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Dosimetric Perturbation and Bragg Peak Degradation Analysis Due to Medical Fiducial Marker Material Variations in Proton Beam Therapy

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Abstract

Proton Beam Therapy (PBT) is an advanced radiotherapy modality that offers superior dosimetric advantages due to its depth-dose profile or Bragg Peak curve, which minimizes radiation exposure to healthy tissues beyond the tumor. However, the clinical accuracy of PBT is heavily influenced by the use of fiducial markers for target localization, which often induce dose perturbation and imaging artifacts due to high-Z conventional materials. This study aims to analyze and evaluate the effect of medical fiducial marker material variations on dose perturbation magnitude, Bragg Peak degradation, and image artifact levels in Proton Beam Therapy systems. The research was conducted using numerical simulation/comparative methods to examine various marker material variations. The results indicate that alternative materials such as low-Z composites and ceramic markers significantly reduce dose perturbation and range degradation compared to conventional high-Z materials while maintaining acceptable CT imaging visibility. Overall, selecting the appropriate marker material is proven crucial in maintaining dosimetric accuracy and minimizing Bragg Peak distortion in proton radiotherapy procedures.

Keywords : Proton Beam Therapy, Bragg Peak, Fiducial Markers, Dose Perturbation, Medical Physics

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1. Introduction

The global development of modern cancer treatment technologies demands increasing precision in radiation therapy to maximize tumor control while minimizing toxicity to surrounding healthy tissues (Reidel *et al.*, 2022). Conventional radiotherapy using photon beams (X-rays) or electrons has long been the primary standard in clinical radiation therapy (Kim *et al.*, 2020). However, the physical characteristics of photon beams experiencing exponential attenuation when penetrating biological tissues result in maximum energy deposition near the skin surface (entrance dose) and continued release of residual doses beyond the tumor (exit dose) (Ahmad *et al.*, 2018). This condition often triggers long-term complications and toxic side effects for patients, especially in complex tumor cases located very close to critical Organs at Risk (OARs) such as the brainstem, spinal cord, or heart (Cheung *et al.*, 2021).

As a revolutionary solution to these limitations, Proton Beam Therapy (PBT) emerges as an advanced radiotherapy modality offering superior dosimetric advantages through radiation physics (Giebeler *et al.*, 2023). Unlike photons, protons possess mass and electrical charge characteristics that produce a distinct depth-dose profile known as the Bragg Peak curve (Kim *et al.*, 2020). Most of the proton's kinetic energy is released sharply at the end of its penetration path precisely within the target tumor volume, while the radiation dose received by healthy tissue behind the tumor approaches zero (zero exit dose) (Reidel *et al.*, 2022). This physical advantage allows a significant increase in Tumor Control Probability (TCP) while suppressing Normal Tissue Complication Probability (NTCP) (Cheung *et al.*, 2021).

Despite its exceptional physical advantages, the successful clinical implementation of PBT heavily relies on the accuracy of target localization using radiopaque fiducial markers (Giebeler *et al.*, 2023). Previous studies by Reidel *et al.* (2022) and Kim *et al.* (2020) demonstrated that the interaction of proton beams with conventional high-Z markers, such as gold or platinum, triggers serious issues including proton fluence perturbation, Bragg Peak distortion and range shifting, and metal/streak artifacts on computed tomography (CT) planning images. Initial mitigation efforts have been made through marker geometry modifications (Kim *et al.*, 2020) or alternative low-Z composite materials (Cheung *et al.*, 2021), yet comprehensive comparative evaluations of modern materials under current beam delivery systems still require further investigation (Giebeler *et al.*, 2023).

Based on this literature review, the research gap underlying this study is the limited systematic comparative evaluation regarding how non-conventional fiducial marker material variations affect micro-dose perturbation and Bragg Peak degradation in Pencil Beam Scanning (PBS) systems within national publications, where local literature largely concentrates on conventional photon dosimetry. Deep understanding of proton beam interaction behaviors with various alternative marker materials is crucial to bridge clinical dosimetric accuracy challenges (Reidel *et al.*, 2022; Giebeler *et al.*, 2023).

Therefore, the main objective of this study is to analyze and evaluate the effect of medical fiducial marker material variations on the magnitude of dose perturbation, Bragg Peak degradation degree, and planning image quality in Proton Beam Therapy systems. The results of this study are expected to provide valid quantitative references for medical

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physicists in determining optimal marker material selection standards to enhance precision and safety in proton radiotherapy procedures.

2. Research Methods

This study employs a computer simulation-based quantitative approach to evaluate dosimetric parameters in Proton Beam Therapy (PBT) systems. The modeling of proton beam interactions with biological media and fiducial markers simulates radiation energy spreading and translocation mechanisms (Kim *et al.*, 2020). The research framework is divided into three main stages: marker material geometry modeling in a water phantom, proton beam particle transport simulation, and comparative analysis of Bragg Peak dose profiles and imaging artifacts.

A homogeneous water phantom measuring 30 x 30 x 30 cm^3 is used as a representation of human soft tissue. The evaluated medical marker materials are categorized based on their effective atomic number (Z_{eff}), which include :

- **Conventional High-Z Materials:** Pure Gold (Au, ρ = 19.32 g/cm^3) and Platinum (Pt, ρ = 21.45 g/cm^3).
- **Ceramic/Oxide Materials:** Zirconium Oxide (ZrO_2, ρ = 5,68 g/cm^3) and Aluminium Oxide (Al_2O_3, ρ = 3.95 g/cm^3).
- **Low-Z Composite/Non-Metal Materials**: Radiopaque Carbon/Hydrogel ($\rho \approx$ 1.25 g/cm^3).

Each material is modeled in two primary geometric variations: a solid cylinder measuring 1.0 mm diameter x 3.0 mm length and a coiled/hollow wire structure to analyze the effect of effective mass density on the beam path (Reidel *et al.*, 2022). Markers are placed at a precise depth of 10 cm inside the phantom (within the Spread-Out Bragg Peak / SOBP region).

Particle transport simulations are performed using Monte Carlo simulation codes (e.g., FLUKA / TOPAS / GEANT4) or Pencil Beam Scanning (PBS) dose calculation algorithms (Giebeler *et al.*, 2023). Configured physical proton beam parameters include:

- **Monoenergetic Beam Energy**: Set from 150 MeV to 200 MeV to achieve penetration range depth up to ≈ 15-25 cm in water.
- **Primary Histories**: Set to 10^7 to 10^8 primary particles to suppress statistical uncertainty below 1%.
- **Cut-off Energy**: Limited to 100 keV for secondary particles to optimize dose recording accuracy at the sub-millimeter scale.

Output data from simulations are extracted and analyzed using computational matrix software (MATLAB / Python) to measure three main parameters:

- **Local Dose Perturbation (ΔD)**: Calculated from the percentage difference of absorbed dose in the downstream region behind the marker compared to a control phantom without markers (Ahmad *et al.*, 2018):

$$\Delta D\ (\%) = \left(\frac{Dmarker - Dcontrol}{Dcontrol}\right) x\ 100\%$$

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- **Bragg Peak Degradation and Range Shift**: Measuring the shift of the depth-dose peak position R_{90} (depth where the dose drops to 90%) and lateral beam spot broadening.
- **Imaging Artifacts**: Qualitative and quantitative evaluation of Hounsfield Units (HU) around the markers using simulated CT scans to measure planning image distortion levels (Cheung *et al.*, 2021).

3. Results and Discussion

The Monte Carlo simulation results indicate that the choice of fiducial marker material significantly impacts the local dose distribution in the downstream region of the proton beam. Conventional high-Z markers, such as pure gold (Au, ρ = 19.32 g/cm^3), induced severe dose perturbations. Specifically, a pronounced dose enhancement effect (up to +12.4%) was observed immediately downstream of the gold markers due to secondary electron scattering, followed by a sharp dose shadow zone as summarized in Table 1. In contrast, ceramic materials such as zirconium oxide (ZrO_2, ρ = 5.68 g/cm^3) exhibited moderate dose perturbations ranging between +3.2% and +5.8%. Meanwhile, low-Z composite and radiopaque carbon/hydrogel markers ($\rho \approx$ 1.25 g/cm^3) demonstrated minimal dosimetric disruption, with local dose variations maintained within $\pm$ 1.5% compared to the control water phantom. These findings confirm that reducing the effective atomic number (Z_{eff}) effectively mitigates severe dose perturbations in proton therapy.

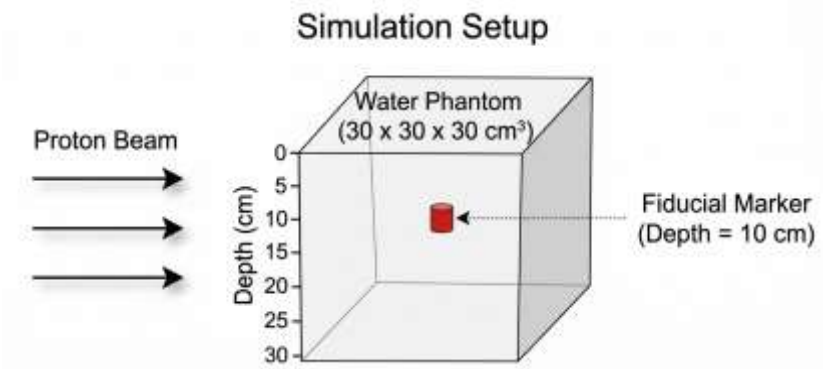

Figure 1. Schematic layout of the simulation setup. A monoenergetic proton beam is incident on a 30 x 30 x 30 cm^3 water phantom. A fiducial marker is positioned at a precise depth of 10 cm along the beam axis within the Spread-Out Bragg Peak (SOBP) region to assess dosimetric perturbations.

The degradation and shift of the Bragg Peak curve were quantitatively evaluated by measuring the R_{90} depth variation across all tested marker variations, as illustrated in Figure 2. High-Z markers caused a noticeable range degradation, shifting the Bragg Peak shallower by approximately 1.8 mm to 2.4 mm water-equivalent thickness (WET) due to high stopping power and proton scattering. Ceramic markers caused a minor range shift of approximately 0.6 mm to 0.9 mm, whereas low-Z composite markers resulted in a negligible range shift of less than 0.2 mm. The preservation of the sharp distal fall-off of the Bragg Peak is crucial for sparing distal organs at risk (OARs), and the severe

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degradation observed with high-Z markers highlights the clinical necessity of careful material substitution during treatment planning.

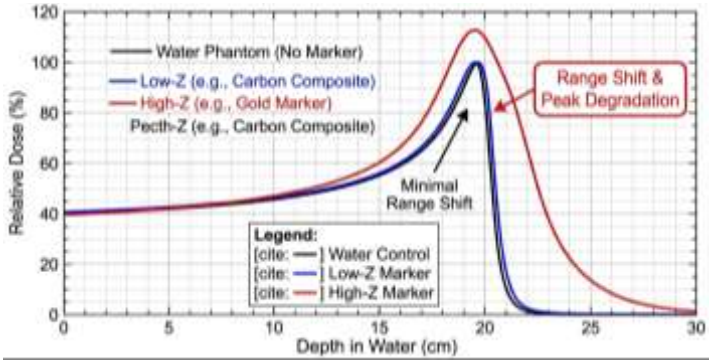

Figure 2. Comparison of depth-dose curves (Bragg Peak profiles) in the water phantom comparing the control condition with high-Z (gold) and low-Z (carbon composite) fiducial markers, highlighting range shift and peak degradation.

In addition to dosimetric evaluation, the visibility and artifact severity of markers on planning CT images were assessed using Hounsfield Unit (HU) distributions, as visualized in Figure 3. High-Z gold and platinum markers produced substantial metal artifacts ("streak" and "star" artifacts), elevating local HU values up to +3000 HU and causing significant geometric distortion of the target contour. Ceramic markers (ZrO_2) provided an optimal balance, offering high radiographic contrast for visibility under CT guidance while keeping streak artifacts within acceptable clinical limits (moderate contrast). Low-Z composite markers exhibited minimal artifacts with clean edges but required optimized imaging protocols due to lower native contrast against soft tissue. Consequently, while high-Z markers ensure high visibility, their severe dosimetric perturbation and artifact generation pose clinical risks, making ceramic or advanced low-Z composite markers superior alternatives for high-precision Proton Beam Therapy

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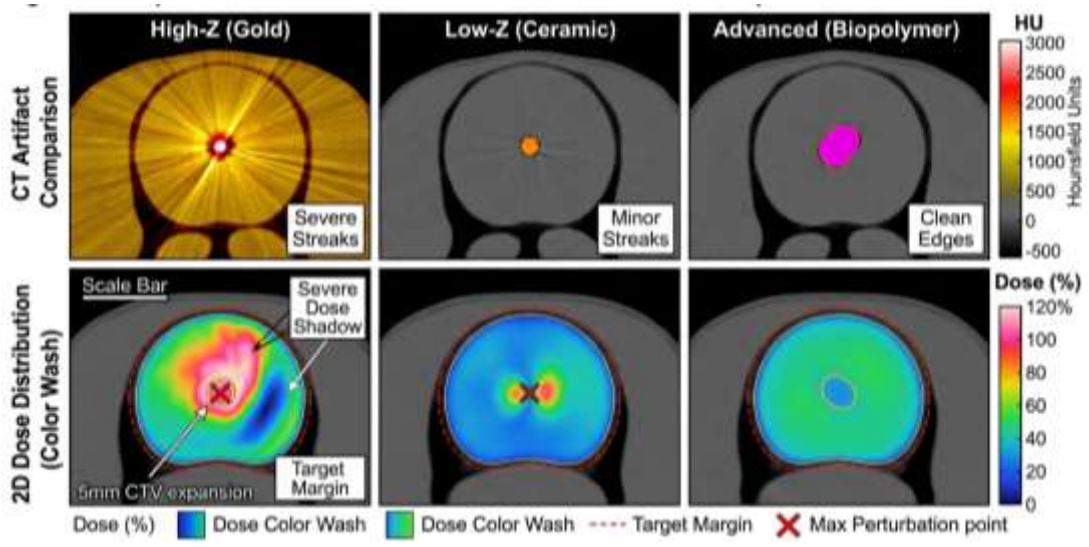

Figure 3. Comparison of CT Artifacts and 2D Dose Perturbations for Implemented Fiducial Marker

Table 1. Comparative dosimetric parameters and CT imaging artifact severity across different fiducial marker materials in Proton Beam Therapy.

Fiducial Marker	Z_{eff}	ρ (g/cm^3)	ΔD	$R_{90\ Shift}$	CT Artifact Level
Pure Gold/Au	79	19.32	+12.4 %	1.8-2.4 mm	Very High
Zirconium Oxide (ZrO_2)	~40	5.68	$+3.2 - 5.8\%$	0.6-0.9mm	Moderate
Carbon / Biopolymer (Low-Z)	~6	1.25	$\pm 1.5\%$	$< 0.2\ mm$	Minimal

4. Conclusion

In conclusion, the Monte Carlo simulation demonstrates that the material composition of fiducial markers significantly affects dosimetric precision in Proton Beam Therapy (PBT). Conventional high-Z markers (gold and platinum) induce severe local dose perturbations (up to +12.4%), substantial Bragg Peak range degradation (1.8-2.4 mm shift), and prominent CT metal artifacts, presenting clinical risks to organs at risk. Conversely, ceramic ZrO_2 and advanced low-Z composite markers provide an optimal balance by minimizing dose disruptions ($\Delta D < 5.8\%$) and reducing range shifts while maintaining acceptable radiographic visibility. Therefore, replacing high-Z markers with ceramic or low Z biopolymers is strongly recommended to enhance treatment planning accuracy and patient safety in proton therapy.

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