Modeling and Maximizing Cherenkov Emissions from Medical Linear Accelerators: A Monte Carlo Study

by

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Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Medical Physics Graduate Program in the Graduate School of Duke University

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ABSTRACT

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Abstract

**Purpose:** Cherenkov light is a natural byproduct of MV radiotherapy; although typically disregarded, recent results demonstrate that it can be utilized to activate the drug psoralen. Psoralen is a compound which is biologically inert until photoactivated by UV light; upon activation, it contributes to cytotoxicity and can also provoke an immune system response. The purpose of this thesis work is to investigate Cherenkov radiation produced by common radiotherapy beams using Monte Carlo, as well as methods to maximize Cherenkov production per unit dose using filters placed in the beam path for the purpose of increased psoralen activation.

**Methods:** GAMOS, a GEANT4-based framework for Monte Carlo simulations, was used to model primary photon beams using spectra from a Varian linear accelerator and mono-energetic electron beams. Cherenkov photon spectra and track length along with dose were scored when irradiating a sphere of water with radius 50cm and source-surface distance (SSD) of 50cm for 100,000 histories. Further simulations were then run with photon beams irradiating a 17.8cm³ cubic water phantom at 1mm³ detectors with depths of 8 to 9cm; SSD was set to 94cm, and 100 million histories were run. Finally, simulations were run with filters of varying material and thickness placed 15cm below a 10MV flattening filter free (FFF) beam source. Filter materials included aluminum, iron, and copper with thicknesses of 2cm, 4cm, 10cm, and 20cm (aluminum only for 20cm).
Histories used depended on the level of attenuation from the filter, ranging from 200 million for 2cm filters to 2 billion for 10cm iron/copper filters or the 20cm aluminum filter. Comparing average dose per history also allowed for evaluation of dose rate reduction for different filters.

**Results:** Simulations found Cherenkov spectra to have strong overlap with the psoralen absorbance spectrum; dose and Cherenkov photon track length measurements established that higher beam energies had greater Cherenkov production per unit dose, with 18MV providing greater Cherenkov/dose than 6MV by a factor of 4. Simulations with filters suggest that copper and iron filters increase Cherenkov per dose more than aluminum for a given filter thickness, but that aluminum yields a greater boost for a given dose rate.

**Conclusion:** This work shows that the Cherenkov spectrum produced by radiotherapy beams is well suited for activation of psoralen, and that higher energy photon beams will result in more psoralen activation due to greater Cherenkov radiation per unit dose. We have also demonstrated that significant boosts in Cherenkov/dose can be achieved with the use of filters without overly compromising dose rate. Future work should expand analysis to include optical properties of tissues as well as additional filter materials.
# Contents

Abstract ........................................................................................................................................... iv

List of Figures .................................................................................................................................... viii

Acknowledgements .......................................................................................................................... x

1. Introduction .................................................................................................................................. 1
   1.1 Cherenkov Radiation ............................................................................................................... 1
      1.1.1 Cherenkov Formulae ......................................................................................................... 2
      1.1.2 Current Cherenkov Research ............................................................................................ 3
   1.2 Optical Properties and the Complex Index of Refraction ....................................................... 4
   1.3 Psoralen .................................................................................................................................... 7
      1.3.1 Existing Psoralen Therapies ............................................................................................. 8
      1.3.2 Kilovoltage Activation and X-PACT ............................................................................... 8
      1.3.3 CLAP ............................................................................................................................... 9

2. Materials and Methods ................................................................................................................. 10
   2.1 Initial Geometry ....................................................................................................................... 10
      2.1.1 Optical Properties ........................................................................................................... 12
      2.1.2 Beam Energy Spectra ...................................................................................................... 13
   2.2 Initial Measurements and Validation ..................................................................................... 14
   2.3 Updated Geometry .................................................................................................................. 15
   2.4 Maximizing Cherenkov Radiation per Unit Dose ................................................................... 18

3. Results and Discussion .................................................................................................................. 20
3.1 Initial Geometry Results.................................................................20
  3.1.1 Spectral Results........................................................................20
  3.1.2 Cherenkov Production Results................................................25
3.2 Updated Geometry Results.............................................................28
  3.2.1 PDD Validation........................................................................29
  3.2.2 Cherenkov per Dose for Unfiltered Beams...............................32
  3.2.3 Comparison to Measured Data..................................................35
  3.2.4 Cherenkov per Dose Results with Filters.................................38
    3.2.4.1 Beam Energy Distributions after Filtration.........................39
  3.2.5 Cherenkov per Dose Versus Dose Rate Reduction........................41
4. Conclusion .......................................................................................43
References ............................................................................................44
List of Figures

Figure 1: Cherenkov photons emanating along a charged particle path .......................... 2
Figure 2: Real index of refraction in water from 10nm to 10m [11] ................................. 5
Figure 3: Imaginary index of refraction in water from 10nm to 10m [11] ......................... 6
Figure 4: Initial geometry diagram .................................................................................. 10
Figure 5: Visualization of example histories using the initial geometry ......................... 11
Figure 6: Zoomed in visualization of example histories .................................................. 12
Figure 7: Primary photon energy distributions for Varian linac beams [13] .................... 13
Figure 8: Primary photon energy distributions for Varian linac FFF beams .................. 14
Figure 9: Updated geometry diagram ............................................................................. 16
Figure 10: Visualization of several histories with the new geometry ............................... 17
Figure 11: Cherenkov spectra resulting from photon beams .......................................... 21
Figure 12: Real index of refraction in water from 0-1000nm [11] ................................. 22
Figure 13: Imaginary index of refraction in water from 0-1000nm [11] ....................... 22
Figure 14: Normalized Cherenkov spectra resulting from photon beams ....................... 23
Figure 15: Cherenkov emission spectrum compared to psoralen absorbance spectrum [14] ......................................................................................................................... 25
Figure 16: Initial geometry Cherenkov vs photon beam energy ..................................... 26
Figure 17: Initial geometry Cherenkov/dose vs photon beam energy ............................. 26
Figure 18: Initial geometry Cherenkov vs electron beam energy, compared to published data [7] .................................................................................................................... 27
Figure 19: Initial geometry Cherenkov/dose vs electron beam energy .......................... 27
Figure 20: Simulated dose vs depth curve for 6MV photon beam.................................29
Figure 21: Simulated dose vs depth curve for 15MV photon beam...............................30
Figure 22: TPS-generated vs simulated PDD for 6MV beam.......................................31
Figure 23: TPS-generated vs simulated PDD for 10MV FFF beam.................................31
Figure 24: TPS-generated vs simulated PDD for 15MV beam.......................................32
Figure 25: Cherenkov vs depth for 6MV photon beam.............................................33
Figure 26: Cherenkov vs depth for 15MV photon beam.............................................33
Figure 27: Cherenkov/dose vs depth for 15MV photon beam....................................34
Figure 28: Relative Cherenkov/dose for photon beams with no added filters.............35
Figure 29: Experimental setup for Cherenkov/dose measurements...............................36
Figure 30: Simulated Cherenkov/dose compared to measured values..........................37
Figure 31: Relative Cherenkov/dose for photon beams with filter placed in beam path....39
Figure 32: Photon energy distributions before filter (10MV FFF) and after aluminum filter for 2, 4, 10, and 20cm thickness.................................................................40
Figure 33: Photon energy distributions before filter (10MV FFF) and after aluminum, copper, and iron filters of 10cm thickness.........................................................41
Figure 34: Relative boost in Cherenkov/dose vs Dose Rate........................................42
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1. Introduction

1.1 Cherenkov Radiation

Cherenkov radiation and its possible applications in Medical Physics have been of increasing interest in recent years. Cherenkov radiation is a natural byproduct of megavoltage radiation therapy, but has generally been ignored until recently. To understand the growing interest in Cherenkov radiation and its potential applications, let us first explore Cherenkov radiation itself.

Cherenkov radiation, named for Pavel Alekseyevich Cherenkov who first experimentally detected it in 1934, is electromagnetic radiation that is emitted when a charged particle travels in a dielectric medium with speed greater than the phase velocity of light in that medium. Although the speed of light in a vacuum is a constant (c), the speed at which light propagates in a given medium is not, and is less than c. Thus, it is possible for a charged particle to have a greater speed than light in that medium. Normally, a charged particle’s electric field polarizes the medium through which it is traveling, with the polarization relaxing back to equilibrium as the charged particle passes. However, when the charged particle’s speed exceeds the phase velocity of light, it creates a disturbance in its wake faster than the polarization can relax back to equilibrium, and the resulting energy stored in the formed dipoles radiates out as a shockwave. The process is often compared to the sonic boom that occurs when an object exceeds the speed of sound.
1.1.1 Cherenkov Formulae

The Cherenkov radiation emanates out along the charged particle path with an angle determined by:

\[ \cos \theta = \frac{1}{n\beta} \]

where \( n \) is the refractive index of the medium, and \( \beta \) is the charged particle’s speed divided by \( c \).

![Diagram of Cherenkov photons](image)

**Figure 1: Cherenkov photons emanating along a charged particle path**

This formula tells us about the direction of Cherenkov photons; the Frank-Tamm Formula, on the other hand, tells us about the number of photons produced [1].

Specifically:
\[
\frac{d^2N}{dEdx} = \frac{\alpha Z^2}{\hbar c} \sin^2 \theta \approx 370Z^2 \sin^2 \theta (E)
\]

The Frank-Tamm Formula, named for Ilya Frank and Igor Tamm who shared the Nobel Prize in 1958 with Pavel Cherenkov for their work in developing the theory of the Cherenkov effect, tells us the number of photons produced per unit of length traveled and per unit of energy of the charged particle. In the formula, \(\alpha\) is the Fine-structure constant, \(Z\) is the charge number, \(\hbar\) is the reduced Planck constant, \(c\) is again the speed of light in a vacuum, and \(\theta\) is the Cherenkov critical angle. Crucially, this equation tells us that the quantity of photons produced is not only per unit of length traveled, but also per unit of energy of the charged particle. Thus, we should expect that higher energy charged particles will generate more Cherenkov radiation.

1.1.2 Current Cherenkov Research

Recent research interests within medical physics involving Cherenkov radiation have had a variety of different aims. One of the primary applications has been as an optical imaging modality in combination with positron emission tomography (PET) imaging agents. This method, called Cherenkov Luminescence Imaging (CLI) [2], utilizes optical imaging instruments to detect Cherenkov radiation created as a result of radionuclide emissions and is being explored as a means of allowing molecular imaging [3], cancer therapy monitoring [4], image-guided cancer surgery [5], and more, with several clinical trials already underway. In addition to imaging, Cherenkov has been explored as a potential tool in Photodynamic Therapy (PDT), using Cherenkov
generated as a result of radionuclides to noninvasively activate photosensitizers. Initial findings suggest that Cherenkov radiation can, in fact, activate PDT using appropriate, clinically relevant photosensitizers, and suggest that a phototherapeutic effect could be achieved in vivo [6].

There is also a great deal of interest in Cherenkov radiation produced during external beam radiation therapy, which has the potential to generate secondary electrons of higher energy and thus create more Cherenkov photons. In addition to phototherapy and imaging applications [7, 8], there is also potential for use as a dosimetric tool for treatment plan verification and entrance/exit surface dose imaging, since there is a correlation between Cherenkov radiation produced and dose delivered to a medium [9].

1.2 Optical Properties and the Complex Index of Refraction

In addition to production of Cherenkov radiation, it is useful to understand how the process and resulting photons are affected by the material properties of a medium – specifically its complex index of refraction. As the name suggests, the complex index of refraction is composed of two parts – a real part and an imaginary part. The real component is the “ordinary” index of refraction – for example, in water, the index of refraction is commonly assumed to be n=1.33. In reality, the index of refraction depends on the wavelength of the photon traveling through the medium, and can vary significantly – this is the cause of dispersion, and is responsible for the commonly seen splitting of white light into its constituent colors in prisms, rainbows, etc.
The imaginary component of the complex index of refraction is related to the absorption coefficient in the material for the given photon wavelength. Specifically, the relationship is:

\[ \text{Imaginary} = \lambda \times 10^{-9} \times \frac{\mu_a}{(4\pi)} \]

where \( \lambda \) is the wavelength of the incident photon in nm, and \( \mu_a \) is the absorption coefficient [10]. As with the real index of refraction, the imaginary component and absorption coefficient vary significantly with wavelength – to an even greater extent than the real index of refraction [11]. The following two figures illustrate the variation by wavelength seen in both the real and imaginary index of refraction:

\[ \text{Real Index of Refraction} \]

\[ \text{Index of Refraction} \]

\[ \text{Wavelength (nm)} \]

Figure 2: Real index of refraction in water from 10nm to 10m [11]
Notice that in Figure 2, the x axis is logarithmic, but in Figure 3, both the x and y axes are logarithmic. The variation in the imaginary index of refraction is especially important when considering Cherenkov radiation, as the largest fluctuation occurs in a range of interest with a dip of several orders of magnitude centered around ~400nm.

In this work, optical properties of water will be used as it has the best available data for low wavelengths in the 10 to 200nm range. Some work exists investigating optical properties of tissues, but available data is far more sparse than for water – one paper, for instance, determines the complex index of refraction at eight wavelengths from 325nm to 1557nm, but only for skin tissues [15], while another investigates several different types of tissue, but provides the complex index of refraction only at a wavelength of 632.8nm [16]. Optical properties for tissue vary a great deal between
tissue types, and even for the same tissue type can vary greatly between patients. Thus, we have run our simulations using water expecting that relative Cherenkov photon production values established in water should translate to tissue, even if absolute values would not.

1.3 Psoralen

To understand the motivation behind our proposed application of Cherenkov production, it will be useful to have a basic understanding of psoralen. Psoralens are biologically inert compounds in a family of natural products called furocoumarins, and are found in nature in several plants and seeds. Although normally inert, they have been shown to exhibit anti-cancer and immunogenic properties when photo-activated by ultraviolet radiation [14]. The molecules can penetrate cell membranes and remain intercalated in the DNA double helix for about 24 hours until excreted, unless they are photo-activated. Upon activation by exposure to ultraviolet radiation, psoralens form mono-adducts and di-adducts with DNA which leads to tumor cytotoxicity and apoptosis [17]. Psoralen can also, upon photo-activation, block oncogenic receptor tyrosine kinase signaling leading to apoptosis, and can affect immunogenicity as well as photochemical modification of cellular proteins in treated cells [14, 18]. In addition to its effects on DNA, there is evidence that changes at the cell surface occur which enhance immunogenicity, which can lead to elimination of both treated and untreated tumor cells [22].
1.3.1 Existing Psoralen Therapies

Psoralen plus UVA therapy, known as PUVA, has been shown to be clinically effective in treatment of skin problems such as psoriasis, eczema, and vitiligo [19]; it can also promote a strong long-term clinical response in the treatment of cutaneous T Cell Lymphoma by extracorporeal photopheresis [20]. Results in these treatment types suggest that psoralen is capable of provoking a long-lasting immune response; complete long-term response over the course of decades has been observed in a sub-set of patients, even when only a small fraction of malignant cells were treated.

1.3.2 Kilovoltage Activation and X-PACT

Despite these promising results, psoralen therapies have until recently been restricted to superficial or extracorporeal applications because of the difficulty in reaching deeper tissues with UV light, which has a penetration depth of <1mm. One attempt to address this challenge utilized a nanoscintillator tethered to psoralen; upon exposure to X-rays, the nanoscintillator would emit UVA light to activate the psoralen [21]. A limitation of this method is that the tethering of the scintillator, which is larger than psoralen, interfered with the ability of psoralen to intercalate into DNA strands, reducing its effectiveness. Another more recent proposal to solve this challenge is a novel solution called X-ray Psoralen Activated Cancer Therapy (X-PACT); X-PACT utilizes kilovoltage x-ray beams along with intermediary phosphor particles which absorb x-rays and re-emit ultraviolet radiation in-situ, allowing for activation of
psoralen at the tumor site [12]. Despite the potential of this technique, implementation in a clinical setting faces two main obstacles: the requirement for intermediary phosphor particles within the tumor, and the high skin and bone doses that are associated with kilovoltage irradiation.

1.3.3 CLAP

An alternative approach which avoids these obstacles is to activate psoralen with Cherenkov radiation, which is already generated in the body during megavoltage radiation therapy. This technique of delivering radiation dose to a tumor while simultaneously photo-activating an anti-cancer photo-therapeutic, such as psoralen, is being called Cherenkov Light Activated Phototherapy (CLAP). One of CLAP’s primary challenges is the relatively low fluence of Cherenkov radiation from radiation therapy, estimated to be in the range 1-100 µW cm⁻² per Gy s⁻¹ [8], which may not be sufficient for many phototherapy applications. This work will seek to address this challenge by investigating Cherenkov production due to radiotherapy beams, as well as techniques to boost Cherenkov production per unit dose in order to increase psoralen activation.
2. Materials and Methods

To investigate Cherenkov production, simulations were run using GAMOS, a GEANT4-based framework for Monte Carlo simulations. GAMOS, which stands for GEANT4-based Architecture for Medicine-Oriented Simulations, was chosen for its flexibility, ease of use, and built-in support for modeling Cherenkov processes. Simulations aimed to score both dose delivered to a target and Cherenkov fluence within the target so that Cherenkov production per unit dose could be evaluated.

2.1 Initial Geometry

The initial geometry was very simple – the target was a sphere of water with 50cm radius, with a monodirectional beam of photons or electrons directed at the center from 100cm away (50cm from the surface).

![Initial geometry diagram](image)

Figure 4: Initial geometry diagram
Figure 5: Visualization of example histories using the initial geometry

Figure 5 shows an example visualization of 10 histories in the initial geometry; green lines in the visualization represent photons. The incident source photons approach the target from the top of the screen; some scatter is seen, as well as a fan of Cherenkov photons being generated by a secondary electron. Figure 6 shows a zoomed in view of the secondary electron (represented by the red line) being liberated, then generating Cherenkov photons along its path.
2.1.1 Optical Properties

As part of setting up the geometry, the wavelength-dependent optical properties of the medium need to be established – we used water as the medium, since there is comprehensive data available for optical properties of water at very low wavelengths (UV-C and below) in which we are interested. For 198 different wavelengths ranging from 71.94nm to 900 nm, the corresponding Refractive Index and Absorption Length were defined; GAMOS can then interpolate for wavelength values in that range. For wavelengths below 71.94nm, the refractive index in water drops below unity (seen in Figure 2), so Cherenkov production of photons of those wavelengths will not occur.
To obtain these optical properties, we used the wavelength-dependent complex index of refraction for water [11]. As mentioned previously, the real component of the complex index of refraction is the refractive index, while the imaginary component is related to the absorption coefficient, which is the inverse of the absorption length [10].

### 2.1.2 Beam Energy Spectra

In order to model the photon beams, data from literature was used providing the energy distribution of primary photons divided into 0.25 MeV bins for several Varian linac beams [13] – see Figure 7 below. This information was used in GAMOS to set the probability that the primary photon for each history would have any given energy.

![Energy Distributions](image)

**Figure 7: Primary photon energy distributions for Varian linac beams [13]**

To model the Flattening Filter Free (FFF) beams, which were not found in existing papers, we used Varian’s proprietary phase space files from VirtuaLinac,
available at myvarian.com, for the FFF beams of interest: 6MV FFF and 10MV FFF. MatLab code was used to extract the energy distributions for these beams from the phase space files, with results seen in Figure 8.

![Energy Distributions](image)

**Figure 8: Primary photon energy distributions for Varian linac FFF beams**

### 2.2 Initial Measurements and Validation

Values scored in this initial geometry for all beam energies included dose delivered to the entire phantom (in Gy), as well as track length (in mm) of optical photons created by Cherenkov processes. Since attenuation of optical photons varies significantly with wavelength, track length is a better indicator of intensity than number of photons, as some photons will attenuate faster and contribute less to intensity in a given volume. Track length was also divided into 198 bins by photon energy, ranging from 1.3784 eV (or wavelength 900nm) to 17.2344 eV (wavelength 71.94nm),
corresponding to the energies for which the optical properties were defined. This allowed for investigating the spectrum of the Cherenkov photons.

In addition to measurements made with simulated clinical photon beams, simulations were also run with mono-energetic electron beams with energies of 6, 9, 12, 15, and 18 MeV. This allowed for comparison to previously measured values of Cherenkov production resulting from electron beams found in literature [7]. All simulations in the initial geometry were run with 100,000 histories; while this number of histories is relatively small compared to most Monte Carlo simulations regarding radiation transport, each secondary electron generates a large number of Cherenkov photons – for instance, roughly 5,000 Cherenkov photons were produced on average per primary photon when modeling a 15MV beam. Thus, 100,000 histories was sufficient to minimize statistical noise when modeling Cherenkov light output.

2.3 Updated Geometry

After gathering data with the initial geometry, a new geometry was set up with the goal of being more realistic, as well as mirroring an experimental setup being used for in vitro measurements so that results could be compared. Additionally, a filter was added to the geometry which could be optionally included. The new geometry used a cubic water phantom 17.8cm on a side, set up with SSD=94cm and a detector at 9cm depth. Rather than a monodirectional beam, the beam was changed to have a point source, with the direction of the particles randomly determined within a cone such that
the beam would have diameter 10cm at the surface of the phantom. In addition, filters with 17.8cm sides in the x and y direction and of varying material and thickness were placed with the center 15cm from the source. A square detector was also added between the filter and the target to measure the energy spectrum of the beam after passing through the filter, in order to see the extent of beam hardening that occurred due to the filter.

![Updated geometry diagram](image)

**Figure 9: Updated geometry diagram**
Figure 10: Visualization of several histories with the new geometry

This new geometry was used to collect dose and Cherenkov track length data in 1mm cubic areas along the central axis, from the surface of the phantom to 9cm depth (and later to 10cm depth), including the detector at 9cm depth set to mirror the position of the detector used during in vitro measurements. This allowed for PDD curves to be generated as a form of validation – to see if the PDD curve was reasonable for the beam energy – as well as investigation of Cherenkov production as a function of depth.
In order to validate the simulated PDD curves, we generated PDDs from the treatment planning system. The treatment planning system, which utilizes data measured during commissioning in a water tank using a Wellhofer CC13 ion chamber (volume=0.13cc, length=5.8mm, radius=3mm), had conditions input to mirror the simulation setup; 94cm SSD, and a circular field with radius 5cm at the surface. In order to directly compare the generated SSDs against the simulation SSDs, the simulation dose values at depths between 0.5cm above and below the expected depth of maximum dose were averaged; the maximum percent depth dose in the TPS-generated PDD curve divided by this average value was then used to normalize the dose per history values.

2.4 Maximizing Cherenkov Radiation per Unit Dose

In addition to collecting data for each beam energy with the new geometry, data was also collected with a variety of filters in place. Materials used include Aluminum, Copper, and Iron – for each material, data was collected with filters of thickness 2cm, 4cm, 10cm, and 20cm (aluminum only). With the filters in place, the square detector in the beam path (between the filter and the target) was used to measure the energy spectra of the beam. Additionally, dose rate could be determined by comparing the dose per history values of simulations with a filter to the 10MV FFF dose per history. Knowing that a Varian Truebeam linear accelerator with a 10MV FFF energy mode can deliver at a dose rate of 2400 MU/min, the effective dose rate after the beam passes through the filter can be calculated by multiplying 2400 by the ratio of the dose per history values.
Simulations in the updated geometry were run with 100 million histories when no filter was in place, and with histories ranging from 200 million to 2 billion with filters in place, depending on the thickness of the filter. Although plenty of Cherenkov could be generated with fewer histories, the increased number of histories reduced noise in the dose measurements, allowing for better Cherenkov/dose and dose rate comparisons.
3. Results and Discussion

3.1 Initial Geometry Results

In the initial geometry, data was gathered with modeled photon beams of 4MV, 6MV, 10MV, 15MV, and 18MV (excluding FFF beams, as the energy distributions for those had not yet been obtained) as well as mono-energetic electron beams with energies of 6MeV, 9MeV, 12MeV, 15MeV, and 18MeV.

3.1.1 Spectral Results

One of our primary interests while taking measurements in the initial geometry was to investigate the spectral properties of the Cherenkov radiation being produced. We know from theory that the Cherenkov spectrum is continuous, without any characteristic spectral peaks, and that its relative intensity is proportional to the frequency in the visible light range. However, we are interested in the spectrum at lower wavelengths than the visible range. The spectrum of the Cherenkov radiation produced in simulations of the various photon beams is shown in Figure 11.
Figure 11: Cherenkov spectra resulting from photon beams

Figure 11 shows that the relative intensity of the Cherenkov radiation falls off sharply below 200nm wavelength due to the increasing absorption coefficient, although the values continue to be nonzero until about 70nm, at which point the index of refraction drops below unity and Cherenkov production is no longer possible. For reference, the real and imaginary index of refraction from 10nm to 1000nm is provided in Figures 12 and 13.
Figure 12: Real index of refraction in water from 0-1000nm [11]

Figure 13: Imaginary index of refraction in water from 0-1000nm [11]

We can gain further insight by normalizing the area under the curves of the spectra, as shown in Figure 14.
Figure 14: Normalized Cherenkov spectra resulting from photon beams

Clearly, the relative distribution of wavelengths among Cherenkov photons produced is not dependent on the beam energy; rather, it is dependent on the optical properties of the medium. This result is consistent with the theoretical prediction that the spectrum is continuous without spectral peaks, and that the relative intensity is proportional to frequency in the visible spectrum, and indeed demonstrates that this continues to be true into the UV-C range as well. The sharp drop off just below 200nm coincides with an extreme jump in attenuation in water; for reference, the absorption coefficient at 200nm is 7 orders of magnitude smaller than the absorption coefficient at 162nm (see Figure 13). The number of photons produced actually continues to increase below 200nm, but the contribution of these photons to intensity within the phantom...
becomes comparatively tiny due to the rapid attenuation. While we would expect the Cherenkov spectrum to change to some extent in tissue due to differing optical properties, it should continue to follow these trends with greater fluence as wavelength decreases. It is difficult to compare the sudden change in water’s absorption coefficient below 200nm to values for tissue, as any data for tissue at that wavelength range is difficult to find. However, we can compare values for water and skin at 633nm to get some idea of the difference. At this wavelength, water has a real index of refraction of 1.331 and an imaginary index of refraction of 1.53*10^-8 [11], while skin tissue has reported real indices of refraction of 1.436 [15] and 1.382 [16], and imaginary indices of refraction of 0.011 [15] and 0.0049 [16]. Predictably, skin shows higher absorption of light in the visible spectrum than water, but it is difficult to draw conclusions from this data about what happens at lower wavelengths.

Of particular interest is how this Cherenkov spectrum compares to the absorbance spectrum of psoralen [14], shown in Figure 15, since our goal is activation of psoralen with Cherenkov radiation.
We see that there is phenomenal spectral overlap between Cherenkov radiation production in a water phantom and psoralen’s absorbance.

### 3.1.2 Cherenkov Production Results

In addition to spectral measurements, we also investigated relative Cherenkov track length in the target for the different clinical photon beams, as well as for mono-energetic electron beams. With a measure of total dose delivered to the target, we could also determine Cherenkov production per unit dose. The following were the resulting measurements of relative Cherenkov intensity in the water phantom, as well as relative Cherenkov intensity per unit dose, for 4, 6, 10, 15, and 18MV photon beams, as well as mono-energetic 6, 9, 12, 15, and 18 MeV electron beams.
Figure 16: Initial geometry Cherenkov vs photon beam energy

Figure 17: Initial geometry Cherenkov/dose vs photon beam energy
Both the simulated results and published, measured results show linear growth in Cherenkov production for electron beam energies, with a slight difference in the
slope. However, there are also key differences in the methodology for measuring the
Cherenkov output; critically, in the measured results, the intensity in a 2D plane was
captured and the average intensity was taken in a square region of 1cm² centered at the
maximum intensity pixel. As the intensity was measured around the point of greatest
Cherenkov signal, whereas the simulation measured all Cherenkov within the target, the
slightly lower slope from the simulated results is not surprising.

3.2 Updated Geometry Results

Updating the geometry to a more realistic model provided several benefits. Since
the geometry matched the experimental setup being used for measurements, it offered a
chance to compare results. Rather than scoring values throughout the entire target, the
new geometry had a series of 1mm³ detectors along the central axis, from the surface of
the target to 9cm depth (10cm depth once filters were added). This gives more
meaningful results, since the psoralen that we are ultimately seeking to activate will be
along the beam path, so dose and Cherenkov delivered 20cm away from the central axis
is not relevant to the psoralen that is ideally activated; however, if psoralen uptake in
normal tissues proves to be an issue, further investigation of off-axis Cherenkov
intensity may be warranted. Finally, having dose measurements at the detectors along
the central axis allows for percent depth dose (PDD) curves to be extracted from the
data, which provides another source of validation when compared to expected PDD
curves for a given clinical photon beam.
3.2.1 PDD Validation

The first results from the updated geometry to check are the scored dose values along the detector line, which can be compiled to form a PDD curve.

![Dose vs Depth (6MV)](image)

**Figure 20: Simulated dose vs depth curve for 6MV photon beam**

The dose vs depth results for the 6MV beam (with flattening filter but no extra filtration) shows a plausible curve, with the maximum dose occurring at the expected depth for this energy of 1.5cm.
Likewise, the dose vs depth plot obtained when simulating the 15MV beam shows the curve maximum at about the expected depth of 3cm.

However, for a more rigorous validation of the dose distributions in the simulations, they were also compared to PDDs generated by the treatment planning system. Figures 22 through 24 show comparisons of the percent depth dose curves obtained from the TPS against those resulting from simulations.

Figure 21: Simulated dose vs depth curve for 15MV photon beam
Figure 22: TPS-generated vs simulated PDD for 6MV beam

Figure 23: TPS-generated vs simulated PDD for 10MV FFF beam
Both for the beams whose energy profiles were taken from literature and for those taken from Varian’s phase space files, we see that there is good agreement between the PDD predicted by the treatment planning system and the PDD scored in simulations.

**3.2.2 Cherenkov per Dose for Unfiltered Beams**

In addition to measuring dose at the detector line along the central axis, Cherenkov track length was also measured at each detector, allowing for plots of Cherenkov vs depth to be generated.
The first thing to notice is that, since there are so many Cherenkov photons produced per secondary electron, the Cherenkov vs depth curves are unsurprisingly better defined than the dose vs depth curves. The curve also does not change much.
between 6MV and 15MV, although the 15MV curve does reach its maximum at a slightly greater depth – 8.5cm, versus 7.8cm for the 6MV curve. After reaching the maximum, the Cherenkov values plateau.

With both dose and Cherenkov track length data for different depths, the next step is to compare Cherenkov production per unit dose versus depth.

![Graph of Cherenkov/Dose vs Depth (15MV)](image)

**Figure 27: Cherenkov/dose vs depth for 15MV photon beam**

Clearly, the Cherenkov/Dose vs depth curve begins to lose coherence as depth increases. In order to compare Cherenkov/Dose values amongst different beam energies, then, it became clear that simply using the values obtained by the detector at 9cm depth would result in too much error, as variation amongst the detectors was greatest at that point. Instead, the Cherenkov/Dose values were averaged for the detectors from 8 to 9
cm for all beam energies in order to determine more accurate relationships between the quantities.

![Relative Cherenkov/Dose, 8-9cm](image)

**Figure 28: Relative Cherenkov/dose for photon beams with no added filters**

In terms of which beams produce more or less Cherenkov radiation per unit dose, results line up with expectations: higher energy beams produce superior Cherenkov per dose. Furthermore, a FFF beam will have lower average energy than the same beam with the flattening filter in place, and we indeed see the 6MV FFF beam and 10MV FFF beam having lower Cherenkov production per dose than their flattening filter-included counterparts.

### 3.2.3 Comparison to Measured Data

As mentioned previously, a separate project was carried out by members of our research group to obtain in vitro measurements of Cherenkov and dose values in a
water tank. Although the updated Monte Carlo geometry was designed to mirror this setup, shown in Figure 29, there were some differences as well.

![Experimental setup for Cherenkov/dose measurements](image)

**Figure 29: Experimental setup for Cherenkov/dose measurements**

Notably, while dose and Cherenkov intensity were both measured at the same point along the central axis in the simulations, only the dose was measured along the central axis in the experimental setup. Quinine sulfate was also added to the water for in vitro measurements with a concentration of 0.5 g/L in order to absorb the Cherenkov radiation and emit blue light isotropically.

With data acquired from the geometry created to mirror the experimental setup for measurements being performed, we can now compare the results from the two.
The data agree in some respects: both have greater yield from higher energy beams, with FFF beams showing lower yield, but with the 10MV FFF’s Cherenkov/dose still greater than the 6MV. However, the magnitude of change between beam energies is clearly not in agreement between the two sets of results. There are a few possible causes of this: the simulation is performed with a cubic phantom of pure water, while the measurements are being performed with water which may not be pure, and additionally has quinine sulfate added to boost the detectable Cherenkov signal.

It is also possible that the placement of the optical fiber resulted in lower Cherenkov readings than would have occurred had it been able to be placed right along the central axis at a depth of 8cm or greater, which could result in the lower relative changes seen between beam energies. Alternatively, since quinine sulfate in the water was absorbing lower wavelength Cherenkov radiation and emitting blue light
isotropically, this could have averaged out the detectable reading throughout the water, rather than having higher intensity along the central axis, again leading to lower relative changes between the beam energies. Note that the block in the diagram was not used for the measurements being compared – it was used as a filter for additional measurements, though ultimately it was determined that having the filter placed adjacent to the phantom is not ideal because it increases surface dose and is not a clinically realistic geometry for adding a specialized filter.

3.2.4 Cherenkov per Dose Results with Filters

With measurements completed for standard beams with no extra filtration added, the next step was collecting data with filters placed in the path of the 10MV FFF beam. As mentioned previously, filters used included Aluminum, Copper, and Iron with thicknesses of 2, 4, 10, or 20cm, although only Aluminum was simulated with a 20cm thick filter.
Figure 31: Relative Cherenkov/dose for photon beams with filter placed in beam path

From these results, it is clear that Aluminum provides less increase to Cherenkov/Dose per cm of filter than either Copper or Iron. Copper and Iron are comparable in their increases, with Copper showing slightly higher boosts at 2cm and 4cm, and Iron slightly higher at 10cm – meanwhile, 10cm of Aluminum is about equivalent to 4cm of Copper or Iron, and 20cm of Aluminum is about equivalent to 10cm of either of the other two materials. The 10MV (with flattening filter), 15MV and 18MV beams are provided again for comparison.

3.2.4.1 Beam Energy Distributions after Filtration

A detector placed roughly halfway between the filter and the surface of the water target allowed for measurement of the energy distributions of the beams after passing through the filter, so that beam hardening effects could be observed and compared with
changes in Cherenkov production per unit dose. Results were as expected with beam hardening, and thus higher average energy of photons and secondary electrons, resulting in increased Cherenkov production per unit dose.

Figure 32: Photon energy distributions before filter (10MV FFF) and after aluminum filter for 2, 4, 10, and 20cm thickness
Figure 33: Photon energy distributions before filter (10MV FFF) and after aluminum, copper, and iron filters of 10cm thickness

For the aluminum filters, a clear progression can be seen of beam hardening as filter thickness increases, corresponding with the increased Cherenkov/dose; similarly, when looking at 10cm filters, the aluminum filter has noticeably hardened the beam compared to the unfiltered beam, but copper and iron have both hardened the beam to a significantly greater degree than aluminum and have nearly identical beam profiles.

3.2.5 Cherenkov per Dose Versus Dose Rate Reduction

Finally, having determined which materials provide the greatest boost to Cherenkov/dose per unit thickness of the filter, we investigate the accompanying reduction in Dose Rate.
In Figure 34, the diameter of the circle corresponds to the filter thickness, with the largest representing 20cm (aluminum only). From these results we can see that, although aluminum provides less Cherenkov/dose per centimeter of thickness, it has a more desirable Cherenkov/dose vs dose rate curve. For instance, a 10cm aluminum filter provides a greater intensity boost while also maintaining higher dose rate compared to 4cm of iron or copper.
4. Conclusion

Here, we present results of early stage investigations into Cherenkov production resulting from megavoltage radiotherapy beams. Monte Carlo simulations have demonstrated that the spectrum of Cherenkov radiation is extremely well suited to activation of psoralen as part of CLAP; we have also shown that higher beam energies result not just in greater Cherenkov production in a target, but in better Cherenkov production per unit dose delivered as well.

We have also begun investigating means of maximizing Cherenkov production with the use of filters, and have found that significant increases can be obtained without overly compromising dose rate. Aluminum has been identified as a promising initial candidate as the filter material, showing better Cherenkov/dose improvements than copper or iron when controlling for dose rate reduction. However, in a scenario where psoralen is being utilized in a one-time boost treatment and lower dose rates are acceptable, copper and iron would provide greater Cherenkov/dose boosts given practical filter thickness restraints. Further work is warranted to investigate other materials and filter effects with higher beam energies, as well as expanding simulations to include optical properties of tissues.
References


