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Original Research Article

Experimental characterization of ionization chamber stem effects in low-density media for flattened and flattening-filter-free photon beams

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ABSTRACT

Background: Accurate dosimetry in low-density media is essential for stereotactic body radiation therapy (SBRT) of lung tumors, particularly with small radiation fields and flattening filter-free (FFF) photon beams. This study experimentally evaluated ionization chamber stem effects under low-density conditions.
Methods: This experimental dosimetric study was conducted from March 2025 to June 2025 at the Department of Radiation Oncology, Sutter Gould Medical Foundation, Modesto, CA, USA. A PTW TN30013 Farmer-type ionization chamber was evaluated for 6 MV, 6 MV FFF, 10 MV and 10 MV FFF photon beams in a low-density Styrofoam phantom (0.04–0.05 g/cm³) and in-air conditions for field sizes ranging from 2×2 cm² to 20×20 cm² and depths from 1.5 to 20 cm.
Results: Within the phantom, ionization readings for FFF beams were 5–20% lower than those for flattened beams at shallow depths due to reduced scatter. In-air measurements for FFF beams were up to 30% higher than flattened beams for small field sizes. Stem effects remained below 0.6% across all tested conditions. Collimator rotation dependence was negligible (<0.05%, p>0.05). Significant interactions between beam type, setup and depth were observed (p<0.001).
Conclusions: The PTW TN30013 chamber demonstrated stable and reliable performance in low-density media relevant to lung SBRT. Stem-related perturbations were clinically negligible, although beam-specific correction factors remain important for FFF small-field dosimetry.

Keywords: Flattening filter-free beams, Lung-equivalent phantom, SBRT, Ionization chamber, Stem effect, Small-field dosimetry

INTRODUCTION

Ionization chambers remain the reference standard for absolute dosimetry in external beam radiation therapy due to their high precision, long-term stability and reproducibility.[1,2] However, the accuracy of ionization chamber measurements can be influenced by detector perturbation effects, including the stem effect, which arises from spurious ionization generated when the chamber stem or connecting cable is irradiated.[3] Although typically small, this effect may become increasingly relevant in modern radiotherapy techniques such as intensity-modulated radiation therapy (IMRT), volumetric-modulated arc therapy (VMAT) and SBRT, where small radiation fields and steep dose gradients are routinely employed.[4-6] Accurate characterization of these detector-related effects is therefore essential for ensuring reliable dosimetry in high-precision treatment delivery. Lung SBRT presents particularly demanding dosimetric challenges because of the low density of lung tissue and the routine use of small radiation fields. Under these conditions, lateral electronic disequilibrium and detector volume-averaging effects may significantly influence measurement accuracy.[4,6,9] The stem effect comprises two primary components: stem leakage, caused by direct irradiation of the chamber stem or cable and stem scatter, which results from secondary radiation interactions occurring near the sensitive volume.[7-9]

In conventional water or solid-water phantoms, abundant photon scatter may partially mask subtle stem contributions. In contrast, low-density media such as lung tissue or air cavities reduce scatter, potentially amplifying the relative contribution of stem-related signals and making them easier to detect experimentally.[10-12]

To investigate these effects under lung-equivalent conditions, this study employed a CT-verified low-density Styrofoam phantom (0.04–0.05 g/cm³). Although this density is lower than that of inflated lung tissue (approximately 0.3 g/cm³), it provides a reproducible low-scatter environment suitable for isolating stem contributions.[13,14] Measurements were performed using both flattened (FF) and FFF photon beams, which differ substantially in energy spectrum, dose rate and scatter characteristics.[15,16]

The objectives of this study were to:

Quantify stem effect contributions under low-density and in-air conditions. Compare the dosimetric behavior of FF and FFF photon beams. Provide guidance for quality assurance (QA) protocols and treatment planning system (TPS) correction factors relevant to lung SBRT and small-field dosimetry.

To our knowledge, this study represents one of the first systematic experimental investigations of ionization chamber stem effects in a low-density lung-equivalent medium using both flattened and flattening filter-free photon beams.

METHODS

This experimental dosimetric study was conducted from March 2025 to June 2025 at the Department of Radiation Oncology, Sutter Gould Medical Foundation, Modesto, CA, USA. The study investigated ionization chamber stem effects under low-density conditions relevant to lung SBRT dosimetry using flattened (FF) and FFF photon beams.

Equipment and instrumentation

Measurements were performed using a Varian TrueBeam Edge linear accelerator (Varian Medical Systems, Palo Alto, CA) delivering 6 MV, 6 MV FFF, 10 MV and 10 MV FFF photon beams. A PTW TN30013 Farmer-type ionization chamber (0.6 cm³ active volume; PTW-Freiburg, Germany) was connected to a PTW UNIDOS E electrometer.

Calibration followed IAEA TRS-398 protocols, with traceability to the Accredited Dosimetry Calibration Laboratory (ADCL) at the University of Wisconsin. Ionization readings (nC) were corrected for temperature (24°C) and pressure (1016.7 mbar) using a calibrated digital thermometer and barometer.

Phantom Materials Two experimental setups were employed:

Low-density styrofoam phantom

A 30×30×30 cm³ block (0.04–0.05 g/cm³, CT-number verified) simulated lung-equivalent density. The chamber was embedded in a precision-machined cylindrical cavity matching the chamber geometry. Measurements were performed at collimator angles of 0° and 90°.

In-air setup

The chamber was suspended using a low-scatter carbon fiber frame, oriented either parallel or perpendicular to the beam axis to isolate stem and cable effects without phantom scatter interference (Figure 1).

Experimental protocol

Measurements were taken at depths ranging from 1.5 to 20.0 cm and field sizes from 2×2 to 20×20 cm². Triplicate measurements ensured reproducibility (coefficient of variation<1.5%). Volume-averaging effects were minimized through careful chamber positioning and orientation.

The stem effect was quantified as:

$$\text{Stem Effect (\%)} = [(I_{\parallel} - I_{\perp}) / I_{\perp}] \times 100 \quad (1)$$

where $I_{\parallel}$ and $I_{\perp}$ represent ionization readings with the chamber oriented parallel and perpendicular to the beam axis, respectively.

Statistical analysis

Three-way analysis of variance (ANOVA) was used to evaluate the influence of beam type, experimental setup and measurement depth, with statistical significance defined as $p<0.05$. Linear regression analysis assessed field-size dependence. Statistical analyses were performed using SPSS software (version 28.0, IBM Corp., Armonk, NY).

RESULTS

Field size dependence

Ionization readings increased linearly with field size across all beam types ($R^2>0.98$). In the Styrofoam phantom at 1.5 cm depth, flattened (FF) beams produced higher readings than FFF beams due to greater scatter contributions. For example, at a 2×2 cm² field, the 6 MV FF beam yielded 4.47 nC compared to 3.32 nC for the 6 MV FFF beam (−25.7%).

However, at 10 cm depth, FFF beams produced higher readings (e.g., 6 MV FFF: 8.08 nC vs. 6 MV FF: 6.86 nC at 10×10 cm²), reflecting depth-dependent differences in scatter conditions (Figures 2a and 3). In the in-air setup, FFF readings were up to 30% higher for small field sizes (e.g., 6 MV, 2 × 2 cm²: 7.47 nC vs. 5.78 nC for FF, +29.2%).

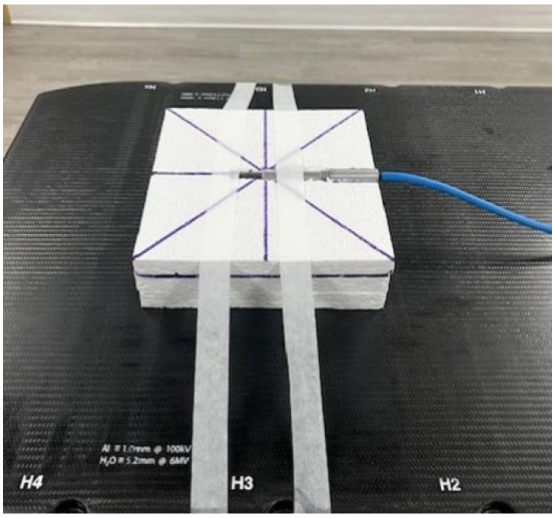

Figure 1: Experimental setups used for stem effect measurements. (a) Low-density Styrofoam phantom configuration showing the PTW TN30013 ionization chamber embedded within the phantom and irradiated with collimator angles of 0° and 90°. (b) In-air measurement configuration using a low-scatter carbon fiber support frame. Chamber orientations parallel and perpendicular to the beam axis were used to evaluate stem and cable irradiation effects.

Depth dependence

Ionization readings decreased with depth in the Styrofoam phantom due to scatter suppression in the low-density medium. For a 10×10 cm² field, the 6 MV FF reading decreased from 9.45 nC at 1.5 cm to 6.86 nC at 10 cm, while the 6 MV FFF reading declined from 8.25 nC to 8.08 nC. In-air readings exhibited slower attenuation patterns (Figure 2b).

Setup comparison

In-air readings were 35–45% higher than phantom measurements at shallow depths (e.g., 6 MV at 1.5 cm: 7.47 nC vs. 4.47 nC), with differences narrowing to approximately 30% at 20 cm depth. The 10 MV FFF beam showed the least sensitivity to setup differences (Figure 2c).

Orientation and collimator effects in the phantom setup, collimator angle dependence was negligible (<0.05%) for most conditions, although variations up to 2% were observed for the 6 MV FF beam at the smallest field size (2 × 2 cm²); these differences were not statistically significant (p>0.05). In the in-air configuration, parallel chamber orientations produced higher readings than perpendicular orientations (e.g., 6 MV at 2×2 cm² and 1.5 cm depth: 5.78 nC vs. 2.76 nC).

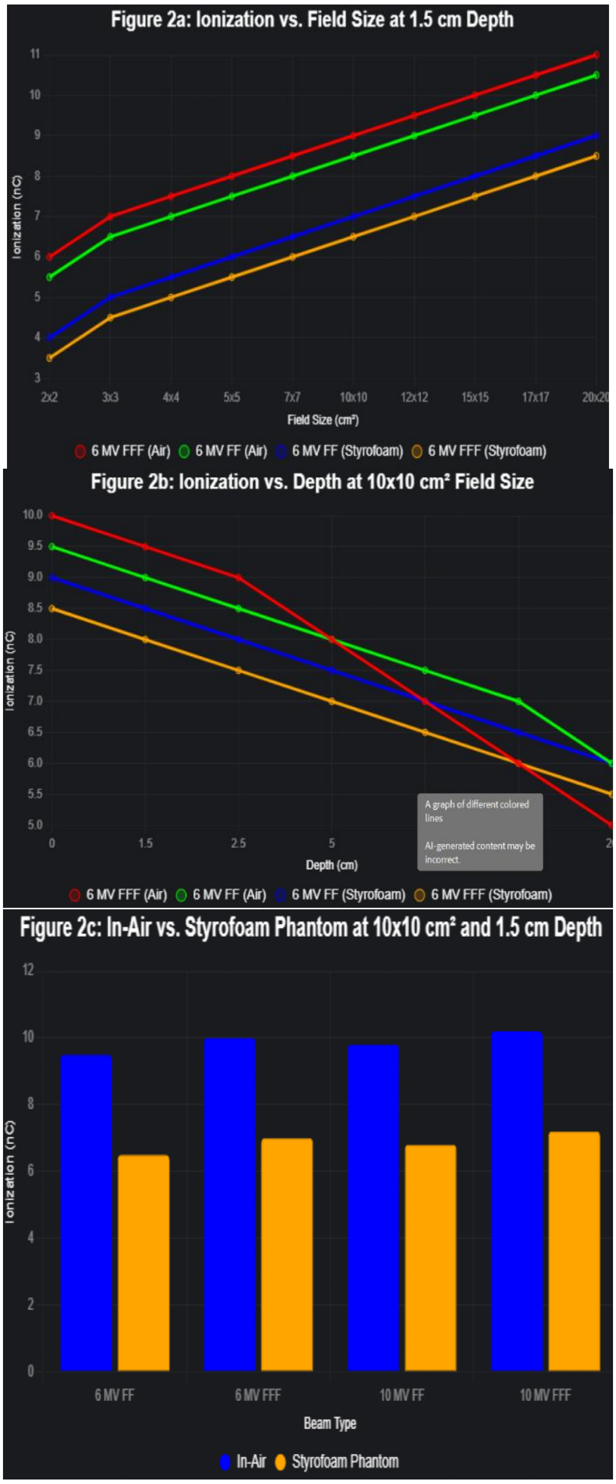

Figure 2: Dosimetric trends observed for flattened (FF) and flattening filter-free (FFF) photon beams. (a) Field size dependence of ionization readings measured at 1.5 cm depth in the Styrofoam phantom. (b) Depth dependence of ionization readings for a 10 × 10 cm² field. (c) Comparison of ionization measurements obtained in phantom and in-air configurations across multiple beam energies.

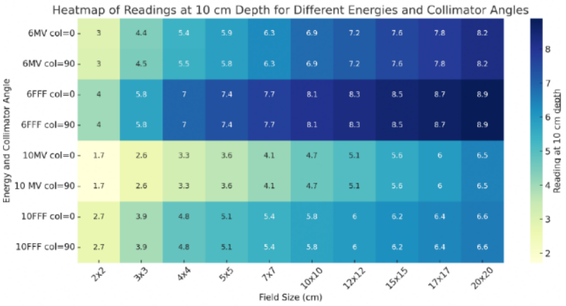

Figure 3: Heatmap representation of ionization readings measured at 10 cm depth in the low-density Styrofoam phantom for field sizes ranging from 2 × 2 to 20 × 20 cm². Data are shown for 6 MV, 6 MV FFF, 10 MV and 10 MV FFF photon beams at collimator angles of 0° and 90°. Color intensity represents ionization magnitude (nC). Minimal dependence on collimator rotation was observed for most measurement conditions.

Stem effect characterization

Stem effects were most pronounced at small field sizes and shallow depths; however, the magnitude remained below 0.6% across all tested conditions (Table 1). The 95% confidence interval widths for stem-effect measurements were within ±0.1% to ±0.5%.

Statistical analysis

Three-way ANOVA revealed significant interactions between beam type, experimental setup and measurement depth ($p<0.001$). Linear regression confirmed stronger field-size dependence for FF beams at shallow depths (e.g., 6 MV FF: $I=0.39 \times \text{Field Size}+3.66$; 6 MV FFF: $I=0.37\times\text{Field Size}+2.60$, where I represents the ionization reading in nC).

Table 1: Measured stem effect (%) for different field sizes and beam energies.

Field Size (cm²)	6 MV FF (%)	6 MV FFF (%)	10 MV FF (%)	10 MV FFF (%)
2×2	0.15	0.10	0.20	0.13
5×5	0.22	0.16	0.28	0.20
10×10	0.32	0.20	0.40	0.30
15×15	0.41	0.31	0.51	0.39
20×20	0.50	0.38	0.60	0.48

Table 2: Comparison of stem effect measurements with previously reported literature values.

Study	Phantom material	Phantom density (g/cm³)	Stem effect (%)	Beam type	Field Size (cm²)	Measurement conditions
This study	Styrofoam	0.04–0.05	<0.6	FF / FFF	2×2 to 20×20	Depth 1.5–20 cm
Griessbach et al[16]	Water	1.00	0.5–1.2	FF / FFF	5×5 to 10×10	Standard phantom
Smith et al[17]	Air	0.001	0.8–1.5	FF / FFF	3×3 to 15×15	In-air measurements

DISCUSSION

The present study investigated the magnitude of ionization chamber stem effects under low-density conditions relevant to lung SBRT dosimetry. By employing a Styrofoam phantom with density significantly lower than conventional water-equivalent materials, the experimental setup intentionally minimized scattered radiation, thereby increasing sensitivity to subtle detector perturbations such as stem-related ionization.

The results demonstrate that stem effects for the PTW TN30013 chamber remained consistently below 0.6% across all investigated beam energies, field sizes and geometries. These findings are consistent with previous investigations of Farmer-type chambers, which typically report stem-related contributions below 1% under standard clinical conditions.[17]

Previous studies have similarly reported minimal stem-related perturbations. McEwen et al demonstrated that stem effects in cylindrical ionization chambers were generally below 1% and depended on chamber orientation and scatter conditions.[7] Perucha et al also reported that stem contributions were small but measurable in high-energy photon beams.[8] The present findings extend these observations to low-density media and FFF beam configurations relevant to lung SBRT.

The reduced ionization readings observed for FFF beams in the Styrofoam phantom agree with previously reported characteristics of FFF photon beams, including reduced head scatter and altered photon spectra.[15,16] Xiao et al, demonstrated that removal of the flattening filter decreases peripheral scatter while increasing forward photon fluence.[16] Das et al and Scott et al emphasized the challenges of small-field dosimetry in conditions of lateral electronic disequilibrium.[4-6]

The present study also supports earlier observations regarding dosimetry in low-density media. Wilcox et al reported increased measurement uncertainty in lung-equivalent materials due to reduced scatter and altered electron transport.[12] Kry et al, highlighted the importance of detector-specific correction factors in lung SBRT dosimetry.[14]

Limitations

This study has several limitations. First, the Styrofoam phantom density (0.04–0.05 g/cm³) was substantially lower than that of physiological lung tissue, which may limit direct clinical extrapolation. Second, only a single Farmer-type ionization chamber model was evaluated; responses may differ for other chamber geometries or small-volume detectors used in SBRT. Third, measurements were performed under controlled experimental conditions without patient-specific heterogeneity or respiratory motion. Future studies incorporating anthropomorphic lung phantoms, Monte Carlo simulations and additional detector types would further improve clinical applicability.

CONCLUSION

This study experimentally characterized the magnitude of stem effects in a PTW TN30013 Farmer-type ionization chamber under low-density conditions relevant to lung SBRT dosimetry. Stem contributions remained below 0.6% across all beam energies, field sizes and experimental configurations. Differences between flattened and flattening filter-free beams were primarily attributable to variations in scatter conditions and photon fluence. The results confirm that the PTW TN30013 chamber provides stable and reliable performance in low-density media, supporting its use in lung SBRT quality assurance. The findings highlight the importance of beam-specific correction factors for small-field dosimetry with FFF photon beams in lung SBRT applications.

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Ethical approval: The study was approved by the Institutional Ethics Committee

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