Cherenkov radiation dosimetry in water tanks – video rate imaging, tomography and IMRT & VMAT plan verification

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Abstract. This paper presents a survey of three types of imaging of radiation beams in water tanks for comparison to dose maps. The first was simple depth and lateral profile verification, showing excellent agreement between Cherenkov and planned dose, as predicted by the treatment planning system for a square 5cm beam. The second approach was 3D tomography of such beams, using a rotating water tank with camera attached, and using filtered backprojection for the recovery of the 3D volume. The final presentation was real time 2D imaging of IMRT or VMAT treatments in a water tank. In all cases the match to the treatment planning system was within what would be considered acceptable for clinical medical physics acceptance.

1. Introduction
Cherenkov light emission from gamma-ray and electron beam delivery to water tanks has recently been shown to be detectable and could be used in some applications for 3D dosimetry. The major potential benefit of Cherenkov imaging is that it is a way to image beams in real time with over 30 frames per second. As such, it is feasible to image IMRT and VMAT treatment beams in water tanks dynamically [1], and create composite visualizations of the treatment plans. This imaging can be used to verify new treatment plans prior to application to patients, or to quickly verify new machines, or testing in situations where access is limited. The strength of this optical imaging is that it is simple to implement, and provides immediate feedback. The drawbacks are related to minor differences between Cherenkov emission and dose, which make it not an exact measurement of dose.

The average emission intensity detected is in the range of 10’s of nanoWatts/cm², and so typically would require the room lights to be off, but has been reliably imaged using standard CMOS cameras[2, 3]. However, since LINACs deliver radiation in 3microsecond pulses near 200 Hz repetition, the instantaneous emission intensity of Cherenkov is actually 10’s of milliWatts/cm². Thus, if imaging is gated to this emission pattern, it is possible to image this with the room lights on using gated intensified cameras [4, 5]. The relationship between delivered dose and Cherenkov light emission is largely linear when the spectrum of electron energies is not changing significantly [6]. In most cases, the Cherenkov/Dose ratio does not vary by more than 20%, and under certain situations can vary as little as 1-2%. The situations where there is a high degree of linearity between Cherenkov...
emission and Dose deposited are when imaging broad surfaces, imaging lower energy beams and imaging symmetric treatment plans. Even in the cases where there is not good linearity, there is potential to calibrate the ratio based upon well-known estimates from Monte Carlo simulations or from measurements.

In this paper, a review of the approaches used to date is given. The use of a water tank doped with trace amounts of fluorophore was used, and the emission imaged laterally through the wall with a camera. The relationship between Cherenkov induced emission imaged and the expected radiation dose in water is shown. The steps attempted going from 2D planar beam imaging through to rotational 3D tomography are outlined. Finally, 2D temporal imaging of IMRT and VMAT treatment plans are examined to determine the value of exploiting the real-time value of Cherenkov imaging at near video rate.

2. Methods and Results
The setup and use of these systems is simply done with a cubic water tank, initially with 20cm length sides, and later increased to 30cm diameter sides. The lateral and back walls were blackened off with flat black paint, in order to minimize reflections. Addition of 1g/L quinine sulphate to the water is done to act as a fluorophore. This is done to absorb the large amount of UV-blue Cherenkov emission, which is unfortunately being emitted in a cone at a 41° emission angle from the direction of travel, and to re-emit it as blue fluorescence, which is isotropic in emission angle. An image of the emission from a 5cm diameter square beam are shown in figure 1(a), along with the linearity of emission versus dose in (b), and the expected square root dependence of Signal to Noise ratio (S/N) in (c). Measures of lateral and depth beam profiles along with the predicted dose lines from the Treatment Planning System (TPS) are shown in (d) and (e), respectively. Note that the lateral beam profile agreement between dose and measured signal is outstanding for either Cherenkov or the fluorescence signal. However for the depth dose profile agreement to signal, the Cherenkov signal decays faster than the dose. Yet the depth-fluorescence signal agrees quite well with depth dose curve.

Figure 1. (a) Photograph of Cerenkov-induced fluorescent emission from quinine in water, (b) the linearity of image intensity with applied dose, (c) the signal to noise, following a shot noise limited square root function. In (d) a lateral beam profile is shown fluorescent beam (crosses) overlaid on the known beam profile (showing outstanding agreement), and (e) the depth dose curve is shown for the treatment planning system (TPS) along with Cerenkov and Cerenkov-fluorescence.

One of the more interesting opportunities is the ability to do 3 dimensional (3D) imaging of Cherenkov emission as a way to potentially image a surrogate of 3D dose distributions. The benefit is that the imaging is high resolution and rapid, so full 3D beam images could be obtained in a few minutes. The trickier aspects of this are that full recovery of the volume would require back projection reconstruction from the 2D projection images. Additionally, the geometry to avoid refraction through the water tank walls is problematic, yet the easiest solution to this is to keep the camera and water tank wall in a fixed geometry and rotate the water tank. Rotational imaging around the water tank is possible but with refraction at the water tank surface, it is better to rotate the tank with the camera [3, 4]. An illustration of this is shown below in figure 2.
Figure 2. Schematic of the initial experiment set up is shown (left) with the LINAC beam entering the water tank. Čerenkov-induced fluorescence was imaged with the camera laterally, and repeated 1800 rotational angles. This lateral projection data was then combined in a sinogram (right) with tomographic reconstruction. This was completed experimentally on two test beams, rotating the camera, and imaging a simple square beam (right - top row) and a highly irregular beam (right bottom row). The full 3D visualizations of these beams are shown (far right) [7].

Perhaps the largest strengths of Čerenkov imaging as a surrogate for dose imaging, is that the emission capture is very fast and high resolution, so while 3D imaging is interesting, the rotation around the beam is problematic for imaging of off-axis beams. However the most readily implementable use of this technology to medical physics QA is in single projection video imaging of beam dynamics through one side of a pre-existing water tank. As such, the ability to image the beam delivery dynamics of IMRT and VMAT is easily possible. Admittedly the single planar view through one surface does not provide a complete image of the deposited dose, rather is a projection through one direction view perspective of the beam. Yet it provides the fast feedback required for real-time verification, which could have distinct advantages in busy Medical Physics departments. An illustration of this is shown below in figure 3.

Figure 3. In raw images shown in gray scale, (a) shown after median filtering over 24 images (b), with VMAT on top and correlated IMRT images in (c) and (d). The blue images of the beam (right) are shown from a VMAT treatment for 8 positions of the dynamic beam, illustrating the fidelity of being able to capture images throughout the treatment verification process. These images can be integrated together to create deposited Čerenkov maps, which agree with dose maps to within 96% accuracy for gamma parameter of 3% and 3mm to agreement [1].

3. Discussions
This paper has presented a survey of three types of imaging of radiation beams in water tanks for comparison to dose maps. The first was simple depth and lateral profile verification, showing excellent agreement between Čerenkov and planned dose, as predicted by the treatment planning system for a square 5cm beam. The second approach was 3D tomography of such beams, using a rotating water
tank with camera attached, and using filtered backprojection for the recovery of the 3D volume. The final presentation was real time 2D imaging of IMRT or VMAT treatments in a water tank. In all cases the match to the treatment planning system has been within what would be considered acceptable for clinical medical physics acceptance. Comparison to ionization chamber data has also been demonstrated, however because the situations of agreement and disagreement are so unique, better insight is provided by Monte Carlo simulations. This Monte Carlo study, previously published [6], showing that for broad beam profiles, and higher energy beams there is optimal match, and at the lower beam energies and smaller beam sizes the match will be less accurate. Still, the match in IMRT and VMAT treatment plans for a complex C-shaped treatment has been outstanding and so further experimental verification of different beam sizes and more complex treatment plans should be carried out to determine the limits of where there is good versus unacceptable match between Cherenkov and dose.

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5. References
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