PhD Thesis Title: Cherenkov emission-based in-water photon and electron beam dosimetry

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ABSTRACT:

External beam radiotherapy (EBRT) with photon and electron beams, generated by medical linear accelerators (linacs), is a mainstay cancer treatment modality. EBRT is prescribed in terms of radiation absorbed dose, defined as the energy deposited in the patient per unit mass. The measurement of absorbed dose, termed dosimetry, is critical for ensuring that a sufficient dose is delivered to the patient while minimizing the dose to surrounding healthy tissues. This includes linac beam calibration and commissioning via reference and relative dosimetry. Reference dosimetry measures absolute dose, whereas relative dosimetry measures relative dose (e.g., spatial dose distribution). Dosimetry is primarily performed in water, as it is the main constituent of soft tissue, and with the use of radiation dosimeters. Modern EBRT dosimeters are not composed of tissue or water, which leads to necessary material conversion, beam perturbation, and volume averaging.

We investigated Cherenkov emission (CE) as a potential solution to these challenges. CE is an anisotropic optical signal generated by high-energy radiation in dielectrics, including water. We first evaluated CE for reference dosimetry of broad beams on beam axis in water, which is done for beam calibration with standard uncertainty ($k = 1$) of ~1%. The overall objective of the thesis is to develop a clinically-implementable CE-based dosimetry formalism and to thus motivate and inform future dosimetry system development.

First, we proposed a CE-to-dose conversion formalism, designed the Monte Carlo (MC) simulation code for the calculation of CE-to-dose conversion data used by the formalism, and validated the code experimentally in a relative sense with a preliminary detector design. The experimental validation demonstrated agreement with the simulations within 1%. In addition, the CE spectrum, angular characteristics, measurement robustness, and background signal contributions were evaluated and appropriate recommendations were made for CE-based dosimetry system and protocol development.

Secondly, motivated by the experimental validation, we MC-calculated CE-to-dose conversion data for a clinically representative library of electron beam qualities, investigated beam quality specification (a measurable quantity necessary to select the conversion data specific to the user's beam), and estimated a potentially achievable dosimetric uncertainty budget at a reference depth in water. We demonstrated that a combined standard dosimetric uncertainty ($k = 1$) of the order of 1% could be achievable. This motivates further CE-based dosimetry system development.

Finally, we performed an MC charged particle step-size dependence study of the CE-to-dose conversion with both photon and electron beams. The goal of this study was to understand the physics and determine whether corrections to the code and the formalism are warranted. For electron beams, the deviations from terse step control are up to 1%. Therefore, we recommend using the results of this study to augment the uncertainties to electron beam CE-to-dose conversion data or to guide step control in future calculations with the current version of the code. For photon beams, the deviations can be up to 10% depending on the

optical detection system configuration. Therefore, we recommend using the results of this study to guide further MC code and formalism development for CE-based photon beam dosimetry.

This work demonstrates the feasibility and the clinical viability of CE-based photon and electron beam radiotherapy dosimetry. The results of this thesis motivate and inform CE-based dosimetry system and future protocol development efforts. The next step is MC code and formalism development for CE-based photon beam dosimetry, followed by dosimetry system development. This research could ultimately lead to a 3D, micrometer-resolution, perturbation-free, in-water dosimetry technique that can be used in external beam radiotherapy of cancer.

References to author publications that relate specifically to the dissertation:

Papers

1. **Y. Zlateva**, B. Muir, I. El Naqa, and J. Seuntjens, "Step-size effect on calculated photon and electron beam Cherenkov-to-dose conversion factors." *Physica Medica*, 78(Focus Issue):32-7, 2020. https://doi.org/10.1016/j.ejmp.2020.08.015

2. **Y. Zlateva**, B. Muir, J. Seuntjens, and I. El Naqa, "Cherenkov emission-based external radiotherapy dosimetry: II. Electron beam quality specification and uncertainties." *Medical Physics*, 46(5):2383-93, 2019. https://doi.org/10.1002/mp.13413

3. **Y. Zlateva**, B. Muir, I. El Naqa, and J. Seuntjens, "Cherenkov emission-based external radiotherapy dosimetry: I. Formalism and feasibility." *Medical Physics*, 46(5):2370-82, 2019. https://doi.org/10.1002/mp.13414

Abstracts

1. **Y. Zlateva**, B. Muir, I. El Naqa, and J. Seuntjens, "Cherenkov emission-based dosimetry is a promising perturbation-free technique." *Radiotherapy and Oncology*, 133(Suppl. 1):S146-7, 2019. https://www.sciencedirect.com/search?qs=zlateva&pub=Radiotherapy%20and%20Oncology&cid=271320

2. **Y. Zlateva**, I. El Naqa, and J. Seuntjens, "Cherenkov emission-based photon and electron beam dosimetry." 2018 AAPM Annual Meeting Program: WE-FG-KDBRA1-05. *Medical Physics*, 45(6):e630, 2018. https://doi.org/10.1002/mp.12938

3. **Y. Zlateva**, B. Muir, I. El Naqa, and J. Seuntjens, "Laying the groundwork for accurate Cherenkov emission-based electron beam dosimetry." *Radiotherapy and Oncology*, 129(Suppl. 1):S21, 2018. https://www.researchgate.net/publication/329515337_Laying_the_groundwork_for_accurate_Cherenkov_emission-based_electron_beam_dosimetry

4. **Y. Zlateva**, J. Seuntjens, and I. El Naqa, "Cherenkov dosimetry via directional Cherenkov-to-dose conversion factors: Monte Carlo protocol and experimental feasibility." 2017 COMP Annual Scientific Meeting: Scientific Session 1:YIS-04. *Medical Physics*, 44(8):4369-70, 2017. https://doi.org/10.1002/mp.12446

5. **Y. Zlateva**, J. Seuntjens, and I. El Naqa, "Cherenkov dosimetry via stopping-to-Cherenkov power ratios: Protocol and experimental feasibility." 2017 AAPM Annual Meeting Program: SU-K-FS2-08. *Medical Physics*, 44(6):2996-7, 2017. https://doi.org/10.1002/mp.12304

6. **Y. Zlateva**, J. Seuntjens, and I. El Naqa, "Towards clinical Cherenkov emission dosimetry: Stopping power-to-Cherenkov power ratios and beam quality specification of clinical electron beams." 2016 AAPM Annual Meeting Program: SU-C-201-07, *Medical Physics*, 43(6):3317, 2016. https://doi.org/10.1118/1.4955547

7. **Y. Zlateva**, J. Seuntjens, and I. El Naqa, "Stopping power-to-Cherenkov power ratios and beam quality specification for clinical Cherenkov emission dosimetry of electrons: Beam-specific effects and experimental validation." 2016 COMP Annual Scientific Meeting: Sci-Thur AM: YIS-04, *Medical Physics*, 43(8):4929, 2016. https://doi.org/10.1118/1.4961754