is close to 1 and γ can be approximately replaced by u in equation (7).

The initial recombination factor can be found from ‘Jaffé-plot’ method, which is plot the relationship between one over the voltage bias adding to ion-chamber ($1/V$) and one over the charge reading ($1/Q$) and illustrating the extrapolation of $1/Q$ vs. $1/V$ to $1/V = 0$, yielding $1/Q$, and by ‘Jaffé-plot’ method, we can also find the ion recombination corrections factor in any bias voltage. In this case, by comparing the p_{ion} calculated by ‘two-voltage’ method and ‘Jaffé-plot’ method, we can evaluate the validation of ‘two-voltage’ method under different setups.

Experiment set-ups:

First part of this study is to Verify the validity of the TG-51 ‘two-voltage’ method using ‘Jaffé-plot’ method and find the suitable bias voltage pairs for p_{ion} measurement. For this experiment, we want to simulate the condition as we are doing dose calibration. The measurement set-ups are shown in Table.1. at SSD = 100 cm, field size at 10 *10 cm² as TG-51 recommendation.

Table. 1 Measurement Conditions for ‘Two-voltage’ method

Instruments	Bias voltages	Energies	Measurement Depth	Dose rate
<u>LINAC: VersaHD.</u>	100 V, 150 V,	6 MV	5.2 cm	300 MU/min
<u>Water phantom:</u>	200 V, 300 V,	10 MV	10.2 cm	300 MU/min
<u>Bluephantom2.</u>	400 V, 500 V.	6 MV FFF	5.2 cm	700 MU/min
<u>Electrometer: Dose2.</u>		10 MV FFF	10.2 cm	1100 MU/min
<u>Ion chamber: FC65-G.</u>				

Under each measurement condition, charge collected should be measured three times and record the average charge and deviation to reduce noise and all p_{ion} factor under different voltage was calculated by ‘two-voltage’ method and ‘Jaffé-plot’ method respectively.

Second part of this study is discussing the relationships between p_{ion} and dose rate, types of chamber and electrometers. p_{ion} factors were calculated for each energy in dose rate at: up to 700 MU/min for 6 MV and 10 MV photon beams and up to 1400 MU/min for 6 MV FFF photon beams and up to 2200 MU/min for 10 MV FFF photon beams using FC65-G chamber and IBA Dose2 electrometer. p_{ion} factors were calculated by data collected by CC01, CC13, FC65-G and PTW parallel plane chamber at set-ups in Table.1 at SSD = 100 cm, field size at 10 *10 cm² as TG-51 recommendation for each energy. The electrometer used in this experiment is IBA Dose2. The bias voltage is 300 V-100 V and p_{ion} factors were calculated by ‘two-voltage’ method. Then compare the differences between different p_{ion} factors collected by different chambers. p_{ion} factors were determined by data collected by IBA Dose2, PTW Unidose and Standard-imaging CDX-2000B electrometers separately in

each energy at set-ups in Table.1 at SSD = 100 cm, field size at 10 *10 cm² as TG-51 recommendation for each energies. The bias voltage is 300 V-100 V using FC65-G ion chamber and p_{ion} factors were calculated by ‘two-voltage’ method.

Third part of this study is discussing the relationships between p_{ion} and depth in water phantom. p_{ion} factors were collected in different depth under water up to 30 cm at SSD = 100 cm, field size 10 *10 cm² with CC13 ion chamber and IBA Dose2 electrometer. Dmax of different energies (1.62 cm for 6 MV, 2.22 cm for 10 MV, 1.74 cm for 6 MV-FFF and 2.34 cm for 10 MV-FFF beams) were measured additionally.

4. Results

4.1 Verify the validity of the TG-51 ‘two-voltage’ method using ‘Jaffé-plot’ method

and find the suitable bias voltage pairs for p_{ion} factors measurement.

Good repeatability was observed for all charges measurements. Correspondingly, the results show consistent p_{ion} values, varying no more than 0.3% for all measurement under same set-ups. Standard deviations of all measurements are smaller than 0.3%.

Results of readings of electrometers at different voltage are shown in Table.2.

Table.2 Charge collected (nC) at different bias voltage.

Bias voltage (V)	Energy			
	6 MV	10 MV	6 MV-FFF	10 MV-FFF
100	18.09±0.02	15.02±0.02	17.85±0.02	14.69±0.03
150	18.15±0.01	15.11±0.02	18.00±0.03	14.88±0.01
200	18.18±0.02	15.14±0.01	18.08±0.02	14.99±0.03
300	18.22±0.01	15.19±0.02	18.17±0.03	15.09±0.03
400	18.24±0.01	15.21±0.02	18.21±0.02	15.14±0.02
500	18.27±0.01	15.24±0.01	18.26±0.02	15.17±0.02

Using Table.2, any two bias voltage pairs under the same beam energy can be used to calculate p_{ion} factors of that beam by ‘two-voltage’ method mentioned above. Using Equation.2, the p_{ion} factors calculated by these ‘Two-voltage’ pairs are shown in Table.3. To verify the validity of ‘two-voltage’ method, the $1/Q$ versus $1/V$ curve were plotted in Figure.1. Since the measured signal showed a good linear relationship between $1/Q$ versus $1/V$, linear best-fit lines were extrapolated to $1/V = 0$ to find the value of no recombination condition and were shown on Figure.1. The p_{ion} factors calculated by ‘Jaffé-plot’ method are shown in Table.4.

Table.3 P_{ion} results calculated from different bias voltage pairs for different energies.

Bias voltage pairs	Energy			
	<i>6 MV</i>	<i>10 MV</i>	<i>6 MV-FFF</i>	<i>10 MV-FFF</i>
100 V-200 V	1.005	1.008	1.013	1.021
150 V-200 V	1.002	1.002	1.004	1.007
100 V-300 V	1.004	1.006	1.009	1.014
150 V-300 V	1.004	1.005	1.010	1.014
200 V-300 V	1.004	1.007	1.010	1.014
100 V-400 V	1.003	1.004	1.007	1.010
150 V-400 V	1.003	1.004	1.007	1.011
200 V-400 V	1.003	1.005	1.007	1.010
300 V-400 V	1.003	1.004	1.007	1.010
100 V-500 V	1.002	1.004	1.006	1.008
150 V-500 V	1.003	1.004	1.006	1.008
200 V-500 V	1.003	1.005	1.007	1.008
300 V-500 V	1.004	1.005	1.007	1.008
400 V-500 V	1.007	1.008	1.011	1.008

Figure.1 Plot of $1/V$ vs. $1/Q$ of different beam energies.

(a) 6 MV (b) 10 MV (c) 6 MV-FFF (d) 10 MV-FFF

Table.4 P_{ion} calculated by 'Jaffé-plot' method.

Voltage	Energy			
	6 MV	10 MV	6 MV-FFF	10 MV-FFF
200 V	1.007	1.009	1.015	1.020
300 V	1.004	1.006	1.010	1.013
400 V	1.003	1.005	1.007	1.010
500 V	1.002	1.003	1.005	1.008

Since we assume that 'Jaffé-plot' method is a validate method to calculate p_{ion} factors.

'Two voltage' method, however, is easy to operate in clinic, so we want to find the

suitable bias voltage pairs for all energies by compare Table.2 and Table.4.

100 V-300 V, 200 V-300 V, 100 V-400 V, 150 V- 400 V, 200 V-400 V, 300 V-400 V are the bias voltage pairs that have less than 0.1% differences between two methods, we define all these bias voltage pairs as ‘suitable bias voltage pairs’. 100 V-300 V bias voltage pair shows few differences between two methods. In this case, we select 100 V-300 V bias voltage pair for further measurement and discussion.

4.2 Discuss the relationships between p_{ion} factors and dose rate, types of ion chambers and electrometers.

Results of p_{ion} factors vs. dose rate are shown in Figure.2. p_{ion} factors vs. different chambers are shown in Table.5 and p_{ion} factors vs. different electrometers are shown in Table.6.

Figure.2 P_{ion} factors vs. dose rate

Table. 5 P_{ion} factors vs. types of chamber

Types of chamber	Energy			
	6 MV	10 MV	6 MV-FFF	10 MV-FFF
CC01	1.005	1.008	1.005	1.011
FC65	1.004	1.006	1.009	1.014
CC13	1.005	1.007	1.011	1.016
Parallel-plate chamber	1.005	1.009	1.006	1.011

Table.6 P_{ion} factors vs. electrometers

Bias Voltage	Energy			
	6 MV	10 MV	6 MV-FFF	10 MV-FFF
Dose2	1.004	1.006	1.009	1.014
Uni-Dose	1.003	1.006	1.009	1.014

Standard-Image	1.002	1.004	1.005	1.007
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4.3 Discuss the relationships between p_{ion} factors and depth in phantom (under water)

The results of this part are shown in Figure.3

Figure.3 P_{ion} value vs. Measurement depth.

5. Discussion

‘Jaffé-plot’ method is more convincing than ‘two-voltage’ method in our opinion is that not only because we discussed the theory of this method above, but also it can plot the function of $1/V$ and $1/Q$ by several points instead of 2 points to determine the p_{ion} factors. Since the uncertainty in readings of electrometers and setups are minimal, the main uncertainty introduced in ‘two-voltage’ method appears to be the approximation used by this method (approximate 0.2%). We can also find from Table.2 that FFF beams have larger uncertainty than traditional flattened beams which shows same results as Kry et al ^[4] and has been discussed by them that this larger uncertainty in FFF beams is

because of potential partial volume effects. As we mentioned above, ‘Jaffé-plot’ method is more convincing than ‘two-voltage’ method. However, ‘Jaffé-plot’ method is hard to operate than TG-51 recommended ‘two-voltage’ method. In this case, we want to find the bias voltage pairs when they show good consistency to use ‘two-voltage’ method ‘Jaffé-plot’ method. In our study, for all beams and ion chambers, p_{ion} factors was well described with the two-voltage method. Under our bias voltage pair (100 V-300 V), the p_{ion} factor agreed within 0.1% with ‘Jaffé-plot’ method. If the choice of the bias voltage pair is inappropriate, the differences between these two methods can be as larger as 1.25% which is hard to accept. Correspondingly, we conclude that ‘two-voltage’ is validate in p_{ion} factor calculation only if we choose the ‘validate bias voltage pairs’ mentioned above or other bias voltage pairs which also show good consistency between these two methods.

The ion recombination effect caused by different dose rate is not substantially different. Attix ^[2] concluded that higher dose rate will cause higher p_{ion} values. By his theory, the p_{ion} values will change as the dose rate changes in same energy photon beams, but we have the opposite results as his hypothesis in Table.2. Before experiment, we imagine that p_{ion} factors should increase as dose rate increases since ion in chamber has more chance to collide and recombine if the number of ion in the chamber increases. It shows no relationships, however. We assume that the reason of which is that Elekta Versa HD changes dose rate by changing number of pulses instead of changing dose

per pulse. Since the dose per pulse did not change when adjust dose rate, it shows no correlation between p_{ion} factors and dose rate.

The differences of p_{ion} factors between different chamber and electrometers are less than 1% for each energy. All chamber and electrometers that show on this study can be used for absolute or relative dose measurement. Although differences are minimal, but we still recommend a p_{ion} factors measurement on each chamber before measuring dose.

The differences of p_{ion} factors on different depth in water changes more than 2% in different depth for 10 MV-FFF beams, more than 1% in different depth for 6 MV-FFF beams and less than 1% for 10 MV and 6 MV photon beams.

In our setup, the p_{ion} factor changes more than 1% when the measurement depth in water changes in FFF beams which cannot be ignore in clinic because if we have larger than 1% differences in data collection for TPS or instrument commissioning in the first place, it will cause larger variation in treatment. When treat the patients, more uncertainty maybe introduced in the system and it may cause more than 5% differences than we planned in the TPS, which is unacceptable. Therefore, we recommended a thoroughly p_{ion} measurement in commissioning and quality assurance procedure.

Previous works gives a partial discussion of the photon ionization recombination effect, this work aims at giving a thorough analysis of this effect and give recommendations in different conditions.

6. Conclusion

TG-51 recommended ‘two-voltage’ method is still a validate method for high dose rate flattening filter free radiation beams. p_{ion} factors changes minimal when dose rate, chamber and electrometer changes but it changes due to depth in water. We recommend a thoroughly p_{ion} measurement in commissioning and quality assurance procedure.

7. Declaration

7.1 Ethics approval and consent to participate

This manuscript doesn’t report on or involve the use of any animal or human data or tissue so that this section is not applicable.

7.2 Consent for publication

This manuscript does not contain data from any individual person, hence this section is not applicable.

7.3 Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

7.4 Competing interests

The authors declare that they have no competing interests.

7.5 Funding

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7.6 Authors' contributions

Bo Yang performed most of the experiments and wrote the manuscript; Zhiquan Wang and Bei Wang performed some experiments and provided the discussion. Xia Liu and Rui Li provided the discussion and materials. Xiao Liu wrote and edited the manuscript; Fuquan Zhang and Jie Qiu conceived the presented idea, designed experiments, wrote research grant. All authors read and approved the final manuscript.

7.7 Acknowledgements

Not applicable

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Figures

Figure 1

Plot of $1/V$ vs. $1/Q$ of different beam energies. (a) 6 MV (b) 10 MV (c) 6 MV-FFF (d) 10 MV-FFF

Figure 2

P ion factors vs. dose rate

Figure 3

P ion value vs. Measurement depth.