ZnSe Nanowire Optically Stimulated Luminescence for Accurate Radiation Dosimetry in Radiotherapy

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ABSTRACT

Purpose
Accurate radiation dosimetry is critical for patient safety and treatment quality in radiotherapy. Conventional thermoluminescent dosimeters have limitations in re-readability and flexibility. This study aims to explore ZnSe nanowire-based optically stimulated luminescence dosimeters (OSLDs) as a novel solution, leveraging defect-engineered nanostructures to achieve precise, repeatable dose measurements suitable for wearable and adaptable applications in radiotherapy.

Method
ZnSe nanowires were synthesized using controlled growth techniques to optimize deep-trap formation essential for OSL. These nanowires were integrated into prototype OSLDs fabricated on biocompatible substrates. Experimental characterization was conducted under clinically relevant conditions using an 18 MV photon beam from a Varian TrueBEAM linear accelerator. Optical measurements included steady-state photoluminescence (PL) before and after irradiation to assess trap activation, and time-resolved OSL decay analysis to evaluate luminescence kinetics. Dose–response behavior was quantified across the 0–1 Gy range to determine linearity and sensitivity.

Results
PL spectra revealed a significant increase in the donor–acceptor emission peak at ~630 nm post-irradiation, confirming activation of radiation-sensitive deep traps while near-band-edge emission remained stable. Time-resolved OSL decay curves exhibited bi-exponential behavior with two components: a fast free-carrier term and a slower deep-trap term. OSL lifetimes decreased with increasing dose (≈400 ms to ≈250 ms), indicating dose-dependent kinetics. Moreover, a strong linear correlation between inverse OSL lifetime and dose was observed, validating proportionality and enabling quantitative dose estimation.

Conclusions
Prototype ZnSe nanowire OSLDs demonstrated clear radiation sensitivity, reproducible dose-dependent luminescence, and linear dose–response under clinical photon beams. These findings confirm the underlying mechanism for accurate dose readout and highlight the potential of nanowire-based OSLDs as flexible, re-readable, and precise dosimetry tools for radiation safety and device quality assurance in radiotherapy. Future work will focus on optimizing device architecture and extending testing to broader dose ranges and clinical scenarios.

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INTRODUCTION

Accurate and reliable radiation dosimetry is essential for ensuring patient safety and treatment quality in radiotherapy. Conventional thermoluminescent dosimeters (TLDs) offer high sensitivity but are limited by single-use readout, lack of re-readability, and restricted geometric flexibility. Optically stimulated luminescence dosimeters (OSLDs) overcome several of these limitations by enabling non-destructive, repeatable dose readout [1]. Recent advances in nanomaterials have enabled defect-engineered structures with enhanced radiation sensitivity. In particular, ZnSe nanowires exhibit tunable deep-level defects that can act as efficient charge traps for optically stimulated luminescence [2]. This study investigates the feasibility of ZnSe nanowire-based OSLDs for radiotherapy dosimetry by characterizing their photoluminescence (PL) and OSL behavior under clinical megavoltage photon irradiation.

METHODS AND MATERIALS

ZnSe nanowires were synthesized using controlled growth techniques designed to enhance the formation of radiation-sensitive deep traps. The nanowires were incorporated into prototype OSLD devices fabricated on flexible, biocompatible substrates. All irradiations were performed using an 18 MV photon beam from a Varian TrueBEAM linear accelerator, under clinically relevant conditions. Optical characterization included: Steady-state PL measurements before and after irradiation to assess radiation-induced defect activation (Fig.1). Time-resolved optically stimulated luminescence (OSL) measurements to analyze luminescence decay kinetics (Fig. 2). Dose-response behavior was characterized over the 0–1 Gy range. OSL decay curves were fitted using a bi-exponential model, separating fast free-carrier recombination from slower deep-trap-mediated luminescence. The inverse OSL lifetime was evaluated as a quantitative dosimetric metric (Fig. 3).

RESULTS

PL spectra acquired before and after irradiation are shown in Fig. 1. Three emission components are observed: near-band-edge emission at ~465 nm and two donor–acceptor (DA) transitions at ~550 nm and ~630 nm. Following irradiation, a pronounced increase in the ~630 nm DA peak is observed, while near-band-edge emission remains nearly unchanged. This indicates selective activation of deep radiation-sensitive defects without structural degradation. Time-resolved OSL decay curves (Fig. 2) exhibit clear bi-exponential behavior, consisting of a fast component associated with free carriers and a slower component corresponding to deep-trap recombination. As dose increases, the decay curves become steeper, with OSL lifetimes decreasing from approximately 400 ms to 250 ms, demonstrating dose-dependent kinetics. Fig. 3 shows a strong linear relationship between inverse OSL lifetime and delivered dose across the 0–1 Gy range. This linearity confirms that OSL lifetime provides a robust and reproducible quantitative dosimetric parameter under clinical linac irradiation.

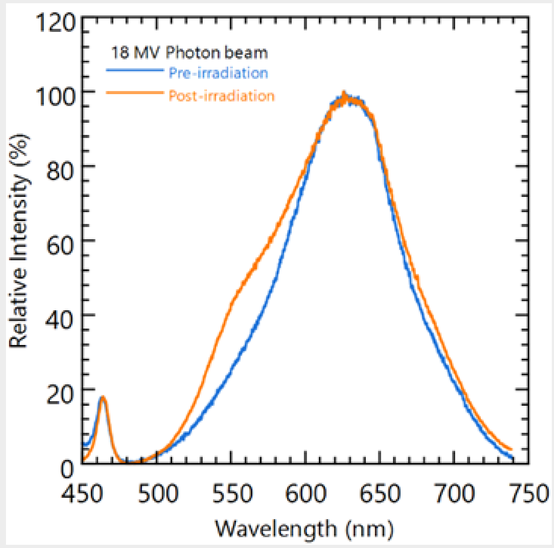

Figure 1. Photoluminescence spectra (pre- and post-irradiation of 0.25 Gy, 18 MV clinical photon beam) showing enhanced 630 nm DA peak.

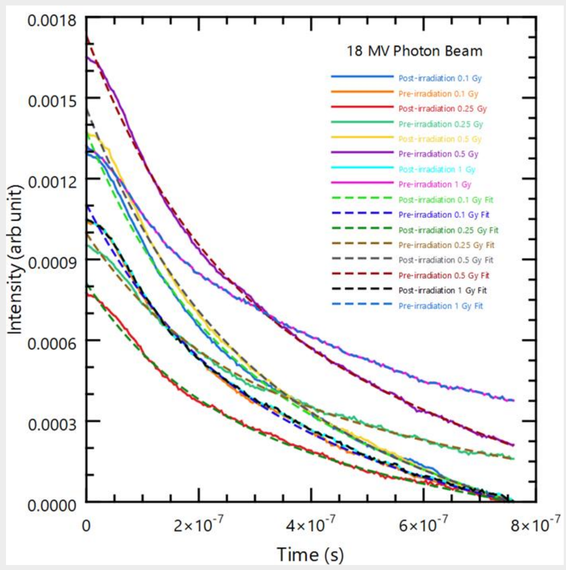

Figure 2. Time-resolved OSL decay curves fitted with bi-exponential model.

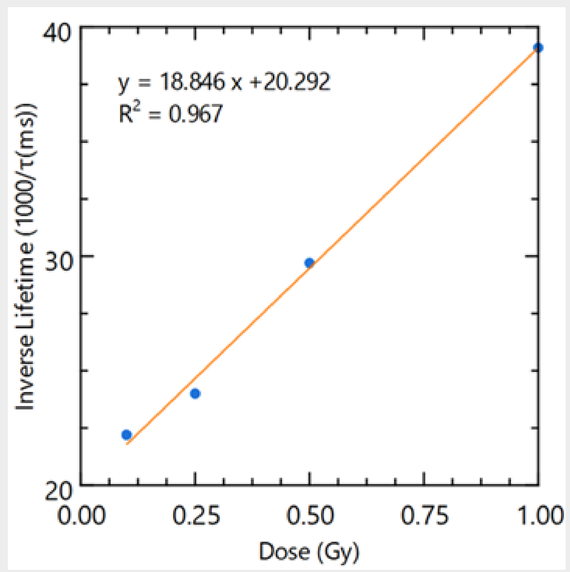

Figure 3. Inverse lifetime vs. dose plot showing linear relationship (0–1 Gy).

DISCUSSION

The results demonstrate that ZnSe nanowire-based OSLDs exhibit clear and reproducible radiation sensitivity under megavoltage photon beams. The PL measurements (Fig. 1) confirm that irradiation primarily enhances donor–acceptor transitions associated with deep defects, while leaving near-band-edge emission unchanged. This behavior is essential for stable dosimetry, as it indicates that dose information is stored in defect populations rather than structural modification of the nanowires. The bi-exponential OSL decay behavior observed in Fig. 2 reflects the coexistence of fast radiative recombination and slower deep-trap-mediated emission. The systematic reduction in OSL lifetime with increasing dose provides direct kinetic evidence of trap filling and recombination dynamics. Importantly, this behavior remains well-defined under clinical 18 MV photon irradiation, demonstrating applicability in real radiotherapy environments. The linear relationship between inverse OSL lifetime and dose (Fig. 3) establishes a physically meaningful and practically useful dosimetric metric. Unlike intensity-based readout methods, lifetime-based analysis is less sensitive to optical coupling, signal drift, and readout conditions. Combined with optical stimulation and re-readability, this gives ZnSe nanowire OSLDs clear advantages over conventional TLDs and bulk OSL materials.

CONCLUSIONS

This study demonstrates that ZnSe nanowire-based optically stimulated luminescence dosimeters provide accurate, linear, and reproducible dose measurement under clinical megavoltage photon irradiation. Radiation-induced activation of deep defect traps, evidenced by enhanced donor–acceptor photoluminescence and dose-dependent OSL decay kinetics, forms the physical basis of the dosimetric response. The strong linear correlation between inverse OSL lifetime and dose enables reliable quantitative readout while preserving the advantages of optical stimulation, re-readability, and flexible device integration. These results highlight the potential of ZnSe nanowire OSLDs as next-generation dosimeters for radiotherapy safety, quality assurance, and wearable or in vivo applications, with future work focusing on device optimization and expanded clinical testing.

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