Real time radiotherapy verification with Cherenkov imaging: development of a system for beamlet verification

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Abstract. Cherenkov imaging has been shown to allow near real time imaging of the beam entrance and exit on patient tissue, with the appropriate intensified camera and associated image processing. A dedicated system has been developed for research into full torso imaging of whole breast irradiation, where the dual camera system captures the beam shape for all beamlets used in this treatment protocol. Particularly challenging verification measurement exists in dynamic wedge, field in field, and boost delivery, and the system was designed to capture these as they are delivered. Two intensified CMOS (ICMOS) cameras were developed and mounted in a breast treatment room, and pilot studies for intensity and stability were completed. Software tools to contour the treatment area have been developed and are being tested prior to initiation of the full trial. At present, it is possible to record delivery of individual beamlets as small as a single MLC thickness, and readout at 20 frames per second is achieved. Statistical analysis of system repeatability and stability is presented, as well as pilot human studies.

1. Introduction
Cherenkov imaging has been in embryonic testing in the past 5-6 years, with the first clinical images demonstrated in 2014 [1]. This trial demonstrated for the first time that it was possible to record the delivery of radiation to human tissue with a camera in the treatment room. This imaging was achieved by gating the Intensified CCD camera (ICCD) to the short linac pulses, 3-4 microsecond bursts with a repetition rate of 200-360 Hz, such that the signal could be recorded with the room lights on and not interfering too much with the image. Background room light subtraction and median filtering were added into the image processing to produce images of Cherenkov emission which are isolated to the beam entrance and exit surfaces. The signal appears to come from 4-6mm average depth, based upon Monte Carlo studies and tissue phantom tests. The nest phase of this work has been to develop a clinical viable approach to testing this in whole breast radiotherapy, where the cameras were permanently mounted in the treatment room, and the image capture was automated and analysis simplified. This report discusses these latest developments.
2. Methods

2.1 Hardware setup

The new Cherenkov imaging system was developed by DoseOptics LLC and customized for installation at the Norris Cotton Cancer Center in the 10MV LINAC Varian treatment room used for 6MV and 10MV irradiation in whole breast and chest wall cases. Previous work, published in 2014[1], is illustrated in the top two images of Figure 1, where the ICCD camera (Princeton Instruments, PI-MAX4) [2] was used on a tripod for temporary deployment in the room, synchronized to the LINAC output pulses and capturing Cherenkov emission images of either entrance or exit beam. The processed image of one patient is shown at top right, overlaid on the 3D profile from the CT from the treatment plan. This matched the planned dose quite well, as recently published[3]. The new system utilizes an intensified CMOS camera design, with two such cameras installed in the ceiling of the treatment room (bottom left). Initial pilot testing of one of the cameras demonstrated the ability to resolve a single MLC stripe (5mm thickness) on a patient’s tissue (bottom right in Figure 1).

Figure 1. Illustration of the original trial (top left) with an ICCD camera on the tripod, synced to the LINAC and capturing a single view of the patient getting whole breast irradiation. This image is overlaid on the CT scan surface (top right) for visual comparison to the dose. The new system (bottom left) using two ICMOS cameras (DoseOptics LLC) is illustrated mounted to the ceiling and the image from an entrance beam showing a single MLC beamlet is shown (bottom right) for the field in field part of the treatment.

2.2 Image Processing

Image processing is required to ensure clean image data results, as are shown from a sequence of images in Figure 2. The raw intensified images have significant numbers of saturated pixels across the image
(see Fig 2a). This noise is thought to come from stray gamma rays in the room, coming from both the linac head and the tissue being treated. The noise increases significantly with decreasing distance to the target, and at the distance of the cameras positioned, encompasses less than 10% of the pixels on the camera. After median filtering the image is significantly cleaned up, Fig 2b. Then when a background image is captured and subtracted from the original, the image is predominantly only containing the Cherenkov image data, Fig 2c.

![Images of raw Cherenkov imaged with full noise and background signal (a) and then with median filtering to remove the saturated pixels of noise (b). The background subtracted image is then shown in (c), and a threshold contoured version of the beam shape in (d).](image)

**Figure 2.** Images of raw Cherenkov imaged with full noise and background signal (a) and then with median filtering to remove the saturated pixels of noise (b). The background subtracted image is then shown in (c), and a threshold contoured version of the beam shape in (d).

### 2.3 Software Analysis of beam position

A custom contouring algorithm was developed for extraction of the beam shape from the observed Cherenkov beam, as illustrated in Figure 2d, for the processed image in Figure 2c. This contour has a range of features required, but the most important being the ability to robustly outline the viewed Cherenkov in a way which is a faithful representation of the image, even in the presence of moderate signal to noise, and rapidly changing beam shapes such as field in field, or dynamic wedge treatment. The algorithm to compare to dose reads in the treatment plan and extracts out the predicted dose contour at a depth comparable to the origin of the Cherenkov signal, calculated to be approximately 4mm below the surface, as illustrated in Figure 3. A range of depths were examined for superior match based upon patient studies, and the ideal depth was chosen.
3. Results
The results of the preliminary set up and testing have demonstrated that the new cameras are capable of achieving high signal to noise level, with onboard processing for first pass noise removal. The gain levels and signal to background trade off was optimized for the expected imaging setting for the clinical trial. The ability to image a single 5mm beamlet from one leave of the MLC was taken as our metric of success, to ensure that we could contour and image the smallest feature expected in a dynamic treatment. The signal level from a breast treatment imaged at 20 frames per second is consistent with signal levels from single photon imaging in each pulse. Since the LINAC pulse rate is 360 Hz, a readout of 20 fps means that each frame has $360/20 = 18$ pulses integrated together in it. The signal is integrated on the CMOS camera and read out, and successive readout frames are median filtered to suppress the highest salt and pepper noise features from the images.

4. Discussion & Conclusions
This work is a preliminary report of the set-up of an ongoing trial, with the goal of providing real time 3D surface verification of beam position, and eventually surface dosimetry. The choice of camera design was developed after extensive testing in previous studies, and through optimization of the cost-performance trade off of what can be achieved. The constraints in imaging Cherenkov during external beam radiotherapy are:

1) Low signal level: near single photon counting in each LINAC pulse
2) High noise environment with substantial salt and pepper type noise from stray gamma radiation
3) Background levels which are comparable to the Cherenkov signal requiring subtraction
4) Limited perspective view of the treated tissue, based upon line of sight

The strengths of the approach proposed here are:
1) High clean intensifier gain, and fast CMOS based readout
2) Multiple camera imaging allows simultaneous readout of entrance and exit surfaces
3) Mounting of the cameras lateral to the bed on the ceiling provides a reasonably good line of sight, with close proximity to the patient to maximize signal detected.
4) Contouring of the treatment dynamically allows extraction of features to compare to the treatment plan and to compare between daily fractions.

The full results of the clinical trial will be completed by the time of the conference and preliminary analysis of performance will be presented.

5. Acknowledgments
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6. References
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