Two-dimensional real-time quality assurance dosimetry system using \( \mu \)-\( \text{Al}_2\text{O}_3: \text{C}, \text{Mg} \) radioluminescence films

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**ABSTRACT**

Background and purpose: There is a continual need for more accurate and effective dosimetric systems for quality assurance (QA) as radiotherapy evolves in complexity. The purpose of this project was to introduce a new system that minimally perturbs the main beam, while assessing its real time 2D dose-rate and field shapes. The system combined reusability, linear dose-rate response, and high spatial and time resolution in a single radiation detection technology that can be applied to surface dose estimation and QA.

Materials and methods: We developed a 2D prototype system consisting of a camera, focusing lenses and short pass filter, placed on the head of a linear accelerator, facing an \( \text{Al}_2\text{O}_3: \text{C}, \text{Mg} \) radioluminescent film. To check the appropriateness of multi-leaf collimator, stability/reproducibility QA tests were prepared using the treatment planning system: including the routinely used alternating leaves, chair and pyramid checks.

Results: The \( \text{Al}_2\text{O}_3: \text{C}, \text{Mg} \) film did not perturb the dose vs. depth dose curves determined with a point detector (-0.5% difference). Our results showed a dose-rate linear film response (\( R^2 = 0.999 \)), from 5 to 600 MU/min. Measured output factors agreed with reference data within -1%, indicating a potential for small field dosimetry. Both chair and pyramid measured profiles were comparable with those obtained with the treatment planning system within 1%. The alternating leaves test showed an average discrepancy in the valleys of 14%.

Conclusions: The prototype demonstrated promising results. It obviated the need for corrections regarding the relative position of the camera, confirming accurate dose-rate delivery and detection of radiation fields.

1. Introduction

Quality assurance (QA) is important to the successful implementation of radiation treatments. The technology to verify dose delivery by direct dose measurement for every beam, every fraction, and every patient is not always practical. Hence, there are numerous solutions to verify the pre-treatment delivery to a phantom [1,2]. However, pre-treatment QA is the least sensitive tool to detect errors out of all control checks in radiation oncology [3], highlighting the need for real-time patient specific QA.

Several authors have proposed solutions to assess real-time patient doses during treatment. Such solutions included diodes [4], metal-oxide semiconductor field effect transistors [5], organic and inorganic scintillation detectors [6,7], radioluminescent (RL) crystals [8], Cherenkov emission [9], transmission detectors [10] and electronic portal imaging devices [11].

In general, point and 2D scintillators/RL detectors were reliable solutions, but they had some specific differences, such as time/spatial resolution, film homogeneity, quenching, optical scattering, glaring effects and interference from Cherenkov emission [12,13]. Moreover, most dose measurements from these systems presented an integration time of 150 ms when using Electron Multiplying Charge Coupled Device (EMCCD) cameras or a few seconds when using Charge Coupled Device (CCD) cameras, in order to accumulate a good signal-to-noise ratio [14,15]. The primary aim for this study was to present an independent QA tool that combines real-time dose-rate assessment with high spatial resolution. The system consisted of a thin RL film based on \( \text{Al}_2\text{O}_3: \text{C}, \text{Mg} \) [16] and a digital camera that images the RL signal with intensity proportional to the radiation dose rate and shape.

Our system has a novel method to visualize in real-time the entrance of radiation beams at a phantom or patient surface, with an improved time resolution of 20 ms, using a camera fixed to the head of the linear accelerator (LINAC). This increased time resolution, compared to previous systems, is a clear advantage for treatments involving many small
and irregular multileaf collimator (MLC) fields or segments that are delivered in dynamic mode, such as intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT). In addition, we present, for the first time, Al\textsubscript{2}O\textsubscript{3}:C,Mg RL with high energy scattered photons. The pixel intensity signal used for the dosimetric characterizations of each film consisted of the average RL signal by a noise removal filter to remove saturated pixels caused by high-energy scattered photons. The pixel intensity signal used for the dosimetric characterizations of each film consisted of the average RL signal over a specified region of interest subtracted by the average background signal. Background images (around 50) were acquired by averaging images prior and post irradiation at the same sampling rate used for the images acquired during irradiation (one image every 20 ms). The standard deviation (SD) of the background light did not exceed 0.5%.

2.2. Irradiations and tests

We irradiated the films using a TrueBeam Varian (Varian Medical Systems Inc., Palo Alto, CA), with 6 MV photons in flattening filter mode (SSD). The real time images (Fig. 3 a) from films irradiated with various square fields showed sharp field edges and reasonable uniformity from 100 mm\textsuperscript{2} down to 10 mm\textsuperscript{2}. The measured output factors (Fig. 3 b) presented good reproducibility even for the smallest field sizes. The relative standard deviation of the output factors for the measurements was <1.7% (1 SD). It is noteworthy that a good agreement was obtained from the differences in output factors from the films and ionization chamber (upper image, Fig. 3 b).

3.3. Output factors

The capacity to check the stability of the multi-leaf collimator (MLC) and the reproducibility of the gap between leaves was studied by chair, pyramid and alternating leave QA tests [21–23]. The air chamber was a 100 mm\textsuperscript{2} field containing an irregular shaped MLC forming a chair figure. The alternating leaves test was a 100 mm\textsuperscript{2} field that had 5 mm open-closed leaves. The pyramid test had squared MLC fields of 25, 50, 75, 100, and 150 mm\textsuperscript{2} with monitor units distributed equally between the different field sizes.
nine, from left to right, respectively. The full width at half maximum (FWHM) for the planned was 4.9 mm, while the film presented an average of 6.7 ± 0.2 mm.

3.5. QA chair test

The real time image acquired from the planned chair test (Fig. 5a) outlined different profiles along the crossline and inline fields that correctly resembled a chair. To quantify the accuracy of the image, we chose two crossing lines from the chair image (line 1 and 2, Fig. 5a) and plotted, in Fig. 5b, the film’s pixel intensities (normalized to the maximum value) against length (mm), compared to the same lines from the TPS plan.

We observe similar results from measured and planned profiles. The upper graph of Fig. 5b presents the FWHM for the TPS of 74 mm, whilst the film presented an average of 74.2 ± 0.4 mm. For the lower graph, the FWHM for the TPS was 18.7 mm for both profiles, while the film gives 18.8 ± 0.3 mm and 18.8 ± 0.4 mm for the first and second profiles, from left to right, respectively.

The secondary axis from Fig. 5b presents the difference between measured and planned profiles. For line 1, the difference is below 1% for the interval 20 to 80 mm, and below 1.8% for the profile edges (<20 mm and >80 mm). For line 2, the difference is below ±1% for the interval 12 to 35 mm and 70 to 92 mm, and below 2% for the profiles edges (<12 mm and >90 mm).
The superposition of squared profiles acquired with the RL film provided a pyramid-like light distribution image (Fig. 6a). The film’s pixel intensities (normalized to the maximum value) against length was compared with the profile from the planned test in the TPS (line ‘L’ from Fig. 6a, plotted in Fig. 6b). The curves increased smoothly with length to reach the maximum value around 75 mm, decreasing in a mirrored way to reach a minimum at 160 mm. The differences between both curves (upper image, Fig. 6b) were mostly within ±1% for the interval ±120 mm, reaching a maximum of 4% at both extremities.

4. Discussion

We have successfully demonstrated the feasibility of using Al₂O₃:C, Mg for 2D dosimetry in real-time radiotherapy. Real-time beam tracking offers several advantages, for example, the ability to monitor beam position and shapes during treatment delivery. The key findings of the study were: (a) the depth dose curves measured with and without the presence of the film did not present a significant change both at isocenter or out-of-field; (b) the dose-rate response was linear; (c) measured output factors showed potential for small field dosimetry; d) measured QA checks were reasonably consistent with TPS tests.

The difference between the curves (Fig. 1a) were within the uncertainty of the optical fibre system (~0.3%) [24]. These results are comparable with the perturbation measured with transmission detectors (MagicPlate and monolithic silicon detector) [25,26], and other systems somewhat similar to ours in concept, such as the GOS scintillator film (~0.6%) [27]. c) In out-of-field, the difference between the curves (Fig. 1b) did not exceed ~4%, which is also comparable with the optical fibre detector accuracy at such low dose (≈10 mGy) and energies (≈ 50 keV).
We have presented a good linear dose-rate response ($R^2 = 0.999$). Most of plastic scintillators studies integrate the dose over a specific time span [6], whereas our results are presented in terms of dose-rate. GOS composite materials were linear with absorbed dose [28]. However, a study presenting a similar system to ours (camera + GOS scintillating material) only reported dose-rate measurements from 200 to 600 MU/min [27]. Another promising scintillating material, BCF-12, has low $Z_{\text{eff}} \sim 6.56$ and decay time (3 ns), but a low light yield, which limits its use for low dose and dose rate applications using cameras [29].

Accurate measurement of small radiation fields is a well-known challenge, due to loss in charged particle equilibrium. The potential of $\text{Al}_2\text{O}_3$:C point detectors for small field dosimetry was successfully accessed by many authors [30,31]. Several works demonstrated that plastic scintillators measured higher output factors than an ionization chamber, silicon diode and/or radiographic film [32], due to difficulties to correct for the Cherenkov radiation and the differences in the active volumes of the detectors. Our 2D film agreed well (within $\leq 1\%$) with reference data (Fig. 3b).

Our system QA checks showed good general agreement with the TPS. The profiles from Fig. 4 presented in detail the alternating peaks and

![Fig. 5. Chair test in a 100 mm$^2$ field a) captured by the RL system and b) profile comparison with TPS for line 1 (upper graph) and line 2 (lower graph). Secondary axis from the plots are the differences between measured (film) and planned (TPS) profiles. The average difference for the out of field region between the profiles is 1%.

![Fig. 6. Pyramid test a) captured by the RL system, with the superposition of various square field sizes and b) profile comparison with TPS for the top-to-bottom line ‘L’. Upper plot is the difference between measured (film) and planned (TPS) profiles.]
valleys according to the open and closed leaves. At such small delivered fields, our system had a lower measured resolution, i.e. a larger FWHM consistent with the reported values (6.7 ± 0.2 mm) in this study. A similar issue with lower resolution was also reported for 2D planar and cylindrical diode arrays [33], while other studies presented discrepancies of 20–40% between Monte Carlo simulations, TPS and measurements [34,35]. When we integrated a sequence of 10 images (resulting in a 200 ms integrated image), the signal-to-noise ratio improved and the difference observed in the valleys were 2–3%, with FWHM = 5.5 ± 0.2 mm. It is possible that part of the overresponse observed in the valley region were due to the films material’s specific energy dependency for energies below 100 keV [30,36].

Chair and pyramid tests from GafChromic films and ionization chambers were comparable with the profiles measured using our RL system (Figs. 5 and 6) [23]. Lambert et al. [37] presented pyramid fields measured by a plastic scintillator. The dose readings agreed to within 1% with the reference ionization chamber, inside the main field, with no information, however, about the edge region of the pyramid field to account for lower dose resolution. For the chair check, we compared our results with other publications focusing on lateral profile dependence results, as we could not find similar tests. Ponisich et al. [38] showed a series of liquid scintillator measurements for different field sizes. Their results were in good agreement with the dose profile except at the shoulder and tail (not quantified by the authors). Guillot et al. [39] demonstrated that arrays of plastic scintillation detectors could be used for QA in clinics, with step-and-shoot plans.

The main difference between the cited studies and the results presented in our work was that we achieved comparable results with the TPS with images acquired with high time resolution (20 ms) and (crucially) that our films could be used for surface dose assessments, due to our high time resolution (20 ms) and the difference observed in the valleys were 2–3%, with FWHM = 5.5 ± 0.2 mm. It is possible that part of the overresponse observed in the valley region were due to the films material’s specific energy dependency for energies below 100 keV [30,36].

Real-time in vivo dosimetry is highly necessary in several applications, for instance, in hypofractionated treatments. An ideal dosimetric system should be able not only to measure dose accurately, but also to detect other sources of discrepancies independently (such as set-up errors). Our system would provide independent safety checks in addition to the existing technologies. ImageDosis will be further developed so in the future radiation therapists/medical physicists could use this as a safety feature to stop treatment if the radiation delivery appears to be incorrect.

In conclusion, we have presented data of a prototype system for ensuring the accurate and safe delivery of radiation in clinical practice. This study differed from other scintillators/RL systems in that the camera is placed at the head of the LINAC, facing the isocenter of the beam and the film. This simplified the need for corrections regarding the relative position of the camera, as it is always fixed in the same position related to the beam. We demonstrated that the films minimally perturb the main beam, confirming accurate dose-rate delivery and detection of radiation field shapes (from jaws and multileaf collimators).

Declaration of Competing Interest

The whole concept of the ImageDosis system was developed in SCK CEN primarily by dr. Luana de Freitas Nascimento. Dr. Mark Akselrod (Landauer Inc.) is a long-time collaborator, his role was to provide dosimetric materials (and help with questions concerning the dosimetric properties of the material he grows), in special, we asked for micro-crystals, much smaller than the ones Landauer Inc. normally uses in their commercial business. Dr. Akselrod also provided the first films we tested, but the homogeneity of the films had to be improved – again, these films are not commercially available. This is when we reached AGPA (Dr. Leblans), as they have a long experience in coating and printing. They agreed to coat Dr. Akselrod’s micro-crystals for us. All of these happened in a pure collaborative manner and there are absolutely no competing financial or personal interests at play here.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2020.09.008.

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