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Original Research Article

Cherenkov imaging combined with scintillation dosimetry provides real-time positional and dose monitoring for radiotherapy patients with cardiac implanted electronic devices

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ABSTRACT

Background and purpose: Cardiac implanted electronic devices (CIED) require dose monitoring during each fraction of radiotherapy, which can be time consuming and may have delayed read-out times. This study explores the potential of Cherenkov imaging combined with scintillation dosimetry as an alternative verification system.
Methods and materials: Time-gated, complementary metal–oxide–semiconductor (iCMOS) cameras were used to collect video images of anthropomorphic phantoms and patients undergoing radiation treatment near chest wall cardiac devices. Scintillator discs and optically stimulated luminescence dosimeters (OSLDs) were used for dose measurement. Accuracy of spatial delivery was assessed by overlaying predicted surface dose outlines derived from the treatment planning system (TPS) with the Cherenkov images. Dose measurements from OSLDs and scintillators were compared.
Results: In phantom studies, Cherenkov images visibly indicated when dose was delivered to the CIED as compared to non-overlapping dose deliveries. Comparison with dose overlays revealed congruence at the planned position and non-congruence when the phantom was shifted from the initial position. Absolute doses derived from scintillator discs aligned well with the OSLD measurements and TPS predictions for three different positions, measuring within 10 % for in-field positions and within 5 % for out-of-field positions. For two patients with CIEDs imaged over 18 fractions, Cherenkov imaging confirmed positional accuracy for all fractions, and dose measured by scintillator discs deviated by <0.015 Gy from the OSLD measurements.
Conclusions: Cherenkov imaging combined with scintillation dosimetry presents an alternative methodology for CIED monitoring with the added benefit of instantly detecting deviations, enabling timely corrective actions or proper patient triage.

1. Introduction

Cardiac implantable electronic devices (CIEDs), such as pacemakers (ICPs) and defibrillators (ICDs), are vulnerable to ionizing radiation. Exposure during radiation can result in device malfunctions, posing potentially life-threatening risks. It is therefore imperative during radiotherapy treatment planning and delivery to ensure that CIEDs do not exceed the dose specified by the manufacturer, which is often as low as 2 Gy over the course of treatment. When a device is located within 10 cm of the treatment field, a thorough dose assessment is advised per AAPM TG-203 [1]. Although treatment planning systems (TPS) can estimate the dose to CIEDs, these are accurate only if the device is within 3 cm from the treatment field edge [2–4]. Additionally, TPS estimates do not factor in inaccuracies in patient setup or patient movement during

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treatment. Devices positioned within 3–10 cm from the treatment field edge necessitate a phantom or on-patient dose measurement [1]. While dosimeters like optically-stimulated luminescent dosimeters (OSLD) or thermoluminescent dosimeters (TLD) are commonly used for CIED on-patient dose measurements, they have several drawbacks including the potential to overestimate out-of-field dose [5], increased staff overhead time, and delayed read-outs.

Cherenkov imaging has emerged as a method for on-patient treatment verification [6,7]. Using intensified cameras that are time-gated to the linac pulses, the low light emission resulting from the interaction of radiation in tissue, known as the Cherenkov effect, can be captured in real-time during external beam radiation therapy (EBRT) treatments. These images provide spatial maps of the radiation dose delivery, ensuring accuracy of patient positioning in relationship to the beam throughout the treatment, and have been used to detect incidents of patient setup inaccuracies, intrafraction patient motion, and sub-optimal treatment planning [7]. While the adaptation of Cherenkov imaging for quantitative dosimetry is limited by patient specific factors that affect the Cherenkov-to-dose relationship (hemoglobin, melanin, adipose tissue, etc.), prior studies have demonstrated that scintillator discs, which also emit light through a different physical mechanism, may be used to overcome this challenge [8–10]. Positioned on the patient's surface, these discs emit light when exposed to radiation, and the intensity of this light is proportional to the dose deposited at that location, with previous results showing 3–5 % agreement with OSLDs *in vivo* [8–11]. Cherenkov imaging systems have the capacity to detect scintillator light emissions without the need for camera modifications or change in clinic workflow, making scintillation dosimetry using Cherenkov imaging systems an efficient and effective option for on-patient dose measurements.

For radiation fields close to CIEDs, especially those targeting the breast or chest, consistent daily monitoring is optimal but often cumbersome. We propose that Cherenkov imaging to assess positional accuracy, combined with absolute dosimetry using scintillation discs, offers an efficient and accurate solution for daily monitoring of cardiac devices. This method of verification has the potential to: (1) provide direct visualization of the treatment beam's relationship to the cardiac device, (2) confirm daily patient setup accuracy and treatment fidelity for each treatment fraction using the predicted surface outline as a guide, and (3) directly measure the delivered dose to the CIED in real-time with the use of scintillating discs. This study first tests this approach using phantom measurements and then explores its clinical potential in patients with CIEDs located in close proximity to their prescribed radiation treatment fields.

2. Materials and methods

2.1. Radiation simulation, planning, and treatment

The imaging setup and phantom plan used are shown in Supplementary Fig. 1a–f. An anthropomorphic phantom with Medtronic pacemaker (Minneapolis, MN) positioned on the left chest and covered by 3 mm bolus to mimic a subcutaneous implantation (Elasto-Gel, southwest technologies inc., North Kansas City, MO) was used to simulate a breast treatment scenario (Sup Fig. 1a). Simulation CT scans were acquired on a SOMATOM go.OPEN PRO (Siemens Healtheneer, Munich, Germany) and treatment plans were generated using the Eclipse™ treatment planning software (Varian, Palo Alto, CA). For the phantom study, a treatment plan consisting of two tangential treatment fields was designed with a prescribed dose of 2.66 Gy per fraction (Sup Fig. 1b–d). Both the pacemaker and scintillator disc were contoured on the phantom CT scan, and TPS dose estimates were taken as the mean dose to the disc as reported in Eclipse™. Treatment delivery was on a Varian™ TrueBeam™ linear accelerator (Palo Alto, CA).

2.2. Cherenkov imaging

Imaging was performed using the BeamSite™ camera and software system (DoseOptics LLC, Lebanon, NH), which consisted of two ceiling-mounted, time-gated, intensified cameras as shown in Supplementary Fig. 1e. A video of the Cherenkov emission was displayed in real-time at the treatment console (Sup Fig. 1f) and viewed daily by the therapy team. The Cherenkov video and cumulative images of each beam were also saved for post-treatment review and data processing. Image acquisition and processing have been described previously in detail [12]. The predicted surface dose outline overlay was generated in BeamSite™ by first importing the Dicom files associated with the treatment plan, including the RTPlan file, RTDose files for each beam, and CT scans. The CT scans were used to construct a high-resolution surface of the patient using a Hounsfield unit threshold. At each point on the CT surface, a planned surface dose value was estimated by sampling 5 mm down into the dose volume and calculating the average value at that point. The rationale behind this technique is that the strong majority of Cherenkov emission comes from the first 5 mm of tissue, and thus is reflected by the dose within this volume. For positional comparisons, the projected surface dose was thresholded by 16 % of the maximum surface dose to create an outline that may be compared to the Cherenkov field, a value that has been historically used based on empirical comparisons. The surface was then oriented and positioned relative to the cameras based on intrinsic and extrinsic camera properties relative to isocenter for direct comparison to the Cherenkov imaging data. If a treatment plan is delivered accurately and there is no deviation in the patient's anatomy from the time of planning, the Cherenkov image shape and size will align with the TPS surface dose outline. On the other hand, a positional discrepancy between the plan outline and the Cherenkov image indicates either an imprecise spatial delivery or anatomical change. For the purpose of CIED monitoring, a congruent TPS surface dose outline overlay indicates that the treatment was administered as planned by the physician and as a result, the dose to the pacemaker would be in accordance with the plan or prior measurements.

2.3. Scintillator imaging

For scintillator disc imaging, custom-machined plastic EJ-262 scintillators (Eljen Technology, Sweetwater, TX), 1 mm thick × 15 mm diameter, were placed on the phantom or on the skin surface of patients over the palpable edge of the CIED that was closest to the treatment fields. Scintillator light emissions (peak at 480 nm) were captured synchronously by the same BeamSite cameras (fitted with a 780 nm shortpass filter). Background-subtracted, cumulative Cherenkov images were post-processed in MATLAB (MathWorks, Natick, MA) and spatial and temporal filtered for the removal of salt-and-pepper noise. Images of the discs were fit with a Gaussian-convolved elliptical function, and the amplitude of the Gaussian was taken as the relative output. This value was then converted to dose using camera-specific calibrations as previously described [11]. Dose calculations were from a single camera's point of view. The resulting dose values estimated via scintillators were then compared to the average value of the two corresponding OSLD measurements (10 mm size, nanodot with the microSTARii dosimetry system by Landauer, Inc, Glenwood, IL), as well as the TPS (Varian, Palo Alto, CA). Scintillator-to-dose calibration is shown in Supplementary Fig. 2.

2.4. Patient imaging

Two patients with cardiac implantable electronic devices (CIEDs) who were planned for radiation treatment, were identified and enrolled on this study. The study protocol was approved by the Institutional Review Board (IRB), and both patients provided informed consent prior to participation. The first patient had a CIED in the left chest, located 5 cm from the tangential radiation field, and was prescribed 40 Gy in 15 fractions to treat a left sided breast cancer. The second patient had a CIED in the right chest, located 5.5 cm from the nearest thoracic radiation field, and was prescribed 20 Gy in 5 fractions to treat a lymphoma in the left lung. The treatment team conducted daily Cherenkov imaging for 14 of 15 fractions for the patient with breast cancer and 3 of 5 fractions for the patient with lymphoma, visually confirming the device's spatial relationship to the treatment beams. Treatments delivered without Cherenkov imaging occurred when patients were switched to an alternate linac that was not yet fitted with BeamSite cameras. The treatment plans for the enrolled patients were designed based on standard guidelines for their specific disease and also adhered to the recommended safety measures for patients with CIEDs. For dose measurements, a single scintillator disc and two OSLDs were positioned on the inferior edge of each cardiac device for a minimum of three fractions per patient.

3. Results

3.1. CIED Cherenkov imaging and dose measurements

Tangential treatment fields planned to abut the inferior extent of the pacemaker were delivered to the left breast of an anthropomorphic phantom (Fig. 1a and b) and assessment by Cherenkov imaging demonstrated emission just inferior to the pacemaker (Fig. 1c and d). Conversely, when identical treatment fields were delivered at different positions with respect to the pacemaker- by offsetting the phantom such that the treatment fields were either overlapping or distanced 5 mm or 3 cm from the pacemaker, Cherenkov light was visible on the pacemaker (Fig. 1i and j) or with a visible gap (Fig. 1o, p and u, v), respectively. After completion of treatment delivery, an outline of the predicted surface dose from the TPS superimposed on the cumulative Cherenkov showed congruence when the treatment was delivered as planned (Fig. 1e and f), but was misaligned when longitudinal shifts were made before the treatment's delivery (Fig. 1k, l, q, r, w, x).

Dose measurements to the CIED using three methods (scintillating discs, OSLD, TPS) showed good agreement and are summarized in Fig. 2 with the accompanying graph. The percent error of the scintillator disc estimation relative to the OSLD measurement for out of field measurements agreed within 5 %, with a maximum absolute difference of <0.010 Gy. The percent error for in-field measurements showed less correlation between OSLD and scintillator disc, on the order of 10 %. When the fields were abutting the pacemaker, both OSLDs and scintillating disc measurements were highly variable, with measurements ranging from 0.015 to 1.56 Gy.

3.2. Cherenkov imaging and scintillator disc measurements in patients with CIEDs

Daily visual monitoring of the Cherenkov emissions for two patients receiving standard of care radiation treatment (17 fractions in total) confirmed that the cardiac devices were never close to the treatment fields, as was prescribed. Supplementary Video 1 and 2 show recordings of a representative treatment for each patient, illustrating the treatment team's live view during each fraction. The static, cumulative Cherenkov images are shown in Fig. 3b, c, and f, g and compared to the treatment plan (a and e). The daily positional accuracy was verified with the plan outline overlay for each imaged fraction, as shown in Fig. 3d and h.

For CIED dose measurement in the first patient, the daily OSLD average dose measurement and standard deviation was 0.0390 ± 0.007

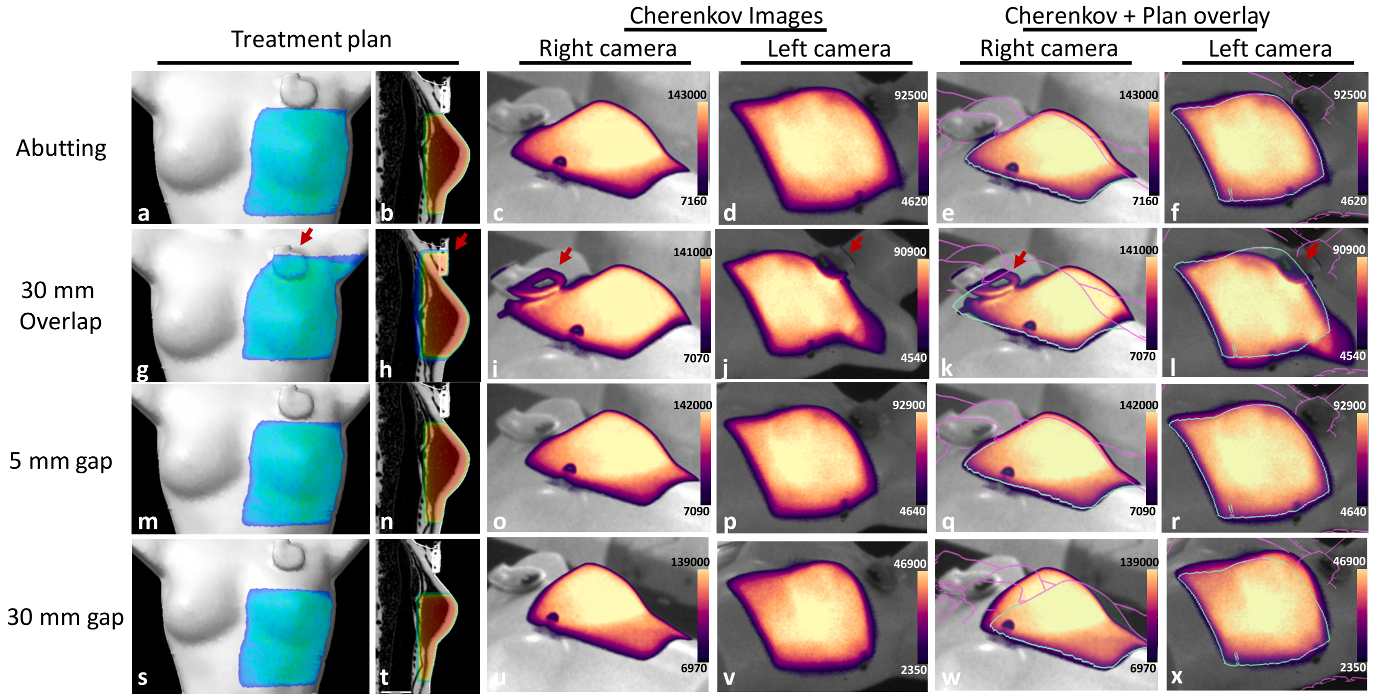

Fig. 1. Cherenkov imaging of breast tangent fields delivered to a phantom with a pacemaker on the left chest wall. The first two columns are the TPS surface dose (a, g, m, s) and CT scan sagittal view (b, h, n, t). The next columns are the Cherenkov images (c, d, i, j, o, p, u, v) with the overlay of the predicted surface dose and patient outline shown in the last two columns (e, f, k, l, q, r, w, x). The top row uses a treatment plan that abuts the pacemaker. The second row is the same plan delivered after a 30 mm longitudinal shift so that the treatment fields are overlapping the pacemaker. The 3rd row is a 5 mm shift from the original abutting plan, giving a 5 mm gap between the radiation dose and the pacemaker. Finally, the bottom row is an additional 25 mm shift, giving a 30 mm gap between the radiation dose and the pacemaker. The Cherenkov emissions are seen overlaying the pacemaker in i–l (red arrow), but not in c–f, o–r nor u–x. The overlay of the expected surface dose outline (yellow lines) derived from the treatment plan and patient outline (purple lines) is shown in e, f, which verifies that the treatment delivery matches the treatment plan. When the phantom is shifted, the surface overlay outline from the TPS no longer matches the Cherenkov image shape (k–l, q–r, w–x). Color scale is in arbitrary units, representing the light signal received by the camera. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

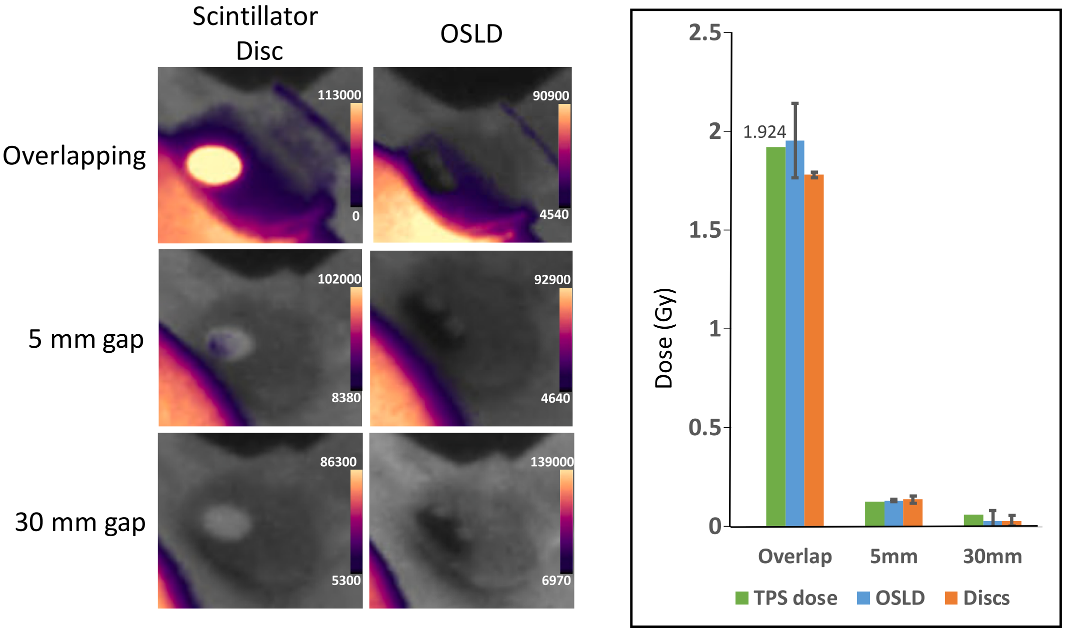

Fig. 2. Measurement of the dose delivered to CIEDs. Scintillator discs (left column) or OSLDs (right column) were placed on the inferior aspect of the pacemaker using palpation and/or visualization of the device, during delivery of tangential treatment fields. All measurement were made in triplicates and compared to the estimated mean dose from the TPS at equivalent locations. Treatment deliveries are shown from three positions- overlapped, 5 mm gap and 30 mm gap as described in Fig. 1. The graph displays these OSLD and scintillator disc measurements compared to the estimated dose derived from the treatment planning system at the corresponding locations.

Gy, and the corresponding scintillator disc measurement was 0.0460 ± 0.002 Gy. Both measurements were in close agreement (<0.001 Gy) with the daily maximum dose for the device as modeled by the TPS, at 0.0420 Gy. For the second patient, daily OSLD average and standard deviation was 0.014 Gy ± 0.003 Gy, while the scintillator disc measurements were negligible- with no signal above background on any day. These were also consistent with the TPS's daily maximum dose of 0.011 Gy.

4. Discussion

We report here a robust and effective methodology, utilizing Cherenkov imaging cameras, for monitoring daily treatment delivery for patients with implanted cardiac devices. In this study, we also present a new tool for assessing positional accuracy of the delivered dose using a predicted dose overlay derived from the TPS. Finally, we show that the dose to the cardiac device can be measured using scintillators that are simultaneously imaged by the Cherenkov cameras with the measurements comparing favorably to OSLD and TPS measurements in both phantom and patients.

In this methodology, the Cherenkov imaging that is obtained simultaneously has several benefits to the treatment team. (1) The Cherenkov image shows the extent and location of the delivered dose relative to the dosimeter and CIED, assisting in the interpretation of the dose measurements. For example, when adjacent dosimeters give discordant readouts, review of the Cherenkov image shows the location of each dosimeter in the beam, which is especially important for interpretation of dose measurements in high dose gradients. (2) The Cherenkov image can guide scintillator placement to areas of concern and/or visualized unintended dose. For the purposes of CIED monitoring, it is important for the team to place the dosimeter on any area that the Cherenkov image shows dose on or near the cardiac device. (3) The Cherenkov image also gives information on how to rectify any dose measurements that are above the planned dose, i.e. the image will show the direction needed to shift the CIED out of the field. (4) Finally, no changes in the Cherenkov camera or workflow at the machine are needed to detect the scintillation emissions, making scintillation dosimetry a seamless, efficient option to combine with Cherenkov imaging to achieve the benefits of both positional and dose verification.

Considering the importance of on-patient monitoring, Prisciandaro et al. at the University of Michigan studied a formal workflow for communication and monitoring of patients with CIEDs [13]. In 69 patients, they found differences in estimated and measured CIED doses when using published peripheral dose data and TPS calculations, leading to the continued recommendation for direct measurements of devices within 10 cm of the treatment field or receiving estimated doses of >1 Gy for defibrillators or >2 Gy for pacemakers. In their established process for the first day of treatment, they recommend (1) *in vivo* dosimetry measurements, (2) verification that imaging fields do not irradiate the CIED, (3) estimation of fractional dose and total dose based on dosimetry readings, and (4) reporting of doses exceeding tolerance to the responsible physicians. Our methodology described above, satisfies their recommendations for day 1 monitoring. Moreover, Cherenkov and scintillation imaging has the advantage of providing instantaneous feedback directly at the treatment console. Should unexpected dose be detected at the pacemaker, treatment can be stopped immediately and adjustments made as necessary. Moreover, with the use of scintillator discs, dose information is immediately accessible, allowing for timely decision-making even before the patient leaves the treatment room. While the analysis done here was completed post-treatment in MATLAB, current Cherenkov imaging software can be adapted to automatically detect and calculate the output to dose immediately after the treatment is completed. This stands in contrast to other in vivo dosimeters such as OSLDs and TLDs, which do not offer real-time data and have delays in dose availability of up to 24 h [14]. Finally, though not shown here, this approach can be adapted to measure real-time dose rates using a methodology involving monitoring the live Cherenkov videos rather than the cumulative images [15,16]. Dose rate monitoring is valuable in this context because high dose rates are known to cause transient, but potentially detrimental interference of CIEDs [17].

The limitations of Cherenkov and scintillation imaging in this study must also be noted. First, the percent error of 10 % between scintillator

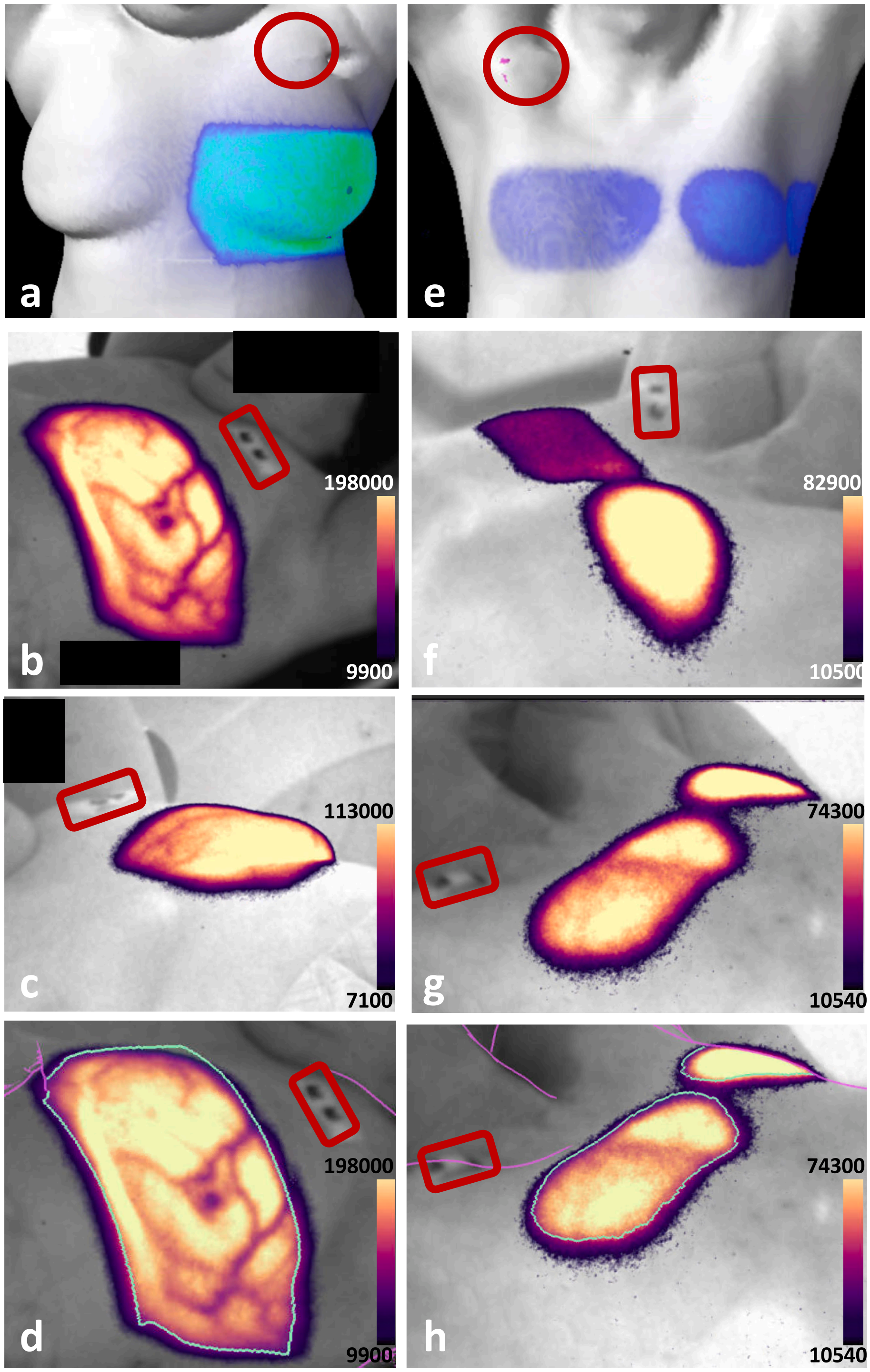

Fig. 3. Clinical Cherenkov imaging of two patients with CIEDs. Top row shows the predicted surface dose from the TPS with CIED positions circled in red. Cherenkov images are shown in b–d and f–h with cardiac device and OSLD/scintillator discs noted in red boxes. The first patient (a–d) received 15 fractions of radiation to the left breast using tangential fields that were modified superiorly to avoid the CIED. Cherenkov images of patient 1 from 2 cameras are shown in b, c with surface dose outline overlay in d. The second patient (e–h) received 5 fractions of radiation to a left lung lesion for treatment of a lymphoma using a 3D conformal treatment plan. One of the fields, LPO, exited through the right chest wall, inferior to the patient's CIED. Cherenkov images from each camera are shown in f and g. The cumulative Cherenkov image with the TPS outline overlay is shown in h. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and OSLD measurements for in-field locations in this study was higher than previously reported [11], likely due to measurements being near the penumbra, where small positional differences can result in large dose differences. In addition, the size differences in the two dosimeter types (2 mm vs. 10 mm) and differing methods for calculating dose, may also contribute to the discrepancies, especially over dose gradients. A general drawback to the method presented here is that for effective monitoring of the entire treatment delivery, both the device and the treatment area must be within the line of sight of the Cherenkov cameras. During VMAT treatments and some gantry angles used in 3D treatments, the cameras may be obscured by the gantry. In our setup, the cameras are ceiling mounted on the patient's left and right sides, thus limiting analysis to the anterior surface of the patient. A third camera at the foot of the couch or use of a tripod mounted camera could increase the field of view and minimize gantry obstruction. We also note, at very low doses signal may be below the current threshold for scintillator detection, as seen in the second patient case. Finally, this study was limited to 3D planning techniques, which are commonly utilized for breast irradiation. Work is ongoing to apply similar methodologies to VMAT deliveries, which for absolute dosimetry using scintillating discs is more complex, needing to account for the changing angular dependency, as well as the difference in exit and entrance beams encountered during arc therapy.

In conclusion, this study introduces an innovative approach to daily monitoring of the positional accuracy and dose to CIEDs. This method offers real-time in vivo imaging of the treatment beam location, the potential for immediate dose measurements and rectifications of deviations, no additional radiation exposure, and a stream-lined process that is easily integrated into normal clinical workflow.

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CRediT authorship contribution statement

Savannah M. Decker: Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Allison L. Matous:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Rongxiao Zhang:** Writing – review & editing. **David J. Gladstone:** Supervision, Writing – review & editing. **Evan K. Grove:** Writing – review & editing. **Benjamin B. Williams:** Data curation. **Michael Jermyn:** Methodology, Software, Writing – review & editing. **Shauna McVorran:** Data curation, Writing – review & editing. **Lesley A. Jarvis:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: L. A.J. has a financial interest in DoseOptics, the manufacturer of cameras used in this study. She has a conflict of interest management plan at Dartmouth College and Dartmouth-Health, which includes an independent review of the research integrity before publication. The following authors have patents related to Cherenkov imaging: US10940332 (L.A. J., R.Z. and D.J.G.) and US10201718B2 (R.Z. and D.J.G). Patents are assigned to The Trustees of Dartmouth College. M.J. is employed by DoseOptics and S.M.D is a consultant for DoseOptics.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2024.100642.

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