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# Surface Dose Enhancement Using a Silicon Rubber–Tungsten (SR-W) Bolus: RED, Absorbed Dose, and PDD Analysis for LINAC-Based Radiotherapy

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## ABSTRACT

This study investigates the dosimetric performance of a Silicon Rubber–Tungsten (SR–W) composite bolus designed for external beam radiotherapy using 6-MV and 10-MV photon energies. The bolus was manufactured by integrating 6 wt% tungsten powder into an RTV-52 silicone matrix and fabricated in five thickness variations (2–10 mm). Relative electron density (RED) was quantified from CT-derived Hounsfield Unit conversion, while absorbed dose and percentage depth dose (PDD) were measured in a solid-water phantom using a Farmer-type ionization chamber under standardized LINAC conditions. The RED remained stable and tissue-equivalent for 2–8 mm (1.043–1.047), while the 10-mm sample showed increased density (1.102) attributable to enhanced effective electron density. The incorporation of tungsten significantly improved dose build-up, yielding higher absorbed dose and PDD values, with optimal enhancement observed at 16–18 mm for 6 MV and 18–20 mm for 10 MV, without introducing excessive attenuation. These findings demonstrate that the SR–W bolus provides reliable surface-dose amplification and consistent dosimetric behavior, indicating strong potential for clinical implementation in megavoltage LINAC radiotherapy.

***Keywords:*** Silicon Rubber–Tungsten bolus; Relative Electron Density; Absorbed dose; Percentage Depth Dose; LINAC radiotherapy.

## INTRODUCTION

Radiotherapy delivered using linear accelerators (LINACs) remains a cornerstone modality for cancer management due to its ability to generate megavoltage (MV) photon beams with high penetration and precise dose distribution [1]. Despite these advantages, MV beams inherently exhibit a skin-sparing effect, where the surface dose is substantially lower than the dose delivered at the depth of maximum dose (dmax) [2]. This characteristic, while beneficial for sparing healthy skin in many clinical scenarios, becomes a limitation in cases requiring increased surface dose, such as superficial tumors, postmastectomy chest wall irradiation, and treatments involving irregular patient anatomy [3].

To address this limitation, bolus materials are routinely applied to shift the build-up region toward the surface, enhance dose deposition at shallow depths, and compensate for contour irregularities. The effectiveness of a bolus depends critically on its physical and dosimetric characteristics—particularly its relative electron density (RED), flexibility, and stability during irradiation. Conventional bolus materials such as paraffin, superflab, and tissue-equivalent gels have been widely used; however, these materials often exhibit limitations including inadequate conformity, variable density, and susceptibility to deformation, which can compromise dose accuracy and reproducibility [4].

Silicone-based bolus materials have been explored extensively due to their mechanical flexibility, biocompatibility, and electron-density similarity to soft tissue. Recent research has demonstrated that silicone elastomers can effectively improve surface dose under MV photon irradiation [5]. To further enhance dosimetric performance, studies have incorporated high atomic number (high-Z) fillers—such as copper, bismuth, and tungsten—into silicone matrices. These fillers increase photon interaction probability, promote secondary electron generation, and consequently elevate surface dose levels. Tungsten, in particular, offers a favorable combination of high density and biocompatibility, making it a promising candidate for bolus enhancement [6].

While previous investigations have shown the potential of tungsten-infused bolus materials, several research gaps remain. Many studies focus on single-energy beam evaluations, lack comprehensive analysis of RED, absorbed dose, and percentage depth dose (PDD) relationships, or do not evaluate behavior across multiple bolus thicknesses under consistent, clinically relevant irradiation conditions. Moreover, limited attention has been given to correlating material density variations with build-up region modification. [7,8].

The present study aims to address these gaps by developing and characterizing a Silicon Rubber–Tungsten (SR–W) composite bolus and evaluating its performance under 6-MV and 10-MV photon beams from a clinical LINAC. The study provides a systematic assessment of RED, absorbed dose, and PDD across multiple thicknesses to determine the bolus's suitability for enhancing surface dose in external beam radiotherapy. Through this combined analysis, the research seeks to clarify the dosimetric benefits of tungsten integration and identify optimal thickness ranges for clinical application.

## MATERIALS & METHODS

### Bolus Fabrication

The Silicon Rubber–Tungsten (SR–W) bolus was synthesized by integrating 6 wt% tungsten powder into an RTV-52 silicone rubber base. To enhance homogeneity and ensure uniform particle dispersion, PEG 4000 (20 g) and distilled water (10 mL) were added to the mixture. The components were stirred magnetically for 60 minutes, followed by ultrasonic agitation for an additional 10 minutes. Afterward, 2 vol% curing catalyst was incorporated, and the mixture was poured into molds measuring 20 × 20 cm. Five thickness variations were produced—2, 4, 6, 8, and 10 mm—and cured at room temperature for 24 hours. The resulting samples were designated as SR–W bolus materials.

### Relative Electron Density (RED) Measurement

RED values were determined using CT imaging acquired at 160 kV and 80 mA. For each bolus thickness, five regions of interest (ROIs) were selected to measure average Hounsfield Unit (HU) values. The HU-to-RED conversion was performed using established calibration equations [9]:

$$\rho_a = 1.052 + 0.00048N_{CT} \quad (1)$$
$$\rho_b = 1.000 + 0.001N_{CT} \quad (2)$$

where separate models were applied for HU values above and below 100. This method ensured accurate estimation of electron density, a critical property for evaluating tissue equivalence and photon interaction behavior [9].

### Dosimetric Setup and Absorbed Dose Measurement

Absorbed dose measurements were conducted using a Varian Clinac RapidArc LINAC operating at photon energies of 6 MV and 10 MV. As illustrated in Fig. 1, each SR–W bolus sample was positioned on top of a solid-water phantom. A Farmer-type ionization chamber was placed 1 cm below the phantom surface to measure absorbed dose under reference conditions. Irradiations were performed at a source-to-surface distance (SSD) of 100 cm and a field size of 18 × 18 cm², with a reference dose of 100 cGy per 100 MU. Measurements were recorded for the no-bolus scenario as well as for bolus thicknesses ranging from 2 to 10 mm. All readings were corrected for temperature and pressure variations according to the IAEA TRS-398 protocol.

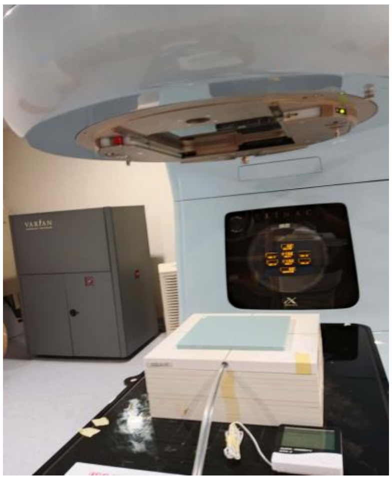

**Figure 1. Position of absorbed dose measurement with Bolus SR-W using a solid phantom on a LINAC**

### Percentage Depth Dose (PDD) Determination

PDD values were calculated using measured dose at depth $D_d$ relative to the maximum dose $D_{d0}$ according to standard PDD formulations [1]:

$$\text{PDD} = \frac{D_d}{D_{d0}} \times 100\% \qquad (3)$$

PDD curves were generated for each bolus thickness using both 6-MV and 10-MV photon beams. The analysis focused on evaluating build-up region shifts and assessing the bolus's influence on surface-proximal dose enhancement.

### Data Analysis

Absorbed dose and PDD data were analyzed using OriginPro and Microsoft Excel. Graphical analyses were used to visualize trends in dose enhancement and build-up modification as functions of bolus thickness. Statistical comparisons were performed to determine optimal thickness ranges for clinical application.

## RESULT

### Relative Electron Density (RED)

The Relative Electron Density values of the SR–W bolus across the five thickness variations are summarized in Table 1. The RED remained highly consistent and tissue-equivalent for the 2–8 mm samples, ranging from 1.043 to 1.047. These values reflect stable material uniformity and indicate that the silicone–tungsten composite closely mimics the electron density of soft tissue within this thickness range. A notable increase occurred at 10 mm, where the RED rose to 1.102. This reflects the cumulative influence of tungsten content at greater material volume, resulting in elevated effective density and increased photon interaction probability.

**Table 1. Relative Electron Density values of the SR-W bolus at various thicknesses**

| Thickness (mm) | RED |
|---|---|
| 2 | 1,045 |
| 4 | 1,047 |
| 6 | 1,043 |
| 8 | 1,047 |
| 10 | 1,102 |

The data confirm that the SR–W composite maintains soft-tissue equivalence at lower thicknesses while offering enhanced density characteristics at higher thicknesses, which may contribute to increased surface-dose build-up.

### Absorbed Dose

Absorbed dose measurements for both 6-MV and 10-MV photon beams showed a consistent upward trend with increasing bolus thickness. Without a bolus, the 6-MV absorbed dose was 98.61 Gy, increasing to approximately 102–103 Gy at thicknesses between 14 and 20 mm. A similar pattern was observed at 10 MV, with absorbed dose increasing from 89.18 Gy (no bolus) to 103–105 Gy at thicker configurations.

These results demonstrate that the SR–W bolus effectively enhances photon energy deposition near the surface. The largest rate of increase occurred between 10–16 mm, after which the absorbed dose plateaued, indicating diminishing returns for thicknesses beyond ~18 mm.

**Table 2. Absorbed dose and percentage depth dose (PDD) values of the SR-W bolus at various thicknesses for an 18 × 18 cm² field size**

| Thickness (mm) | Dose (Gy) | | Percentage Depth Dose (%) | |
|---|---|---|---|---|
| | 6 MV | 10 MV | 6 MV | 10 MV |
| 10 (no bolus) | 98,61 | 89,18 | 96,37 | 85,17 |
| 12 (with bolus) | 101,72 | 96,17 | 99,41 | 91,85 |
| 14 | 102,23 | 99,43 | 99,91 | 94,96 |
| 16 | 102,54 | 101,83 | 100,21 | 97,25 |
| 18 | 102,61 | 103,90 | 100,29 | 99,22 |
| 20 | 102,19 | 105,04 | 99,88 | 100,32 |

## Absorbed Dose Trend Visualization

Figure 2 illustrates the absorbed dose variations as a function of bolus thickness for 6-MV and 10-MV beams. The dose enhancement trend is clearly upward for both energies, with 10 MV demonstrating a slightly steeper increase. Beyond 16–18 mm, the dose gradient began to stabilize, suggesting that optimal dose enhancement occurs within this range.

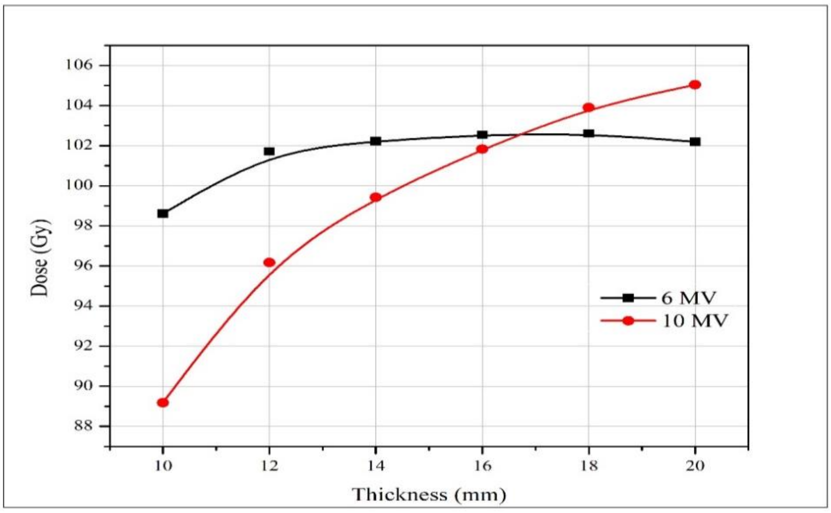


**Figure 2. Absorbed dose as a function of SR-W bolus thickness for 6 MV and 10 MV photon beams at a field size of 18 × 18 cm². MV; Megavolt.**

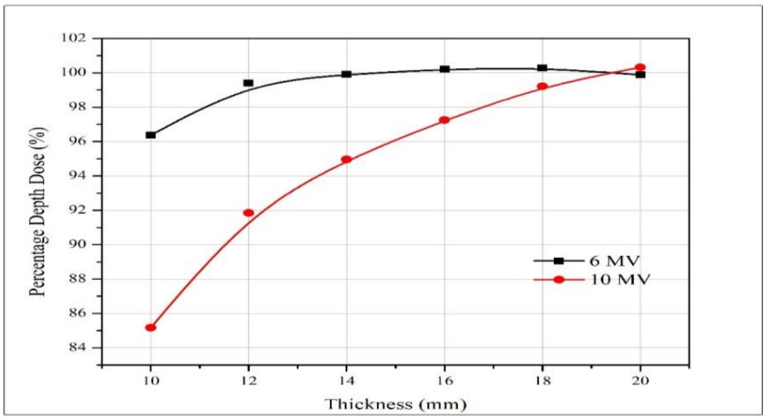


**Figure 3. Percentage depth dose (PDD) as a function of SR-W bolus thickness for 6 MV and 10 MV photon beams at a field size of 18 × 18 cm². MV; Megavolt**

**Percentage Depth Dose (PDD)**

PDD results, presented in Figure 3, reveal that increasing bolus thickness systematically shifts the build-up region toward the surface. For 6 MV, PDD values approached and slightly exceeded 100% at 16–18 mm thickness, while for 10 MV the same effect occurred at approximately 18–20 mm.

## DISCUSSION

The results of this study provide a detailed characterization of the physical and dosimetric performance of the Silicon Rubber–Tungsten (SR–W) bolus, highlighting its relevance for surface-dose enhancement in megavoltage radiotherapy. The RED analysis demonstrated that the SR–W composite maintains soft-tissue-equivalent electron density across thicknesses of 2–8 mm, with only marginal variation. This consistency is clinically advantageous because bolus materials with stable RED values minimize beam perturbation and reduce the risk of unintended spectral modification during treatment [10]. The substantial increase in RED observed at 10 mm reflects a higher effective electron density due to greater tungsten mass per unit volume, indicating that tungsten plays a dominant role in modulating photon interaction probability within thicker bolus layers [11]. These findings were in agreement with the results reported by Endarko et al. (2021) and Sekartaji et al. (2020), who indicated that bolus materials with RED values within the range of 1.0–1.1 were suitable for LINAC-based radiotherapy applications [4,12].

Furthermore, the progressive increase in absorbed dose and Percentage Depth Dose (PDD) with bolus thickness confirmed the dosimetric efficiency of SR–W in modifying the build-up region. The presence of tungsten contributed to enhanced secondary electron generation and scattering, resulting in higher dose deposition near the surface. The relationship observed between bolus thickness and absorbed dose showed that the optimal dosimetric performance was achieved at 16–18 mm for 6 MV photon beams and 18–20 mm for 10 MV photon beams [13]. Beyond these thicknesses, further increases produced minimal dose enhancement, indicating a saturation effect typical of high-Z material interactions under megavoltage photon irradiation. This behavior was consistent with theoretical expectations described by Flinton (2019), which state that surface dose enhancement occurs as a result of contaminant electron interactions intensified by high-density bolus materials [2].

Clinically, these results demonstrated that the SR–W bolus not only achieved effective surface-dose enhancement but also maintained dose uniformity and reproducibility, essential for reliable LINAC radiotherapy procedures. The silicone rubber matrix provided sufficient flexibility and conformability, enabling good adaptation to irregular anatomical contours without compromising the dosimetric integrity [14]. Compared with conventional bolus materials such as Superflab or paraffin, the SR–W composite offered superior dose build-up behavior while retaining mechanical stability and patient comfort. In line with previous research by Boopathi et al. (2023), Chen et al. (2024), and Takei et al. (2020), this study further confirms that integrating high-Z elements, such as tungsten, into silicone-based matrices can significantly improve surface-dose characteristics for clinical radiotherapy applications. Thus, the SR–W bolus demonstrated promising potential as an advanced, flexible, and dosimetrically stable material suitable for surface-dose enhancement in LINAC-based external beam radiotherapy [5, 8, 15,16].

## CONCLUSION

The Silicon Rubber–Tungsten (SR–W) composite bolus demonstrated physical and dosimetric characteristics that meet the requirements of LINAC-based radiotherapy, indicated by stable soft-tissue-equivalent RED values at 2–8 mm thickness and a significant enhancement of surface dose through increased absorbed dose and PDD, with optimal thicknesses of 16–18 mm for 6 MV and 18–20 mm for 10 MV without causing excessive dose overshoot; based on these findings, recommended future studies to evaluate the performance of SR–W in realistic anatomical geometries using CT-based planning and in vivo assessments, as well as examine its clinical usability in terms of conformability and comfort when applied to patient body contours.

## *Declaration by Authors*

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