



Original paper

Assessment of ion recombination correction and polarity effects for specific ionization chambers in flattening-filter-free photon beams

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ABSTRACT

Purpose: To investigate ion recombination correction and polarity effects in four ion chamber models in flattening-filter-free (FFF) beams to (1) evaluate their suitability for reference dosimetry; (2) assess the accuracy of the two-voltage technique (TVA) against the Bruggmoser formalism; and (3) examine the influence of the accelerator type on the recombination correction.

Methods: Jaffé plots were created for a variety of microchambers, small-volume and Farmer-type chambers to obtain k_S , the recombination correction factor, using two different types of accelerators. These values were plotted against dose-per-pulse and Jaffé plots for opposite polarities were created to determine which chambers meet the AAPM TG-51 addendum recombination and polarity specifications.

Results: Nearly all small-volume chambers exhibited reference-class behavior with respect to ion recombination and polarity effects. The microchambers exhibited anomalous recombination and polarity effects, precluding their use for reference dosimetry in FFF beams. For the reference-class chambers, agreement between TVA-determined k_S values and Jaffé and Bruggmoser formalisms-determined k_S values was within 0.1%. No significant differences were found between the k_S values obtained with the two different accelerators used in this work.

Conclusions: This study stresses the need to characterize ion recombination correction and polarity effects for small-volume chambers and microchambers on an individual chamber basis and with the more rigorous criteria of the AAPM TG-51 addendum. Furthermore, the study demonstrated the suitability of the TVA method for chambers that exhibit reference-class behavior in FFF beams. Finally, this work has shown that the recombination correction does not depend on the type of accelerator but on its dose-per-pulse.

1. Introduction

High dose rate flattening-filter-free (FFF) beams are becoming increasingly popular, especially with the advent of volumetric modulated arc therapy (VMAT) techniques in radiotherapy. Despite providing several clinical advantages over conventional beams with flattening filter, FFF beams also require particular considerations regarding accurate reference dosimetry [1] due to differences in the beam quality, dose-per-pulse and profile shape. The new IAEA/AAPM TRS-483 dosimetry protocol [2] includes recommendations for FFF beam dosimetry, as does the American Association of Physicists in Medicine's (AAPM) report on FFF accelerators [3]. Recombination effects in these higher dose-per-pulse beams, are of particular interest in this study; the raised dose-per-pulse results in increased ion recombination and a larger correction factor is therefore required [3]. Concerning this matter, the

AAPM TG-51 (hereinafter, TG-51) addendum [4] noted that, at least for one type of FFF linac, the ion recombination correction was consistent with the correction for linacs with flattening filter [5]. Despite evidence that beam filtering has no impact on the determination of ion recombination correction [6], the possible impact of multiple commercial implementations of FFF technology, which may use very different subsystems and components for dose delivery [1,3,7], has not yet been addressed in a quantitative way.

Regarding the current methods used to account for ion recombination effects in FFF beams, several groups [5,8–12] have demonstrated that the ion recombination correction factor k_S (or P_{ion} equivalent factor in the TG-51 protocol), determined by the TVA method, offers an accuracy comparable to that of conventional flattened beams. However, despite the TG-51 and TRS-398/483 protocols recommending the TVA method, several authors [13–15] have challenged the suitability of this

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technique for accurately determining the ion recombination correction. The TG-51 addendum report [4] recommends characterization at different polarizing voltages and DPP ranges (e.g., as described by Bruggmoser et al. [16] and Palmans et al. [17]) as part of the ionization chamber commissioning. The objectives of such a rigorous characterization are to assess the suitability of the chamber for reference dosimetry measurements and ability to accurately determine the recombination correction. This is particularly relevant in FFF linacs, whose high dose-per-pulse values result in large ion recombination effects; special care is therefore required for accurate determination of the recombination correction for such linacs.

The formalism of Bruggmoser et al. [16] is based on the experimental determination of chamber-type-specific coefficients. According to this formalism, if a given chamber is well characterized in terms of the variation in k_S versus DPP and if the DPP of the beam is known, the determination of k_S by using reported values of Bruggmoser coefficients for that chamber model should be straightforward [16]. However, several researchers [18,12] have reported discrepancies between the Bruggmoser coefficients obtained in their works and those published in the literature for certain cylindrical chambers. These researchers suggested that such discrepancies were likely due to chamber-to-chamber variations, different ranges of DPP values and polarity effects, indicating that further research should be performed to show whether these factors caused the discrepancies. Furthermore, while Kry et al. [5] have shown that compared with Jaffé plots, the TVA method in FFF beams is accurate within 0.3% for Farmer-type chambers, to the authors' knowledge, no similar work has been conducted to benchmark the accuracy of this technique in FFF linacs against a more detailed method, such as the Bruggmoser formalism.

Furthermore, the TG-51 addendum [4] and TRS-483 [2] protocols recommend that a short collecting volume chamber be used for reference dosimetry in FFF beams due to the possibility of underestimating the dose at the central axis with Farmer-type chambers [19,20]. Alternatively, a correction must be applied to take into account the volume averaging effects [4]. However, the suitability of small-volume chambers as reference-class detectors is unclear due to their well-documented anomalous polarity and recombination effects in conventional photon beams [4,18,21–24]. In fact, the TG-51 addendum does not recommend the use of ion chambers with measuring volumes less than 0.05 cm³ [3] (microchambers). These factors may be the reasons why Farmer-type chambers remain the most common choice for reference dosimetry of photon beams [25]. Moreover, a calibration certificate is usually provided with the purchase of small-volume chambers and microchambers, which could be problematic, as chambers with calibration certificates can potentially be used for reference dosimetry. In this context, several groups [6,8,12,26] have investigated ion recombination and polarity effects for small-volume chambers and microchambers, demonstrating the suitability of certain chamber models for reference dosimetry in FFF beams. Nevertheless, several groups have shown that the recombination correction can be polarity-dependent for small-volume chambers, giving rise to the incorrect calculation of k_S values [18,27]. The sources of such an effect have been described in the literature [28,29] in terms of the voltage-dependent polarity effect. The main cause of the voltage-dependent polarity effect is the distortions of the electric field lines in the sensitive volume of the

chamber due to the small potential difference between the guard and the inner collecting electrode. As a consequence, the effective collecting volume, as defined by the electric field lines within the air cavity, is modified, yielding an altered dose response [29]. Miller et al. [30] recently investigated this effect for cylindrical chambers, showing that its magnitude is inversely proportional to the volume of the chamber. Furthermore, the authors showed that there is a volume threshold, which is on the order of the volume of the microchambers, below which the voltage-dependent polarity effects may be significant. They proposed that certain simple measurements could be performed to determine whether such effects occur.

Based on these factors, the motivations of this work were multifold: to determine the accuracy of the TVA method for FFF beams by comparison with the Bruggmoser formalism and to determine whether the coefficients of the Bruggmoser formalism can be used as reference values to determine the recombination correction for single chambers of the same chamber model. Furthermore, two different linacs with FFF capabilities (Siemens Artiste and Elekta Versa HD) were used in this work to address the possible impact of the accelerator type.

Finally, the need to identify current models of small-volume chambers and microchambers suitable for reference dosimetry in FFF beams is also addressed in this study. For this purpose, two models of such chambers (the small-volume Semiflex PTW 31010 and the PinPoint PTW 31016 microchamber) were investigated in this work. Moreover, the new small-volume chamber model Semiflex PTW 31021 and the PTW 30013 Farmer-type chamber were also included in this work to better support the findings of this investigation.

2. Materials and methods

2.1. Chamber types

A total of nine ion chambers were evaluated in this work: three Farmer-type (PTW 30013 with SN 008681, 003265 and 001376), four small-volume Semiflex-type (two PTW 31010 with SN 002003 and 001051 and two PTW 31021 with SN 142013 and 141866), and two microchamber-type (PinPoint PTW 31016 with SN 000187 and 000189) chambers, all from the same manufacturer (PTW GmbH, Freiburg, Germany). These chambers were grouped according to their model and active volume, the latter being the main factor affecting the results of this investigation. The classifications of the chambers investigated here and additional parameters are summarized in Table 1.

2.2. Measurements in flattened and unflattened photon beams

The study was conducted at two different institutions. The measurements at Institution 1 were carried out on a Siemens Artiste linear accelerator (Siemens AG, Erlangen, Germany), hereafter referred to as the Artiste linac, using two X-ray beams with nominal energies of 6 MV and 7 MV FFF. The measurements at Institution 2 were collected with an Elekta Versa HD linear accelerator (Elekta Instrument AB, Stockholm, Sweden), hereafter referred to as the Versa linac, using 5 different photon beams with nominal energies of 6 MV, 6 MV FFF, 10 MV, 10 MV FFF and 15 MV. The beam characteristics of these linacs are listed in Table 2.

Table 1

Ion chamber characteristics according to the manufacturer's specifications.[31] The nominal voltage refers to the voltage of operation for each chamber recommended by the manufacturer. * Pinpoint 31016 chamber is out of production from 2018.

	PTW Farmer 30013	PTW Semiflex 31010	PTW Semiflex 31021	PTW PinPoint 31016*
Nominal volume	0.6 cm ³	0.125 cm ³	0.07 cm ³	0.016 cm ³
Length of sensitive volume	23.0 mm	6.5 mm	4.8 mm	2.9 mm
Radius of sensitive volume	3.05 mm	2.75 mm	2.4 mm	1.45 mm
Collection time	140 μs	121 μs	118 μs	60 μs
Nominal voltage	400 V	400 V	400 V	400 V

Table 2

Beam characteristics of the Artiste and Versa linacs used in this work. All dosimetric quantities are given for a $10 \times 10 \text{ cm}^2$ field at 100 cm source-to-surface distance (SSD).

	Versa linac					Artiste linac	
	6 MV FFF	10 MV FFF	6 MV	10 MV	15 MV	7 MV FFF	6 MV
Nominal energy (MV)	6 MV FFF	10 MV FFF	6 MV	10 MV	15 MV	7 MV FFF	6 MV
Nominal dose rate (MU/min)	1200	2000	470	390	470	2000	300
Measured PRF (Hz)	400	303	400	200	199	221	221
Dose per pulse on beam axis at d_{max} (mGy/pulse)	0.63	1.21	0.23	0.35	0.44	1.5	0.23
d_{max} (cm)	1.7	2.5	1.5	2	2.7	1.8	1.6

All measurements were performed at the nominal dose rates used for clinical treatments (see Table 2). Measurements in the Artiste linac were performed in a water phantom (MP1, PTW-Freiburg) with dimensions $32 \text{ cm} \times 32 \text{ cm} \times 37 \text{ cm}$ using a vertical geometry. An electrometer (TANDEM dual channel, PTW-Freiburg) with the ability to measure the collected charge was used to supply polarizing voltages from 150 to 400 V in steps of 50 V, in accordance with the manufacturer-stated limits. Furthermore, measurements in the Versa linac were performed using a water phantom (RFA-300, Scanditronix Wellhöfer) with dimensions $58 \text{ cm} \times 61.4 \text{ cm} \times 58 \text{ cm}$ using a vertical geometry. An electrometer (PTW UNIDOS® E, PTW-Freiburg) was used to supply the same range of voltages used for the measurements in the Artiste linac. A calibration factor ($k_{\text{elec}} = 1.000$) with deviations below 0.5% in all ranges was given for both electrometers by the calibration laboratory, which was traceable to standards of the German National Laboratory (PTB).

For the measurements of the recombination correction factor k_S in both linacs, the ionization chambers were positioned in the water phantom perpendicular to the beam axis and centered at the depth of the maximum dose, and the nominal field size was set to $10 \times 10 \text{ cm}$ [2]. All chambers were preirradiated for a sufficient time to achieve a stable reading. Special considerations were made to account for the small-volume chambers and microchambers, as these chambers require a longer irradiation time to ensure an equilibrium reading [18]. Leakage currents were measured before and after irradiation for all chambers, were always less than 0.1% of the measurement current, and had the same sign as the measurement current. Variations in the accelerator output were considered using an external monitor chamber, which was positioned at a measurement depth of approximately 4 cm lateral to the chamber being tested, as recommended in the IAEA TRS-398 Code of Practice [32]. The convention of the polarity setting used in this work was as follows: positive polarity refers to positive charge collection at the inner collecting electrode, and negative polarity refers to negative charge collection at this electrode.

2.3. Pulse repetition frequency of the linacs

To safely assume that the total ionization per pulse occurs instantaneously and that the ions produced by each pulse are collected before the onset of the next pulse, the pause time between the radiation pulses of the linac must be greater than the ion collection time of the ionization chamber under study [33].

The interval between pulses for both linacs ranged from 2.5 to 5 ms and was large enough relative to the ion collection time of the ionization chambers, which is 60–140 μs according to the manufacturer's specifications [31].

The pulse repetition frequency (PRF) for all photon energies was measured with an oscilloscope by taking the output signal of the linacs. The PRF measured values for both linacs are listed in Table 2.

2.4. Dose-per-pulse

The DPP was varied between approximately 0.2 and 1.8 mGy/pulse for both linacs. Different values of the DPP were obtained varying the SSD from 60 to 130 cm and the energy of the linacs. The measurements

were performed using the methodology described in Section 2.2, with a PTW 30013 Farmer calibrated chamber and a Semiflex PTW 31010 chamber as an external monitor chamber to normalize variations in linac output.

The DPP was obtained after integrating the dose over 10 s and dividing by the number of pulses within that time:

$$\text{DPP} = \frac{D_w}{N_p}, \quad (1)$$

where D_w is the absorbed dose to water and N_p ($N_p = \text{PRF} \cdot t$) is the number of pulses. In this case, t is the integration time of the reading.

2.5. Measurement of the recombination correction factor k_S

2.5.1. Determination of k_S by the two-voltage analysis (TVA) method

The simplified TVA method recommended by the TRS-398 Code of Practice [32] and AAPM TG-51 protocol [34] was used to determine the recombination correction factor k_S for all ionization chambers evaluated in this work. The TG-51 protocol [34] recommends a limit value of 1.05 for the correction factor for which the simplified TVA method is appropriate.

2.5.2. Determination of k_S by the Jaffé plot method (multivoltage analysis)

The inverses of the readings, $1/M$, versus the inverse chamber voltages, $1/V$, known as Jaffé plots or multivoltage analysis (MVA), were measured for the chambers discussed above for the range of DPP values used in this study. For every Jaffé plot, each measurement point represents the average of a minimum of three readings according to the methodology described in Section 2.2. All measurements were performed during positive charge collection by applying polarizing voltages (150, 200, 250, 300, 350, 400) V, and the sequence used was randomized to prevent bias in the obtained readings [18]. Differences in the charge readings, normalized to the external monitor chamber, between the first and last measurements (both at 150 V) were less than 0.05%, assuring no significant chamber drift.

Finally, the recombination correction factor k_S for every DPP value and chamber under test was determined from the Jaffé plots by extrapolating the $1/M$ readings to infinite voltage.

2.5.3. Determination of k_S by the formalism of Bruggmoser et al. [16]

Plots of the Jaffé-determined k_S values as a function of the DPP were created for the chambers with two objectives. The first objective was to compare the γ and δ coefficients obtained from these plots between the different linacs used in this work and to benchmark these coefficients with those published in the literature. The second objective was to investigate whether a single chamber meets the TG-51 addendum ion recombination specifications for reference dosimetry (i.e., the ion recombination correction factor should vary linearly with the DPP, and the initial recombination coefficient, the γ/V value in the Bruggmoser formalism, should be less than 0.2%). Coefficients and k_S values were obtained according to the following equation of Bruggmoser formalism [16]:

$$k_S = 1 + \frac{(\gamma + \delta \cdot \text{DPP})}{V}, \quad (2)$$

where the coefficients γ and δ are related to the initial and general recombination, respectively, DPP is the D_w per linac pulse, and V is the polarizing voltage of the ionization chamber. The γ and δ coefficients in Eq. (2) were determined from the linear fit parameters of the Jaffé-determined k_S versus DPP plots, where δ was taken from the slope of the straight line and γ from the intercept at zero DPP [16].

2.6. Measurement of the polarity effect

The polarity correction, as defined in TRS-398/TRS-483 and TG-51, was determined for all the chambers used in this work. Readings were taken once equilibrium was reached and a minimum 30-minute stabilization time was applied when the polarity was changed [18].

Additionally, Jaffé plots were created for opposite polarities at the nominal dose rates of the linacs used in this work for those chambers that were subject to polarity effects and showed potential ability for reference dosimetry, i.e., those small-volume chambers that met the TG-51 addendum polarity specification that is, the polarity correction should be within 0.4% of unity and vary by less than 0.5% for the total range of energies [4]. Miller et al. [30] proposed performing such measurements as an alternative to the time-consuming measurements required in the TG-51 addendum (plots of Jaffé-determined k_S values as a function of the DPP for opposite polarities) to determine whether the recombination correction is polarity-dependent.

2.7. Uncertainties

The combined standard uncertainty in the DPP was determined according to the ISO Guide on Uncertainty in Measurement [35]. In addition, the error propagation method and the LINEST function from Microsoft® Office EXCEL 2013 were utilized for uncertainty calculations. This EXCEL function determines the best linear fit to the data with the least squares method and provides the estimated uncertainty in the regression parameters. All values are given as one relative standard uncertainty, with a coverage factor $k = 1$.

3. Results

3.1. Jaffé-determined k_S factors

The Jaffé plots were linear for the Farmer and Semiflex chambers for all flattened and FFF beams used in this work. Fig. 1 (a) and (b) show Jaffé plots for the Farmer and Semiflex PTW 31010 chambers, respectively, for a variety of DPP values. The chamber-to-chamber variation in the Jaffé-determined k_S values for the Farmer and Semiflex

chambers was within type A uncertainty of measurements of less than 0.1% (given as one relative standard uncertainty with $k = 1$).

On the contrary, measurements with PinPoint chambers showed Jaffé plots that deviated greatly from a straight line for certain dose rates, as shown in Fig. 2(a). In this case, applying the TVA method for the 6 MV beam of the Artiste linac would not have been appropriate. However, this behavior was less obvious for the higher-DPP FFF beams, as previously reported for other microchamber models [12]. This behavior is illustrated in Fig. 2(b), which shows linear Jaffé plots for the PinPoint chambers in the 7 MV FFF beam of the Artiste linac. In addition, the chamber-to-chamber variation in the experimentally determined k_S values for these chambers was up to 0.5%, despite the chambers being from the same batch and year of manufacturing.

3.2. k_S factor as a function of the dose-per-pulse

Fig. 3 (a) and (b) show the linear fits of the k_S factor as a function of the DPP for similar ranges of DPP values for Farmer chambers measured in the Artiste and Versa linacs, respectively. Predictably, the Farmer chambers exhibited nearly ideal behavior, showing k_S values that vary linearly with the DPP. As a result, reliable fit parameters were obtained from these plots for the determination of the γ and δ coefficients of the Bruggmoser formalism. Furthermore, the intercepts of the fitted plots of Fig. 3 (a) and (b) yielded initial recombination coefficients, γ/V , within 0.2% of unity. Thus, the Farmer chambers used in this work meet the TG-51 addendum [4] requirements pertaining to the ion recombination effects for reference dosimetry in all evaluated flattened and FFF beams, confirming the results of previous studies [7,14,18,20,36].

Regarding the Semiflex chambers, Figs. 4 and 5 illustrate the variation in k_S as a function of the DPP values for the Semiflex PTW 31010 and PTW 31021 chambers, respectively, for similar ranges of the DPP. The linearity of the fits of these plots and the fact that the initial recombination values were within 0.2% of unity demonstrate that the Semiflex chambers also meet the TG-51 addendum's [4] requirements pertaining to recombination effects. Consequently, solid fit parameters were also obtained from these plots for the determination of the Bruggmoser coefficients.

For the PinPoint chambers, the fit of the k_S versus DPP plot corresponding to Fig. 6 resulted in data that substantially deviated from a straight line fit, and repeat measurements with the other PinPoint chamber yielded similar results. As a consequence, reliable linear fit parameters could not be obtained from these plots. Furthermore, because the specification for linearity between k_S and the DPP was not met, this chamber model could not be deemed suitable for reference dosimetry.

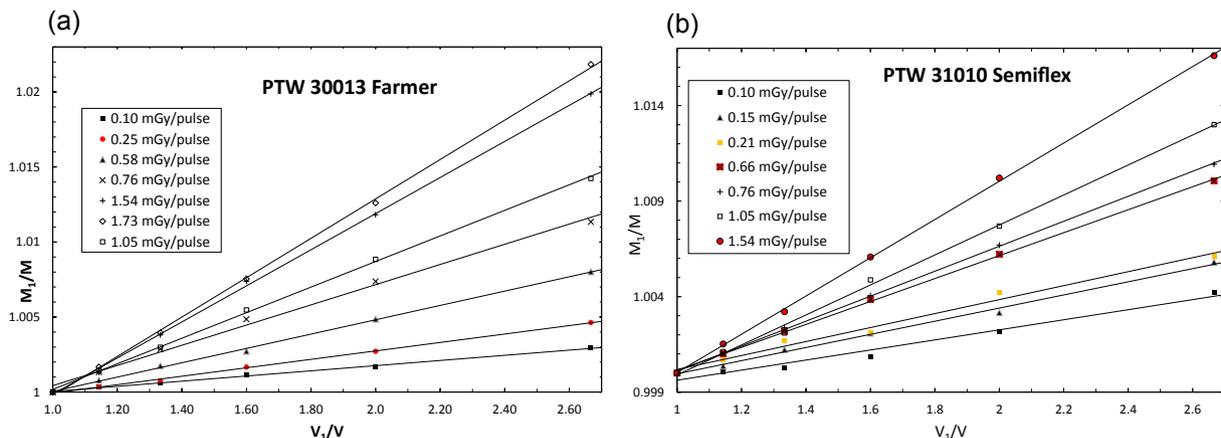


Fig. 1. Jaffé plots for a) a PTW 30013 Farmer chamber and b) a PTW 31010 Semiflex chamber. A variety of DPPs are shown, the chamber voltage varied between 150 and 400 V, and the axes are normalized to the usual voltage, V_1 (400 V), and the corresponding reading Q_1 .

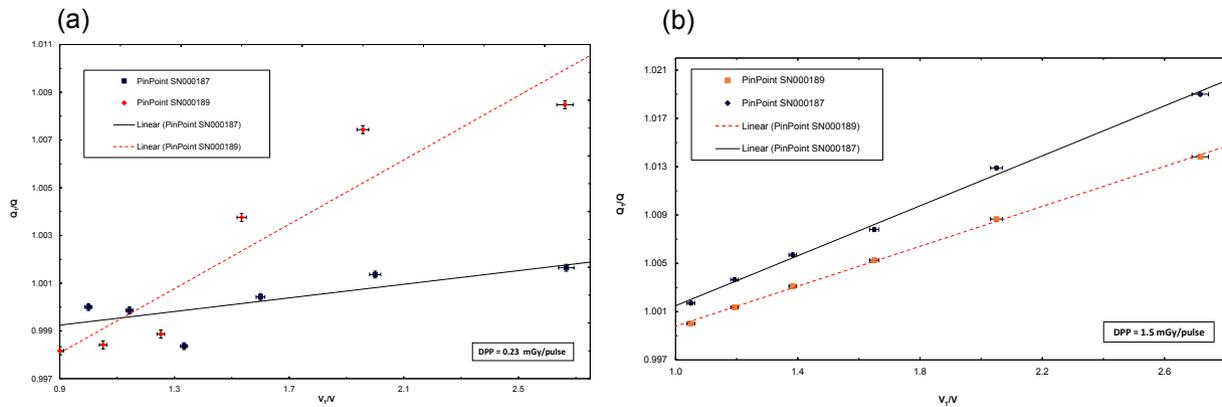


Fig. 2. Jaffé plots for PinPoint PTW 31016 microchambers with serial numbers 000187 and 000189 for a) the DPP of a 0.23 mGy/pulse of the 6 MV flattened beam of the Artiste linac and b) the DPP of a 1.5 mGy/pulse of the 7 MV FFF beam of the Artiste linac. A chamber voltage between 150 and 400 V was applied, and the axes are normalized to the usual voltage, V_1 (400 V), and the corresponding reading, Q_1 (uncertainty bars represent one standard deviation).

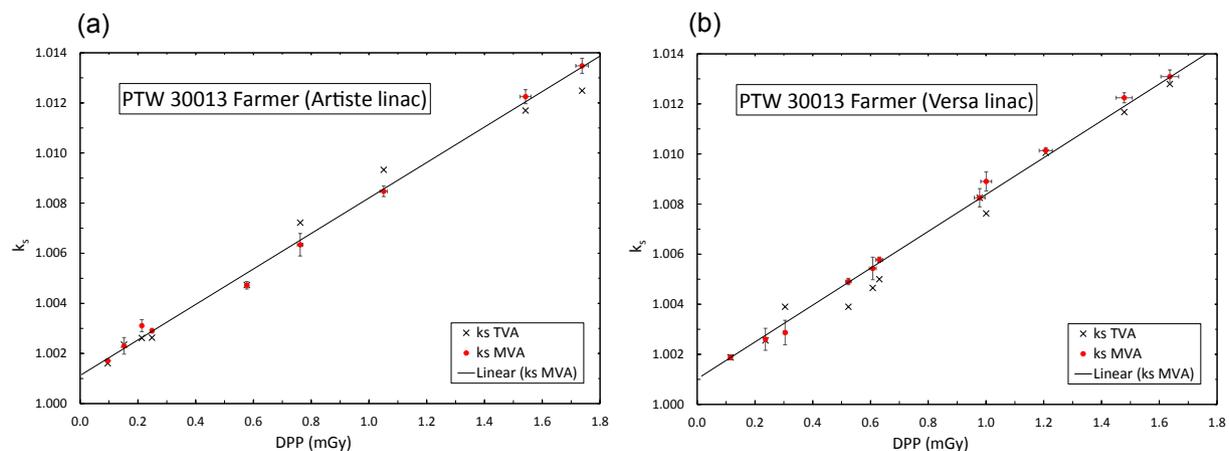


Fig. 3. Jaffé-determined k_s values as a function of the DPP for Farmer-type chambers (a) in the Artiste linac and (b) in the Versa linac. Data in Fig. 3 (a) are representative of the two Farmer chambers measured in the Artiste linac, as the chamber-to-chamber variation in the Jaffé-determined k_s values was within type A uncertainty of measurements of less than 0.1%. For comparison, the results obtained with the TVA method are included. The linear fit with the MVA data is shown with uncertainty bars representing one standard deviation.

For comparison, the TVA method-determined k_s values were added to all k_s versus DPP plots. The two methods for determining the k_s factor (TVA and MVA) for a given DPP value showed a maximum difference of 0.1% for Farmer chambers, 0.1% for Semiflex chambers and 0.9% for PinPoint chambers.

3.3. Initial and general ion recombination coefficients of the Bruggmoser formalism

While several groups [13,15,16,37–40] have investigated the relationship between k_s and the DPP for a variety of ion chamber types in

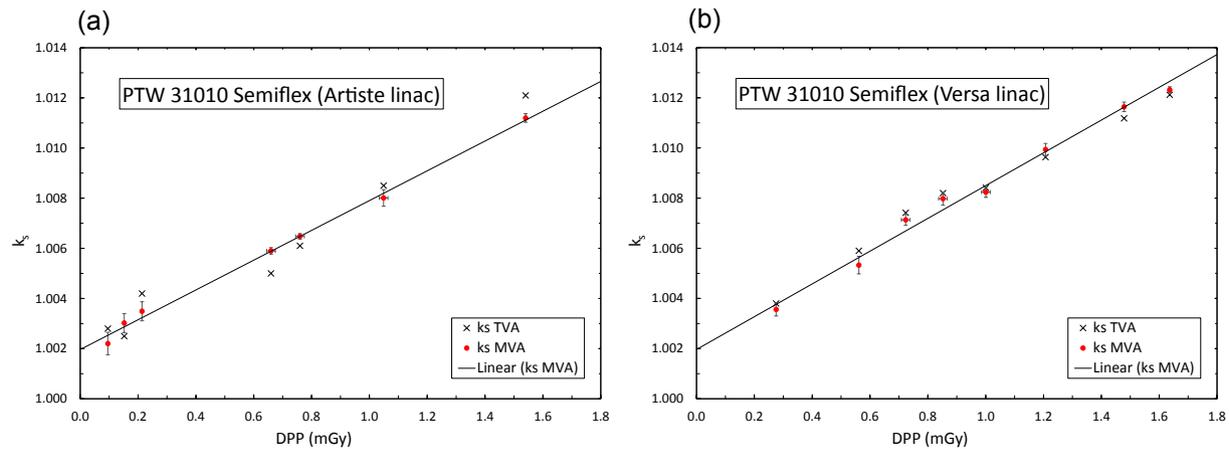


Fig. 4. Jaffé-determined recombination correction factor k_s as a function of the DPP for (a) the Semiflex PTW 31010 chamber measured in the Artiste linac and (b) the Semiflex PTW 31010 chamber measured in the Versa linac. For comparison, the results according to the TVA method are included. The linear fit with the MVA data is shown with uncertainty bars representing one standard deviation.

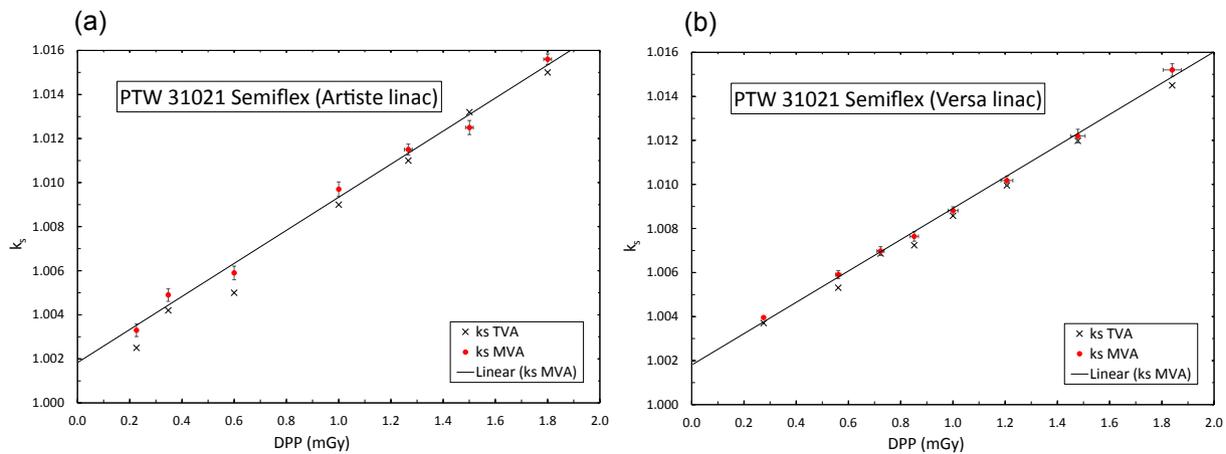


Fig. 5. Jaffé-determined recombination correction factor k_s as a function of the DPP for (a) the Semiflex PTW 31021 chamber measured in the Artiste linac and (b) the Semiflex PTW 31021 chamber measured in the Versa linac. For comparison, the results according to the TVA method are included. The linear fit with the MVA data is shown with uncertainty bars representing one standard deviation.

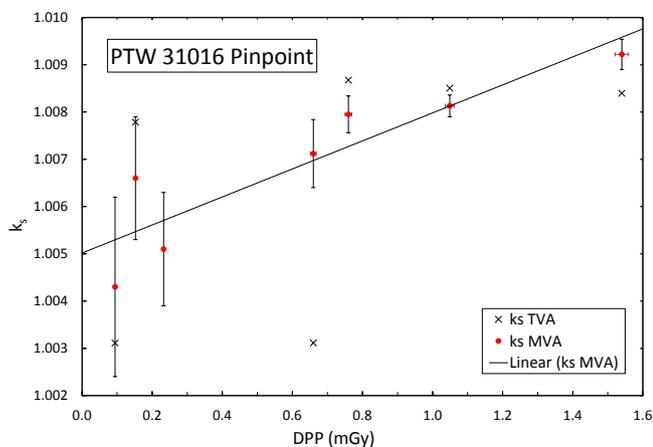


Fig. 6. Jaffé-determined k_s factor as a function of the DPP for a PinPoint PTW 31016 chamber measured in the Artiste linac. For comparison, the results according to the TVA method are included. The linear fit with the MVA data is shown with uncertainty bars representing one standard deviation.

photon and electron beams, only a few studies [6,12,16,18] have reported the initial and general ion recombination Bruggmoser coefficients γ and δ for small-volume chambers in megavoltage photon beams.

Table 3 shows the γ and δ Bruggmoser coefficients obtained from the plots in Figs. 3–5 for the Farmer and Semiflex chambers. The values reported by McEwen et al. [18] and those from the two works by Bruggmoser et al. [6,16] are also listed for comparison. The γ and δ values obtained from measurements in the Artiste linac and those in the Versa linac are in good agreement (i.e., within their estimated uncertainties, which are shown in brackets in Table 3) for the evaluated

chambers. This suggests that the ion recombination correction is not affected by the type of linac used. Furthermore, the discrepancies between the γ and δ values in this work and those in the literature [18,6,16] shown in Table 3 could be due, in principle, to chamber-to-chamber variations and differences in the ranges of DPP values utilized [12,16]. However, although the chambers were from different batches and years of manufacturing, there were no significant differences between their γ and δ values in similar DPP ranges. In contrast, discrepancies in the γ and δ values were observed when different ranges of DPP were used. This result suggests that varying the DPP, not chamber-to-chamber variations, is the main factor that impacts the determination of the γ and δ coefficients for a certain chamber model. To quantitatively assess this finding, γ and δ coefficients were obtained for different ranges of DPP values for the Farmer PTW 30013 chamber with serial number 001376. The analysis showed that varying the range of DPP values from 0.12–1.33 to 0.52–1.84 mGy/pulse resulted in significant modifications of more than 75% (from 0.33 to 0.59) for the γ value and 6% (from 2.98 to 2.81) for the δ value.

Furthermore, table 4 (a) and (b) shows the comparison of k_s values for the higher and lower nominal dose rates of the linacs according to the Bruggmoser formalism, the TVA method and Jaffé plots for the Farmer and Semiflex chambers. There is a maximum difference of 0.1% (which is within the statistical deviation of our measurements) between the k_s values obtained from the TVA method and from the Bruggmoser formalism for every chamber model. This result demonstrates the suitability of the TVA method for accurately determining the recombination correction factor for these chambers in flattened and FFF beams.

3.4. Polarity effects

All Farmer and Semiflex chambers met the TG-51 addendum

Table 3

γ and δ Bruggmoser coefficients for the Farmer and Semiflex chambers used in this work and their relative standard deviation ($k = 1$) in brackets. γ and δ coefficients were obtained from the plots in Figs. 3–5. Reported values in McEwen’s [18] and Bruggmoser’s [6,16] works are shown for comparison.

	γ (V)		δ (V. mGy ⁻¹)					
	Bruggmoser	McEwen	This work		Bruggmoser	McEwen	This work	
			Artiste	Versa			Artiste	Versa
Farmer PTW 30013	0.01 (0.02%)	0.24 (17%)	0.44 (0.7%)	0.45 (1%)	3.44 (1.3%)	3.9 (8%)	2.84 (2.7%)	2.92 (4.1%)
Semiflex PTW 31010	0.38 (0.05%)	1.23 (17%)	0.79 (1.1%)	0.81 (1.3%)	2.40 (1.8%)	2.2 (8%)	2.38 (3.1%)	2.49 (4.1%)
Semiflex PTW 31021	0.128	–	0.73 (1.2%)	0.72 (1%)	2.24	–	2.89 (4.1%)	2.84 (2.2%)

Table 4

k_S factors obtained from the TVA method, Jaffé plots and Bruggmoser formalism for the Farmer PTW 30013, Semiflex PTW 31010 and PTW 31021 chambers for the (a) higher and (b) lower nominal dose rates of the linacs used in this work.

a)	k_S (higher nominal dose rates)								
	Artiste Siemens linac			Elekta Versa linac					
Energy	7 MV FFF			6 MV FFF			10 MV FFF		
Dose rate	2000 MU/min			1200 MU/min			2000 MU/min		
DPP at D_{max}	1.5 mGy			0.63 mGy			1.21 mGy		
Chamber model	30013	31010	31021	30013	31010	31021	30013	31010	31021
k_S Bruggmoser	1.0117	1.0109	1.0127	1.0057	1.0060	1.0063	1.0099	1.0095	1.0104
k_S Jaffé	1.0123	1.0112	1.0123	1.0058	1.0061	1.0064	1.0101	1.0099	1.0102
k_S TVA	1.0117	1.0108	1.0125	1.0056	1.0067	1.0060	1.0101	1.0096	1.0099
b)	k_S (Lower nominal dose rates)								
	Artiste Siemens linac			Elekta Versa linac					
Energy	6 MV			6 MV			10 MV		
Dose rate	300 MU/min			470 MU/min			390 MU/min		
DPP at D_{max}	0.23 mGy			0.23 mGy			0.35 mGy		
Chamber model	30013	31010	31021	30013	31010	31021	30013	31010	31021
k_S Bruggmoser	1.0027	1.0033	1.0035	1.0028	1.0035	1.0035	1.0037	1.0042	1.0043
k_S Jaffé	1.0031	1.0030	1.0033	1.0026	1.0040	1.0037	1.0038	1.0045	1.0045
k_S TVA	1.0026	1.0026	1.0035	1.0025	1.0044	1.0035	1.0039	1.0051	1.0042

polarity specification that the polarity correction should be within 0.4% of unity and vary by less than 0.5% for the total range of energies. In contrast, the PinPoint chambers yielded polarity correction factors of 1.0081 and 1.0092, which exceed this limit.

Additionally, Jaffé plots were created at both polarities for those small-volume chambers that met the above polarity specification (i.e., Semiflex chambers) for the nominal dose rates of both linacs. The purpose of such measurements was to determine whether these chambers meet the additional polarity specification of the TG-51 addendum for the recombination correction dependency on polarity [30]. Figs. 7 and 8 show some examples of Jaffé plots at both polarities for the Semiflex PTW 31010 and 31021 chambers, respectively. The response of the PTW 31010 chamber (SN 002003) and that of the PTW 31021 chambers was nearly identical for both polarities, showing similar Jaffé-determined k_S values (within the 0.1% statistical deviation of our measurements). This finding suggests negligible polarity effects for these chambers, although further investigations are required to demonstrate that this conclusion also applies to other beam energies and

dose rates [30]. Furthermore, the significantly different response at opposite polarities for the PTW 31010 chamber (SN 001051) resulted in relatively large differences in the Jaffé-determined k_S values (1.010 and 1.006 for positive and negative charge collection, respectively), as illustrated in Fig. 7. This result indicates that this single chamber did not meet the additional polarity specification of the TG-51 addendum, precluding its use for reference dosimetry despite meeting all other polarity and recombination specifications.

4. Discussion

In this work, ion recombination and polarity effects were investigated for a variety of ion chambers (Farmer chambers, small-volume Semiflex chambers and PinPoint microchambers) in FFF beams. In particular, small-volume Semiflex PTW 31010 chambers and PinPoint PTW 31016 microchambers were investigated to determine their suitability as reference-class detectors in FFF beams. PTW 31016 PinPoint microchambers exhibited anomalous recombination and polarity effects

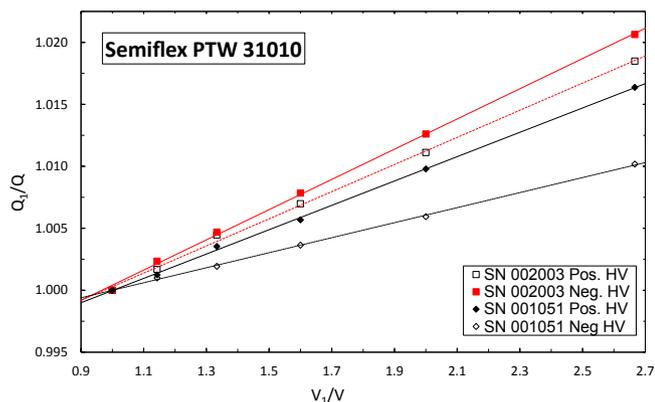


Fig. 7. Jaffé plots for the Semiflex PTW 31010 chambers. The Semiflex PTW 31010 chamber (SN 002003) was measured for the DPP of a 1.5 mGy/pulse in the 7 MV FFF beam of the Artiste linac, and the Semiflex PTW 31010 chamber (SN 001051) was measured for the DPP of a 0.93 mGy/pulse in the 10 MV FFF beam of the Versa linac, for both positive and negative charge collection.

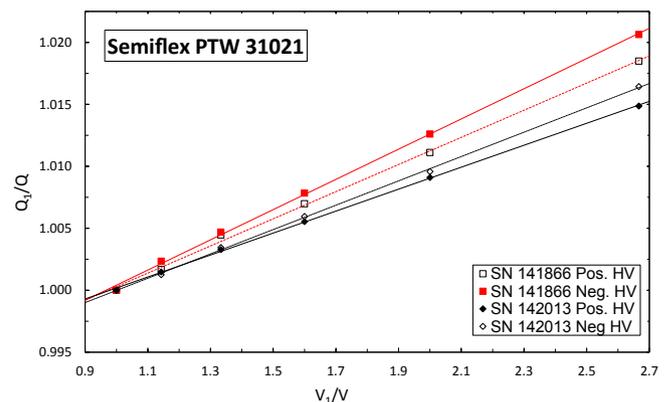


Fig. 8. Jaffé plots for the PTW 31021 Semiflex chambers used in this work. The Semiflex PTW 31021 chamber with SN 142013 was measured for the DPP of a 1.5 mGy/pulse in the 7 MV FFF beam of the Artiste linac, and the Semiflex PTW 31021 chamber (SN 141866) was measured for the DPP of a 0.93 mGy/pulse in the 10 MV FFF beam of the Versa linac, for both positive and negative charge collection.

in FFF beams, as previously described in the case of conventional beams [18], which precludes the use of these chambers for reference dosimetry. However, linear Jaffé plots were obtained for higher-DPP beams. This finding should be interpreted with caution, as some of these Pin-Point microchambers may be erroneously deemed fit for reference dosimetry in FFF beams if they are not characterized according to the more rigorous TG-51 addendum specifications.

Moreover, although one of the PTW 31010 chambers met all the polarity and recombination criteria, the chamber with SN 001051 did not meet the additional polarity specification of the TG-51 addendum for the recombination correction dependency on polarity. This result prevents the use of this chamber for reference dosimetry in FFF beams, which agrees with previous reported results for other chambers of this model in conventional beams [18]. Such discrepancies are likely due to chamber-to-chamber operational characteristic variations. Recombination and polarity effects depend on the characteristics of each specific chamber, as these effects are operational (rather than mechanical/geometric) properties [4], and small-volume chambers might sometimes fall at the boundary limits of such operational feature specifications. For this reason, there is the potential for some of these chambers to meet recombination and polarity specifications while others do not. Furthermore, the Semiflex PTW 31021 chambers exhibited nearly ideal polarity and recombination behavior in FFF beams, consistent with previous results [6]. This result is likely due to the improvements in the ion collection efficiency and polarity effect of this new Semiflex chamber model [31].

Regarding the suitability of the TVA method for FFF beams, Kry et al. [5] showed that compared with Jaffé plots, the TVA method is accurate within 0.3% for Farmer-type chambers. However, the results of this investigation have shown that the TVA method can be accurate within 0.1%, as indicated by comparison with the more detailed Bruggmoser formalism, for the Farmer and Semiflex chambers. In contrast, a previous work [6] recommended the use of Jaffé plots to determine the recombination correction in FFF beams for the Semiflex PTW 31021 chamber model. However, the authors did not provide the accuracy of the Jaffé-determined k_s factors, nor did they compare them with those obtained with a more detailed method, such as the Bruggmoser formalism. In addition, discrepancies were observed between the Bruggmoser coefficients for the chambers used in this work and those of the literature. It has been suggested that the discrepancies between different studies were likely due to chamber-to-chamber variations [12,16] and different ranges of DPP [12,18], although this suggestion was not experimentally verified. The results of this investigation have quantitatively shown that for at least one type of chamber (Farmer PTW 30013), the difference in DPP, and not the chamber-to-chamber variations, is the main factor in such discrepancies. This finding indicates that the use of chamber-type-specific Bruggmoser coefficients based on reported values with different DPP ranges may not be reliable.

Finally, the results of this study show that the use of two different FFF accelerators (Artiste Siemens and Versa Elekta) with very different modes of dose delivery [7], but similar DPP, had no impact on the experimental determination of the Bruggmoser coefficients. This result indicates that the recombination correction is not linac-dependent.

5. Conclusions

Despite the recommendation of small-volume chambers for reference dosimetry in FFF beams [2,4], such chambers may exhibit anomalous recombination and polarity behavior. This study has demonstrated that such effects persist for certain models of small-volume chambers and microchambers in FFF beams, and the results suggest that possible variations between chambers of the same model must first be considered before definitive conclusions can be made regarding its suitability. This highlights the importance of assessing the recombination and polarity effects of small-volume chambers and microchambers on an individual chamber basis using the more rigorous

characterization recommended by the TG-51 addendum.

Furthermore, this study has demonstrated that the simplified TVA method can still be suitable for accurately determining the recombination correction in FFF mode for chambers that meet the TG-51 addendum reference-class criteria. Based on the results of this investigation, the authors of this work do not recommend the use of chamber-type-specific Bruggmoser coefficients based on reported values. Regarding the linear accelerator type, this study has demonstrated that recombination correction is not dependent on the accelerator type.

Finally, it should be noted that all chambers used in this work were from a single manufacturer. Therefore, further research should be performed to corroborate the results of this investigation with chambers from other manufacturers and to find additional models of small-volume chambers and microchambers that are suitable for reference dosimetry in FFF beams.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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