Monte Carlo Simulation of Light Propagation in Oral Tissues for Photobiomodulation Therapy

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ABSTRACT

Purpose: Radiation-induced oral mucositis (OM) is a severe complication in head and neck cancer patients, significantly impacting quality of life. While Photobiomodulation (PBM) is a promising non-invasive management strategy, clinical protocols remain inconsistent regarding wavelength and dosage. A primary barrier to standardization is the limited understanding of light propagation within the complex geometry of the oral cavity. This study aims to utilize Monte Carlo (MC) simulations to characterize light propagation and provide insights to optimize PBM dosing specifically for OM treatment.

Methods: We utilized Monte Carlo simulations to model light transport through anatomically realistic oral tissue structures segmented from human head and neck CT data. The study quantified the spatial distribution of light fluence, specifically characterizing the interaction between soft tissues and underlying mineralized structures to calculate the dose delivered to the mucosal basal layer for OM management.

Results: The simulations demonstrated that light scattering and absorption properties significantly alter the effective fluence delivered to the mucosa compared to surface irradiance. We identified distinct differences in fluence profiles between soft tissue and bone, highlighting the need for site-specific protocol adjustments. Crucially, the results identify tissue optical properties, incident angle, and wavelength as key determinants in balancing maximal mucosal delivery with the thermal safety of adjacent structures.

Conclusion: Monte Carlo simulation provides critical mechanistic insights into PBM dosimetry for radiation-induced oral mucositis. By quantifying light distribution in complex oral tissues, this work supports the transition from empirical to evidence-based prescription. These findings will facilitate the development of standardized, safe, and effective PBM protocols to mitigate OM in cancer patients.

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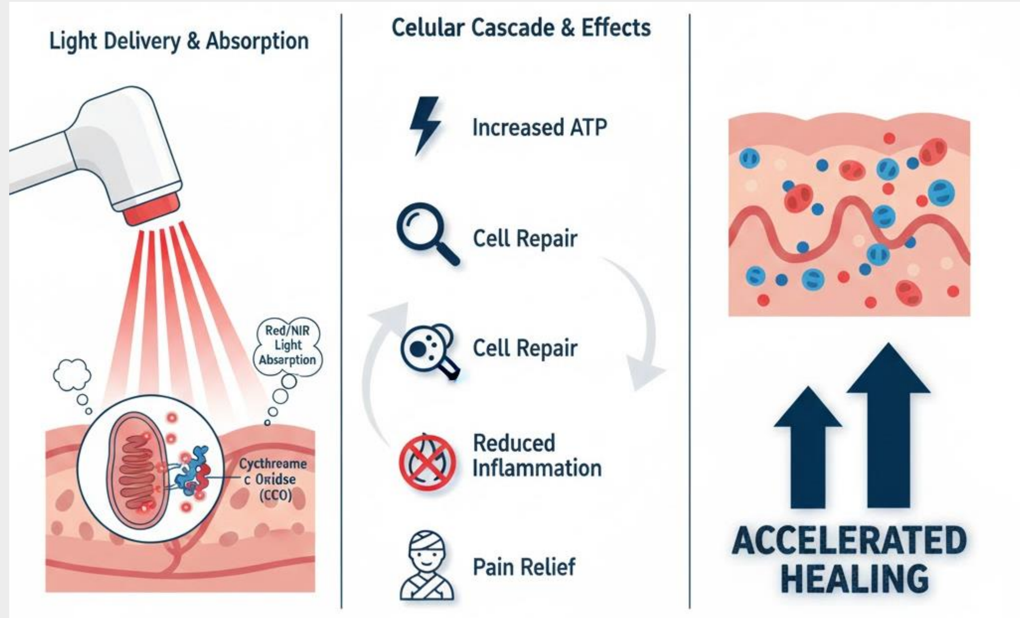
INTRODUCTION

- **Oral mucositis** is painful inflammation, redness, and sores inside the mouth, often a severe side effect of chemotherapy or radiation for cancer, damaging the protective mucous lining and causing difficulty eating, swallowing, and speaking, requiring gentle oral hygiene, pain management, and dietary changes to prevent infection and improve quality of life.
- Photobiomodulation (PBM) is a non-invasive treatment that uses the red or near-infrared light, to stimulate cellular function and promote healing.
- During PBM, photons enter the tissue and interact with the cytochrome c complex within mitochondria. This interaction triggers a biological cascade of events that leads to an increase in cellular metabolism, which can decrease pain as well as accelerate the healing process.



METHODS AND MATERIALS

- To simulate the complex stochastic transport of photons within biological media, we utilized MCmatlab, an open-source Monte Carlo (MC) software package [1]. This framework allows for the 3D voxel-based modeling of light propagation in turbid media by solving the radiative transport equation through the tracking of individual photon packets.
- Anthropomorphic head phantom was developed using anatomical data sourced from embodi3D.com. As illustrated in figure 1, the 3D geometry was contoured into three distinct functional domains-soft tissue, bone, and internal air cavities-to facilitate the modeling of heterogeneous photon paths as light traverses the cranial vault toward intraoral target sites. The optical properties assigned to each segmented structure, summarized in Table 1, were derived from established literature for red and near-infrared wavelengths [2].

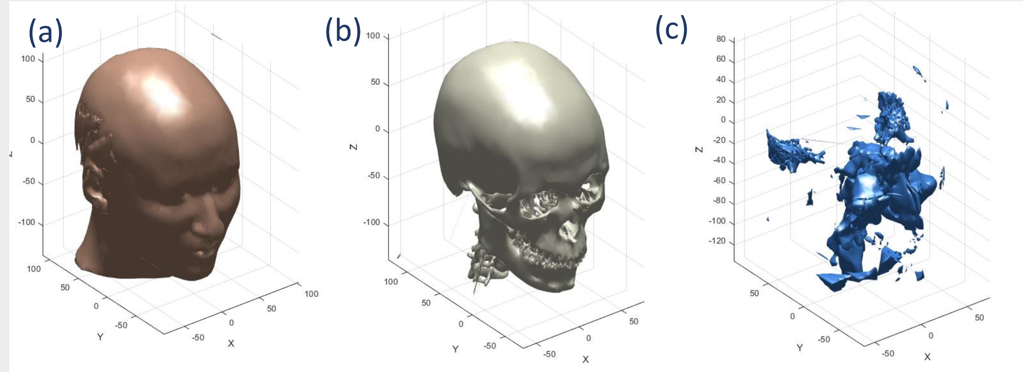


Figure 1. Segmentation of the anthropomorphic human head phantom into three primary functional domains: (a) soft tissue, (b) bone, and (c) internal air cavities.

Table 1. Optical Properties of Anthropomorphic head phantom .

Structure	μ_a(1/cm)	μ_s'(1/cm)	g
Soft Tissue	0.15	8.2	0.9
Bone	0.025	28	0.94
Air	0	0	1

RESULTS

MCmatlab simulations show that increasing the beam incidence angle broadens surface fluence and reduces penetration depth. At high angles (75°), photon energy is concentrated near the tissue surface with negligible penetration beyond 0.2 cm, highlighting the sensitivity of light delivery to beam orientation.

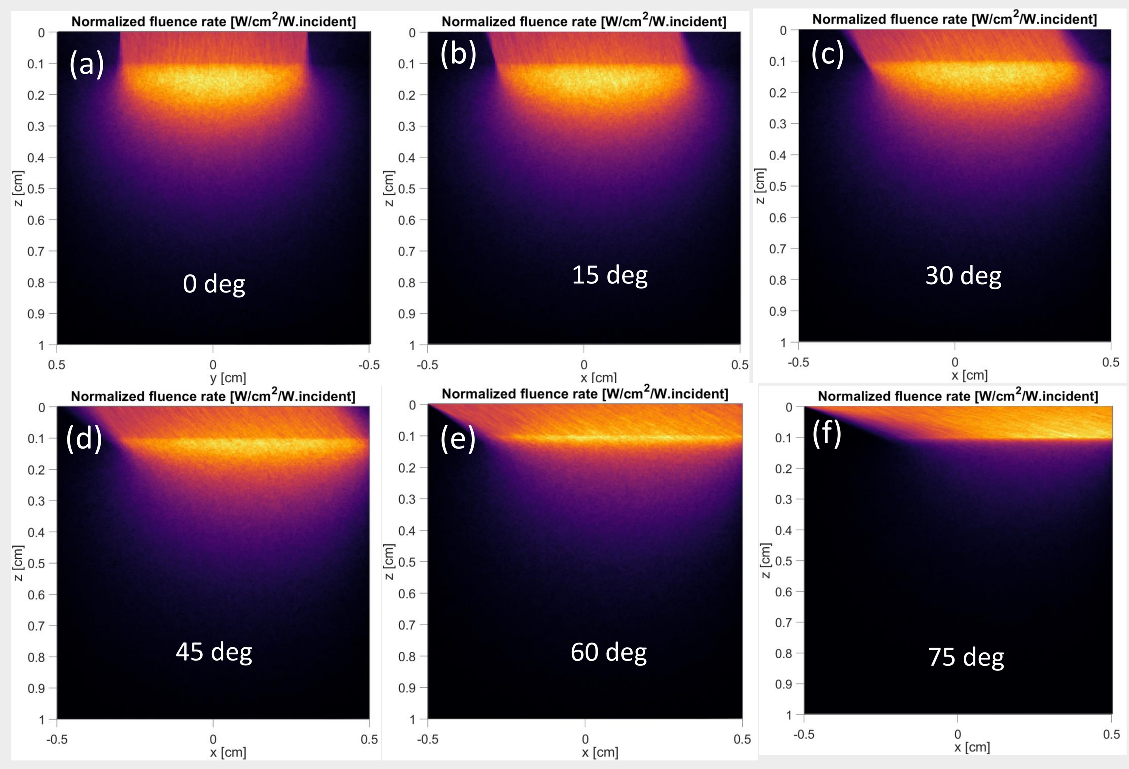


Figure 2. Monte Carlo simulations of normalized fluence rate in the cubic tissue phantom Panels (a) through (f) illustrate the beam propagation at incident angles ranging from 0° to 75°.

Normalized fluence decreases with depth and is strongly affected by beam angle as shown in figure 2. Lower incidence angles maintain higher fluence at greater depths, while oblique angles produce lower peaks and faster attenuation. Fluence drops below 20% beyond 0.6 cm for all angles.

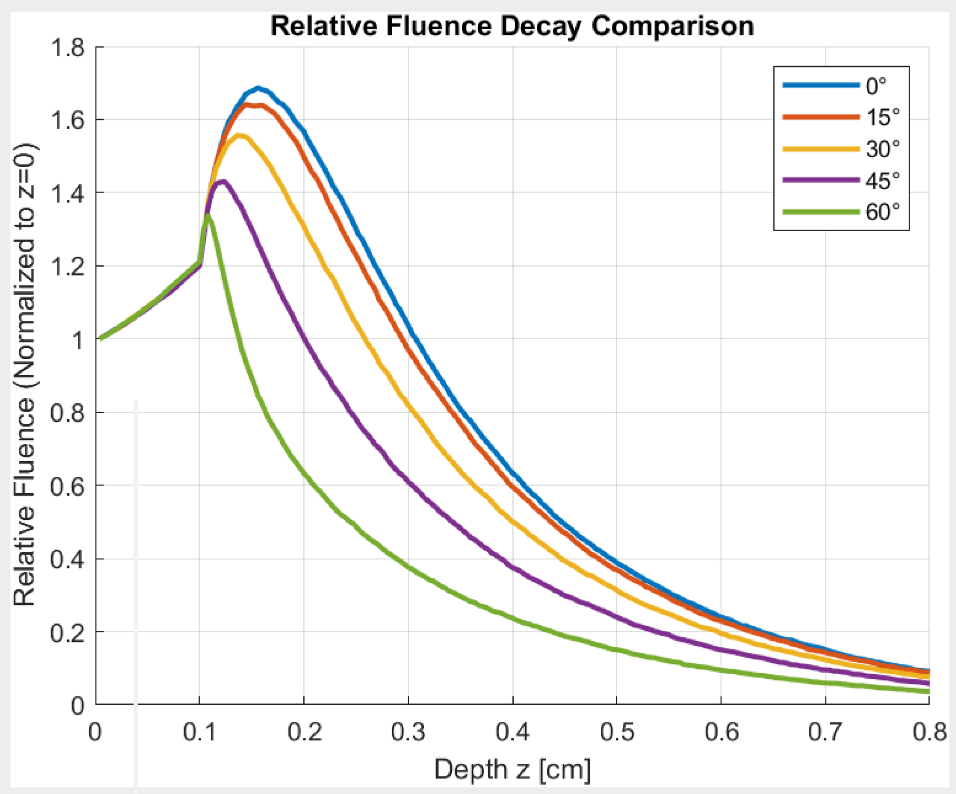


Figure 3. Relative fluence decay as a function of depth (z) along the central axis of the cubic phantom, normalized to the initial surface value at z=0. The curves illustrate the spatial distribution of energy for incident angles ranging from 0 to 60 degrees.

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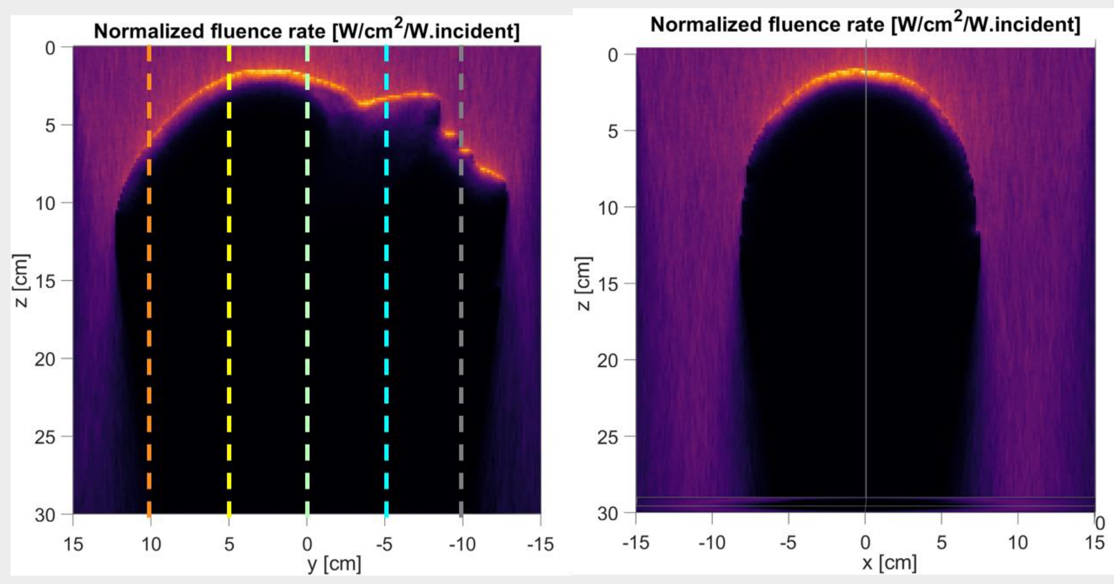

Figure 4. Monte Carlo simulation results of photon transport through the anthropomorphic human head phantom. Panels (a) and (b) display the cross-sectional normalized fluence rate maps in the y-z and x-z planes, respectively.

Figure 4 demonstrates that anatomical heterogeneity strongly influences light transport in the head phantom. Light is primarily confined to superficial scalp and facial tissues, with rapid attenuation caused by scattering and absorption in bone and other structures. Fluence profiles in figure 5 show a steep decline with depth, indicating that extraoral PBM may be insufficient for deep intraoral targets. These findings highlight the need for individualized dosimetry and, when appropriate, intraoral light delivery to achieve therapeutic fluence levels.

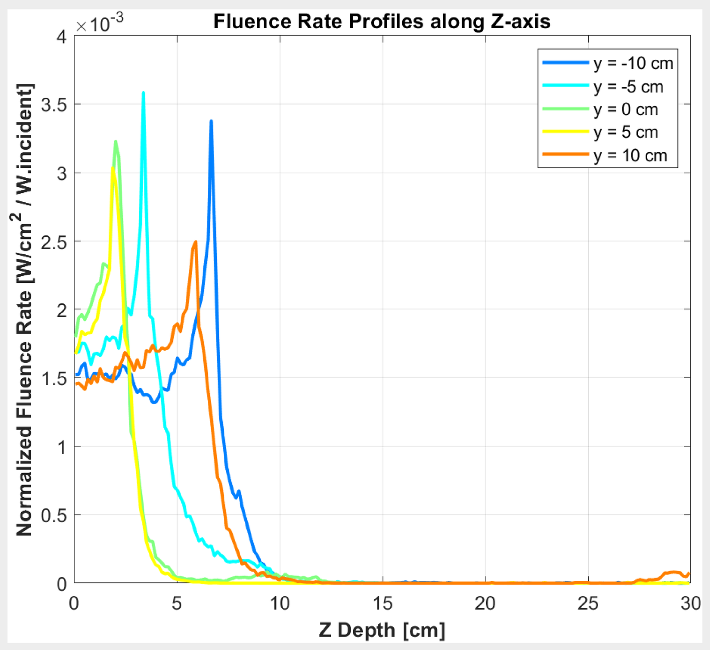

Figure 5. quantitative fluence rate profiles extracted along the z-axis at various lateral positions (y = -10 to +10cm) which is marked in fig. 4 (a) with same color respectively.

CONCLUSIONS

- ✓ Monte Carlo simulations demonstrated that PBM light penetration is strongly affected by beam angle and tissue anatomy. Oblique incidence reduced penetration depth and increased surface dispersion, while heterogeneous structures in the head phantom caused rapid attenuation.
- ✓ Simulation results indicate that therapeutic laser light penetrates only 2–3 mm into oral mucosal tissue, suggesting that intraoral or internal illumination strategies may be more effective than external approaches.
- ✓ These findings highlight the need for anatomy-specific dosimetry and support intraoral delivery for achieving therapeutic fluence in oral mucositis treatment.

REFERENCES

1. Marti, D., Aasbjerg, R.N., Andersen, R.E., and Hansen, A.K., J. Biomed. Opt. 23(12), 121622 (2018)
2. Bashkatov, A. N., Genina, E. A., Kochubey, V. I., Tuchin, V. V., J. Phys. D: Appl. Phys. 38(15), 2543–2555 (2005).