ORIGINAL RESEARCH PAPER
Volume - 15 | Issue - 01 | January - 2026 | PRINT ISSN No. 2277 - 8179 | DOI : 10.36106/ijsr
INTERNATIONAL JOURNAL OF SCIENTIFIC RESEARCH

DOSIMETRIC IMPACT OF VIRTUAL BOLUS POSITIONAL UNCERTAINTY IN RADIOTHERAPY PLANNING – A PHANTOM STUDY

Medical Science

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ABSTRACT

Background: Achieving the therapeutic ratio in radiotherapy depends on various steps, including patient positioning, immobilization, and bolus placement. Sometimes, identifying the need for a bolus during imaging is difficult. In such cases, treatment planning system offer virtual bolus, which can be placed on the skin after imaging. However, accurately replicating this bolus placement on the patient's skin is crucial for achieving the intended dose distribution. This study aims to evaluate the positional uncertainty of replicated bolus and its dosimetric impact. **Material And Methods:** The study was initially conducted under non-clinical conditions using a defined geometry of size 30x30x8 cm^3 water equivalent phantom with a 5×5 cm^2 bolus (0.5cm thick), 6 MV photon beam, and a 10×10 cm^2 field size. Known positional errors of 1cm on 1mm increment on either lateral direction were introduced, and corresponding dose measurements were taken. For a clinical scenario, a CIRS head phantom with a Farmer chamber was scanned, and 10 head-and-neck IMRT QA plans incorporating virtual bolus were created. The phantom was positioned using CBCT, and mean doses of the chamber volume were recorded. Surface dose measurements were taken with EBT3 film placed under the bolus, introducing a 3 mm setup error. All results were compared with TPS-calculated doses. **Results And Discussion:** In the homogeneous phantom, bolus displacement resulted in <2% variation in dose, which was statistically insignificant. However, in heterogeneous phantom, misalignment caused significant surface dose deviations ($p = 0.00065$), while isocenter doses remained statistically unchanged ($p = 0.5161$). **Conclusion:** Virtual bolus placement uncertainty can lead to substantial dosimetric discrepancies. Accurate replication of bolus position, supported by image guidance and verification techniques, is essential for maintaining treatment accuracy, especially in complex anatomical regions.

KEYWORDS

Virtual bolus, CIRS head phantom, Intensity modulated Radiation Therapy, positional uncertainty

INTRODUCTION

A bolus in radiotherapy is a tissue-equivalent material used to modify the radiation dose distribution, ensuring effective dose delivery to superficial tumors or areas requiring buildup. Radiation beams, especially high-energy ones, tend to deposit their maximum dose a few millimeters beneath the skin, creating a "skin-sparing effect"[1].A bolus eliminates this effect by shifting the dose peak closer to the skin surface, making it particularly useful for treating skin cancers, post-mastectomy chest walls, and other superficial targets [2].

Bolus materials can also help to compensate for irregular body surfaces, ensuring a uniform dose distribution in areas like the nose, scalp, or extremities [3].Several types of commercially available bolus materials are often used in radiotherapy units. In clinical practice, it is important that the bolus material is sufficiently elastic and deformable to conform to the surface, unaffected by high dose levels, durable, non-toxic, and cost-effective[4].Additionally, the use of bolus leads to an increase in skin dose, which may heighten the risk of skin toxicities such as radio dermatitis, potentially impacting the overall quality of life for patients[5].

In head and neck cancer patients undergoing Intensity-modulated radiation therapy (IMRT), the treatment typically includes superficial gross disease within the target volume. To ensure adequate dose buildup in these areas, a bolus material is applied over the skin[6]. However, in some clinical situations, it can be challenging to determine the necessity and exact positioning of a bolus during RT imaging.

To address this challenge, treatment planning systems (TPS) incorporate a concept known as the virtual bolus, which can be digitally placed on the skin surface during treatment planning, even after the initial imaging has been completed [7]. While this feature offers flexibility in planning and execution, it introduces a critical question regarding the accuracy of bolus placement in the actual clinical setting.

With better conformance and less air gaps than traditional methods, 3D printing has emerged as a viable technique for producing patient-specific bolus materials in head and neck radiotherapy [8]. According to studies, in difficult sites like the scalp, nose, ears, and postoperative facial areas, these 3D-printed boluses offer better fit and dosimetric dependability[9-10]. However, issues such material biocompatibility, printing time, cost, and workflow constraints continue to impede normal clinical usage. Bolus positional uncertainties have a considerable impact on superficial dose distribution, particularly in highly modified IMRT treatments. Therefore, it is still important to understand the dosimetric impact of these errors.

This study aims to evaluate the dosimetric impact of virtual bolus positional uncertainty by conducting a series of measurements on phantom models under controlled conditions. The study investigates the impact of small positional errors, and their effect on the dose distribution, with a particular focus on head-and-neck IMRT plans.

MATERIALS AND METHODS

Non-Clinical Scenario

Phantom Setup & Imaging:

The non-clinical evaluation was conducted using an IBA RW3 solid water phantom with dimensions of 30 × 30 × 8 cm^3. The phantom was equipped with a Farmer-type ionization chamber insert positioned at the geometric centre to facilitate absolute dose measurements. Computed tomography (CT) imaging of the phantom was performed using a Siemens Somatom Scope 32-slice CT scanner with a slice thickness of 3 mm to ensure adequate spatial resolution for dose calculation and bolus modeling.

The acquired CT images were exported in DICOM format and imported into the Eclipse Treatment Planning System (TPS), version 17.0 (Varian Medical Systems, Palo Alto, USA), for contouring and treatment planning.

Treatment Planning:

Within the TPS, the phantom body and ionization chamber volumes were contoured for dosimetric analysis. A single-field plan was

generated using a source-to-surface distance (SSD) technique with a 6 MV photon beam and a square field size of 10 × 10 cm². The gantry, collimator, and couch angles were all set to 0°, ensuring straightforward beam geometry.

A virtual bolus with a surface area of 5 × 5 cm² and a thickness of 0.5 cm was digitally created and positioned on the right lateral surface of the phantom, between the isocenter and the field periphery,as illustrated in the **Figure:1**.

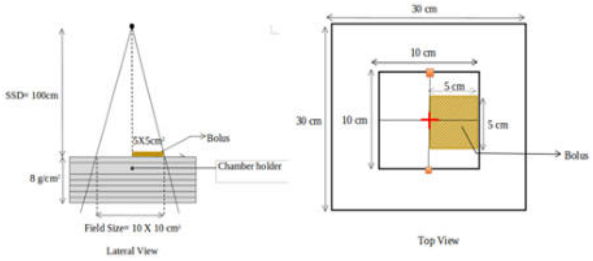

Figure 1: Lateral and top views illustrating the placement of the virtual bolus on the RW3 solid water phantom.

This specific bolus placement was intentionally selected to coincide with periphery of the ionization chamber. Positioning the bolus in this region allowed systematic assessment of dosimetric variations arising from both increased bolus overlap with the measurement point and progressive displacement of the bolus away from it. This configuration was therefore well suited to investigate the impact of small positional uncertainties under controlled conditions.

The prescribed dose was normalized to 100 cGy at the isocenter, and dose calculations were performed using the Anisotropic Analytical Algorithm (AAA), consistent with standard clinical practice.

Measurement & Analysis:

The planned setup was physically reproduced on a Varian TrueBeam SVC linear accelerator (Version 3.0) equipped with a 120-leaf high-definition multileaf collimator (HD-MLC). A 0.5 cm thick Superflab gel bolus was used to replicate the virtual bolus defined in the TPS.

Absolute dose measurements were performed using a Farmer-type ionization chamber (FC65G, IBA Dosimetry) connected to a Wellhofer DOSE-1 electrometer. To evaluate the effect of bolus positional uncertainty, controlled lateral displacements of the bolus were introduced in 1 mm increments up to a maximum shift of 5 mm from the planned position. For each displacement, dose measurements were recorded under identical irradiation conditions. The measured doses were compared against the mean chamber dose calculated by the TPS to quantify percent deviations resulting from bolus misalignment.

Clinical Scenario

Phantom Setup & Imaging:

To simulate a clinically treatment scenario, a CIRS anthropomorphic head phantom with a Farmer-type ionization chamber insert was used. The phantom was scanned using a high-resolution CT protocol with a slice thickness of 0.5 mm to accurately capture surface contours and internal heterogeneities. The CT images were transferred to the Eclipse TPS in DICOM format.

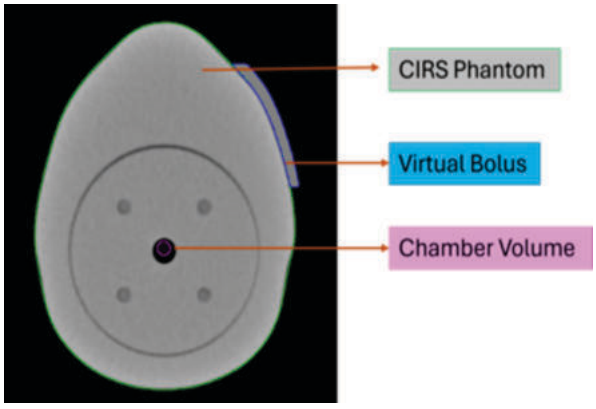

Figure 2: Transverse view of CIRS head phantom with virtual bolus and contoured chamber volume

The external body contour and ionization chamber volume were delineated.**Figure2**: Displays the CIRS head phantom with contoured chamber volume and virtual bolus. Ten head-and-neck IMRT QA plans were generated, representing buccal mucosa treatment cases, which typically involve superficial target volumes requiring bolus application.

Treatment Planning:

A 5 mm thick virtual bolus was designed and applied over the target region, and it was linked to all treatment fields. All IMRT plans were developed using 6 MV photon beams with either 7 or 9 beam arrangements, selected to reflect routine clinical practice. The prescription dose was normalized to 2 Gy at the isocenter.Dose calculations were performed using the AAA algorithm. **Figure 3** provides a visual representation of the beam orientation used in planning.

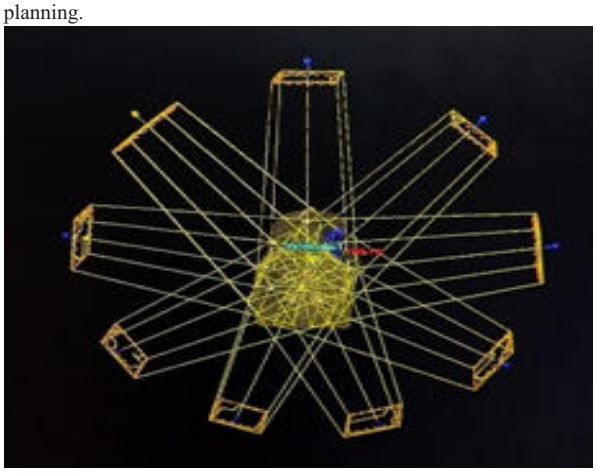

Figure 3: Beam orientation used in planning

Treatment Delivery and Dosimetric Measurements:

The phantom setup was reproduced on the treatment couch using room lasers and reference setup markings.**Figure 4** depicts the CIRS phantom setup. Due to the sensitivity of bolus positioning, cone-beam CT (CBCT) imaging was employed for verification. On average, three CBCT acquisitions were required to achieve acceptable agreement between planned and actual bolus positions.

To simulate bolus positional uncertainty, a controlled displacement of 3 mm was introduced. For each plan, the dose at the isocenter was measured using a Farmer-type ionization chamber. Surface dose measurements were performed using Gafchromic EBT3 radiochromic film placed beneath the periphery of the bolus at the skin–bolus interface.

Figure 4: CIRS phantom setup

Film Dosimetry And Statistical Analysis:

The irradiated EBT3 films were scanned using an Epson Expression

10000XL flatbed scanner under consistent scanning conditions. Optical density values were extracted and analyzed using Radiochromic.com software. A calibration curve was generated using films irradiated over a dose range of 0.25–3 Gy, allowing conversion of optical density to absorbed dose.

Measured doses from ionization chamber and film were compared with TPS-calculated values. Statistical analysis was performed using a Student's *t*-test to assess the significance of dose differences arising from bolus positional uncertainty, with a significance threshold of $p<0.05$.

RESULTS

Non-Clinical Scenario

In the homogeneous RW3 phantom, the introduction of controlled lateral positional uncertainties in bolus placement resulted in minimal dosimetric variation at the chamber point of measurement. For bolus shifts ranging from 1 mm to 5 mm, the measured dose deviation relative to the TPS-calculated value remained within ±2%. When the bolus was displaced away from the isocenter, the maximum observed deviation was −0.81%, while overlapping the bolus toward the isocenter produced a maximum deviation of +1.07%.

Table 1: Dose Deviation For Bolus Positional Error In The RW3 Phantom

Bolus position with known positional error	1mm	2mm	3mm	4mm	5mm
Dose away from isocenter	1.0114Gy	1.01238Gy	1.0148Gy	1.0153Gy	1.0157Gy
% Deviation	-0.38%	-0.48%	-0.72%	-0.77%	-0.81%
Dose overlapping from isocenter	1.004Gy	1.00263Gy	0.9997Gy	0.9967Gy	0.9967Gy
% Deviation	0.34%	0.48%	0.77%	1.07%	1.07%

The quantitative results are summarized in **Table 1**. The observed trend suggests that bolus displacement away from the measurement point reduces scatter contribution, whereas bolus overlap enhances scatter and electron fluence, leading to a modest increase in measured dose. Despite these systematic trends, no statistically significant difference was found between measured and TPS-calculated doses for any of the displacement conditions.

These findings indicate that in a geometrically simple and homogeneous phantom environment, small lateral positional deviations (≤5 mm) of a 5-mm bolus have a negligible impact on depth dose at an isocentric measurement point.

Clinical Scenario

In contrast to the homogeneous RW3 phantom, the heterogeneous CIRS head phantom demonstrated pronounced sensitivity to bolus positional uncertainty, particularly in the surface dose region. Across ten head-and-neck IMRT QA plans, the introduction of a controlled 3-mm bolus overlap resulted in a statistically significant increase in surface dose compared with TPS-calculated values ($p = 0.00065$), as summarized in **Table 2.**

Table 2: Dose At The Surface

Cases	1	2	3	4	5	6	7	8	9	10	p-value
Actual bolus position at TPS (Gy)	0.802	0.376	1.00	1.08	0.964	1.187	0.527	1.203	0.690	1.012	0.0006
Measured with 3mm known bolus overlap (Gy)	1.438	0.822	1.844	1.784	1.549	1.775	0.895	1.934	1.321	1.722	

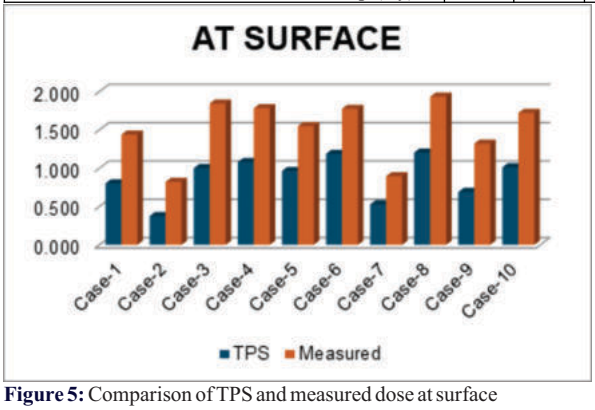

Figure 5: Comparison of TPS and measured dose at surface

The visual representation of the Table 2 is depicted in the **figure 5**. For all evaluated cases, film-measured surface doses exceeded TPS predicted doses when the bolus was displaced 3mm from the actual position. The magnitude of surface dose enhancement varied across plans, reflecting differences in beam modulation, local surface curvature, and heterogeneity within the head-and-neck geometry. The percentage increase in surface dose ranged from approximately 50% to 120% across individual cases.

On average, a 3-mm bolus positional overlap resulted in a **mean surface dose increase of approximately 75%** relative to the TPS calculated dose for the planned bolus position. This substantial deviation highlights the extreme sensitivity of the build-up region to small bolus misalignments in highly modulated IMRT treatments.

At the isocenter, however, no statistically significant difference was observed between TPS-calculated and ion chamber measured doses ($p = 0.5161$), summarized in **Table:3.**

Table 3: Dose At The Isocenter

Cases	1	2	3	4	5	6	7	8	9	10	p-value
Actual bolus position at TPS (Gy)	1.163	1.025	1.209	0.753	1.334	1.971	1.073	1.056	1.508	1.651	0.5161
Measured with known 3mm bolus overlap (Gy)	1.034	0.921	1.114	0.641	1.205	1.848	0.926	0.931	1.366	1.634	

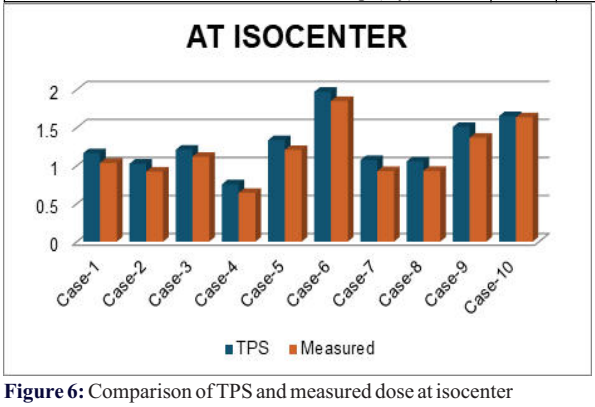

Figure 6: Comparison of TPS and measured dose at isocenter

The visual representation of the Table 3 is depicted in the **Figure 6**.Across the ten IMRT QA plans, the percent dose deviation at the isocenter ranged from −14.8% to -1.03%, with the majority of cases demonstrating negative deviations, indicating a slight reduction in measured dose compared to TPS predictions. The **average percentage deviation across all cases was −9.3%**, confirming that is ocenter dose remains largely insensitive to small bolus positional uncertainties.

DISCUSSION

This study demonstrates that virtual bolus positional uncertainty produces minimal dosimetric perturbation at depth in a homogeneous RW3 phantom (≤2% deviation) but causes significant and clinically relevant changes in surface dose for head-and-neck IMRT delivered to a heterogeneous CIRS head phantom, while isocenter doses remain comparatively unaffected.

The observed findings are in strong agreement with the clinical study by Salagean et al. who investigated the dosimetric consequences of daily bolus positioning variability in post-mastectomy breast cancer radiotherapy. Their retrospective analysis of 12 patients revealed that bolus displacement resulted in relatively minor changes (~2%) in PTV 95% coverage and small variations in organ-at-risk (OAR) dose metrics. However, they also reported that individual fractions could exhibit meaningful shifts in hotspot location and superficial dose distribution, particularly when bolus placement deviated from the planned geometry. Similar to our findings, deeper dose metrics remained largely stable, whereas superficial dose regions were more susceptible to daily setup variations. These parallel observations reinforce the conclusion that while virtual bolus modeling is adequate for predicting deep dose delivery, it may not fully capture clinically relevant uncertainties in surface dose unless bolus placement is highly reproducible [11].

The sensitivity of surface dose to air gaps and bolus misalignment

observed in this study is further supported by phantom-based investigations. Gül (2023) demonstrated a clear inverse relationship between air-gap magnitude and surface dose for a 6 MV photon beam using a 5 mm bolus, reporting substantial dose reductions even for millimetre-scale separations. This behaviour directly mirrors our clinical phantom measurements, where a controlled 3 mm displacement of the bolus produced significant reductions in measured surface dose, despite accurate isocenter alignment. These findings emphasize that air gaps introduced by imperfect bolus placement can undermine the intended build-up modification, potentially leading to underdosage of superficial targets [12].

Lobo et al. extended this understanding by evaluating air gaps ranging from 0 to 3 cm beneath gel bolus materials and reporting surface dose reductions of 3–15%, depending on bolus thickness and field size. They also observed a systematic shift of the depth of maximum dose away from the surface with increasing air-gap size. Importantly, their study showed that percent depth dose (PDD) values beyond approximately 0.4 cm depth remained largely unchanged, even in the presence of substantial air gaps. This characteristic pattern significant perturbation in the build-up region with minimal effect at depth is consistently reproduced in both the homogeneous and heterogeneous phantom experiments conducted in the present study, reinforcing the reliability of the observed trends [13].

Study by Khan et al. using a 1.0 cm super-flab bolus, investigated the effects of various scenarios of air gaps between the surface and the bolus on dose distribution. They showed that as the distance between the bolus and the surface increases, the relative dose decreases [14].

In contrast, the study by Jreije et al. highlighted the potential benefits of patient-specific 3D-printed boluses, which were shown to conform closely to irregular anatomical surfaces, thereby reducing air gaps to 0.4–2.2 mm. Improved bolus conformity translated into enhanced surface dose coverage and greater dosimetric reliability [15]. These findings provide a compelling explanation for the minimal perturbations observed in our non-clinical RW3 phantom experiment, where the geometry was simple and reproducible. Conversely, the increased sensitivity observed in the heterogeneous CIRS head phantom reflects the challenges encountered in real-world clinical scenarios involving complex anatomy and variable surface contours.

The clinical implications of bolus positioning uncertainty are further underscored by the work of Kempt and Ostapiak, who compared planned virtual bolus placement with actual clinical bolus positioning in head-and-neck patients. They reported a substantial reduction in minimum clinical target volume (CTV) dose from 84.7% with virtual bolus modeling to 62.7% with real bolus placement as well as a 10.4% decrease in the volume covered by the 95% isodose line [16]. These findings closely mirror the patterns observed in our phantom-based study, emphasizing that bolus-related uncertainties can translate into clinically meaningful undercoverage of superficial targets, even when deeper dose metrics appear acceptable.

Overall, this study confirms that precise and reproducible bolus positioning is essential for the accurate delivery of superficial dose in highly modulated radiotherapy techniques such as IMRT. While deeper dose distributions are relatively insensitive to small bolus displacements, surface and near-surface regions are highly vulnerable to positional uncertainty. Accurate bolus placement can be enhanced through standardized setup protocols, clear bolus alignment markings, robust immobilization devices, and routine image guidance such as CBCT to verify daily positioning. In anatomically complex regions, the adoption of patient-specific 3D-printed boluses offers a promising strategy to minimize air gaps and improve reproducibility. Collectively, these measures can reduce dosimetric uncertainty in the build-up region and help ensure consistent, clinically effective treatment of superficial disease.

CONCLUSION

Bolus positional uncertainties have minimal impact on isocenter dose but can cause clinically significant deviations in the surface dose, particularly in highly modulated IMRT treatments for head-and-neck cancers. Ensuring precise and reproducible bolus placement is critical for maintaining accurate superficial dose delivery and minimizing the risk of underdosage or overdosage.

Implementation of improved QA procedures, better immobilization, and exploration of conformal bolus techniques may help to mitigate these uncertainties in clinical practice.

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