PhD Dissertation Title: "Development and demonstration of 2D dosimetry using optically stimulated luminescence from new Al_2O_3 films for radiotherapy applications"

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ABSTRACT

Purpose: The goal of this work was to develop and demonstrate a 2D dosimetry system based on the optically stimulated luminescence (OSL) from new Al_2O_3 films for radiotherapy applications.

Motivation: With the development of highly conformal and high dose per fraction radiation therapy techniques, such as, stereotactic radiosurgery, devising a robust quality assurance protocol is critically important. Unavailability of a 2-D absolute dose detector, however, is one of the biggest challenges towards such development. Even the most recent report by the Task Group (TG) 120 of the American Association of Physicists in Medicine (AAPM) recommends the use of two detectors combined to obtain accurate 2D dose information: small ion chamber or diodes for measuring the central axis absolute dose, and films for 2D relative dose distribution. This is mainly due to poor resolution of 2D active detectors (ion chamber or diode arrays) and inherent limitations of radiographic (energy dependence) and radiochromic films (narrow dynamic range, non-linear dose response and one-time use). As a result, luminescence techniques, such as thermoluminescence (TL) and OSL, are being extensively studied due to the availability of semiconductor materials with high sensitivity to radiation, linear response over a wide dynamic range and near-tissue equivalence. The OSL technique is already used in computed radiography (CR), except that the image plates are optimized for imaging of diagnostic X-rays employing storage phosphors of high effective atomic numbers (Z_{eff} ~ 50), thus not suitable for dosimetry. Al_2O_3:C, originally developed as a TL detector, has several OSL properties for which it has been used for personal dosimetry for almost two decades and is increasingly used in medical dosimetry. It shows no energy dependence for megavoltage energy beams (Z_{eff} = 11.3), allows extremely low dose measurements, has linear dose response over a wide dynamic range (> 5 decades) accompanied by independence on dose-rate, relatively stable signal at room temperature and little dependence on irradiation angle. Despite the mentioned good dosimetric properties of Al_2O_3:C, its application in 2D dosimetry using laser-scanning technique similar to that used in CR has so far been prevented by the long luminescence lifetime of Al_2O_3:C main luminescence band (F-center peaks at ~415 nm and emits with a lifetime of 35 ms, compared to ~μs for storage phosphors). OSL films could also be imaged using a position sensitive detector, such as CCD camera, but this approach requires highly sensitive cameras, such as electron multiplying CCDs, which are expensive and provide little flexibility compared to laser-scanning approach. Therefore, Al_2O_3:C OSL film has demonstrated ability for point dosimetry and is attractive for 2D dosimetry, but its successful implementation is technically challenging.

Methods: A 2D laser-scanning system consisting of a 532 nm diode laser coupled with a dual-axis Galvo mirror system and a photomultiplier tube coupled with UV bandpass (260 – 395 nm) filter was developed for the readout and two newly developed OSL films (Al_2O_3:C and Al_2O_3:C,Mg) were tested

(Ahmed et al., 2014). The films consist of 47 µm active layer (powder + binder) with median grain (of powder) size of 15 µm deposited on a 75 µm thick polyester substrate and printed in rolls of 30 cm width by 125 µm total thickness. In an image scan, consecutive rows are scanned in alternate directions with each row separated by ~0.17 mm. Each row is scanned with a pixel separation of ~ 0.15 mm and an acquisition time of 327.68 μs. These parameters are adjustable. The total scan time, including readout overhead, is ~7 minutes. A complete dose reconstruction algorithm addressing corrections required for the characteristic material properties and the properties related to the system design was developed. The material property corrections are mostly related to the background phosphorescence and contamination of signal from previously stimulated pixels due to slow luminescence, which we refer to as 'pixel bleeding'. The pixel bleeding correction algorithm takes advantage of the simultaneous detection of emissions from the slow F-center and fast F^+-center (another luminescence center in Al_2O_3 OSL films, peaks at ~330 nm, emits with a lifetime < 7 ns). The algorithm is based on the least squares fitting of two adjacent signal profiles obtained in alternate scan directions, essentially a deconvolution of the signal with a kernel that is based on the lifetime of the two luminescence centers. The major corrections required due to system design are position dependence of light collection efficiency, as a single PMT is used to collect light from the entire image scanning area, and geometric distortion inherent to galvanometer mirror system. A position dependent light collection efficiency function was identified and a matrix ray tracing algorithm was developed to correct for geometric distortion. The dosimetric properties of the system were tested using clinical X-ray (6 MV) beam. The feasibility of small field dosimetry was tested using heavy ion beams (221 MeV proton and 430 MeV ^{12}C beam). For comparison, clinical tests were performed with ionization chamber, diode arrays and commercial radiochromic films (Gafchromic EBT3) when applicable.

Results and Conclusions: The results demonstrate that the developed image reconstruction algorithm enabled > 300x faster laser-scanning readout of the Al_2O_3 films, eliminating the restriction imposed by its slow luminescence decay (Yukihara and Ahmed, 2015). The algorithm facilitates submillimeter spatial resolution, reduces the scanner position dependence (of light collection efficiency) and removes the inherent Galvo geometric distortion, among other corrections (Ahmed et al., 2016a). The system has a minimum detectable dose of < 1 mGy, linearity correction factor of < 10% up to ~4.0 Gy and < 2% dose uncertainty over the clinically relevant dose range of 0.1 – 30 Gy (Ahmed et al., 2016b). The system has a dynamic range of 4 - 5 orders, only limited by PMT linearity. The absolute response from Al_2O_2:C films is higher than Al_2O_2:C,Mg films, but with lower image signal-to-noise ratio due to lower concentration of fast F^+-center emission. As a result, Al_2O_2:C,Mg films are better suited than Al_2O_3:C films for small field dosimetry, which requires precise dosimetry with sub-millimeter spatial resolution (Ahmed et al., 2017).
The dose uncertainty associated with OSL film dosimetry is lower than that associated with EBT3 film dosimetry due to lower background, simpler calibration and wider dynamic range. In conclusion, this work demonstrates potential of the laser-scanning 2D OSL dosimetry system based on Al_2O_3 films for both relative and absolute dosimetry in radiotherapy applications.

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References to author publications that relate specifically to the dissertation:

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