2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

# Impact of Temperature on Cherenkov Photon Generation from Radiotherapy Beams

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## ABSTRACT

**Purpose:**
Cherenkov radiation imaging has become an increasingly more common imaging modality as a real-time beam delivery visualization aid with potential for dosimetry. Dosimetric studies require a comprehensive analysis of factors which affect the optical photon generation and propagation, both of which are dependent on the medium's index of refraction.

To our knowledge, this is the first study to address **the impact of temperature and refractive index on the Cherenkov signal generated** in a theoretical water tank model, supported by experimental results.

**Methods:**
- The **Lorentz-Lorenz relation** was used to calculate changes in index of refraction with temperature.
- Temperature-induced index of refraction change was combined with the energy threshold for Cherenkov photon generation to build a theoretical framework.
- Experimentally, a water tank was heated to temperatures ranging from 70°F to 130°F, representing a relevant clinical/ ambient temperature range.
  - The tank was irradiated with 6MV and 15MV photons at each temperature step.
  - The average optical signal in a region of interest was recorded in the exit beam geometry across all 30 measurements and compared.

**Results:**
The water tank model results showed that *the optical signal measured by the detector decreased as the temperature increased.* From 70°F to 130°F, the theoretical model predicted an approximately 2.05% decrease in Cherenkov photon generation. The experimental results from 6MV and 15MV cases found a 3.13% and 2.09% decrease over the same range, respectively.

**Conclusion:**
There exists a strong agreement between the theoretical and experimental results in a water tank model which highlights a slight decrease in Cherenkov photon generation over increasing temperature. This effect, while possibly necessary to account for in applications which may require high accuracy photon counting, is unlikely to cause any discernable impact on interpretability over clinically relevant temperatures.

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## INTRODUCTION

Cherenkov radiation imaging has become an increasingly valuable tool for real-time visualization of radiotherapy beam delivery and shows promise for quantitative dosimetry[1]. Accurate dosimetric interpretation requires a thorough understanding of factors that influence Cherenkov photon generation and propagation. As both the Cherenkov generation threshold and photon yield depend on the refractive index of the irradiated medium, temperature-induced changes in refractive index may alter the measured optical signal[2]. Despite this dependence, the effect of temperature has not been systematically investigated. This study combines theoretical modeling with experimental measurements to quantify the impact of clinically relevant temperature variations on Cherenkov photon generation in water.

## METHODS AND MATERIALS

A theoretical model was developed to estimate the effect of temperature on Cherenkov photon generation by calculating the temperature-dependent refractive index of water using the Lorentz-Lorenz relation. The resulting refractive index values were incorporated into the Frank-Tamm equation and Cherenkov energy threshold to predict changes in photon yield over a temperature range of 70–130°F (21–55°C)[2].

Experimental validation was performed using a water tank heated uniformly and incrementally across the same temperature range. The phantom was irradiated with 6 MV and 15 MV photon beams while Cherenkov emission was recorded using a time-gated intensified camera synchronized to the linear accelerator pulses. Images were analyzed using a common region of interest (ROI) to determine the average optical signal. A total of 30 measurements were acquired and compared with theoretical predictions to evaluate the temperature dependence of the Cherenkov signal.

Energy Threshold

$$E_{th} = \left(\frac{1}{\sqrt{1-\frac{1}{n^2}}} - 1\right)mc^2$$

Frank Tamm Equation

$$N = \frac{2\pi e^2}{\hbar c}\left(\frac{l}{\lambda_2} - \frac{l}{\lambda_1}\right)\left(1 - \frac{1}{n^2\beta^2}\right)$$

Lorentz - Lorenz

$$\frac{n_{water}{}^2 - 1}{(n_{water}{}^2 + 2)\rho^*} = a_0 + a_1\rho^* + a_2T^* + a_3\lambda^{*2}T^* + \frac{a_4}{\lambda^{*2}} + \frac{a_5}{\lambda^{*2} - \lambda_{UV}^{*2}} + \frac{a_6}{\lambda^{*2} - \lambda_{IR}^{*2}} + a_7\rho^{*2}.$$

**Figure 1.** Theoretical formulation where N is number of Cherenkov photons produced, $\beta = v/c$, $n$ is refractive index, $\rho^*$ is the temperature-dependent density , $\lambda$ is wavelength, $T$ is temperature, $a_0$ to $a_7$ are coefficients, $\lambda^*_{UV}$ is the effective ultraviolet resonance, and $\lambda^*_{IR}$ is the effective infrared resonance.

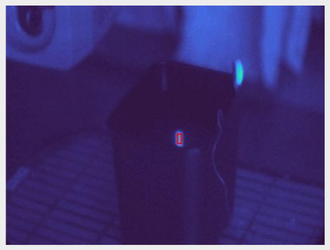
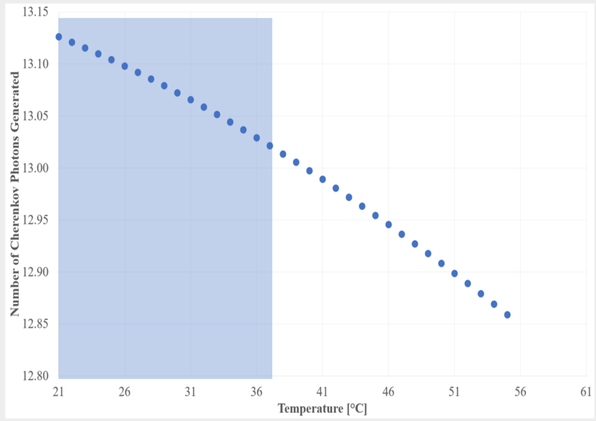


**Figure 2.** Experimental Setup.

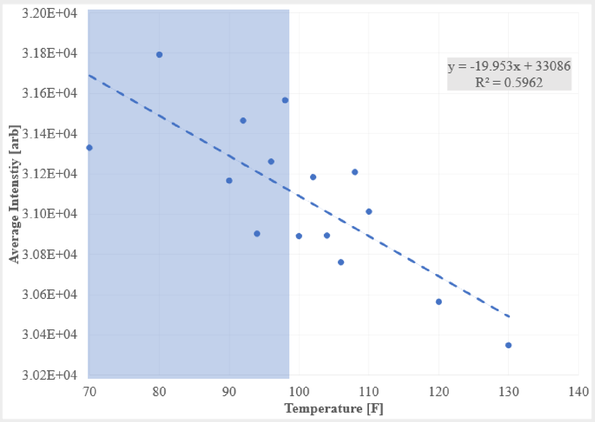
## RESULTS

The theoretical model demonstrated that the refractive index of water decreases monotonically with increasing temperature across the investigated range of 21–55°C. This reduction produced a corresponding increase in the minimum kinetic energy required for Cherenkov emission. These changes resulted in a predicted reduction in Cherenkov photon production as temperature increased. Theoretical modeling estimated a 2.08% decrease in photon yield over the full 21–55°C range, with smaller reductions of 0.80% from room temperature to body temperature (21–37°C, 70–99F°) and 0.66% across the physiological temperature range (31–41°C, 88–106F°).

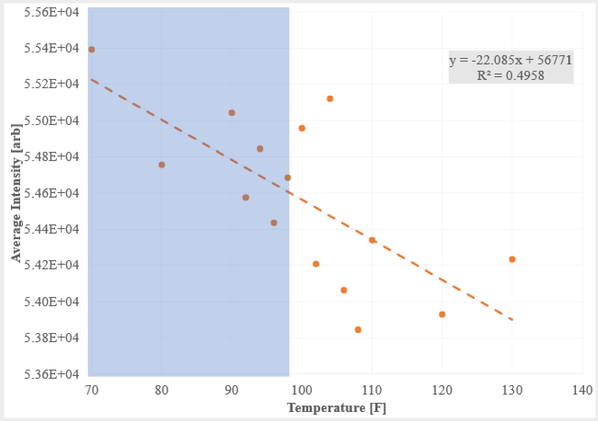
Experimental measurements demonstrated the same temperature-dependent behavior, showing a gradual decrease in Cherenkov signal intensity with increasing water temperature for both photon beam energies. Linear regression analysis predicted decreases of 3.96% (6 MV) and 2.50% (15 MV) across the full temperature range, 1.82% (6 MV) and 1.16% (15 MV) from room temperature to body temperature, and 1.15% (6 MV) and 0.73% (15 MV) across the physiological range.




**Graph 1.** Modeled reduction in Cherenkov photon production for a 535.47 keV electron traversing 0.1 cm of water under different temperatures. Room to body temp range shown as shaded region.




**Graph 2.** Experimental reduction in Cherenkov photon production with increasing temperature for a 6 MV photon beam.




**Graph 3.** Experimental reduction in Cherenkov photon production with increasing temperature for a 15 MV photon beam.

## DISCUSSION

The theoretical and experimental results demonstrated a consistent decrease in Cherenkov signal intensity with increasing temperature, confirming that temperature-dependent changes in the refractive index of water influence Cherenkov photon generation. ***As the refractive index decreased, the Cherenkov energy threshold increased and the predicted photon yield decreased, resulting in a measurable reduction in detected signal intensity*** across all investigated temperature ranges. It should be noted that the highest temperature explored (55°C, 130°F) is not expected in most room or *in vivo* applications.

Although the experimentally measured signal decreases were slightly greater than those predicted by the theoretical model and demonstrated limited linearity coefficients, both approaches exhibited the same monotonic trend and a comparable magnitude. This agreement supports the validity of the theoretical framework while suggesting that additional experimental factors, including the poly-energetic photon beam spectrum, optical transport within the water phantom, detector response, use of small beam geometry, and general measurement uncertainty contributed to the observed differences between theory and experiment[3]. Small beam geometry was selected to limit the possible temperature variation across the irradiated portion of the water phantom, however this likely contributed to the low-signal noise fluctuations of the optical measurements.

These findings establish a validated theoretical framework for assessing temperature-dependent Cherenkov emission and provide a foundation for future investigations in tissue-equivalent materials and clinical imaging applications.

## CONCLUSIONS

***Collectively, these findings indicate that temperature is a small but quantifiable source of uncertainty for quantitative Cherenkov dosimetry.*** While the observed reductions are unlikely to affect routine qualitative visualization of radiation delivery, they should be considered in applications requiring high-precision quantitative imaging or when measurements are acquired under differing thermal conditions.

## REFERENCES

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