Quantifying the Effects of Dose Build-Up and Tissue Optical Properties On Cherenkov Emission During External Beam Irradiation

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INTRODUCTION

What is Cherenkov radiation?

In general, Cherenkov radiation is the emission of light in a dielectric medium when a charged particle travels faster than the phase velocity of light in that medium. The blue glow familiarly seen in underwater nuclear reactors is a common example of this phenomenon.

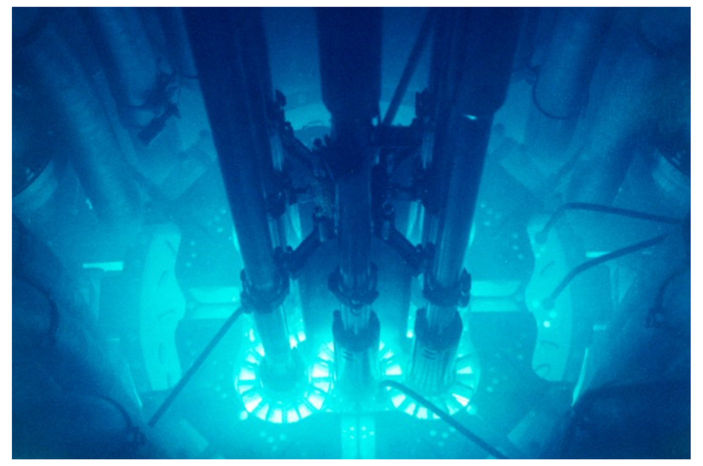

Figure 1: Cherenkov radiation emitted from the core of a nuclear reactor underwater.

How is it used in radiation therapy?

During radiation therapy, Cherenkov light is generated within the patient's tissue, approximately proportional to the delivered dose[1]. Due to optical properties of various tissue types, the light is highly scattered and absorbed[2], and eventually reemitted from the patient's surface. Capturing the reemitted Cherenkov light with intensified cameras has shown to be a noninvasive method of visualizing the treatment in real-time[3,4] and correlating the signal to the surface-dose[5]. **Developing a quantitative understanding of how various properties affect the reemitted Cherenkov signal can provide real-time linear corrections to verify surface-dose delivery .**

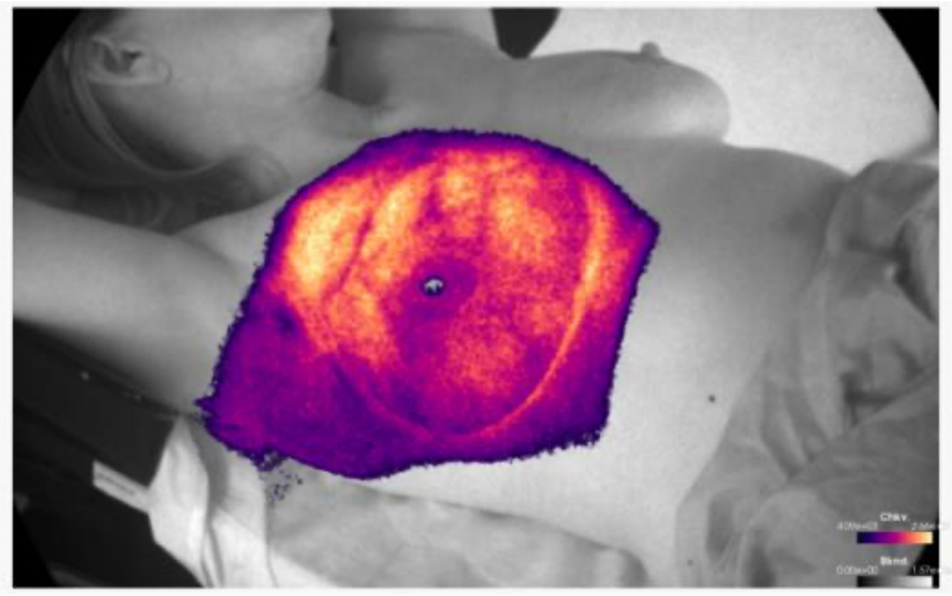

Figure 2: Cumulative Cherenkov image taken during whole-breast radiation therapy. All patients provided informed consent in this IRB approved study.

AIM

To theoretically derive and experimentally verify the effects of dose build-up and tissue optical properties on the reemitted Cherenkov signal during radiation therapy.

THEORY

Following diffusion theory solutions, the reemitted Cherenkov signal was derived as a direct convolution of the surface dose plus the dose build-up gradient.

R: Reemitted signal
φ: Isotropic fluence rate
k_1: surface dose
k_2: build-up slope
D: diffusion coefficient
μ_{eff}: effective attenuation coefficient

$$R_D = -D\,\frac{\partial \varphi(r)}{\partial z}\Big|_{z=0} \qquad (1)$$

$$\varphi(z) = \left(\frac{1}{2D\,\mu_{eff}}\,e^{-\mu_{eff}(z)}\right) * (k_1 + k_2\, z) \qquad (2)$$

METHODS

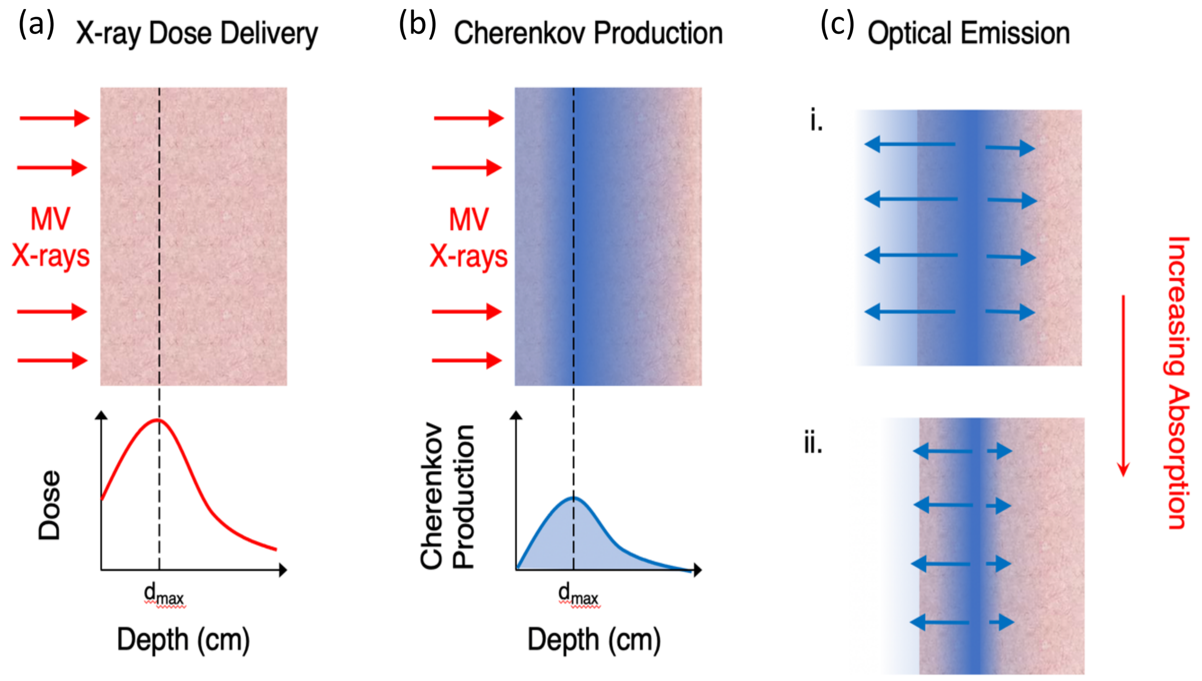

Figure 3. A linear accelerator irradiates various tissue phantoms of different optical properties with 6, 10, and 18 MV x-rays (a) and dose is deposited as a function of depth, represented qualitatively by the graph. The depth at maximum dose, d_{max}, is also the point of maximum Cherenkov light generation (b). As tissue optical properties vary (c), so does the amount of light that escapes the surface.

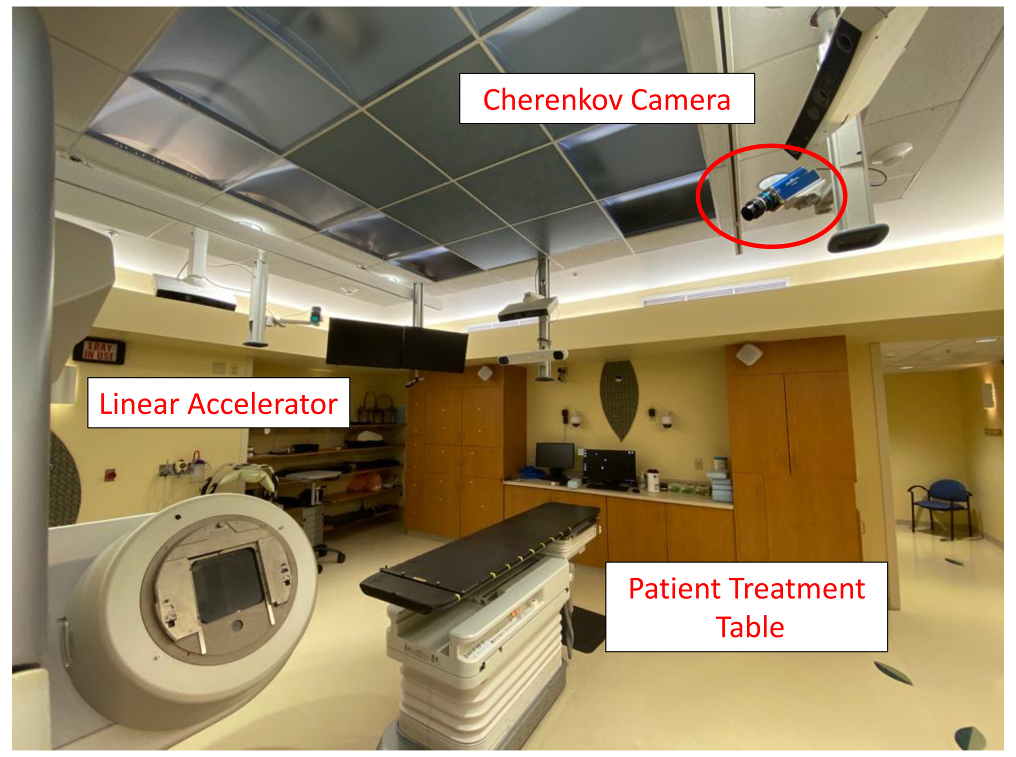

Figure 4. The Cherenkov emission is captured with an intensified CMOS camera that is fixed in the treatment room for clinical imaging. Each phantom was irradiated top-down for entrance surface imaging, as well as from underneath for exit surface imaging. Phantoms were built with the thickness of the depth of d_{max} for each energy.

RESULTS

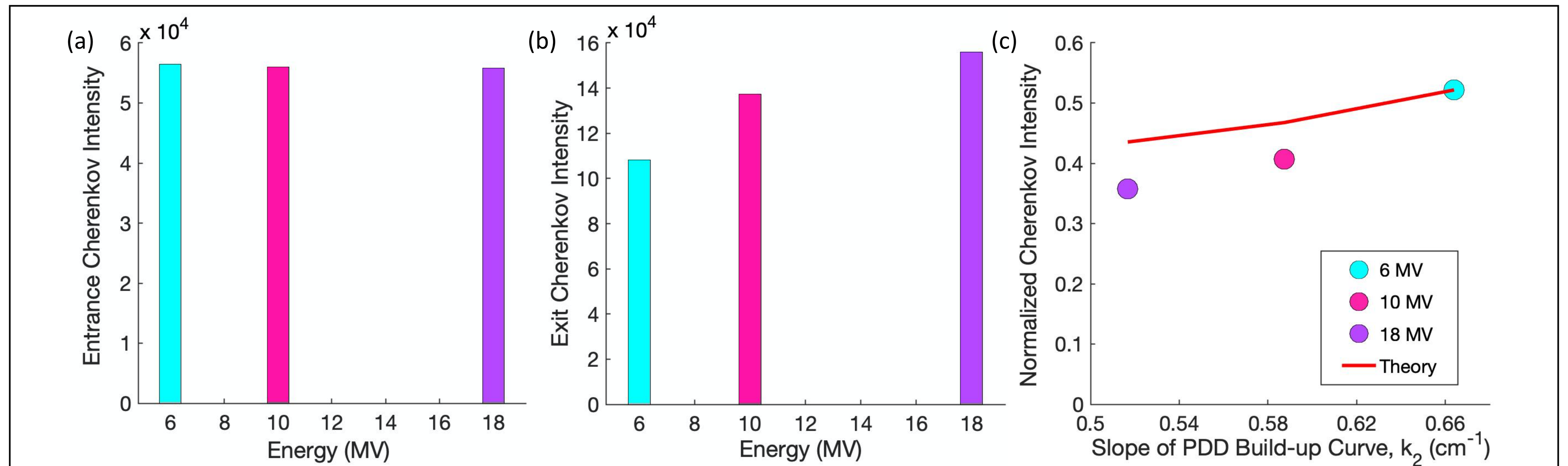

Figure 5. The intensity of Cherenkov signal that escaped the entrance surface (a) and the exit surface (b) of the 1% blood / 1% Intralipid® diffuse liquid tissue phantom as a function of x-ray energy. Figure (c) shows the entrance Cherenkov emission intensities normalized by the exit Cherenkov intensities (proportional to the amount of Cherenkov photons produced with increasing x-ray energy) plotted as a function of the dose build-up slope. Figure (c) also shows the theoretical relative reemitted light signal following Eqns. (1) and (2), which predict the normalized Cherenkov light that escapes the entrance surface. At low energy, a steeper dose build-up slope results in a greater Cherenkov signal per unit dose at d_{max}, a ~46% increase at 6 vs. 18 MV (c). However, at high energy, more Cherenkov photons are generated per unit dose[1], resulting in a ~44% increase in the reemitted signal at 18 vs. 6 MV (b). **Consequently, these competing effects of nearly the same magnitude result in an approximately constant reemitted Cherenkov signal from the entrance surface (a).**

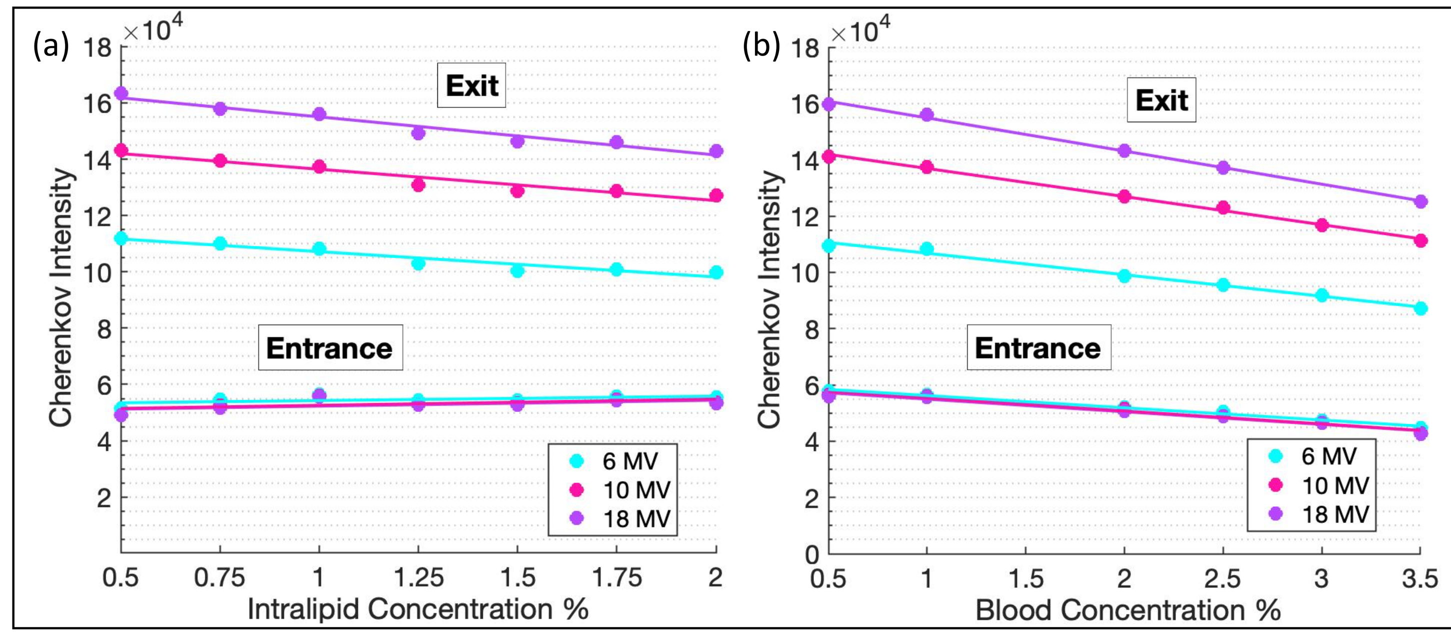

Figure 6. Cherenkov emission intensity as a function of Intralipid® concentration (scattering) is shown in **(a)** and blood concentration (absorption) is shown in **(b)**. Each figure displays the Cherenkov intensities that emerge from both the exit and entrance surfaces. All measurements were taken over the range of linear accelerator x-ray energies: 6, 10, and 18 MV. **With increasing scattering and absorption properties of the tissue phantoms, the reemitted Cherenkov signal increased ~10% and decreased ~20%, respectively.**

ACKNOWLEDGEMENTS

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CONCLUSIONS

The results of this study explain why the reemitted Cherenkov signal during radiation therapy is not strongly dependent on beam energy, despite greater Cherenkov photon generation at higher energies[1]. Quantifying the effects of beam and tissue properties is a progressive step towards verifying surface-dose delivery with Cherenkov light imaging during radiation therapy treatments in real-time.

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Figure List

Figure 1. How a particle racing through a vacuum leaves a trail of blue light. *Nature*. 2019;569(7755):162-162. doi:10.1038/d41586-019-01430-0

Figure 2. Hachadorian RL, Bruza P, Jermyn M, Gladstone DJ, Pogue BW, Jarvis LA. Imaging radiation dose in breast radiotherapy by X-ray CT calibration of Cherenkov light. *Nat Commun*. 2020;11. doi:10.1038/s41467-020-16031-z

Figure 4. Photo by courtesy of Daniel A. Alexander

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