Original Article

# Evaluation of Ion Recombination Correction for Indigenously Developed Farmer Ion Chamber in Flattening Filter-Free Photon Beams

**Parimal T. Patwe, Sudesh S. Deshpande[1], Gajanan R. Mahajan[2]**

School of Physical Sciences, Swami Ramanand Tirth Marathwada University, Nanded, [1]Department of Radiation Oncology, P.D. Hinduja Hospital and Medical Research Centre, Mumbai, [2]Department of Physics, Shri Datta Arts, Commerce and Science College, Hadgaon, Maharashtra, India

## Abstract

**Purpose and Aim:** Modern generation linear accelerator (linac) either generates X-rays with a flattening filter (WFF beam) or without flattening filter free (FFF beam). The FFF beams are associated with a significantly higher dose per pulse compared to WFF beams due to the absence of a flattening filter and the corresponding attenuation caused by it. This results in increased ion recombination and a larger saturation correction factor ($k_s$). In accordance with the IAEA TRS 398 dosimetry protocol, $k_s$ is necessary for the accurate measurement of absorbed dose at a point in water. The objective of this study was to evaluate the $k_s$ for the indigenous FAR 65-GB ion chamber (IC) for the FFF X-rays. **Materials and Methods:** The study was carried out on TrueBeam linac (Varian, A Siemens Healthineers company) which offers 6 MV WFF, 6 MV FFF, 10 MV WFF and 10 MV FFF beams. The two-voltage method was employed to measure $k_s$ in a solid water phantom at a depth of 10 cm for a FAR 65-GB and SNC 600c and 0.6cc PTW 30013 Farmer chambers at 100 cm and 150 cm source-to-chamber distances for a 10 cm × 10 cm field size. **Results:** The $k_s$ values for the FAR 65-GB, PTW 30,013, and SNC 600c were 1.0055 (1.0113), 1.0051 (1.0071), and 1.0033 (1.0066) for the 6 MV WFF (FFF) beams, respectively, and 1.0066 (1.0178), 1.0061 (1.0137), and 1.0035 (1.0119) for the 10MV WFF (FFF) beams, respectively. The $k_s$ values calculated by two-voltage method matches with $k_s$ values obtained from Jaffe's plot. The chamber exhibited a linear dose-response up to 3000 cGy, beyond which a saturation effect was observed. **Conclusions:** Our study reveals that this chamber is suitable for the reference dosimetry for the FFF beams.

**Keywords:** Flattening filter-free beam, ion chamber, ion recombination, Jaffe's plot, TRS-398, two-voltage technique

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## INTRODUCTION

Radiation therapy (RT) is a widely used treatment modality for cancer, with accurate dosimetry measurements being crucial to ensure effective and safe treatment. Medical linear accelerator (linac) comes with flattening filters (WFFs) to achieve a uniform X-ray dose profile at a certain depth. In actual clinical situations, neither the patients nor the tumors are flat, making the use of WFF X-rays inessential for some clinical situations.[1] With the introduction of advanced treatment techniques such as stereotactic radiosurgery (SRS) and stereotactic body radiotherapy (SBRT) into clinical practice, the requirement for a flat profile has been minimized.[1,2]

The introduction of flattening filter-free (FFF) X-rays has brought about significant improvements in RT treatment planning and delivery. FFF beams have steeper dose gradients and higher dose rates, resulting in more conformal dose distributions and shorter treatment times.[3,4] The dose per pulse on the beam axis at a depth of dmax for a reference field size (FS) of 10 cm × 10 cm for a 6MV WFF and 10MV WFF is 0.03 cGy, 0.08 cGy for a 6MV FFF, and 0.13 cGy for a 10MV FFF.[4] FFF beams decrease out-of-field dose, simplify dose modeling for the treatment planning system, and additionally offer more conformal dose distributions and

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**Address for correspondence:** Dr. Gajanan R. Mahajan,
Department of Physics, Shri Datta Arts, Commerce and Science College,
Nanded, Hadgaon - 431 712, Maharashtra, India.
E-mail: drgrmahajan@rediffmail.com

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shorter treatment times.[5] It leads to increased use of FFF beam in RT. However, FFF beams pose a challenge to accurate dosimetry measurements due to their high dose rates and steep dose gradients.

The farmer ion chamber (IC) is a widely used dosimeter in RT due to its ease of use, wide availability, and robustness.[6] Its performance is extensively studied for the WFF beams, and its correction factors are well established. In recent years, several studies have been carried out to assess the significance of ion recombination correction ($k_s$) for various dosimeters for FFF beams, including diodes, ionization chambers, and radiochromic films.

Saminathan *et al*. studied the performance of the Farmer FAR 65-GB IC (manufactured by Rosalina Instruments, Mumbai, India) for Co-60, 6MV, and 18 MV beams.[7] They found that the chamber is suitable for reference dosimetry in radiotherapy and has several advantages, including cost-effectiveness, long-term stability, and a low leakage rate. The measurements showed that the chamber has a linear response with dose, independent of dose rate, and energy. This work confirms that the FAR 65-GB IC can be used for measuring absolute dose in high-energy WFF photon beams.

Vargas Castrillón and Cutanda Henríquez compared percentage depth dose (PDD) curves for 6 MV WFF, 6 MV FFF, 10 MV WFF, and 10 MV FFF beams from a Varian TrueBeam linac, using different detectors such as Scanditronix photon diodes, PTW 31,010 Semiflex scanning chamber, Wellhofer CC04, PTW 31,016 Pin Point chamber, PTW 34,001 Roos, Scanditronix Roos, and NACP 02 parallel-plate chamber.[8] Their findings revealed that parallel-plate ICs could be used for photon PDD measurements and recombination effects should be considered for accurate dosimetry.

Corns *et al*. found that ion recombination had minimal impact on the relative output factor, absolute dose calibration, and field width, but it had a significant effect on the PDD, tissue maximum ratio, and off-axis ratio.[5]

According to the study by Hyun *et al*., various small-volume ICs connected with a digital electrometer fulfilled the reference-class criteria for $k_s$ and polarity correction for the FFF beam.[9] For such chambers, a two-voltage analysis (TVA) agreed well for determining $k_s$. The results also highlighted the importance of careful selection of the reference detector and indicated that thorough evaluation of ICs is necessary for all available X-ray energies before using them for reference dosimetry.

Martin-Martin *et al*. demonstrated that the $k_s$ is not dependent on the accelerator type but rather on its dose-per-pulse.[10] They highlighted the suitability of the TVA for ICs exhibiting reference-class behavior in FFF beams. In addition, in a subsequent study (2020), the authors strongly recommended applying the $k_s$ in the measurement of volume averaging correction factor and PDD measurement before using any IC for FFF beam reference dosimetry.[11]

The dosimetric performance of the PTW T31022 Pin Point three-dimensional (3D) was investigated by Vieillevigne and Arnaud, who studied $k_s$ using Jaffé plots, polarity effect, and various aspects of beam profiles, depth dose curves, and output factors associated with a small field.[12] The study concluded that the T31022 Pin Point 3D IC is a useful detector for the characterization of small and large fields in WFF and FFF beams.

Sutton and Littler found that $k_s$ had a negligible effect on commissioning data when collected with small-volume ICs for FFF beams.[13] The author suggested considering the $k_s$ effect when acquiring relative data with a larger volume chamber such as a Farmer chamber at 10 MVFFF.

These studies collectively underscore the importance of $k_s$ and provide valuable insights into the variability of correction factors based on chamber type, beam energy, and other relevant factors. Due to the higher dose per pulse in FFF beams, ion recombination is expected to be higher than in WFF beams and needs to be evaluated for each ionization chamber.[4,14]

The use of FFF beams for SRS treatments in India is growing. Our investigation focused on the $k_s$ for this specific chamber in FFF beams. We performed a comparison of the $k_s$ value of the FAR 65-GB IC with the commonly utilized PTW Farmer IC 30013 (PTW, Freiburg, GmbH) and SNC 600c (Sun Nuclear Corporation, Melbourne, FL). The study additionally determined the suitability of the present two-voltage technique for FAR 65-GB IC by comparing its results with 1/Q against 1/V Jaffé plots.[15]

## MATERIALS AND METHODS

### Experimental setup

The study was performed on the TrueBeam linac (Varian, A Siemens Healthineers Company) which offers 6 MV WFF, 6 MV FFF, 10 MV WFF, and 10 MV FFF X-ray energies. Water equivalent RW3 (white polystyrene) slab phantom (Sun Nuclear Corporation, Melbourne, FL) with chamber adapter plate was used to position the IC. The phantom consists of 33 RW3 plates with dimensions of 30 cm × 30 cm. By combining plates of different thicknesses, measurements can be made in 1 mm increments up to a depth of 30 cm. The technical description of ICs utilized in this study is given in Table 1. The FAR 65-GB was positioned at a depth of 10 cm inside the RW3 slab phantom and 10 cm × 10 cm FS was projected at a source-to-chamber distance (SCD) of 100 cm. A PC electrometer (Sun Nuclear Corporation, Melbourne, FL) was connected to the IC to measure the charge produced for both WFF and FFF beams for 200 monitor units (MUs).

### Measurements

The charge produced was measured at a normal operating voltage of 300V and a lower voltage of 150V. After a voltage change, IC readings were discarded until a stable signal was measured over multiple readings. For each measurement of charges produced, at least three of these nontrending

**Table 1: Specification of the ionization chambers used for the study**

| Parameter | FAR 65-GB | PTW 30013 | SNC 600c |
|---|---|---|---|
| Active volume (cc) | 0.65 | 0.6 | 0.6 |
| Active diameter (mm) | 6.2 | 6.1 | 6.1 |
| Wall thickness (mm) | 0.4 | PMMA 0.335; graphite 0.09 mm | Graphite 0.43; paint 0.05 |
| Wall material | Graphite (1.82 g/cc) | PMMA (1.19 g/cc); graphite (1.85 g/cc) | Graphite + paint |
| Inner electrode | Aluminum | Aluminum | Aluminum |
| Inner electrode diameter (mm) | 1 | 1.15 | 1.1 |
| Inner electrode length (mm) | 23.1 | 23 | 22.7 |
| Leakage current (Amp) | $10\times10^{-15}$ | $4\times10^{-15}$ | - |
| Polarizing voltage (V) | +300 | ±400 | ±400 maximum |
| Waterproof | No | Yes | Yes |

measurements for 200 MU were collected at each voltage, and the mean value of charges produced was used to calculate recombination correction factor $k_{s.}$ The same setup was used for PTW 30013 and SNC 600c IC.

As per TRS 398 Code of Practice, $k_s$ is then obtained from the equation:

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2$$

where, $a_0$, $a_1$, and $a_2$ are the coefficients of the second-order polynomial, whose values were provided in the TRS 398 protocol for pulsed beam radiation.

$M_1$ and $M_2$ are the measured values of the collected charges at the polarizing voltages (−) 300V and (−) 150V, respectively.

We measured $k_s$ for these ICs for 6MV WFF, 10MV WFF, 6MV FFF, and 10MV FFF beams using the maximum nominal dose rate available, namely, 600, 600, 1400, and 2400 MU/min, respectively. To nullify the effect of dose per pulse, we also measured $k_s$ values for both chambers at an extended SCD of 150 cm. As per the inverse square law, the dose rate ratio was 2.25:1 for these two different SCDs.

The Jaffé-plot was employed to confirm the $k_s$ values obtained from TVA for FAR 65-GB IC. This plot compares the inverse of the collected charge (1/Q) against the inverse of the applied voltage (1/V). Both TVA and the Jaffé plot measurements were conducted under identical setup conditions to ensure consistency and accuracy in the validation process. The collected charge for 200 MU was measured as a function of chamber voltage, which was varied between 50V and 300V in increasing steps of 50V. To estimate the recombination effects at 300 V in the Jaffé plot, the measured signal was extrapolated to 1/V = 0 (infinite voltage).

## RESULTS

The measured $k_s$ values for the FAR 65-GB, PTW 30013, and SNC 600c IC are presented in Table 2 for a 10 cm × 10 cm FS, 10 cm depth, and SCD of 100 cm.

### 3.1 $k_s$ at 100 cm source-to-chamber distance

$k_s$ values for the FAR 65-GB, PTW 30013, and SNC 600c were 1.0055 (1.0113), 1.0051 (1.0071), and 1.0033 (1.0066) for the 6 MV WFF (FFF) beams, respectively. Under the same setup conditions, $k_s$ values for the FAR 65-GB, PTW 30013, and SNC 600c were 1.0066 (1.0178), 1.0061 (1.0137), and 1.0035 (1.0119) for the 10MV WFF (FFF) beams, respectively.

### 3.2 $k_s$ at 150 cm source-to-chamber distance

$k_s$ values for the FAR 65-GB, PTW 30013, and SNC 600c were 1.0043 (1.0109), 1.0047 (1.0026), and 1.003 (1.0051) for the 6 MV WFF (FFF) beams, respectively. Ks values for the FAR 65-GB, PTW 30013, and SNC 600c were 1.0064 (1.0086), 1.0068 (1.0065), and 1.0031 (1.0067) for the 10MV WFF (FFF) beams, respectively. As shown in Table 2, there was <0.5% change in $k_s$ values at two different SCDs.

### Statistical analysis

A paired two-sample Student's *t*-test was used to dosimetrically compare the $k_s$ of these ICs after testing for normal distribution. A difference was considered statistically significant when $P < 0.05$. The high $P$ value implies that there was no statistically significant difference in the $k_s$ values of FAR 65-GB IC when compared with PTW 30013 and SNC 600c IC.

### Jaffe's plot

To validate the results of $k_s$ obtained using the two-voltage method, a graph of normalized 1/charge versus 1/voltage (1/Q vs. 1/V) was plotted (Jaffe's plot) as shown in Figure 1.[1] A straight line was drawn to the data points using the linear trend line option in Excel 2016. The intercept on the Y-axis of the straight-line equation gives the value of ion recombination obtained from Jaffe's plot.

As shown in Table 3, the $k_s$ values derived from Jaffe's plot for the FAR 65-GB chamber were 1.0121 and 1.0187 for the 6MV FFF and 10MV FFF beams, respectively. These values were in close agreement with the $k_s$ values obtained using the two-voltage method.

### Dose linearity in high-dose rate mode

To investigate the dose linearity of FAR 65-GB in high-dose rate mode, IC was placed at 10 cm depth with SCD 100 cm and FS 10 cm × 10 cm. Then, IC was exposed to a series of doses for both the FFF beams operated at maximum dose rates,

**Table 2: The $k_s$ values for the FAR 65-GB, PTW 30013, and SNC 600c**

| Ionization chamber | SCD (cm) | 6MV WFF | 6MV FFF | 10MV WFF | 10MV FFF | *P* |
|---|---|---|---|---|---|---|
| FAR 65-GB | 100 | 1.0055 | 1.0113 | 1.0066 | 1.0178 | |
| | 150 | 1.0043 | 1.0109 | 1.0064 | 1.0086 | |
| PTW 30013 | 100 | 1.0051 | 1.0071 | 1.0061 | 1.0137 | 0.1818 |
| | 150 | 1.0047 | 1.0026 | 1.0068 | 1.0065 | 0.3268 |
| SNC 600c | 100 | 1.0033 | 1.0066 | 1.0035 | 1.0119 | 0.0761 |
| | 150 | 1.003 | 1.0051 | 1.0031 | 1.0067 | 0.0544 |

WFF: With flattening filter, FFF: Flattening filter free, SCD: Source-to-chamber distance

**Table 3: Comparison of $k_s$ calculated using two-voltage method and Jaffe's plot**

| X-ray energy | $k_s$ (two voltage method) | $k_s$ (Jaffe's plot) | Percentage difference |
|---|---|---|---|
| 6MV WFF | 1.0055 | 1.0052 | −0.03 |
| 6MV FFF | 1.0113 | 1.0121 | 0.08 |
| 10MV WFF | 1.0066 | 1.0071 | 0.05 |
| 10MV FFF | 1.0178 | 1.0187 | 0.09 |

WFF: With flattening filter, FFF: Flattening filter free

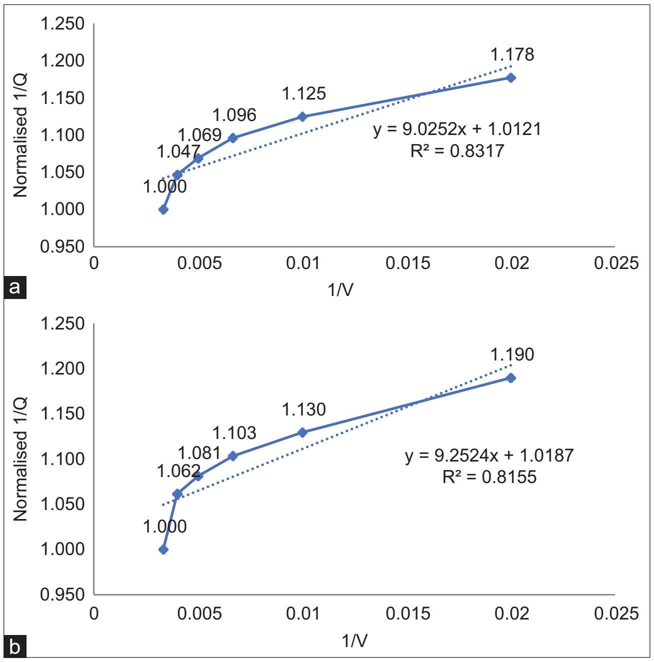

**Figure 1:** (a) Jaffe's plot for the FAR 65-GB for 6MV flattening filter free (FFF). (b) Jaffe's plot for the FAR 65-GB for 10MV FFF beam. FFF: Flattening filter free

beginning with 5 cGy, 10 cGy, 25 cGy, 50 cGy, 100 cGy, and 200 cGy. Thereafter, the doses were increased from 500 cGy to 3500 cGy in steps of 500 cGy. As shown in Figure 2, the chamber showed a linear response for doses up to 3000 cGy, beyond which it exhibited a saturation effect.

## Discussion

One of the earliest observed effects of ionizing radiation is the ionization of a gas. Radiation detectors rely on the same principle of measuring ionization in a gas. In theory, ICs are the simplest type of gas detector. They have a gas-filled chamber between two electrodes, where voltage is applied. The electrometer, which typically consists of a voltage supply and a display unit, is the electronic component necessary to measure the charge (or current). After undergoing changes in track structure due to diffusion and ion drift, the general recombination takes place as positively and negatively charged ions from various tracks drift toward the chamber electrodes, causing them to combine.[16] $k_s$ corrects the signal of an IC to account for ion recombination. There are three methods to determine $k_s$, namely, Boag theory, TVA, and Jaffe's plot.

The Boag theory is a mathematical model that describes the effect of ion recombination on the ionization charge (current) measured in an IC.[17] The theory assumes that the ions are uniformly generated throughout the gas volume of the ionization chamber and that they are not influenced by the space charge created by the collected ions. The theory predicts that the ionization current will decrease as the voltage applied to the IC increases, due to the higher voltage accelerating the ions and making them more likely to recombine before they reach the collecting electrodes. Boag's theory has two limitations, namely, it does not account for small differences between ICs of the same type, and it may not be accurate if the central electrode in a cylindrical chamber is slightly misaligned.[18]

Weinhouse and Meli presented a practical approach to calculate $k_s$ using the two-voltage method, employing a TVA.[19] This technique was also adopted in the TRS 398 protocol for correcting ion recombination effects. When accounting for recombination, the uncertainty introduced by the two-voltage approximation (0.15%) appears to be the primary source of uncertainty.[4] In addition, FFF beams also have uncertainty because of partial volume effects. Specifically, the peaked radiation field will cause partial volume averaging effects in Farmer-type chambers with large volumes. Kry *et al*. analyzed this error by comparing the film profiles of 6 MV FFF and 10 MV FFF beams to the size of Farmer-type ICs (approximately 2 cm in length). The study showed that the true center axis dose would be underestimated by 0.2% for both FFF beams if the signal was averaged over the size of a Farmer-type IC.

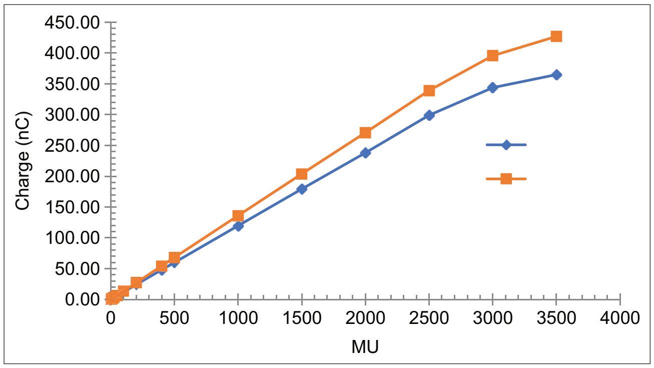

**Figure 2:** Dose linearity in high-dose rate mode for FAR 65-GB chamber. MU: Monitor unit, nC: Nano coulomb, output setting: 1MU: 1 cGy

Lang *et al*. investigated the charge collection efficiency of multiple air-vented and one liquid IC for dose rates up to 31.9 Gy/min for relative and reference dosimetry for the FFF beams.[20] For flattened beams, the ion-collection efficiency of all air-vented ICs (except for the PinPoint chamber) was above 0.995. For 10 MV FFF beam, a study found a reduction in charge collection efficiency of approximately 0.5%–0.9%. The study also suggested that liquid ICs appear to be unsuitable for reference dosimetry for the FFF beams.

The observed variations in $k_s$ values across the examined chambers can be attributed to differences in active volume, electrode size and spacing, and wall thickness. Table 1 demonstrates that the FAR 65-GB IC possesses a larger active volume, only Graphite wall material, a different wall thickness, and a small central electrode diameter. This can result in a variation in the strength of the electric field across the active region of the IC in comparison to the other two ICs, potentially resulting in differing $k_s$ values.

FFF beams have been in clinical practice for over a decade, and many studies have been carried out on the challenges of measuring them accurately. One of these challenges is ion recombination. It is important to evaluate $k_s$ for each ionization chamber that is used to measure FFF beams because the value of $k_s$ can vary depending on the type of chamber. The present work gives a thorough analysis of the recombination factor for FAR 65-GB IC for the FFF beam. The chamber's overall saturation correction factor was found to be lower than the recommended values in the literature.[21] The FAR 65-GB chamber shows reliable performance characteristics for both flat and FFF X-ray beams.

## Limitations

A limitation of this study is its consideration of FFF beams from a single manufacturer, namely, varian and maximum dose rate of 2400 MU/min. Second, to ensure consistency in mass production of IC and to enhance the repeatability of results, incorporating at least two FAR 65-GB would have been beneficial.

# CONCLUSIONS

The utilization of FFF beams has witnessed a notable upsurge within the landscape of SRS and SBRT treatments all over the globe. As a result, it is becoming increasingly important to accurately measure the absorbed dose of water for FFF beams. We measured the indigenously developed FAR 65-GB chamber's recombination correction factors under high-dose rate and high dose per pulse conditions. We found FAR 65-GB chamber is suitable for the reference dosimetry in the FFF beams. However, it is essential to consider the recombination effect of individual IC to minimize uncertainty in dose measurement for the reference dosimetry.

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Nil.

## Conflicts of interest

There are no conflicts of interest.

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