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Extending the Lifetime of Optically Stimulated Dosimeters for Use in Output Checks at IROC- Houston

Hayden Scott

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Extending the Lifetime of Optically Stimulated Luminescent Dosimeters for use in Output
Checks at IROC- Houston


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Title Page

Extending the Lifetime of Optically Stimulated Dosimeters for Use in Output Checks at

IROC- Houston

A

Thesis

Presented to the Faculty of

The University of Texas

MD Anderson Cancer Center UTHealth

Graduate School of Biomedical Sciences

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

by

Hayden Scott, B.S.

Houston, Texas

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Dedication

I would like to dedicate this thesis to my grandmother, Katherine Brumfield, for the amount of love, support, and time she has dedicated to her family.

Acknowledgments

I would like to thank my advisors Dr. Stephen Kry and Paola Alvarez for providing the opportunity for me to work on this project under their supervision as I develop my skills as a scientist. The many hours spent teaching me how to irradiate, read, and interpret my OSLDs was an investment into my future as a physicist, and for that I am thankful.

Additionally, I would like to thank Dr. Rebecca Howell, Dr. Adam Riegel, and Dr. Ryan Sun for their time serving on my committee. My work at IROC could not have been done in a more hospitable environment thanks to my colleagues: Bryan Anderson, Juan Guilyot, Ismael Reyes, Travell Hollingsworth, and Brett Vazquez.

Abstract

Extending the Lifetime of Optically Stimulated Dosimeters for Use in Output Checks at IROC- Houston

Hayden Scott, B.S.

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Purpose: Optically Stimulated Luminescent Dosimeters (OSLDs) are a prominent form of in-vivo dosimeter used both in clinics as well as for the audits of radiological equipment at the Imaging and Radiation Oncology Core (IROC)-Houston. These dosimeters have a recommended dose limit of 10 Gy due to a change in signal response with dose. To assist with the OSLD operation at IROC-Houston, evaluating the signal response of these dosimeters with IROC's methodologies offers the potential to extend the dose limit past 10 Gy, improve the efficiency of handling OSLDs, and reduce the cost and time spent on commissioning OSLDs.

Methods: The signal response of OSLDs were evaluated using the American Association of Physicists in Medicine (AAPM) Task Group (TG)- 191 recommendations. Evaluations of sensitivity and linearity characteristics were performed as accumulated dose increased. To re-use the OSLDs, the dosimeters were bleached. Four different monochromatic and one polychromatic light source was compared to the IROC light source to determine the impact that bleaching wavelength had on signal response. In addition, the OSLDs were evaluated for how the choice of bleaching light and accumulated dose affected signal regeneration. Finally, the response of OSLDs as a function of accumulated dose were

evaluated as a function of different fractions of dose. Every irradiation was performed on a Co-60 beam at the same SSD of 80cm and field size of 24.5 x 24.5

Results: For the IROC system, we found that the signal response of OSLDs are stable within 1% up to 23 Gy. After this point, the sensitivity begins to decrease. The sensitivity of each OSLD relative to each other, $k_{s,i}$ did not change up to 50 Gy showing that the sensitivity change amongst all the OSLDs was applied universally amongst the group. There is a well characterized change in the slope of the linearity correction factor as accumulated history increases. For chromatic effects, we find that lower wavelengths remove signal the fastest, but polychromatic sources preserve the signal response to a greater accumulated dose history. For charge repopulation, we find that the degree of charge repopulation is related to dose, time, and bleaching light though this effect is nonsignificant with the IROC the newly analyzed dose limit of ~15-20 Gy. We find that fractionations at 5 Gy and higher yield a greater signal response compared to reference dosimeters, with larger fractions leading to a greater signal response. The greatest effect measured was with 30 Gy fractions at a value of 6.4% greater signal compared to reference. The greater fractions also exhibited a steeper increase in slope of the linearity correction factor.

Conclusion: IROC can extend the dose limit of 15-20 Gy of accumulated dose. The amount of charge repopulation at this dose level is insignificant, so the OSLDs in storage do not need to be rebleached prior to reintroducing them back into operation. For the application of correction factors, $k_{s,i}$ can re-use its commissioned value whereas a value of k_L needs to be evaluated based on the dose history and fractions used.

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Chapter 1: Introduction

1.1.1 General Problem Area

The Imaging and Radiation Oncology Core- Houston (IROC- Houston) is an entity that supports the National Cancer Institute (NCI) by auditing institutions that participate in NCI-funded clinical trials. Participating institutions have their radiation systems audited to ensure accurate and consistent use of radiological equipment for the use in clinical trials. To conduct these audits, IROC-Houston employs luminescent dosimeters, primarily thermoluminescent dosimeters (TLD) and Optically Stimulated Luminescent Dosimeters (OSLD). These dosimeters are sent to participating institutions who irradiate them prior to being sent back to IROC- Houston for analysis. Due to their ease of use, OSLDs have become a prominent dosimeter for IROC's operations. In terms of scale, IROC- Houston recently commissioned ~50,000 OSLDs for use in their auditing system.

Given the number of OSDLs that IROC employs, being able to re-use these OSDLs provides financial and productivity advantages. To re-use these dosimeters, OSDLs can have their signal removed by being exposed to light, a process known as bleaching. Though this removes signal, it does not remove all the signal in the OSLD. As the dose history of the OSLD increases, the signal response to radiation begins to change, limiting the amount of dose that an OSLD can be used up to. The American Association of Physicists in Medicine (AAPM) Task Group (TG) Report-191¹ suggests that OSDLs be used with a dose limit of 10 Gy of accumulated dose. However, most clinics will utilize an OSLD for a single irradiation before being discarded in order to circumvent the process of bleaching and dealing with the effects of OSLD performance changes.

This thesis is centered around investigating OSLDs signal response with accumulated dose, investigations into the effects of bleaching optics, how the charges within an OSLD migrate over time when stimulated with different bleaching lights, and how different fractions effect the overall signal response of OSLDs. Together, these investigations help to understand the limitations of the system employed in IROC- Houston and extend their lifetime use past 10 Gy. The goal of this thesis is to investigate ways to extend the lifetime use of OSLDs past the 10 Gy dose limit, thereby increasing efficiency in their support of NCI's clinical trial operations.

1.1.2 Specific Problem Area

A variety of researchers²⁻⁵ have all investigated the change in OSLD signal response with accumulated dose history, all with varying results. After reaching 10 Gy of accumulated dose, different investigators begin to see their signal response diverge from one another. Some find the signal response decreases^{2,4,5} while others see their signal response increase^{3,5}. For those that trend in the same direction, the degree of change also differs between investigators. Understanding the underlying factors that contribute to OSLD signal changes is critical to not only understanding why investigators see differing results, but also in establishing reliability in using OSLDs in their high accuracy environment for the use of audit checks.

For most of the research performed into OSLD re-use, only a few investigators have spent the time to characterize the spectra of their bleaching light. Publications from other investogators^{5,6} have shown that there is an influence on OSLD re-use with varying optical sources, though a robust study has not yet been performed amongst multiple spectra.

Because results have varied, it appears that re-use of OSLDs are sensitive to parameters that have not been thoroughly investigated. The goal here is to perform OSLDs investigations that are specific to the IROC workflow and will have clinical significance.

1.2.1 Optically Stimulated Luminescent Dosimetry

Trap Structure of OSLDs

The nanoDot brand of OSLD's produced by Landauer Inc. consists of a radiosensitive $\text{Al}_2\text{O}_3:\text{C}$ disk that is kept within a plastic casing, making it viable for storage and transportation. A picture of a nanoDot is presented in Fig 1. The mechanics of luminescent dosimetry are related to how incident ionizing radiation creates electron-hole pairs and how those pairs move around the conduction band of the aluminum oxide crystal and are ultimately trapped within the forbidden energy band. When irradiated, electrons move from the valence band into an excited conduction band upon de-excitation they may become trapped in metastable energy states. At a later time, this crystal can be stimulated with a laser; the electrons within the metastable states de-excite which causes luminescence. There are three primary metastable states of concern: shallow, dosimetric, and deep trap states. Shallow traps do not require much energy to stimulate which allows them to dissipate within the time scale of minutes. Dosimetric trap states lie deeper within the crystal and require the stimulation of light in order to produce luminescence, this is the direct method of OSL dosimetry. Deep trap states lie further within the crystal structure where light stimulation is not capable of stimulating phototransfer of electrons. Therefore, with each irradiation of an OSLD, there is a progressive increase in the number of electrons occupying deep trap states within the OSLD which is referred to as

deep trap state saturation. This saturation changes the overall signal response of OSLDs and is the cause of the dose limitations that this thesis aims to extend past 10 Gy. Figure 2 is a representation of the OSL trap structure from AAPM TG-191.



(a)



(b)

Figure 1: Picture of ana nanoDot OSLD (a) with the sensitive $Al_2O_3:C$ element exposed

(b)

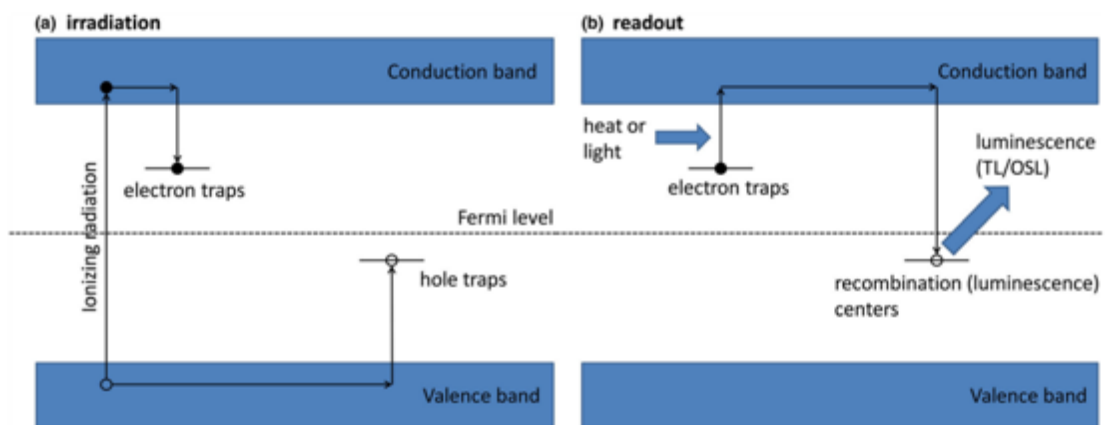


Figure 2: AAPM TG-191 Figure for OSL trap structure¹

OSL Dose Calculation

Dose is defined in TG-191 as:

$$AAPM\ TG-191\ Equation\ 1: D_w = M_{corr} \cdot N_{D,W} \cdot k_F \cdot k_L \cdot k_Q \cdot k_\theta \quad (1)$$

Where M_{corr} is the raw detector reading; collected charge per unit mass. $N_{D,W}$ is the calibration coefficient relating dose to water. k_F is the signal fading correction factor. k_Q is the beam quality correction factor deriving from energy dependence. k_θ is the angular correction factor. k_L is the dose nonlinearity correction factor. Due to the use of using a Co-60 beam that is calibrated to reference conditions, our value of energy correction is unity. We are not irradiating at any oblique angle, only perpendicular to the dosimeter so k_θ is unity. Dose nonlinearity, k_L , is a factor that we calculate with each linearity session that is performed in this project.

Individual Sensitivity Response ($k_{s,i}$)

Individual sensitivity correction factor, $k_{s,i}$, allows us to determine how each OSLD's sensitivity compares to the group mean sensitivity. This is defined by taking the ratio of the average OSLD group response (\bar{M}) to the individual OSLD signal (M_i):

$$k_{s,i} = \frac{\bar{M}}{M_i} \quad (2)$$

Reading (M_{corr})

M_{corr} relates the number of counts to the charge per unit that is detected during the readout process. For each OSLD read, their $k_{s,i}$ value is applied to the reading:

$$M_{corr} = k_{s,i} \cdot \frac{\sum_j (M_{raw,j} \cdot k_d^{j-1})}{J} - M_{bkg} \quad (3)$$

Where J refers to the number of times an OSLD was read. For the Microstar II reader, the upper limit of J is 5. k_d refers to the amount of depletion occurring with each readout. M_{bkg} refers to the background count of the Microstar II reader. Since each reading depletes by such as a small amount (0.03-0.7%) and a the background count is negligible, we can make the approximation of

$$M_{corr} = k_{s,i} \cdot \overline{M_{raw}} \quad (4)$$

Dose Nonlinearity Correction Factor (k_L)

k_L is referred to as the dose-nonlinearity correction factor. OSLDs exhibit a supalinear relationship between dose and signal response. That being, OSLDs that receive larger amounts of dose exhibit a greater signal response per Gy. Generally, the relationship between dose and signal response remains linear up to ~1 Gy. To account for this change in response, we utilize equation 6 from TG-191. From here we normalize the value of k_L so that we get a response of 1 at 100 cGy.

$$\text{AAPM TG-191 Equation 6: } k_L(D) = \frac{D_{exp}}{M(D)_{exp}} / \frac{D_{ref}}{M(D)_{ref}} \quad (5)$$

Where D_{exp} is the nominal dose given to our experimental OSLDs, $M(D)_{exp}$ is the signal that the OSLD exhibits, D_{ref} is the nominal dose that a reference OSLD is given, and $M(D)_{ref}$ is the signal of the reference dosimeter.

System Calibration Coefficient ($N_{D,w}$)

The sensitivity of the Microstar ii reader changes over time, which can affect the accuracy of OSLD readings. To account for the changes in reader sensitivity, we apply

this factor by taking the average readings of three reference dosimeters that have been irradiated to 90 cGy. We use equation 5 from TG-191 to compute $N_{D,W}$ where beam quality and angle are unity due to the use of orthogonal irradiations on a Co-60 beam

$$\text{AAPM TG-191 Equation 5: } N_{D,W} = \frac{D_0}{M_{0,Corr} * k_F * k_K} \quad (6)$$

Fading:

OSL signal decays with time. The signal of OSLDs decays over time after irradiation, which is known as fading. For our experimental group, they are read within a day of irradiating them in order to let spurious signal decay. For our reference dosimeters, some OSLDs were irradiated weeks before being read, which necessitates the use of a fading correction. The fading correction that is applied to OSLD signal comes from the internal IROC experiments where OSLDs were read at different time intervals after irradiations. The following equation characterizes the fading characteristics of the 20k21 batch from IROC:

$$\text{Fading: } 1.005 * (\# \text{ of days since irradiation})^{-0.0072} \quad (7)$$

Depletion

In addition to fading, it is important to consider the amount of signal that is removed from an OSLD with each reading. TG-191 defines the depletion of OSLDs as a marginal effect. However, in some cases, a reference dosimeter was read multiple times in separate reading sessions, with five readings performed during each session. The depletion characteristics were also evaluated by IROC for the 20k21 batch which follows the following linear equation:

$$\text{Depletion: } -4.73e^{-4} * (\text{Number of times OSLD is read}) + 0.99 \quad (8)$$

High Accuracy Uncertainty Budget

Given the goal of re-using OSLDs at accumulated doses higher than is recommended by TG-191 for the use of supporting clinical trials, it is imperative that the OSLDs maintain a high degree of accuracy as their radiation history changes. TG-191 lays out the uncertainty thresholds that each parameter should stay within in order to maintain high accuracy. A chart of the High Accuracy Uncertainty Budget from TG-191 is shown below. The largest effect seen in this chart is worth specific mentioning due to its contribution to the overall standard error that is seen with OSLD use, that being $N_{D,w}$. For the computation of standard error, we maintain a greater accuracy with a larger sample size. For the purpose of this research, each characterization of $N_{D,w}$ will utilize three reference dosimeters in order to provide a more accurate determination of uncertainty.

Dose to Water

To gain a comprehensive analysis of how OSLDs are affected with incident radiation, there are a variety of parameters to consider outside of just signal response to ionizing radiation. Namely, to construct a final calculation of Dose to Water (D_w), we can utilize the TG-191 equation 1. As we increase the dose history of our OSLDs, each of these parameters can be re-analyzed.

In addition to evaluating the inherent change in signal response with dose, we can also assess some external factors such as the effects of bleaching and fractionation on signal response. Namely, we can perform the same analysis of constructing D_w with a

consistent re-evaluation into correction factors while modulating the choice of optical lights and fraction sizes used. Utilizing Jursinic 2009's theory which suggests that different fraction sizes alter OSLD characteristics, evaluations into how fractions effect linearity correction factors and signal sensitivity is important.

Lastly, in addition to evaluations into OSLD characteristics and influences from the environmental conditions, it is also important to consider the practical use and implementation into the IROC workflow. For the use at IROC, thousands of OSLDs have been irradiated, bleached, and are sitting in storage with the hope of being re-used. Prior studies into the effects of charge repopulation^{7,8} suggest that there is a degree of electrons that will migrate out of their deep trap states and settle into dosimetric trap states after they have been bleached. The amount of signal regeneration is an important consideration for the nanoDots sitting in storage. Understanding the magnitude and degree of charge repopulation at different levels of accumulated dose and varying bleaching sources allows us to determine whether OSLDs that are in storage need to go through the resource intensive process of bleaching thousands of dosimeters, or if they can immediately be reinstated into the audit workflow.

1.2.2: IROC Workflow

The Imaging and Radiation Oncology Core- Houston has a systematic procedure in how they distribute, irradiate, read, and bleach their OSLDs. After shipping and receiving detectors to and from their respective institutions, the detectors are read on a Landauer MicroStar II reader which records information about the beam quality, test counts, date of OSLD read, OSLD ID number, and the signal from each of the five readings that the

Microstar II reader outputs with each use. Additionally, before each use of the MicroStar II system, a Quality Assurance (QA) test is run in which the system determines the dark current and background count rate while evaluating the reader performance and consistency.

Once the detector information is read with the MicroStar II reader, the detectors then undergo the bleaching process to bring the signal back down to background. This is done by opening the detectors from their plastic planchettes with a specialized tool in order to expose the Al₂O₃:C area to light. These detectors are then placed within IROC's "bleaching box" which consists of parallel opposed fluorescent lightbulbs. Once placed within this box, the detectors are bleached for a 24-hour period which returns the signal down to baseline. Though IROC's bleaching box is capable of bringing signal down to background signal in under 24 hours, the time is extended to 24 hours to ensure that there is no signal left even from detectors that have the highest amounts of dose. Once leaving the bleaching system, the OSLDs are closed and stored until they are sent to another institution. A record of how much dose an OSLD has received is crucial due to the change in performance that is seen above 10 Gy. There does not exist an inherent way to determine how much accumulated dose the detector has been exposed to in its lifetime, so a record is crucial monitoring each OSLD's dose history.

With each reading session, QA was performed at the beginning and end of a session with three control dosimeters used at the beginning, middle, and end of the session. These controls are recorded dosimeters that are irradiated to a known dose at the ADCL and are used to establish the $N_{D,w}$ correction factor.

Chapter 2: Experimental Methodology

This work is based on the IROC- Houston commissioning batch 20k21 which serves as the basis for auditing clinical radiation equipment. All detectors are irradiated at the Accredited Calibration and Dosimetry Laboratory within MD Anderson Cancer Center on a Co-60 beam. OSLDs were situated inside an acrylic plate that was affixed to a rotating jig that rotates at 10 rpm using a field size of 24.5 x 24.5 at an SSD of 81.75 cm. A picture of this jig is shown below. 100 OSLDs followed the traditional IROC workflow in order to simulate clinical use and is bleached in the same bleaching box that is used for clinically used OSLDs. Another group of 300 detectors from 20k21 were reserved for investigating how wavelength effects on bleaching and charge repopulation. As such, these 300 detectors were bleached in a bleaching box that was built for this experiment.

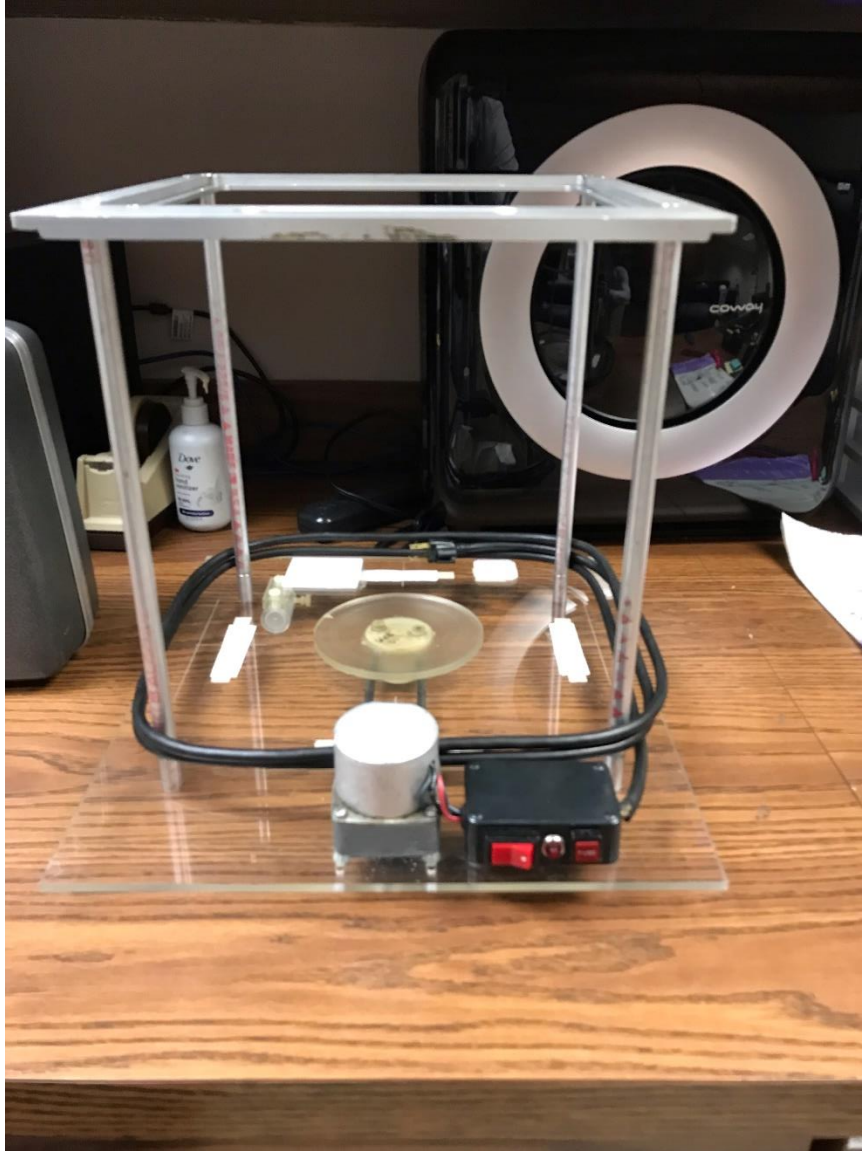


Figure 3: Irradiation Jig used to irradiate OSLDs. The center wheel rotates at 10 RPM.

Field size used was 24.5 x 24.5. SSD is 81.75 cm

Bleaching Box

The bleaching box that IROC uses consists of two parallel opposed halogen bulbs. Between these bulbs is an acrylic plate that is supported on acrylic legs. OSLDs are

opened and placed inside the box for a period of 24 hours. This apparatus is used to bleach OSLDs used in the clinical audit system. Chapter 4 provides further details on the spectra and light intensity of this bleaching box.. A Picture of the bleaching box appears below:



Figure 4: IROC- Houston custom bleaching box. Consists of two parallel opposed halogen bulbs with an acrylic plate to hold OSLDs

The bleaching box that was used to test non IROC light sources was constructed inside of a closeable container. Two parallel opposed LED flood lights (ChangM Smart RGBW Flood Light) were situated equidistant from the top and bottom of where an OSLD

would sit. A piece of acrylic was placed on top of small support boxes to hold the OSLDs in place. For each different optical wavelength that was used, the luminous flux was measured by using a flux meter at varying locations within the bleaching box. Since the flux meter only measures in one direction, separate measurements were taken for each of the parallel opposed light sources. The total luminous flux at the location of the OSLD were determined by summing the average luminous flux from both light sources. Chapter 4 discusses how the number of lumens that impinged an OSLD was quantified for each light source. Below is a picture of the bleaching box that was made to test the non IROC light source. The bleaching process for OSLDs is non standardized, leading to variations in how each institution gets their detectors down to baseline signal for reuse. Pictures of the chromatic lights and bleaching system is shown below:



Figure 5: White LED (polychromatic source)

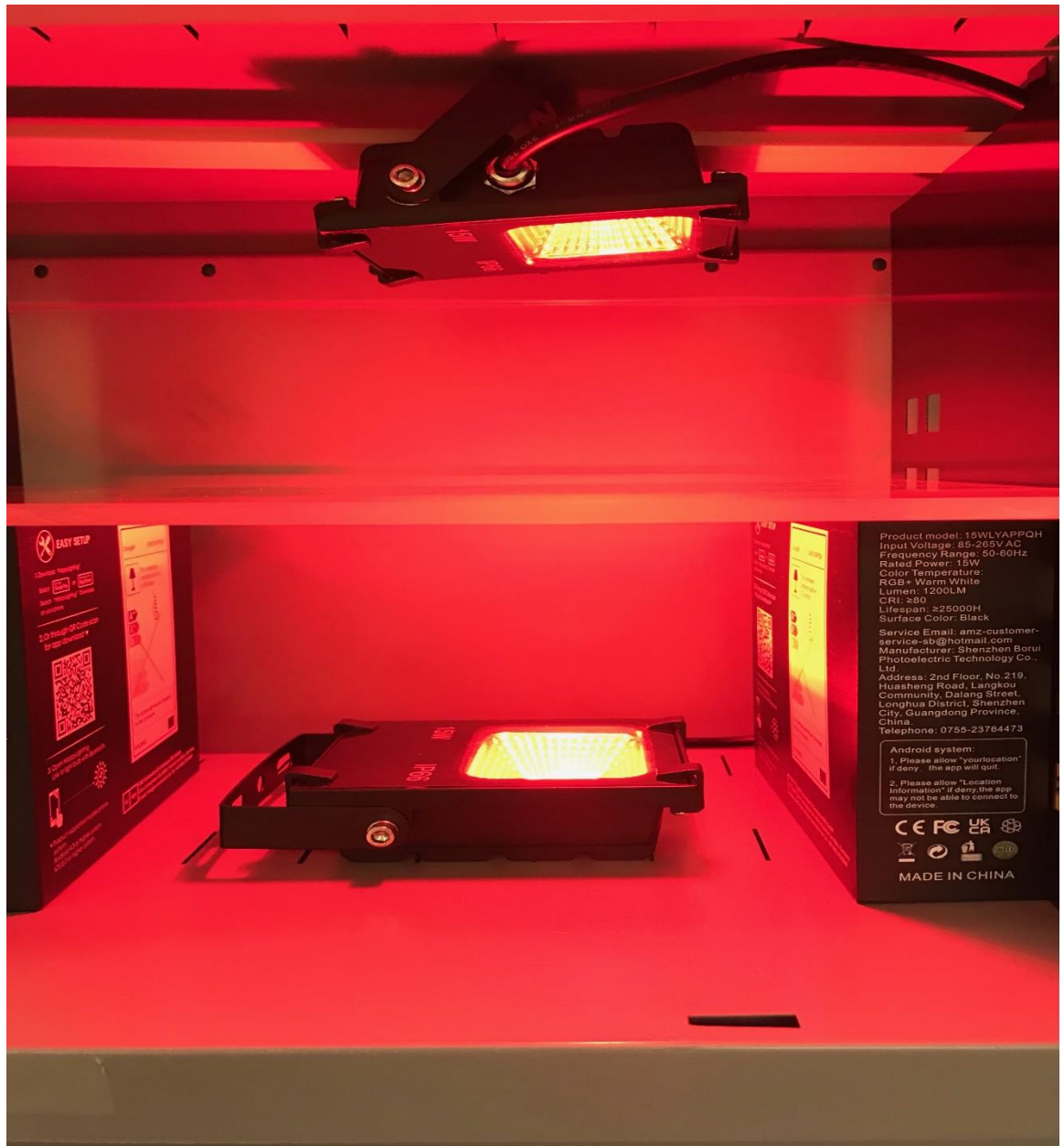


Figure 6: Red LED (monochromatic)

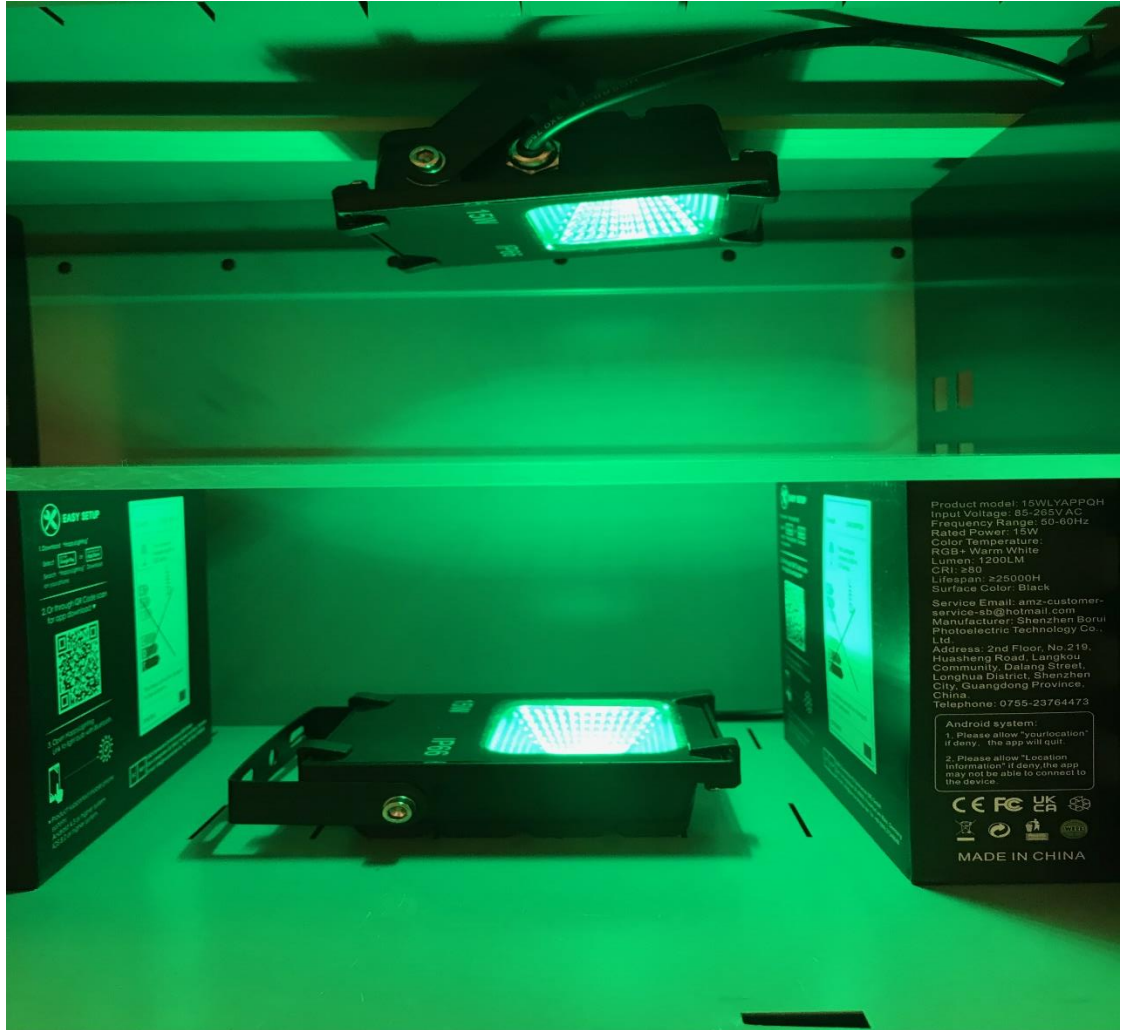


Figure 7: Green source (monochromatic)



Figure 8: Blue Source (monochromatic)

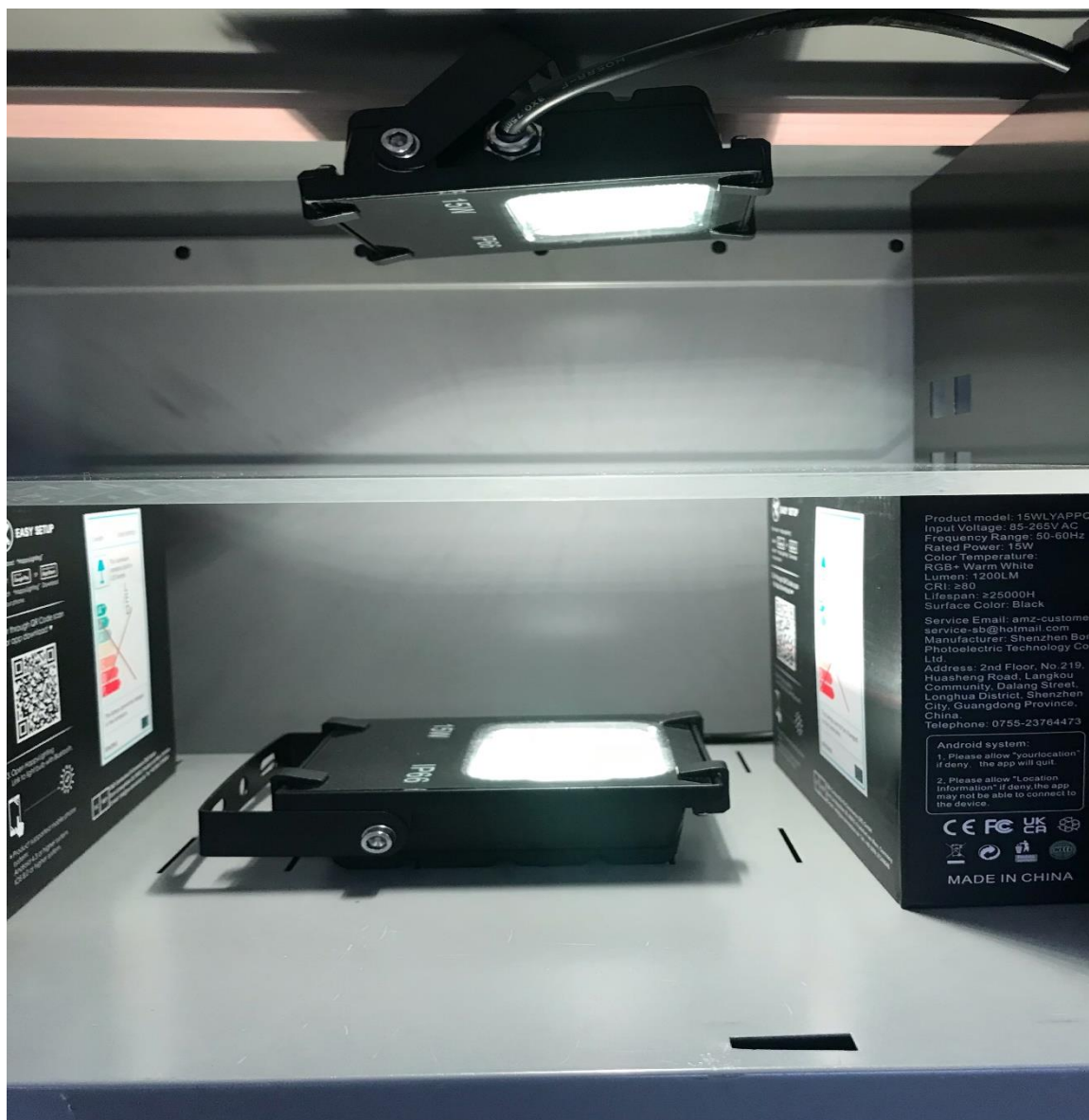


Figure 9: Yellow Source (monochromatic)

nanoDot™ Optically Stimulated Luminescent Dosimeters

nanoDots are the OSLDs used by IROC-Houston. They consist of a disk of Al₂O₃ powder with a diameter of 5mm and a thickness of 0.2mm.. This disk is contained within a black plastic casing with dimensions of 10x10x2 mm³ (Jursinic 2009). The OSLD is irradiated with the powder disk contained inside of the plastic casing, but the

disk is able to be pushed out of its casing to allow for laser stimulation inside the Microstar reader as well as for bleaching.

When the active region of the detector is exposed to ionizing radiation, electrons from the valence band move into the conduction band. This leaves a positive hole in the place where the electron moved from, much like in a semiconductor. The electrons that have migrated into the conduction band then settle into different trap states within the crystal structure. The use of optical stimulation causes the electrons to migrate back into the conduction band which allows the electrons to de-excite and recombine with their hole pair in order to produce luminescence. Shallow trap states require a minimal amount of light to become stimulated and as such, shallow states typically dissipate shortly after exposure to ionizing radiation. Main dosimetry traps are stable and are the main use of radiation auditing. Deep traps exist in forbidden fermi energy points. Deep traps are unable to be liberated which leads to detector saturation as cumulative dose increases. As cumulative dose increases, and more deep traps fill, there exists fewer possible locations in the crystal for shallow and main traps. As a result, the relationship between light emission per unit dose that an OSLD exhibits changes with an increase in accumulative dose due to the filling of deep trap states.

Sensitivity is defined in TG-191 as the relationship between photons counts per unit dose delivered to an OSLD. Each batch of OSLDs, which derive from the same crystal, have a batch sensitivity that is unique to its batch. As such, batch 20k21 has a different batch sensitivity than batch 20k19.

Bleaching is a non-standardized process in which the dosimeters are exposed to light in order to stimulate trap states to migrate charges from the conduction band to

recombination centers in the valence band. This results in the clearing of trap states except for those in deep traps, allowing the re-use of OSLDs.

MicroStar™ II reader

The MicroStar II reader that is used to read out OSLDs is also produced by Landauer Inc. OSLDs are manually inserted into the reader by opening the reader's door which reveals a placement for the dosimeter to be placed in. An identifying barcode is located on each detector, once scanned, the MicroStar reader will keep track of dosimetry data to each dosimeter that is read. Once placed, the door is closed, and the reader will use a few test counts in order to determine whether to use a strong or weak stimulation beam. Strong beams are used when there is little dose in the detectors such as after a detector has been bleached. Weak beams are used when there is substantial dose such as after an irradiation has been performed. A reading that goes in between strong and weak beams produces readings that have drastically different signals, as such strong beam readings cannot be directly compared to weak beam readings. Once the door has been closed to the MicroStar II reader, a pin pushes out the sensitive crystal disk in order for the powder to be stimulated by a laser that falls into the green light spectrum. The resulting luminescent from the OSLD is within the blue light spectrum, as such to read out only the OSLD luminescence and not the stimulation light, a filter is used to prevent the reading of green light. All of the information that is collected by the MicroStar II reader is kept within an IROC database. Below are pictures of the Microstar II reader showing how it looks and what an inserted OSLD looks

Each OSLD is read 5 times inside of the MicroStar reader so that statistical analysis can be performed to show detector stability. The performance metric that is used

for the Microstar reader is coefficient of variation. Before each reading session, a Quality Assurance (QA) needs to be performed in which the system evaluates background counts, dark current from the PMT, as well as the consistency of the same detector used for every QA session. Eventually there is enough depletion in re-reading the QA OSLD to cause for a new QA dot to be commissioned.

The Microstar reader uses two types of light stimulations when readings OSLDs: “Weak Beam” and “Strong Beam”. Weak Beam is used for most dosimetry cases whereas Strong Beam is used in cases where the OSLDs have low doses. In switching to Strong Beam mode, the light used to stimulate the OSLD increases in intensity which leads to a greater signal response compared to Weak Beam. For our investigation into OSLD response to dose we are concerned with readings in both weak beam operation. For the repopulation study, because of their low dose, we care about our readings in strong beam operation. However, for our study into how OSLD signal is removed with different lights we need to be able to get accurate information in both weak beam and strong beam operation. It was determined during this research project that there the increase in signal that comes from using a strong beam has a value of 7.13 times that of a weak beam. Figures 10-12 below are pictures of the Microstar II reader:



Figure 10: Microstar II reader closed



Figure 11: Top View of the Microstar II reader with the loading tray extended



Figure 12: View of the Microstar II reader with a nanoDot OSLD inserted

Chapter 3: Hypothesis and Specific Aims

1. Central Hypothesis

Optically Stimulated Luminescent Dosimeters (OSLD) are a dosimeter that has become a mainstay in evaluating radiation doses in a clinical environment. The Imaging and Radiation Oncology Core (IROC) in Houston, part of the MD Anderson Cancer Center, utilizes these dosimeters by sending them to different institutions around the world to evaluate the clinical reference calibration of institutions' radiotherapy equipment. AAPM TG-191 recommends that OSLDs not be used clinically above 10 Gy due to changes in sensitivity and dose linearity. Evaluations of sensitivities as accumulative dose increases allows us to investigate how each sensitivity distribution is changing while allowing us to establish element sensitivity correction factors ($k_{s,i}$). Linearity assessments allow us to compare how distributions at each linearity dose point compares to similar dose points at different cumulative doses, which also allows us to establish dose nonlinearity correction factors (k_L). Using the IROC bleaching regimen, evaluating how the mean, variability, and correction factors of these sensitivity and linearity distributions changes can allow us to make a determination on if OSLDs are capable of being used past their 10 Gy limit. Extending the use of these detectors past their traditional 10 Gy limit aids in material cost and effort savings.

We hypothesize that by using the IROC bleaching system, each sensitivity and linearity distributions will maintain their variability within 1% while using $k_{s,i}$ and k_L correction factors to account for changes in mean values of each distribution. Additionally, we hypothesize that the use of shorter wavelength monochromatic light for bleaching OSLDs result in a consistent return to baseline across dose levels as well as a

reduction in charge repopulation as compared to larger wavelengths. Dosimeters that receive large fractions should exhibit hypersensitivity compared to reference dosimeters after being bleached.

The specific aims of this hypothesis include

1. **Aim 1: Characterize OSLDs above 10 Gy:**

Rationale: OSLD cannot currently be used beyond 10 Gy. These detectors therefore need to be replaced after limited use. Evaluating how the mean and variability of our sensitivity and linearity distributions change in addition to $k_{s,i}$ and k_L give us insight into if we can extend past the traditional dose limit. Extending their use would provide material cost and effort savings.

Approach: The detector's sensitivity and linearity response at intervals of 5 Gy will be evaluated. Using 100 nanoDots, we will evaluate dose response at levels above 10 Gy. For each interval of 5 Gy of accumulated dose we will evaluate the sensitivity, $k_{s,i}$, linearity, and the k_L of the detectors. Sensitivity is an evaluation of the number of photons that we read out per Gy of dose deposited into the detectors. $k_{s,i}$ is determined by comparing 5 consecutive readings of a detector and comparing its average intensity to the average of the entire group of OSLDs irradiated to the same level. Changes in sensitivity will be evaluated with an Anova test, changes in variance will be evaluated with a Levene test, changes in $k_{s,i}$ will be determined by taking the percent difference between $k_{s,i}$ at each dose interval relative to their initial commissioned $k_{s,i}$. k_L is evaluated by irradiating 8 dots at dose intervals of 25, 50, 75, 100, 150, 200, and 300 cGy where we evaluate the number of photon counts as a function of dose. Changes in k_L will be evaluated with

Anova test and linear regressions, and changes in variance will be evaluated with Levene tests. These parameters yield the variables needed to establish a calibration coefficient as defined in AAPM TG-191.

Expected Outcome: Establishing a relationship between the dose distributions of OSLDs as cumulative dose increases will allow us to determine how far above the traditional 10 Gy threshold these detectors can be used clinically.

2. **Aim 2: Optimize bleaching light for OSLD lifespan extension**

Rationale: Evaluating the bleaching process with different monochromatic light sources (as compared to IROC-Houston's bleaching process which uses white light for 24 hours) will allow us to see if other wavelengths of light are better at minimizing residual signal. Shorter wavelengths on the monochromatic scale have been shown to liberate charges in deep trap states that longer wavelengths are incapable of removing. Those that have the greatest reduction in residual signal should exhibit longer term stability in their dose response.

Approach: Groups of 40 detectors will be irradiated at intervals of 10 Gy and bleached under the IROC bleaching light as well as red, blue, green, yellow, and white LED lights for periods of 1, 4, 8, and 24 hours to see how the signal read from these detectors change as a function of time and accumulated dose. A more efficient bleaching process will bring the signal closer to background than our control using the IROC light box. Evaluations of each light groups dosimetry response as a function of accumulated dose will ultimately determine which light source is best suited for maintaining OSLD signal within our target of 1% variation.

Expected Outcomes: We expect to see that lower wavelength of light, such as blue light, are more efficient at minimizing residual signal in order to bring OSLD signal closer to background. We expect to see lower wavelength light sources minimize residual signal closer to background than larger wavelengths. As such, groups exposed to lower wavelengths should also exhibit dosimetry stability up to a greater threshold compared to larger wavelengths.

3. **Aim 3: Evaluate the Effects of Light Wavelength on Charge Repopulation**

Rationale: After an OSLD is bleached, charges within residual trap states begin to migrate to more shallow traps which can then be read out. This build up can be evaluated by reading the OSLDs immediately after being bleached and continuing to read the OSLDs over time. Different wavelengths of light, such as blue light, have the potential to increase the amount of charge repopulation of bleached detectors due to a more efficient removal of deep trap states.

Approach: Using the same bleaching setup that we will use for Aim 2, we can read out the OSLDs after being bleached by different wavelengths to see how many photons we read. For the first week after bleaching, the detectors will be read every 24 hours. After the first week, the detectors will be read on a weekly basis. The dose levels will increase in steps of 10 Gy to evaluate how accumulative dose effects the buildup rate of the detectors.

Expected Outcomes: We expect to see that blue light is more efficient in liberating deep trap states compared to IROC Houston's bleaching process. We expect to see greater signal from charge migrations at higher dose levels. We expect to see that the

signal resulting from these repopulating charges becomes stable after a period of a few weeks.

4. **Aim 4: Evaluate the Sensitivity Characteristics of OSLDs Exposed to Varying Fractions of Dose**

Rationale: Due to the general single use of Optically Stimulated Luminescent Dosimeters (OSLD), the supralinear performance changes induced by fractionation is not a concern. To re-use OSLDs, investigations into how fractionation effects these dosimeters need to be established.

Approach: Four group of 10 OSLDs were irradiated on a Co-60 beam with fractions of 5 Gy, 10 Gy, 15 Gy, and 30 Gy until they accumulated a total dose history of 30 Gy. After each fraction, the dosimeters were bleached and the sensitivity of the bleached OSLD was compared to reference OSLDS irradiated to the same nominal dose. In another study, 100 OSLDs were irradiated to smaller fractions (3 Gy max) and compared to 40 OSLDs used with larger fractionations (9 Gy max). For this group, sensitivity and linearity information was measured in order to establish Dose to Water (Dw) according to AAPM Task Group 191 recommendations.

Expected Outcomes: We expect to see that OSLDs that are irradiated to greater fractions will result in a greater hypersensitivity compared to reference dosimeters. We

expect to see that the hypersensitivity will increase with each subsequent fractions until an upper limit is reached. For dosimeters that receive 5 Gy fractions, we expect to see no hypersensitivity expressed with any irradiation, and a decrease in sensitivity starting at 20 Gy.

Chapter 4: Lifetime Extension of Optically Stimulated Luminescent Dosimeters Past 10 Gy

The contents of this chapter reflect a manuscript that the committee members for this project have evaluated and has been submitted for publication

Authors: Hayden Scott, Stephen Kry, PhD, Paola Alvarez, MS, Rebecca Howell, PhD, Adam Riegel, PhD, Ryan Sun, PhD

Abstract:

Background: Optically Stimulated Luminescent Dosimeters (OSLDs) are used in clinical radiation dosimetry, but their sensitivity decreases with accumulated dose, limiting their reusability. It is presently unclear why different studies have reported inconsistent results on the sensitivity change at different cumulative doses. Additionally, the change in the detector linearity and element sensitivity correction factors with accumulated dose has not been well established.

Methods:

100 nanoDot™ OSLDs were used, and each dosimeter was irradiated in cycles of 0.9 Gy to determine sensitivity, followed by 0.25-3Gy to determine linearity, and finally irradiations to return all dosimeters to the same total dose history. Dosimeters were read with a MicroStar II reader 5-8 hours following each irradiation, and each OSLD was bleached for 24 hours in the IROC bleaching box prior to every irradiation. A combination of single factor ANOVA tests, Levene tests, and linear regressions were

used to quantify the change in detector characteristics as a function of accumulated dose. Dose to water was calculated following TG-191's Equation 1.

Results:

The signal response of OSLD showed stability within 1% up to 23 Gy before decreasing with dose. The element sensitivity correction factor remained the same with accumulated dose, but the detector linearity showed changes.

Conclusion:

The study provides a better understanding of accumulated dose history and has the potential to directly aid in overall process efficiency by potentially extending the lifespan of the OSLD.

1. Introduction

Optically Stimulated Luminescent Dosimeters (OSLDs) are widely used in clinical radiation dosimetry.⁴ OSLDs provide a simplified reading process compared to Thermoluminescent Dosimeters (TLDs) while maintaining a comparable level of accuracy.^{9,10} The most used OSLD within the clinic is the nanoDot™ (Landauer Inc, Glenwood Il), a class of Al₂O₃:C dosimeter. After irradiation and read-out, these detectors can be bleached and reused. However, this detector exhibits limited reusability due to sensitivity changes as accumulated dose increases,^{2,3,11} prompting a clinical limit of 10 Gy as recommended by the American Association of Physicists in Medicine (AAPM) Task Group Report (TG)-191.¹

OSL dosimetry works through the creation of “hole traps” and “electron traps” by ionizing radiation. Stimulation of these trapped electrons and holes causes recombination and the emission of luminescent photons.⁸ For the purpose of this research, we are concerned with three different depths of trap states. Shallow trap states which lead to short term spurious signal, dosimetric trap states that are used in radiation dosimetry, and deep trap states that lead to detector saturation¹². As OSLDs increase in accumulated dose, they saturate the deep trap states and their response decreases^{2,4}. Even with bleaching, dosimeters show changed sensitivity because the bleaching process is largely unable to empty the deep traps that have been filled. In addition to changes in sensitivity the detector supralinearity characteristics may also change for different detectors.⁶ However, results from the literature are inconsistent. Most notably, different amounts of sensitivity change at different cumulative doses have been reported by different authors.^{3,4,11} It is presently unknown why these different studies have found different results, although the bleaching characteristics likely play a role. Finally, it remains unexamined if, and how, element sensitivity correction factors ($k_{s,i}$) change with accumulated dose.

Therefore, this research investigated changes in the dosimetric response of OSLD as a function of accumulated dose. This was based on the handling procedure at The Imaging and Radiation Oncology Core (IROC), which has a large OSLD program with 10’s of thousands of detectors irradiated up to 10 Gy. Better understanding of accumulated dose history based on the IROC bleaching and handling process not only adds to the scientific understanding of detector response but has the potential to directly

aids in overall process efficiency at IROC by potentially extending the lifespan of the OSLD.

2. Materials and Methods:

2.A. Experimental Techniques

100 nanoDot™ OSLDs from the same batch were used. Each dosimeter consists of a 5mm diameter by 0.25mm thick plate of Al₂O₃:C powder encased in a plastic container with dimensions of 10mm x 10mm x 2mm. The accumulated dose was increased from 2 Gy to 50 Gy in cycles of 0.9 Gy irradiations to determine sensitivity, followed by 0.25-3Gy irradiations to determine linearity, and finally irradiations to return all dosimeters to the same total dose history (Figure 2). Dosimeters were read with a MicroStar II (Landauer Inc, Glenwood Il) reader 5-8 hours following each irradiation to allow for spurious signal from shallow trap states to dissipate. Reference dosimeters were read at the beginning, middle, and end of each reading's session to define reader sensitivity and to account for reader drift. Each OSLD was bleached for 24 hours in the IROC bleaching box prior to every irradiation (Figure 1). The detectors were placed between two parallel opposed fluorescent light sources located 26cm from the OSLD for a period of 24 hours. The measured summed luminosity rate where the active OSLD volume sits was measured to be $3.10E4 \pm 1.42E2$ lumens/minute using a Lux meter (Dr. Meter model LX1332B). The wavelength spectra of this bleaching box consisted of 5 distinct wavelengths: 445nm, 490nm, 550nm, 590nm, and $615 \text{ nm} \pm 2 \text{ nm}$ (as measured using a spectroscope; Eisco Labs model SKU PH100QA). At the end of the 24-hour period, the signal from the detectors reached a baseline (<100 counts).



Figure 13: IROC- Houston custom bleaching box. Consists of two parallel opposed halogen bulbs with an acrylic plate to hold OSLDs

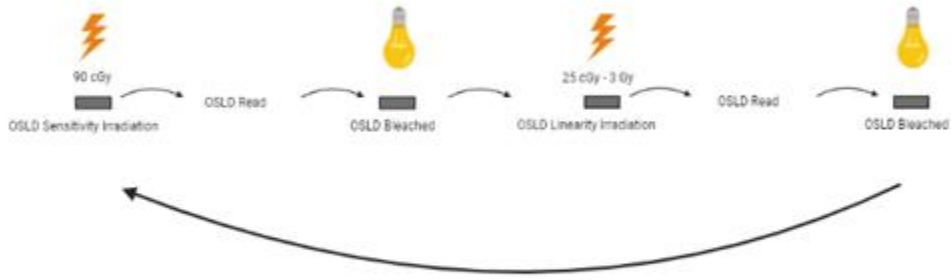


Figure 14: Schematic for the irradiation and bleaching cycles of 4 Gy steps

In this study, we evaluated potential changes in dosimeter response as a function of accumulated dose. We evaluated sensitivity, element sensitivity correction factor, and linearity. A combination of single factor ANOVA tests, Levene tests, and linear regressions, were used to quantify the change in our detector characteristics as a function of accumulated dose.

2.B. Dose calculation

Dose to water (D_w) was calculated following TG-191's Equation 1:

$$D_w = M_{corr} \cdot N_{D,W} \cdot k_F \cdot k_L \cdot k_Q \cdot k_\theta \quad (1)$$

Where M_{corr} is the signal corrected for depletion and element sensitivity, $N_{D,W}$ is the system calibration coefficient for dose to water, k_F is the signal fading correction factor, k_L is the dose nonlinearity correction factor, k_Q is the beam quality correction factor, and k_θ is the angular dependence correction factor. The correction factors relevant to this research were $k_{s,i}$, $N_{D,W}$, k_F , and k_L . Beam quality and angular dependence were unity

due to the orthogonal irradiations performed with Co-60. Fading and depletion were applied, based on IROC's commissioned values, to all results to account for the difference in time between standards and experimental dosimeters and the repeated reading of different dosimeters. Thus, dose from each detector was calculated according to:

$$D_w = M_{raw} \cdot N_{D,W} \cdot k_{si} \cdot k_F \cdot k_L \cdot k_d \quad (2)$$

2.C. Sensitivity

Initial element sensitivity correction factor ($k_{s,i}$) was determined by irradiating each dosimeter to 90 cGy on a Co-60 beam with no other dose history. Element sensitivity correction factors were reevaluated after each 4 Gy of accumulated dose (Figure 3). This was evaluated using equation 9 from TG-191:

$$k_{s,i} = \frac{\bar{M}}{M_i} \quad (3)$$

Where \bar{M} is mean response of all 100 OSLDs and M_i is average of 5 readings of each individual dosimeter response.¹

2.D. Linearity

Linearity was assessed in 4 Gy steps (e.g., 2 Gy, 6 Gy, 11 Gy) of accumulated dose history, with bleaching between each. At each step, linearity was assessed based on irradiations at 25, 50, 75, 100, 150, 200, and 300 cGy. Dose nonlinearity correction factors (k_L) were evaluated during these irradiations by using equation 6 from TG-191:

$$k_L(D) = \frac{D_{exp}}{M(D)_{exp}} / \frac{D_{ref}}{M(D)_{ref}} \quad (4)$$

Where D_{exp} refers to the nominal dose that our experimental dosimeters were irradiated to and $M(D)_{exp}$ refers to the signal read from our experimental dosimeters. Following this, D_{ref} and $M(D)_{ref}$ are the same with reference dosimeters. Consistent with IROC's monitoring program, D_{ref} was defined to be 100 cGy.

3. Results:

3.A: Element Sensitivity Correction ($k_{s,i}$)

The element sensitivity for the 100 OSLD at each level of accumulated dose is shown in Figure 3. A single factor ANOVA test amongst our $k_{s,i}$ distributions show no change over accumulated dose ($P=1$). This figure indicates that overall distribution of element sensitivity correction for the 100 detectors doesn't change with accumulated dose history.

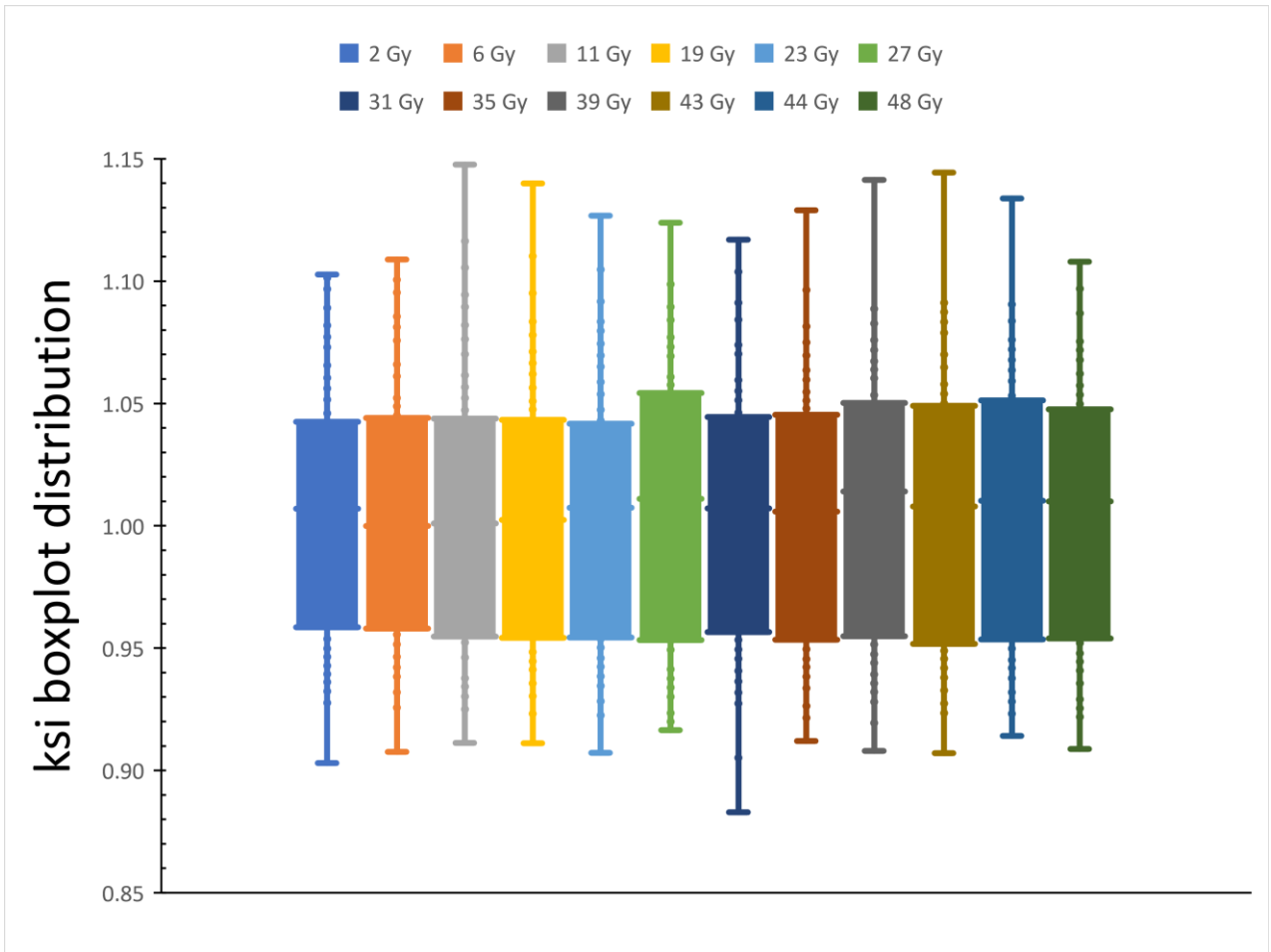


Figure 15: Distribution of 100 $k_{s,i}$ values for each sensitivity dose point evaluated.

The change in individual detector $k_{s,i}$ values is shown in Figure 4. This figure compares the change in element sensitivity correction factors of individual dosimeters from its value with low accumulated dose to its value at high accumulated dose. To minimize noise, each OSLD's $k_{s,i}$ value from 2-10 Gy of accumulated dose were averaged together and compared to the average $k_{s,i}$ values between 40-50 Gy of accumulated dose. Of the 100 OSLD, 26 had a value that changed by more than 1%, 9 had a value greater than 2%, with the greatest change being at -3.3%.

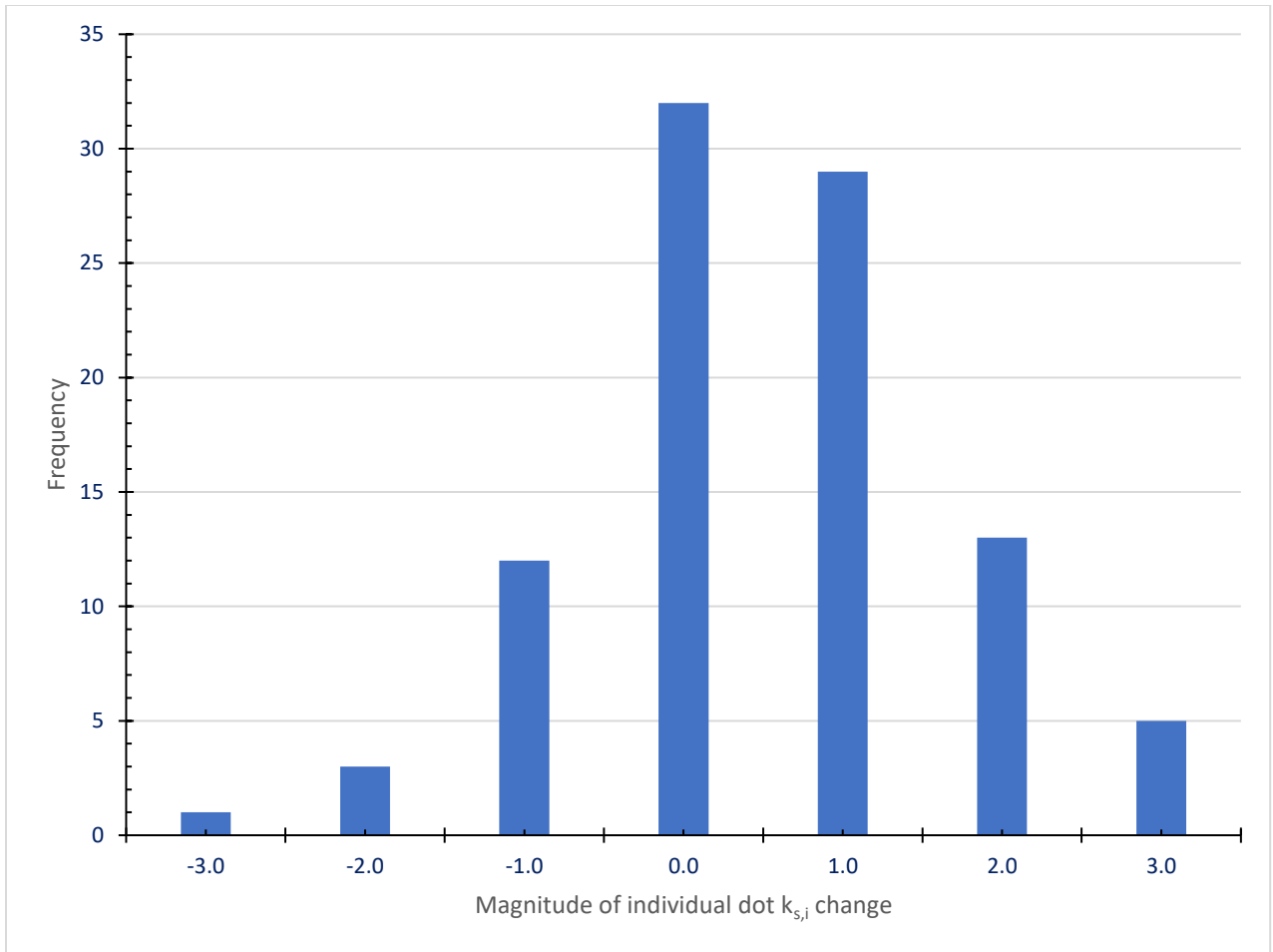


Figure 16: Magnitude of $k_{s,i}$ change between 2-10 Gy Average values and 40-50 Gy Average values

Reference dosimeters used in this work were irradiated to nominal doses at prior periods of time which requires the consideration of signal fading. Irradiating dots with no dose history at the same time as our experimental group allows the circumvention of fading. Evaluating the ratio between our experimental group and these fresh dosimeters,

$$\frac{(M_{corr}/D)}{(M_{corr,0}/D_0)},$$

gives us insight into signal change as a function of accumulated dose without the use of correction factors, which is shown in Figure 5. Each

OSLD was irradiated to the same nominal dose of 1 Gy, the experimental group was bleached prior to being irradiated. The mean values of our ratio groups fluctuate within 1% up to 20 Gy of accumulated dose and then begin to decrease.

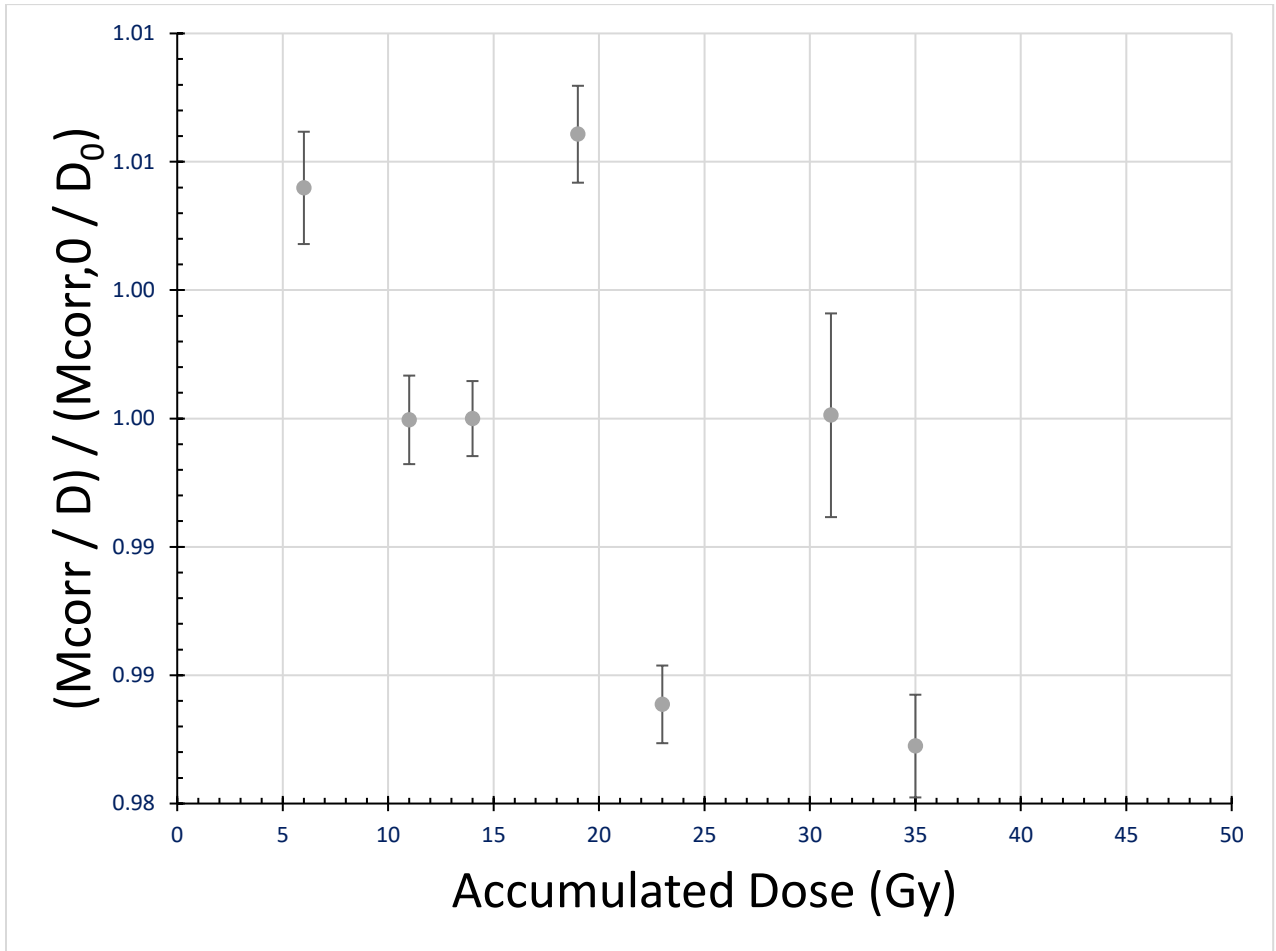


Figure 17: Ratio of Experimental OSLD sensitivity at 1 Gy to reference OSLDs at 1 Gy

3.B: Linearity

The supralinearity of the OSLD response between 0.25 and 3 Gy is shown in Figure 6 for different levels of accumulated dose. To emphasize the supralinearity, a linear fit is included in the figure dose response from 25 – 75 cGy. While the linearity

shows spread as a function of accumulated dose, the general behavior is consistent across accumulated dose levels.

The supralinear response shown in Figure 6 is corrected for by application of an inverse correction factor (k_L), which we normalized to be a value of 1.0 at 100 cGy. k_L for each accumulated dose is plotted in Figure 7, which shows the clear trend that as accumulated dose increases, the slope of the k_L correction increases (meaning the supralinearity effects become more pronounced). To evaluate the relationship between the change in slope of k_L with accumulative dose, we have plotted each k_L 's slope as a function of accumulated dose in Figure 8. This result shows that there is a linear trend with an $R^2 = 0.93$.

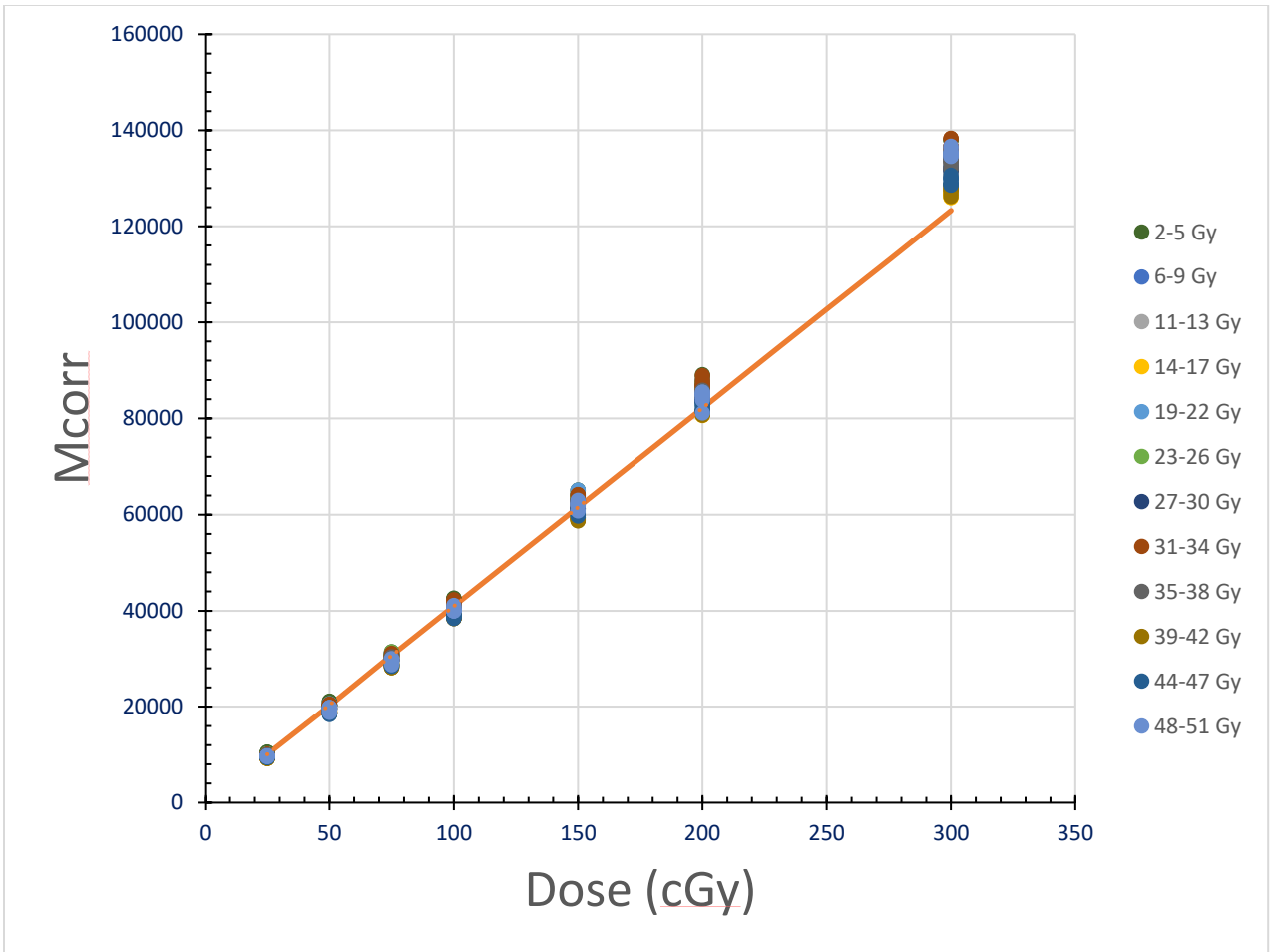


Figure 18: Supralinearity Effects of each Lineairty study. Linear interpolation (orange line) created with a forecast based on the linear response between 25 – 75 cGy.

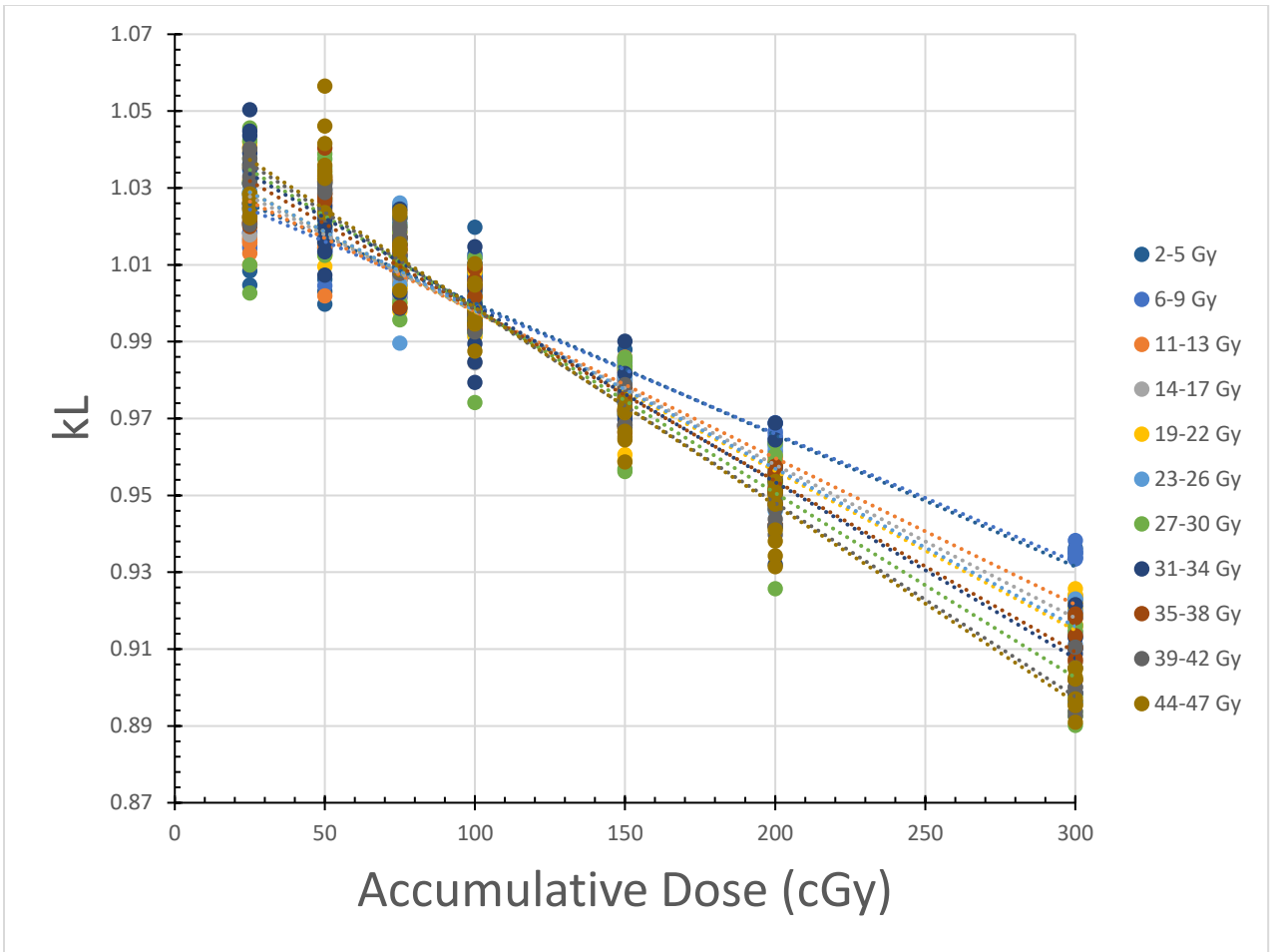


Figure 19: Comparison of dose nonlinearity correction factor (kL) for each linearity assessment to visualize the change in slope as dose increases.

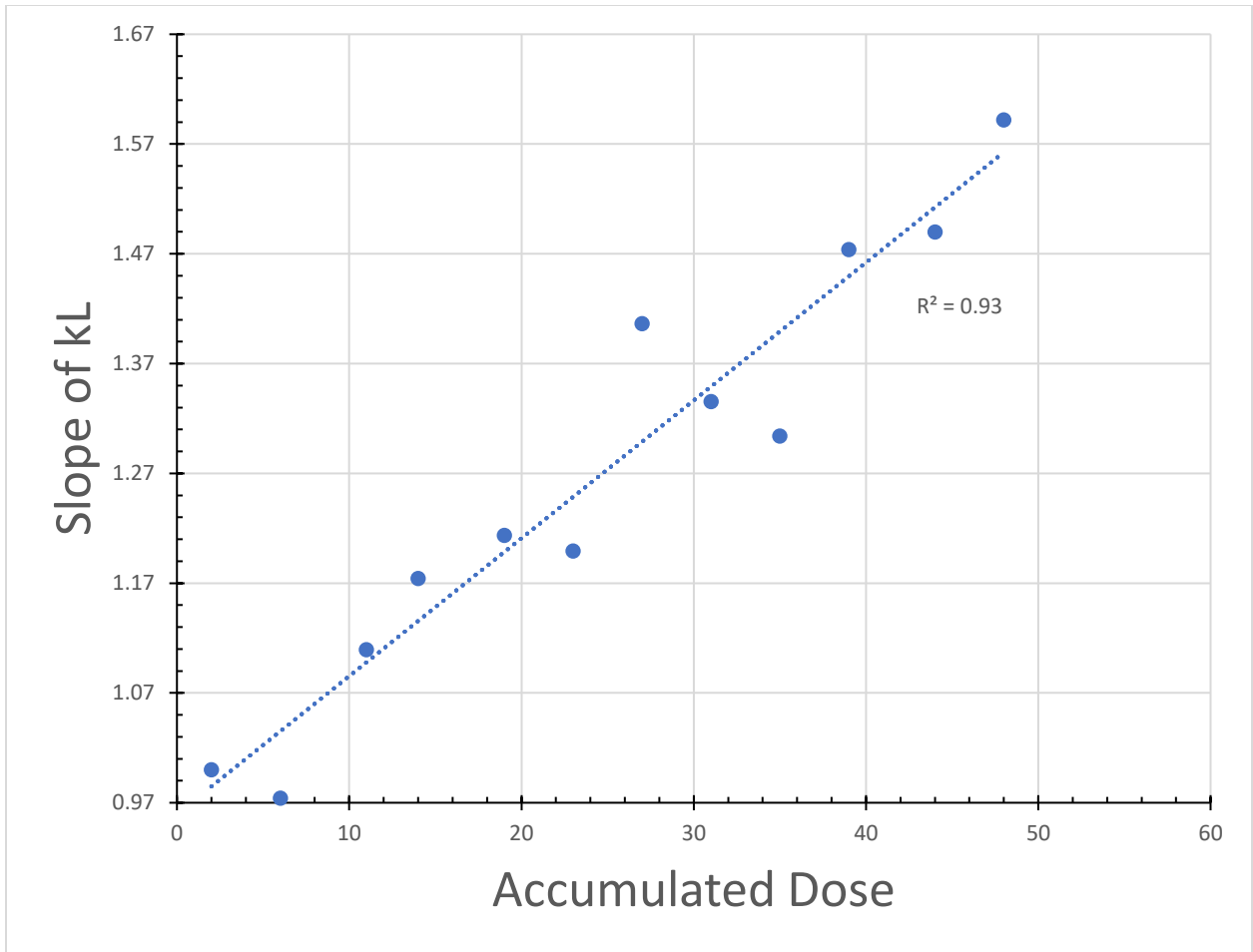


Figure 20: Relationship between the slope of dose nonlinearity correction factor (kL) and dose history. $R^2=0.93$

To understand the practical dosimetric impact of this changing linearity, we compared the actual value of kL at 3 Gy as a function of accumulated dose (Figure 9). Based on zero accumulated dose history, a 3 Gy reading (using a 1 Gy reference dose level) would require a 7% linearity correction; if that same detector had a 50 Gy accumulated dose history, the same 3 Gy reading would require an 11% linearity

correction. This difference is substantial compared to the uncertainty in OSLD dosimetry and needs to be accounted for.

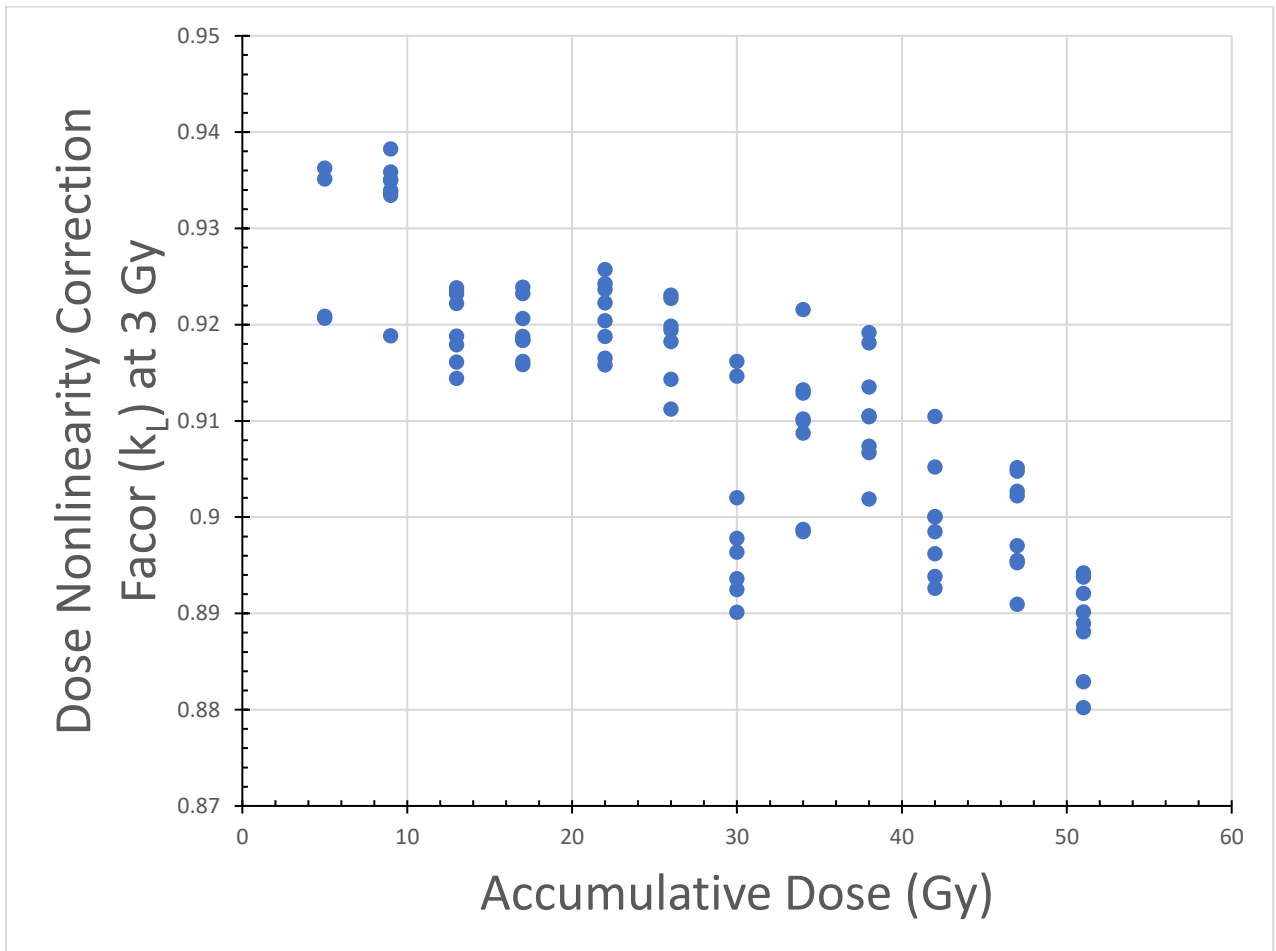


Figure 21: Change in values of k_L as dose history increases. 3 Gy dose points provide the largest supralinearity effect in the linearity range evaluated, allowing for better distinction in evaluating our results

A previous study reported that individual dots experienced different changes to their supralinearity response as a function of accumulated dose⁶. This would manifest as an increased spread in k_L as accumulated dose increased (as different dots changed more

or less). We evaluated this by comparing the variance in the distribution of kL at 3 Gy where the effect size is largest, for each accumulated dose level (that is, the variance in each dose level distribution in Figure 9). No significant difference was found (Levene test, $P = 0.27$). While we saw a clear change in linearity with accumulated dose, we did not find evidence to support that this change was dose dependent.

3.C: System Sensitivity

At each level of accumulated dose, and correcting for linearity according to accumulated dose level, we calculated Dose to Water as a function of accumulated dose (Figure 10). This figure shows the sensitivity of the system changes with accumulated dose. Two sections are apparent: a linear section up to 23 Gy of accumulated dose which has a nonsignificant linear regression ($P = 0.84$) and a portion past 23 Gy where the dose decreases. As the same physical dose is delivered at all levels of accumulated dose, this apparent decrease in dose reflects a decrease in system sensitivity as dose accumulates.

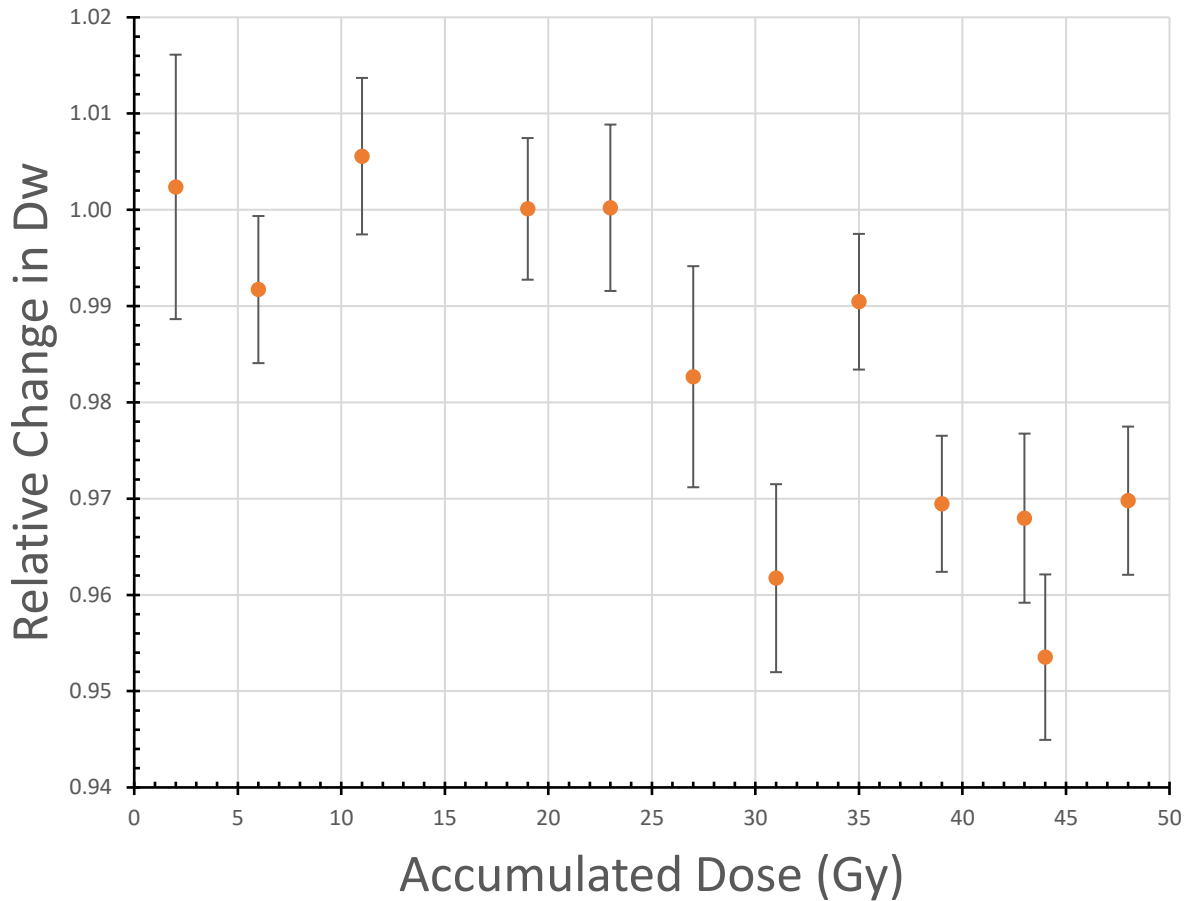


Figure 22: Measured Dw using the correction factors evaluated with each sensitivity and linearity study. All values prior to 23 Gy of accumulated dose falls within a 1% change in sensitivity response and begins to decrease past this point.

Discussion:

Through the systematic evaluation of OSLD sensitivity and linearity correction factors as a function of accumulative dose it has been found that each dosimeter's element sensitivity correction factor did not change up to 50 Gy. Linearity studies performed show that there is a relationship between the slope of the dose nonlinearity

correction factor and the amount of cumulative dose history the OSLD has been exposed to. The linear relationship between the slope of k_L with accumulated dose suggests that OSLD dose response is detector independent. With all these correction factors in consideration, the overall sensitivity shows stability up to 23 Gy with a decrease in sensitivity after this.

IROC- Houston establishes an uncertainty threshold consistent with the uncertainty budget set forth by TG-191's High Accuracy OSLD use of 1.6% for the use of clinical OSLDs.¹ The dosimeters used in this experiment maintain their response within 1% up to 23 Gy. All the parameters evaluated in this study fell within the TG-191 uncertainty budget for the use of OSLDs in a high accuracy environment. As such, the standard error on every Dw measurement falls within the integral 1.6% value. With the OSLDs in our study maintaining stability up to 23 Gy while being within the uncertainty budget, these dosimeters can be re-instituted for clinical use such as output checks at IROC-Houston.

Though there are differing results between investigators into OSLD re-use characteristics, few have characterized their bleaching light spectra. Jursinic⁶ and Omotayo et al⁵ shows that the re-use of OSLDs are effected by the choice of optical bleaching light. Varying optical bleaching wavelengths offers one possible explanation for the difference in OSLD signal results. Given this, it is important for each institution that bleaches their OSLDs to characterize their bleaching system and evaluate how their bleaching system effects the overall stability and longevity of OSLDs.

Dose to water is consistent with the use of IROC up to 23 Gy. Past this point, we see that there is a decrease in our signal. By expanding the dose limit at IROC up to 20

Gy, we can decrease the overall cost and staffing required to operate the clinical trial output checks.

Conclusions:

For the reuse of OSLDs, the recommended dose limit of 10 Gy can be increased with the use of the IROC-Houston bleaching system up to 20 Gy. The element sensitivity correction factors of dosimeters does not change up to 50 Gy. Dose nonlinearity correction factors has a linearly increasing slope with accumulated dose which shows the detector independent nature of OSLDs ($R^2 = 0.93$). The 100 nanoDots used maintained a consistent level of variability, falling within the high accuracy uncertainty budget, throughout their irradiation history.

The reuse of OSLDs assists IROC in cost savings from purchasing new dosimeters as well as the time commitment required to commission new nanoDots. As the bleaching system in this study is unique to IROC, each clinic should determine the dose limit that their bleaching regimen allows.

Chapter 5: Chromatic Bleaching and Fractionation Effects on OSLD Re-Use

Authors: Hayden Scott, Paola Alvarez, MS, Rebecca Howell, PhD, Adam Riegel, PhD, Ryan Sun, PhD, Stephen Kry, PhD

Abstract:

Background:

Characteristic changes in Optically Stimulated Luminescent Dosimeters (OSLD) performance induced through the use of optical bleaching and fractionation have not been thoroughly investigated due to the typical single use nature of OSLDs. For the re-use of OSLDs, the effects of bleaching optics and fractionation sizes on OSLD performance need to be investigated.

Methods:

To evaluate bleaching effects on OSLD re-use, groups of 40 nanoDots™ (Landauer Inc, Glenwood IL) were irradiated to 90 cGy to evaluate signal sensitivity, bleached, irradiated between 25 cGy – 500 cGy to evaluate linearity, bleached, then irradiated to 400 – 875 cGy in order to get all dosimeters to the same nominal dose history, then bleached again. This cycle was repeated until they reached 50 Gy of accumulated dose. Each group was exposed only to a specific wavelength of bleaching light. During the bleaching process, OSLDs were sampled at 1,2,3, and 4 minutes as well as 1,4,8, and 24 hours to evaluate how signal is lost with bleaching. The American Association of Physicists in Medicine (AAPM) Task Group Report (TG)-191's Equation 1 was used to construct a calculation of Dose to Water (D_w) as accumulated doses increased.

Charge repopulation was investigated by irradiated groups of 60 nanoDots™ to nominal doses of 2, 10, 20, 30, 40, and 50 Gy in a single fraction. After irradiation, subgroups of 10 dots were bleached by the six different bleaching lights for a period of 24 hours. These dots were routinely read over a period of 1-3 months to quantify how much signal increases due to the charge transfer from deep traps to dosimetric trap states between different bleaching sources and across accumulated doses.

Fractionation was evaluated through comparing the IROC group that was used to construct D_w to an identical group that used linearity irradiations between 25 cGy – 300 cGy followed by another irradiation between 100 cGy – 275 cGy to get every dosimeter to the same accumulated dose history. Comparisons in D_w and dose nonlinearity correction factors k_L were compared between the two groups. In addition, 4 groups of 10 OSLDs were irradiated at different fractions (5 Gy, 10 Gy, 15 Gy, 30 Gy), bleached, then irradiated to the same nominal dose as reference dosimeters that have no dose history to compare how the sensitivity of our experimental groups compare to reference groups.

Results:

The bleaching rate of OSLDs are related to the wavelengths of light used, with lower wavelengths removing signal faster across all accumulated dose levels. Polychromatic light sources provide the greatest signal stability when comparing determination of D_w . Charge repopulation is related to the choice of optical source, time, and accumulate dose. Generally, polychromatic light sources see a larger amount of charge repopulation

For fractionation, we see that the group that were bleached with the same light and received larger fraction has an earlier decrease in signal response between 10-20 Gy as compared to the smaller fractionation group maintaining signal response within 1% up to 23 Gy. Past this inflection point, the larger fractionation group has a systematically lower signal response to the smaller fractionation group across all accumulated dose levels. For these same groups, we see that both k_L trend linearly with the larger fraction group having a greater increase in slope. When comparing the experimental groups that received distinct fractions and compared to reference dosimeters, all fractions evaluated exhibited hypersensitivity, with larger hypersensitivity exhibited with larger fractions which increased with larger subsequent fractions. The greatest degree of hypersensitivity we evaluated was with the group that received 30 Gy fractions at a sensitivity 6.3% greater than reference dosimeters exposed to the same nominal dose.

Conclusions:

For the re-use of OSLDs, the choice of bleaching light plays a role in how fast a dosimeter is bleached as well as how much accumulated dose a dosimeter can be exposed to while maintaining signal sensitivity. Investigations into charge repopulation has been expanded upon to show that bleaching light plays a role into the migration of deep traps to dosimetric traps after bleaching. A distinct function of k_L needs to be utilized which considers both fraction size and accumulated dose history. To maintain proper dosimeter stability, smaller fraction sizes should be used.

1. Introduction

The use of Optically Stimulated Luminescent Dosimeters (OSLDs) is prevalent in clinical settings for measuring radiation dose, but the accumulation of dose causes changes in their signal response, which limit their reusability. This change is caused by the saturation of deep trap states within the Al₂O₃:C crystalline structure, resulting from exposure to radiation. To remove the signal in an OSLD for it to be re-used, the dosimeter is exposed to light which removes dosimetric traps through a process known as bleaching. Due to deep trap states not being able to be liberated by light, the characteristics of the OSLD change with each bleaching cycle. Due to the inconsistencies that investigators have seen with OSLD re-use, TG-191 recommends a dose limit of 10 Gy. Clinically, these OSLDs are commonly used once before being discarded, circumventing the need to bleach their dosimeters.

Many investigators have published research related to how OSLDs response to radiation through the use of serial irradiations and bleaching. Results from their investigations show inconsistencies with dose history and it's effects on OSLD signal response. Additionally, many of these investigations do not characterize the light source that they are using to bleach their OSLDs. Omotayo and Jursinic 2020 have shown that the signal response that OSLDs exhibit with dose history is influenced by the wavelength of the bleaching optics used. It is hypothesized that the varying results that are seen with investigators may be related to the different in bleaching optics that are used to remove signal.

This study looked into the effects that different optical wavelengths have on OSLD signal response with the accumulation of dose. Four monochromatic light sources within the visual spectra (red, green, yellow, and blue) were used in addition to two

polychromatic light sources (IROC's halogen bulb and a white LED) in order to gain understanding into how the wavelengths and chromaticity influences OSLD re-use effects. In addition to expanding upon the work on bleaching optics for OSLD re-use characteristics, expanding upon the work of Liu 2020 will allow better understanding into how bleaching optics effects the degree of signal regeneration once an OSLD has been bleached. Bleached OSLDs grow in signal over time as their deep trap states migrate into dosimetric trap states, which we evaluated at dose different dose levels. Both the evaluations into OSLD signal response with dose and charge repopulation with bleaching were shown to be related to the bleaching optics used as well as the fractionation schemes that were employed. To better understand the effect that fractionation had on these studies, the signal response of OSLDs that received varying sized fractions was compared to reference OSLDs.

2. Methods

Bleaching Characteristics

The underlying investigation between the three experiments is the use of different bleaching lights used. For our control, we have used to IROC bleaching light that has been used for audit operations for years. This consists of two parallel opposed halogen bulbs that emit a pentachromatic light spectra. Between these lights lays an acrylic plate which the OSLDs lay on. A picture of the IROC bleaching system is shown below. To compare against it, we have constructed our own bleaching system that similarly uses two parallel opposed lights. For our constructed system we have used LED flood lights which can be modulated in order to change the color of light emission. Between these LED sources also lies an acrylic plate for the nanoDot OSLDs to lie on. Four

monochromatic lights (red, green, yellow, and blue) were used in addition to a polychromatic light (white).

To characterize each of the light sources, a diffraction spectrometer was used to quantify the assortment of wavelengths that compose the light spectra. To quantify the amount of light each OSLD was exposed to, the luminous flux of each light source was measured using a Lux Meter (Dr. Meter model LX1332B), and the luminosity rate at the active volume of the OSLD was calculated using the following equation:

$$Lumens = \frac{L_x \cdot OSLD_{area} \cdot T}{T_r} \quad (\text{Eq. 1})$$

Where L_x is the luminous flux determined by the Lux meter, $OSLD_{area}$ is the area of the active OSLD crystal which has a value of $19.6E^{-3}m^2$, T_r is the timing resolution of the Lux meter with a value of $\frac{2 \text{ Readings}}{\text{Second}}$. To determine the optical spectra of each light source, a spectroscope was used (Eisco Labs model SKU PH100QA). The color, associated luminosity rate, and wavelength of each light source are listed in Table 1.

Red	IROC	White	Blue	Green	Yellow
8,715	68,642	114,717	13,441	18,868	30,387
lumens/min	lumens/min	lumens/min	lumens/min	lumens/min	lumens/min
625 nm	445,490,550, 590,615 nm	450-700 nm	460 nm	530 nm	585 nm

Table 1: Characteristics of each bleaching source in regard to luminous flux and wavelength characteristics

Irradiations

All OSLD irradiations were conducted using a Co-60 beam maintained by an Accredited Dosimetry Calibration Laboratory with dose rates directly traceable to NIST. The field size for every irradiation was 24.5 x 24.5 cm with an SSD of 87.5. Each OSLD was irradiated orthogonal to the incident radiation beam. All OSLDs were read with a MicroStar II (Landauer Inc, Glenwood Il).

For the investigation into bleaching effects of signal stability, 240 nanoDot OSLDs were irradiated to evaluate sensitivity and linearity characteristics for every 10 Gy of accumulated dose history until the OSLDs reach a total dose of 50 Gy. For this, sensitivity was evaluated by measuring the signal response with a 90 cGy irradiation. After this sensitivity study, the OSLDs were bleached and irradiated between 25 cGy – 500. After, the nanoDots were bleached again prior to receiving a final irradiation to bring every OSLD to the same dose history. This cycle continues until they have reached 50 Gy. Groups of 40 OSLDs were bleached under 6 different optical spectra, which is shown in figure 1. To assess the signal stability as the accumulated dose history increases, we used equation 1 from the American Association of Physicists in Medicine (AAPM) Task Group Report (TG)-191 to calculate the dose to water.

$$D_w = M_{corr} \cdot k_{Si} \cdot N_{D,W} \cdot k_f \cdot k_L \quad (\text{Eq. 2})$$

Corrections factors relating to energy and angle were unity due to all irradiations being conducted on a Co-60 unit with an en-face irradiation configuration.

For studies into signal repopulation, 60 nanoDot OSLDs were irradiated to doses of 2 Gy, 10 Gy, 20 Gy, 30 Gy, 40 Gy, and 50 Gy in a single fraction. For each dose level,

the 60 OSLDs were subdivided into groups of 10 which were bleached for a minimum of 24 hours until their signal reached >300 counts. Each of these groups of 10 were bleached with a different optical wavelength. Characteristics of the bleaching optics such as wavelength and luminous flux is shown in Figure 1. The signal of the OSLDs were read periodically over the period of the span of a few months to characterize how dose and bleaching effects the degree of signal regeneration exhibited by the nanoDots.

For investigations into fractionation effect, groups of 10 nanoDot OSLDs were irradiated in fractions of 5 Gy, 10 Gy, 15 Gy, and 30 Gy until they reached a total dose history of 30 Gy. After each fraction, the OSLDs were bleached with the IROC light for a period of 24 hours. After this, a 90cGy irradiation was used to determine their sensitivity compared to reference dosimeters that were also given 90cGy, but that have no dose history.

3. Results

The results of our experiments indicate that the rate of signal loss per lumen in OSLDs is related to wavelength. Shorter wavelength light sources, such as blue light, were found to be the most efficient at removing signal per unit of luminous flux, while long wavelengths (particularly red) were notably less efficient. The polychromatic light sources (white light and the IROC light) showed intermediate efficiency. Figure 23 shows the bleaching rate of every light source across all accumulated doses. While bleaching efficiency was found to be a function of wavelength, the rate of signal removal was independent of accumulated dose history [$P > 0.05$ t-test].

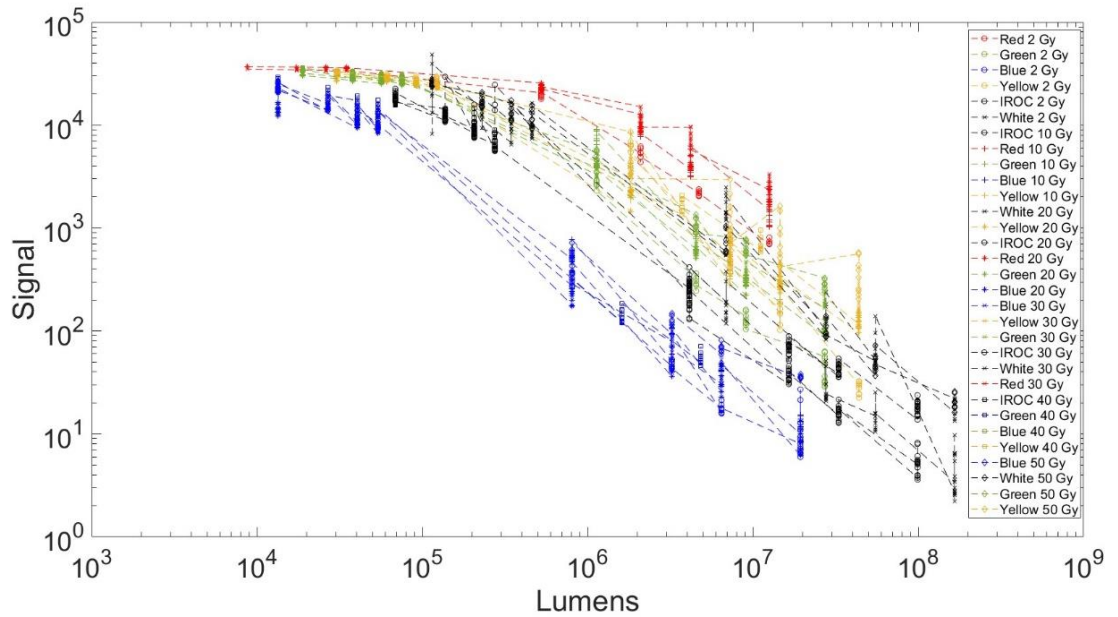


Figure 23: Signal Change in OSLDs after being bleached for 1,2,3,4 minutes and 1,4,8,24 hours between six chromatic lights and across accumulated dose. All signals were irradiated to 90 cGy prior to bleaching

The consistency of detector signal response as accumulated dose increased is shown in Figure 24. Consistency was evaluated in terms of dose to water measure relative to zero accumulated dose history. This figure shows that polychromatic light sources, such as the IROC Halogen bulb and white LED, resulted in the best overall signal preservation at high accumulated doses. Despite being the most effective light source at bleaching signal from the detectors, the blue light was not the most effective at preserving sensitivity. Nevertheless, it was more effective than the green or yellow light sources. The red light source is not included because 24 hours of bleaching with this light source was insufficient to reduce signal to background, resulting in contaminating residual signal.

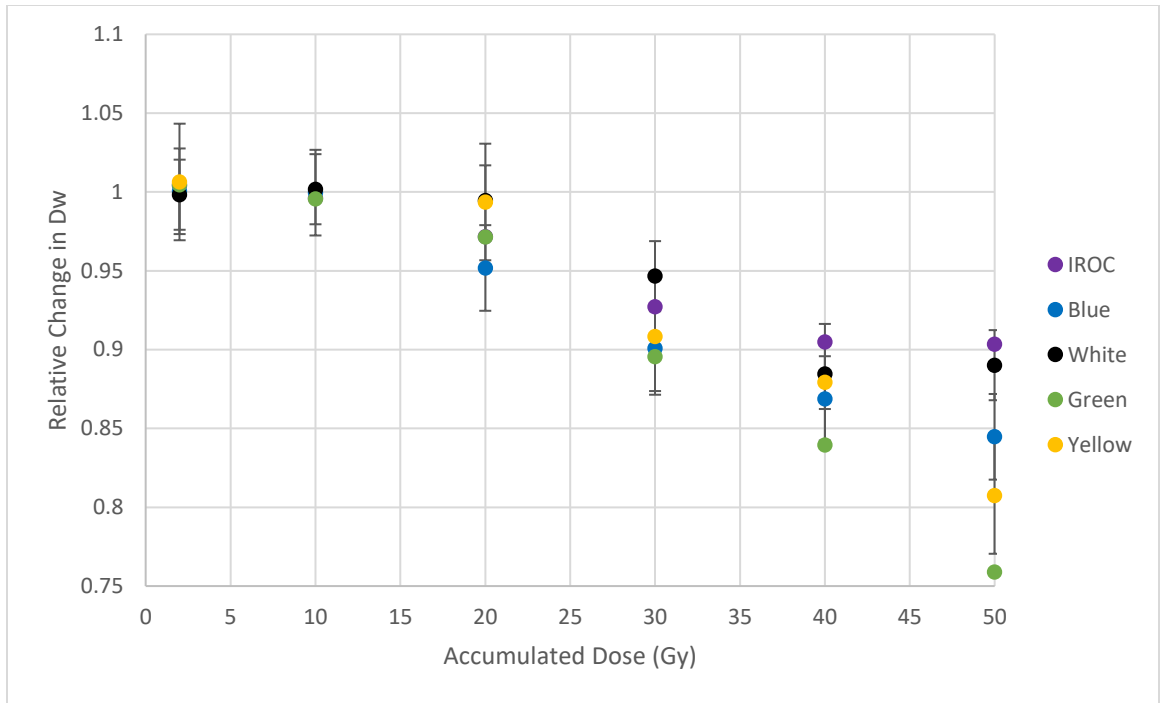


Figure 24: Change in OSLD signal stability with increasing accumulated dose history.

Each point plotted was irradiated to 90 cGy

Charge repopulation for OSLDs was found to be dependent on the accumulated dose, time since bleaching, and light spectrum used for bleaching as shown in Figure 25. The magnitude of charge repopulation was found to increase with accumulated dose; at 2 Gy there was no measurable repopulation, with 30 Gy of accumulated dose the signal repopulation could approach 1 cGy after 45 days, and by 50 Gy of accumulated dose the signal repopulation could exceed 3 cGy by 40 days. Repopulation was most pronounced for the polychromatic light sources. The white light and the IROC light, which were moderately efficient in terms of bleaching but were the best in terms of preserving dosimeter sensitivity, were actually the worst in terms of preventing signal repopulation. The yellow and green light sources, which were the poorest in terms of bleaching

efficiency as well as preserving the dosimeter sensitivity, performed the best in terms of preventing signal repopulation.

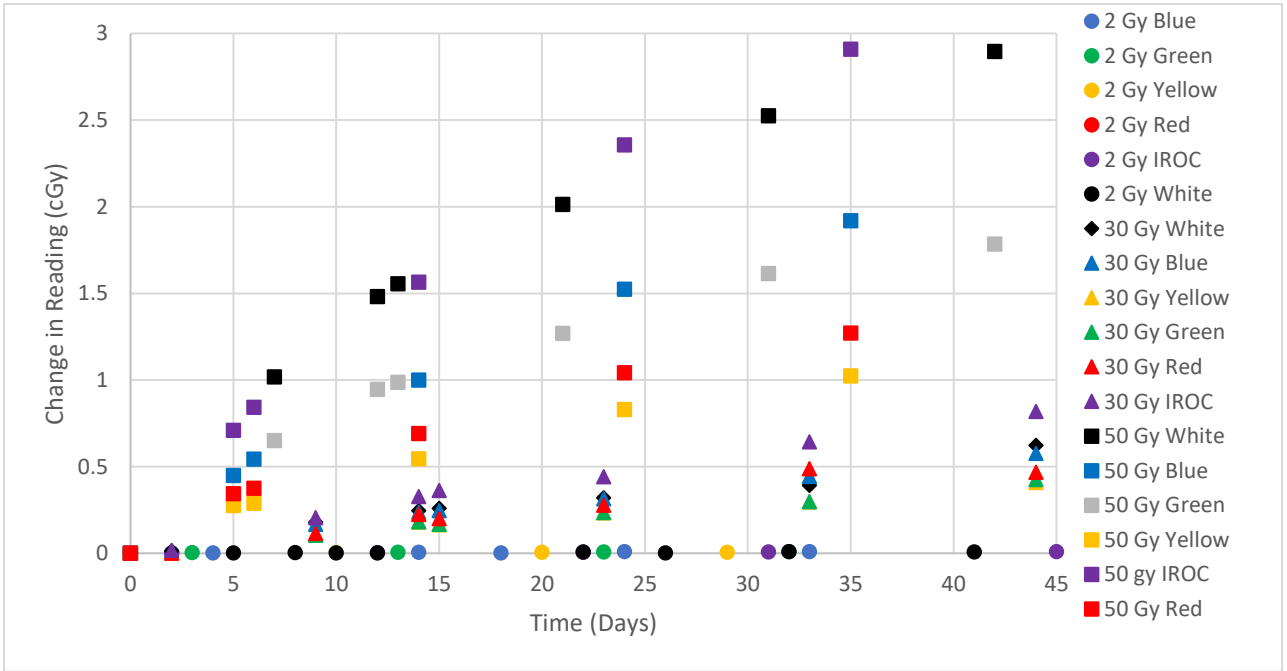


Figure 25: Charge repopulation of OSLDs that were bleached with different lights across different accumulated doses

3.2 Fractionation Effects

An interesting observation was made when comparing our changes in sensitivity with accumulated dose using the IROC light source (from Figure 24), with our prior results on changes in sensitivity using this same light source (from Hayden et al). These two data series are plotted in Figure 4, and show a different behavior in terms of preservation of sensitivity. The only difference between these two data series is the dose step size. The data from our previous study was based on OSLD that were irradiated to, on average, 1.5 Gy and a maximum of 300 cGy. The data from the current study (which

showed a larger impact on sensitivity) was based on OSLD that were irradiated to, on average, 8 Gy and a maximum of 875 Gy in one fraction. The larger fractionation scheme resulted in a 1% change in D_w at an accumulated dose history between 10-15 Gy as compared to the 23 Gy limit that OSLDs exposed to a maximum of 3 Gy had. Once the two groups being to diverge between 10-20 Gy, the larger fractionation group has a systematically lower signal response across all evaluated accumulated dose levels.

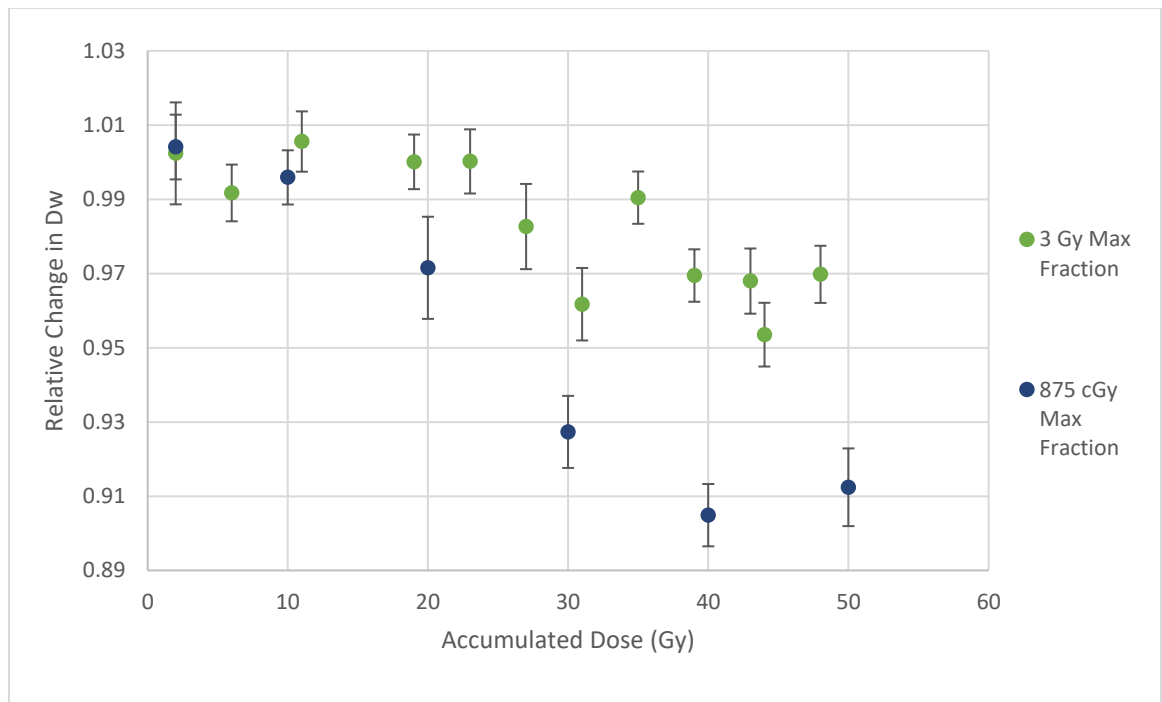


Figure 26: Change in signal stability between small fraction groups (orange) and large fraction groups (blue). The smaller fraction groups received doses in maximum fractions of 300 cGy whereas the large fraction groups received dose in a maximum fraction of

875

The evaluations into signal response through calculations of D_w take into account the correction factors listed in TG-191 which models the process that would be used within the clinic. To evaluate a more direct approach to signal changes with fractions, we

can directly compare the signal response of OSLDs that have received differing fractions to reference dosimeters that have received the same nominal doses but who have no dose history. Figure 27 shows the ratio response of our experimental groups compared to the reference dosimeters. The degree of hypersensitivity was found to increase with larger fractions. The maximum hypersensitivity that was evaluated was with 30 Gy fractions which had a signal that was 6.3% greater than reference dosimeters that were irradiated to the same nominal dose.

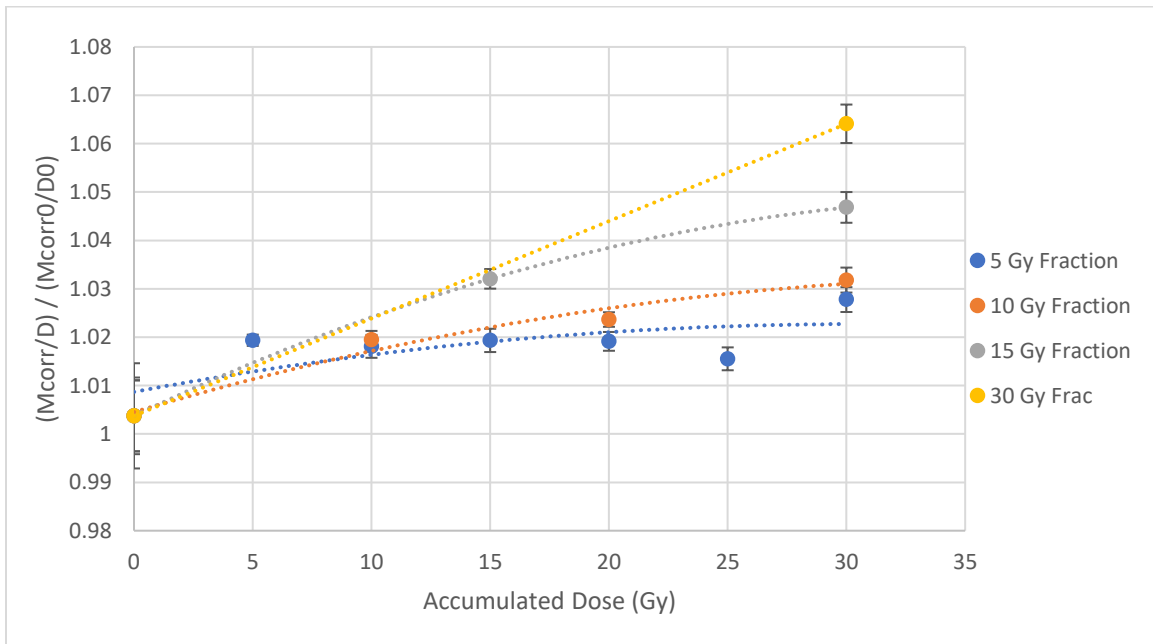


Figure 27: Ratio of experimental OSLDs that were given variable fractions to reference dosimeters with no dose history irradiated to the same nominal dose. Prior to each irradiation, the experimental OSLDs were bleached in the IROC system for 24 hours.

Because sensitivity and linearity are both affected by accumulated dose, we also evaluated if k_L changed with fraction size. Figure 28 shows how the dose nonlinearity correction factor changes with fractionation size. Figure 29 shows that the degree of k_L

changes with fraction size, becoming more pronounced with larger fractions. This effect becomes more pronounced at larger doses. For those that receive larger fractions, larger k_L correction factors need to be used.

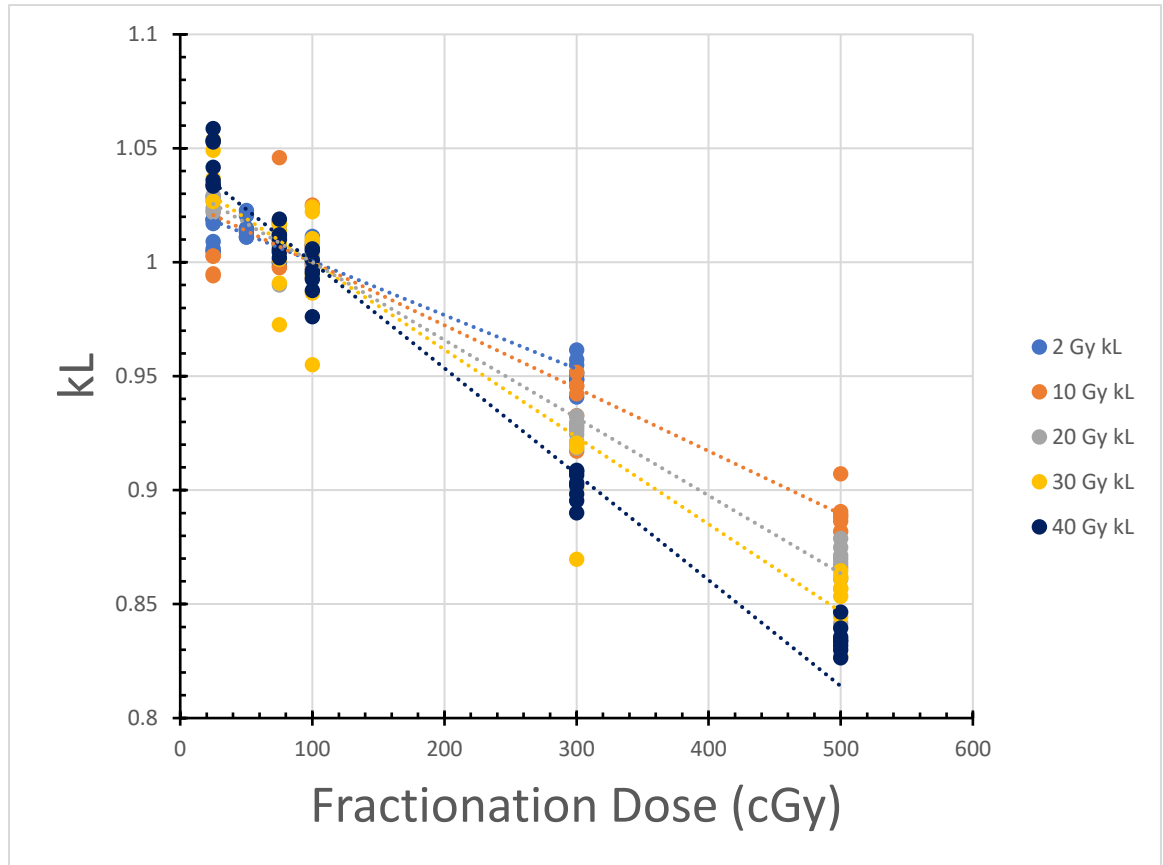


Figure 28: Plot of all k_L evaluations between 2-40 Gy. The slope of k_L increases with accumulated dose

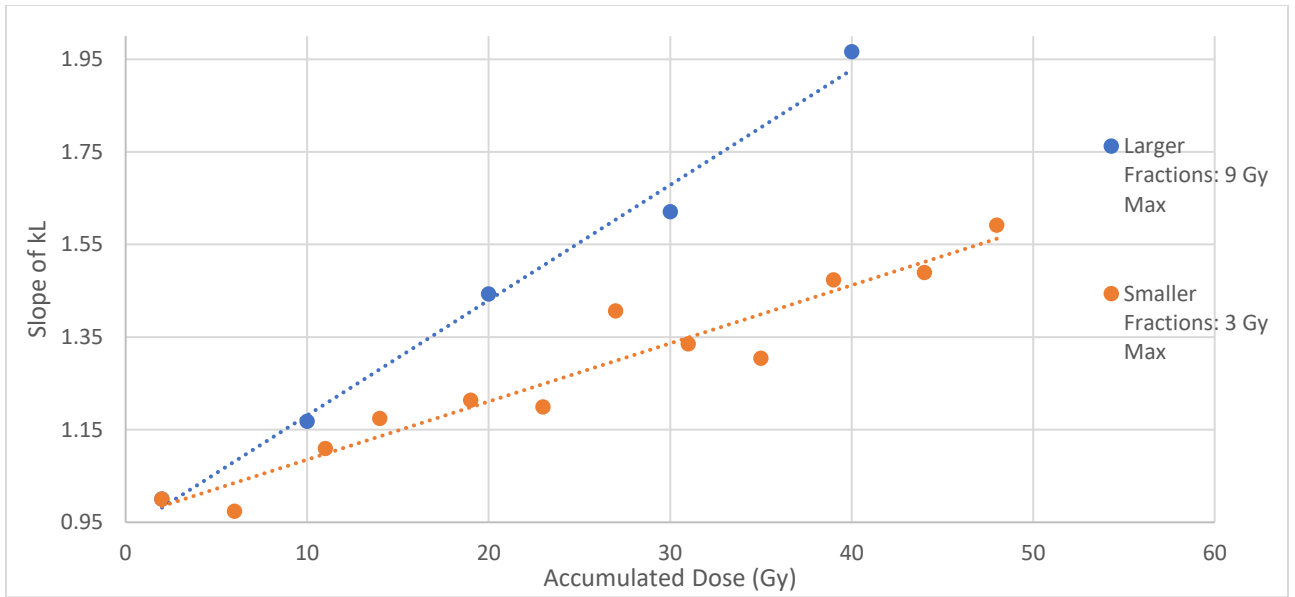


Figure 29: Slope of kL as a function of accumulated dose between small fractions (orange) and large fractions (blue)

4. Discussion

Bleaching efficiency, signal preservation with dose, and signal repopulation was evaluated with a variety of different bleaching light sources. It was found that amount of signal removed per lumen of light is related to wavelength, with lower wavelengths removing more signal than larger wavelengths. For the presentation of signal response, it was found that polychromatic light sources provides a more stable signal response up to a greater dose history. Repopulation was shown to be related to dose history and optical spectra used for bleaching, with a larger degree of charge repopulation observed with greater dose history. There was an observed change in signal response depending on fraction size used. Depending on the desired goal, OSLDs can be re-used to achieve faster bleaching or signal preservation based on the choice of bleaching light used and fractionation scheme employed.

Our results indicate that the efficiency of signal removal from OSLDs is dependent on the wavelength of the light source used for bleaching. Polychromatic light sources were found to provide the best overall stability for re-using OSLDs, despite lower wavelength light sources being more efficient per lumen at removing signal. For the polychromatic groups, maintaining a more stable signal response at greater dose histories suggests that there is a lesser degree of deep trap states that saturate the dosimeter. We hypothesize that the polychromatic light sources are able to stimulate a larger degree of the electron trap structures, allowing for a greater degree of phototransfer of charge carriers from deep trap states to dosimetric trap states.

Charge repopulation has been investigated by other investigators such as Liu 2020⁷ which showed the relationship between charge repopulation with beam energy and dose history. Using a variety of different optical bleaching wavelengths with a constant energy, we were able to expand on this to show that the rate of signal regeneration is dependent on optical bleaching. Though each optical group has a more consistent degree of repopulation at accumulated doses of 2 and 10 Gy, they begin to diverge at larger accumulated dose histories. At the greatest doses, we find that polychromatic wavelengths seem to be stimulate the phototransfer of charge carriers as seen by their greater degree of signal repopulation compared to monochromatic sources.

In this work, there has been two distinctly opposite expressions of signal response with dose history. In Figure 7 we see an increase in the signal response of OSLDs with larger fractions, though in Figure 4 we see a decrease in signal response with OSLDs exposed to larger fractions. Other investigators who have investigated the effects of bleaching optics with fractionation, such as Omotayo et al, have seen similar results. The

intersection of bleaching wavelengths, fractionation, bleaching time, and accumulated dose on signal response has not been explored far enough in order to make a unifying theory. It has been shown in this work and others that the choice of bleaching light plays a heavy role in re-use characteristics^{2,3,8,11-14}, which other investigators should characterize the wavelength and luminous intensity of their optical sources.

For the implementation of re-using OSLDs in a clinical environment, it is important to emphasize how these results effect dose limits, how fractionation and bleaching schemes effect usage, and if it is necessary to re-bleach OSLDs that have been bleached and are sitting in storage. Due to the change in k_L being well characterized and suggesting that their signal response is detector independent, an appropriate correction factor can be utilized based on the dose history and fraction sizes that the dosimeter has been exposed to without the direct need of measuring this factor with each irradiation. Ideally, a broad polychromatic light source needs to be utilized to maintain the greatest signal response stability, though the characteristics and effects of each clinics bleaching system needs to be evaluated. The change in signal response with larger fractions suggests that small fractions are appropriate for OSLDs that want to be re-used. For the implementation of re-using OSLDs that have dose histories at or lower than the recommended 10 Gy dose level, have been bleached, and have been sitting in storage it is unlikely that the amount of signal repopulation is significant.

5. Conclusion

The choice of optical bleaching light and fractionation scheme play an important role in the clinical usage re-use of OSLDs. The choice of bleaching light has a critical impact on the properties and performance of OSLDs including their bleaching rate,

longevity, and charge repopulation. For re-using OSLDs, small fractions are needed in order to maintain signal stability. Hence, when reutilizing OSLDs, it is essential to carefully consider the type of bleaching light and its effects on stability, bleaching rate, and charge repopulation, to ensure that the dosimetric integrity of the OSLDs is maintained. To re-use dosimeters, fractionation effects need to be accounted for, with an emphasis on utilizing smaller fractions for the OSLDs that will be bleached and re-used.

Chapter 6: Conclusion

5.1 General Summary:

For the re-use of OSLDs, we have evaluated parameters that effect the practical usage of OSLDs such as signal response and charge repopulation both for IROC purposes and general usage. For signal response, it was found that the nanoDots used with the IROC protocol can be extended past their 10 Gy threshold up to 15-20 Gy. Performance characteristics of OSLDs such as sensitivity and linearity exhibited results that integrate well with the use of audit checks. Namely, it was found that $k_{s,i}$ does not change with dose, and that k_L trends predictably with dose. Extending our analysis past IROC's protocols, it was found that the signal response of OSLDs change depending on the choice of optical light used to remove signal through bleaching. Though lower wavelengths removed signal at a faster rate across all doses, it was the polychromatic sources that maintained signal stability up to greater doses.

Though many of the experiments performed were centered around seeing how much dose an OSLD is stable up to, other experiments such as charge repopulation and fractionation revealed information related to how OSLDs should be handled and utilized. For OSLDs that have a dose history below the recommended 10 Gy threshold, charge repopulation was marginal. At 30 Gy, after more than a month, there begins to be signal repopulation on the order of 1 cGy. The degree of repopulation becomes greater with greater dose fractions. Fractionation showed that OSLDs exhibit signal response greater than reference OSLDs after receiving fractions above 5 Gy. Greater fractions result in larger signal response, suggesting that smaller fractions should be utilized to maintain stable signal response when re-using OSLDs.

5.2 IROC Implications:

The results from the specific aims of this thesis have uncovered a variety of helpful mechanics that IROC-Houston can employ to assist in reducing the cost and time needed to handle the OSLD program. Namely, pushing the accumulated dose limit to from 10 Gy to 15 Gy is a meaningful extension for the ~20,000 dosimeters that IROC commissioned for the 20K21 group. Analysis into how $k_{s,i}$ remains unchanged from commissioning to upper limits of 50 Gy helps to reduce the amount of times an OSLDs sensitivity response needs to be re-evaluated throughout it's life history. The linear and predictable trend in k_L that was seen allows us to apply a correction factor based on each dosimeters accumulated dose history, which means that we do not have to re-analyze linearity after being commissioned. For the OSLDs that have reached their dose limit and have stayed in storage, the amount of charge repopulation is considered marginal for the typical dose amounts that are used within IROC's audit system and phantom service, meaning that they can be re-instituted into practice without spending the time and resources to bleach the dosimeters. Our studies into fractionation effects on the re-use of OSLDs does add additional considerations given the effects of hypersensitivity and k_L changes with accumulated dose that larger fractions exhibit. For the output checks that IROC performs, the OSLDs used are given fractions of ~1 Gy, making the effects of larger fractions being insignificant. For the phantom program, some OSLDs that receive larger fractions need to have their performance characteristics evaluated prior to being re-instituted.

Clinical Implications:

An important consideration for the application of this thesis for the use of different clinics is that the effects seen within this thesis are unique to the framework that IROC uses. The effects of bleaching optics that this thesis has presented suggest that the ultimate dose limits are specific to the light source that IROC uses, which would be difficult to reproduce. Each clinic that wants to re-use OSLDs, it is recommended that similar research should be carried out to determine how their choice of bleaching optics and choice of fractions effect the overall D_w calculation limits, change in slope of k_L , change in $k_{s,i}$, and overall sensitivity characteristics.

5.3 Future Work

Given that the primary implementation of OSLD re-use at IROC- Houston is focused on the remote audit program which uses 1 Gy fractions as opposed to the larger fractionation schemes presented in this work, performing evaluations into k_L and D_w changes with accumulated dose with single 1 Gy fractions may extend the stability of OSLDs past the 23 Gy limit proposed in Chapter 3. Given that the change in slope of k_L was well characterized for the fractionation schemes in both Aim 1 and Aim 2, with a more prominent change in our correction factor when presented with larger fractions, we hypothesize that the 1 Gy fractionations that the audit program uses will result in a change in the slope of k_L that is less significant.

For the analysis of the optical bleaching systems laid out in Chapter 4, a handheld spectroscope was used. This was able to determine the wavelengths of light sources with an inherent resolution of $\pm 5\text{nm}$. For the White LED, we found and reported a “continuous” spectrum from 400 – 600 nm, however we know that light emission is not continuous less we suffer from the ultraviolet catastrophe. Therefore, a more robust

spectroradiometer would allow for better delineation of spectra composition of the White LED source. In addition, this would allow us to determine the magnitude of each individual light spectra which was not able to be quantified with the spectroscope. Lastly, it was shown by Jursinic 2020 that UV light contributes effects to the re-use of OSLDs. The spectroscope that we used was also unable to quantify into the UV spectra, leaving the magnitude and contribution of UV light as a confounding variable. In conclusion, for analysis into the optical spectra of bleaching systems, more robust information about dose thresholds can be determined with a spectroradiometer or other piece of optical equipment capable of quantifying wavelengths and magnitude.

Chapter 7: Appendix

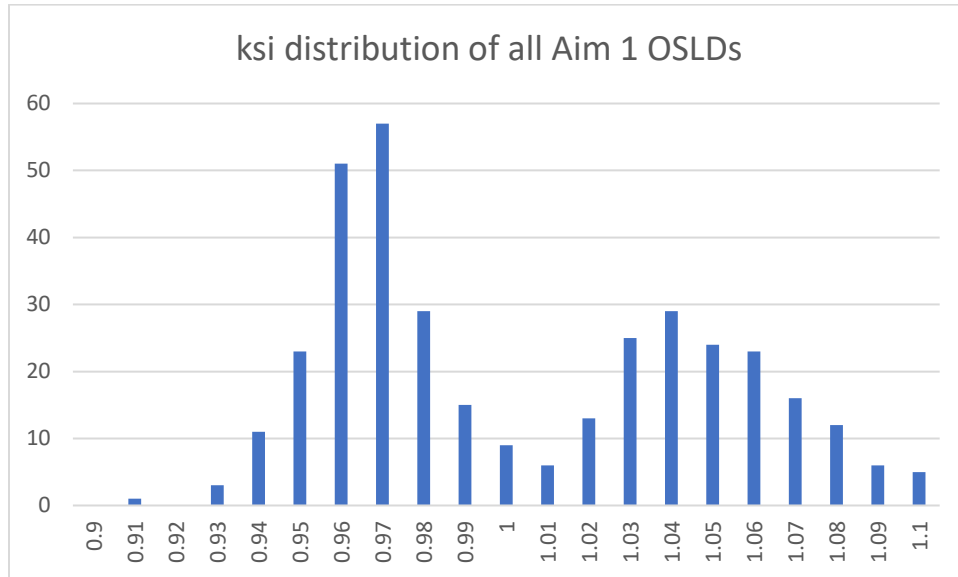


Figure 30: Double Gaussian Example the commissioned ksi distribution utilized in this work. The OSLDs used are made up of dosimeters that failed commissioning for either being too high or too low which results in this double gaussian

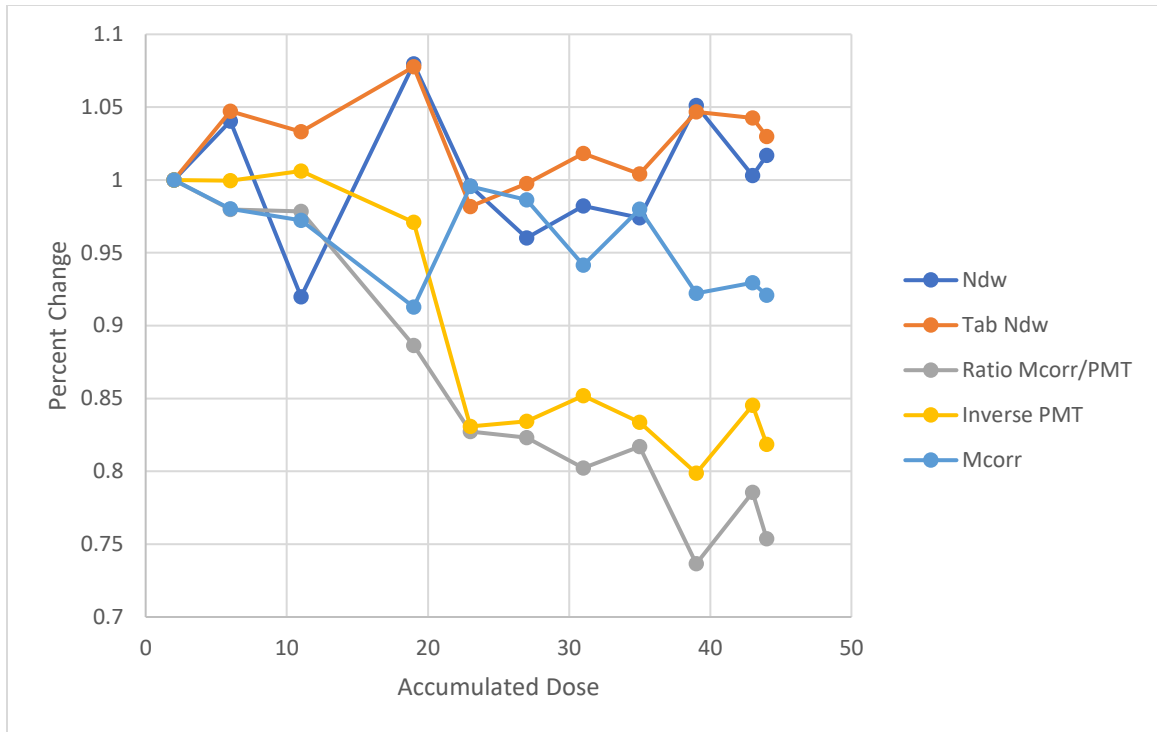


Figure 31: Change in Mircostar II characteristics for each dose evaluation performed with Aim 1's study. Rather than expressing the X axis as time, the X axis corresponds to the readings of sensitivity in Aim 1's study.

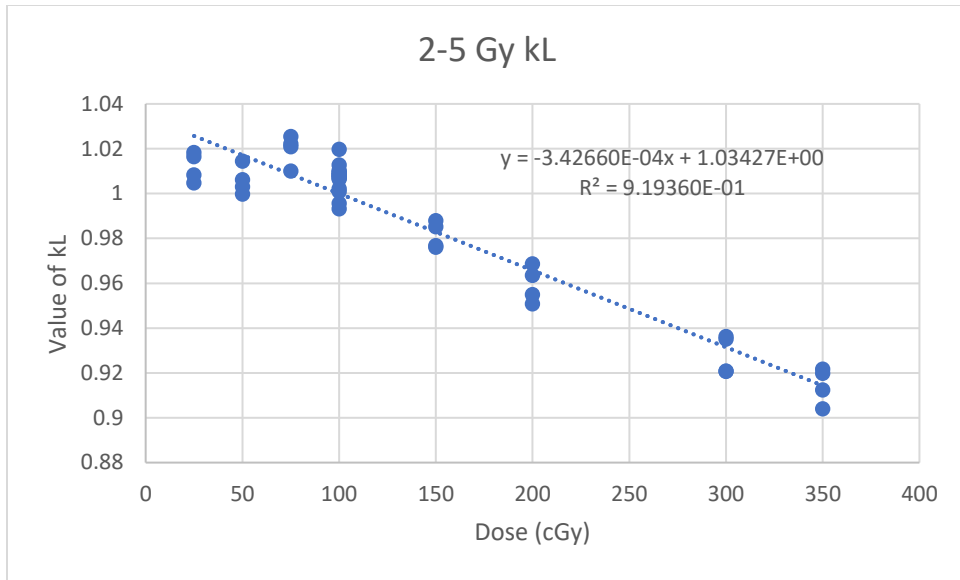


Figure 32: kL of Aim 1's 2-5 Gy linearity. There is a shoulder at the beginning which appears sporadically with each kL

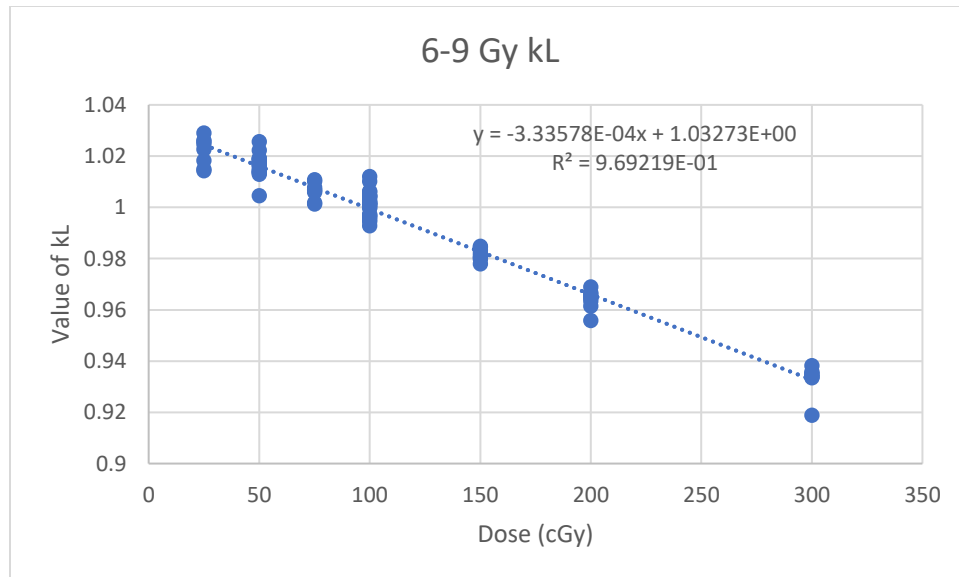


Figure 33: kL of Aim 1's 6-9 Gy Linearity. Here we have no shoulder

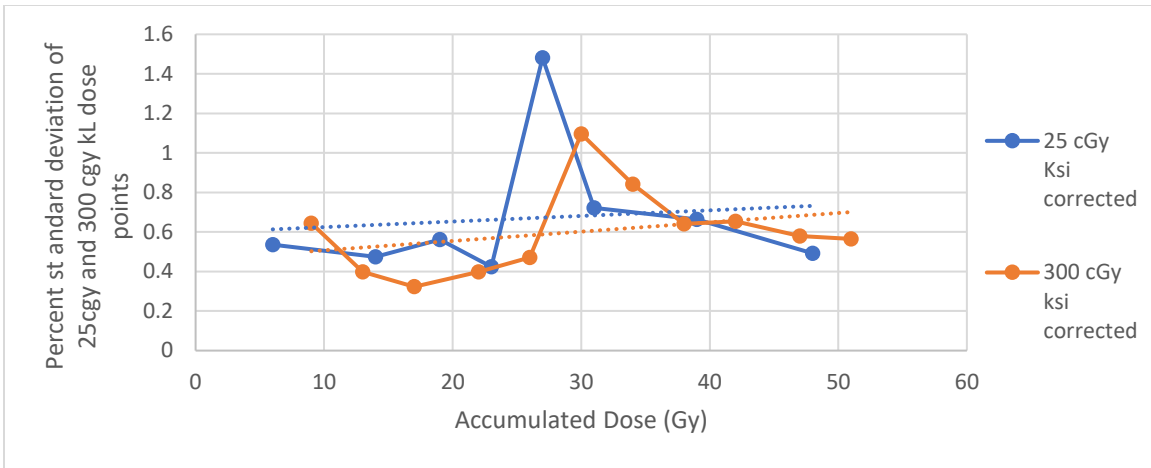


Figure 34: Change in COV for 25 cGy and 300 cGy dose points as a function of accumulated dose in Aim 1's Linearity assessments

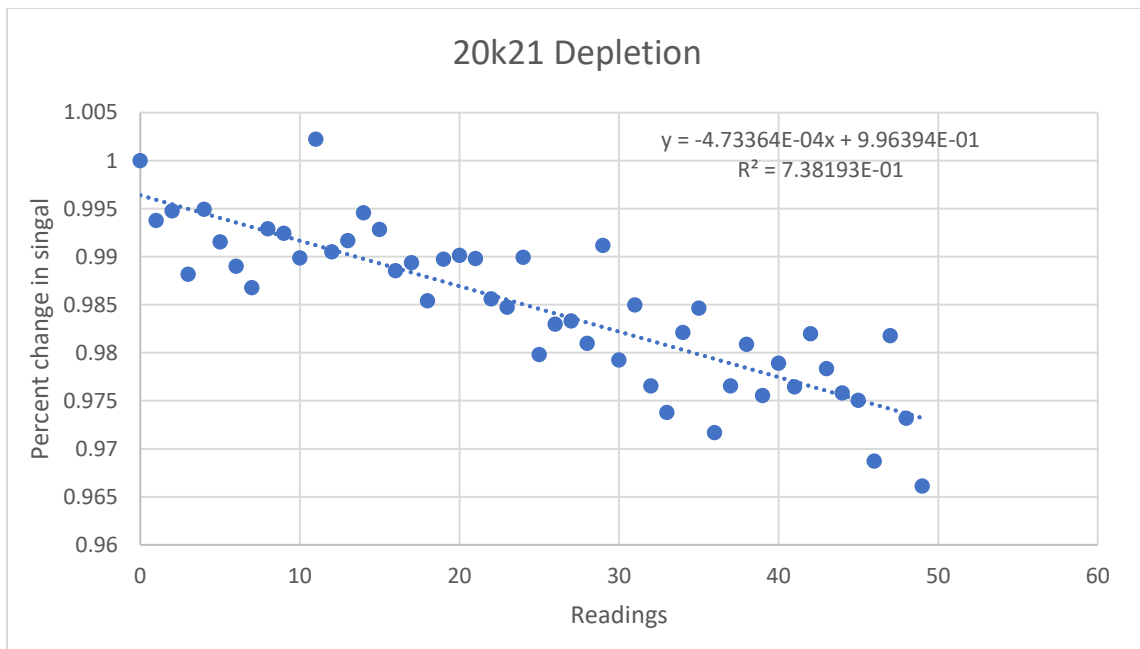


Figure 35: 20k21 OSLDs depletion after 50 readings

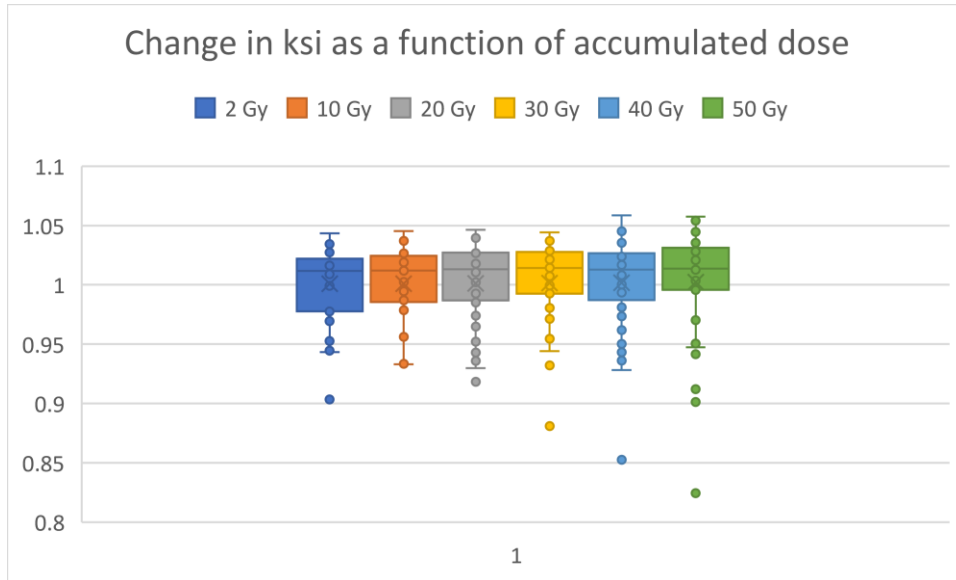


Figure 36: Distribution of ksi for Aim 2's IROC light using larger fractions

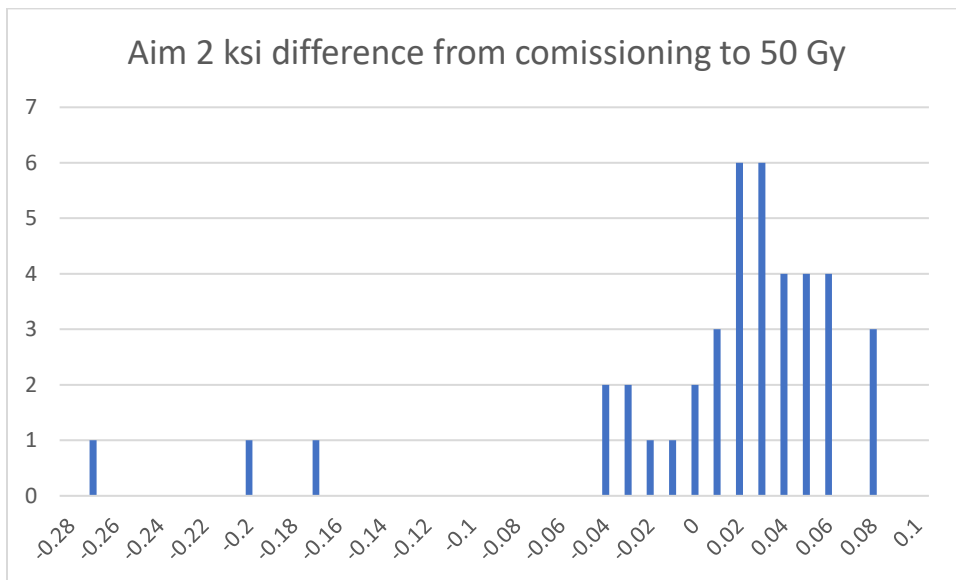


Figure 37: Histogram of change in Ksi values for Aim 2's IROC light using larger fractions

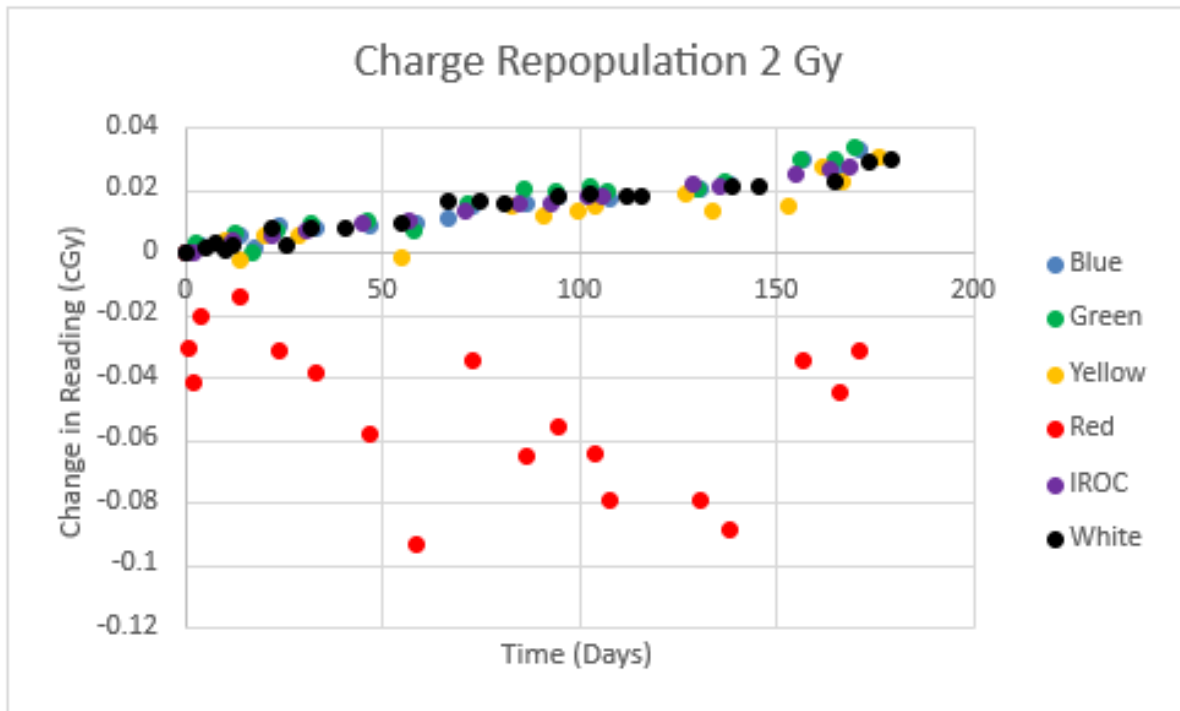


Figure 38: Change in OSLD signal at 2 Gy for varying optical bleaching colors

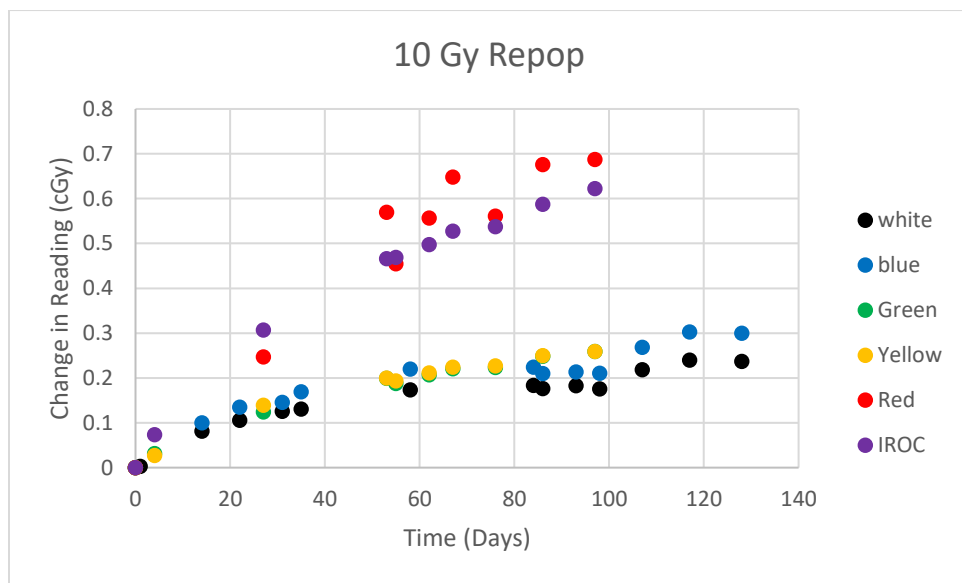


Figure 39: Change in OSLD signal at 10 Gy for varying optical bleaching colors

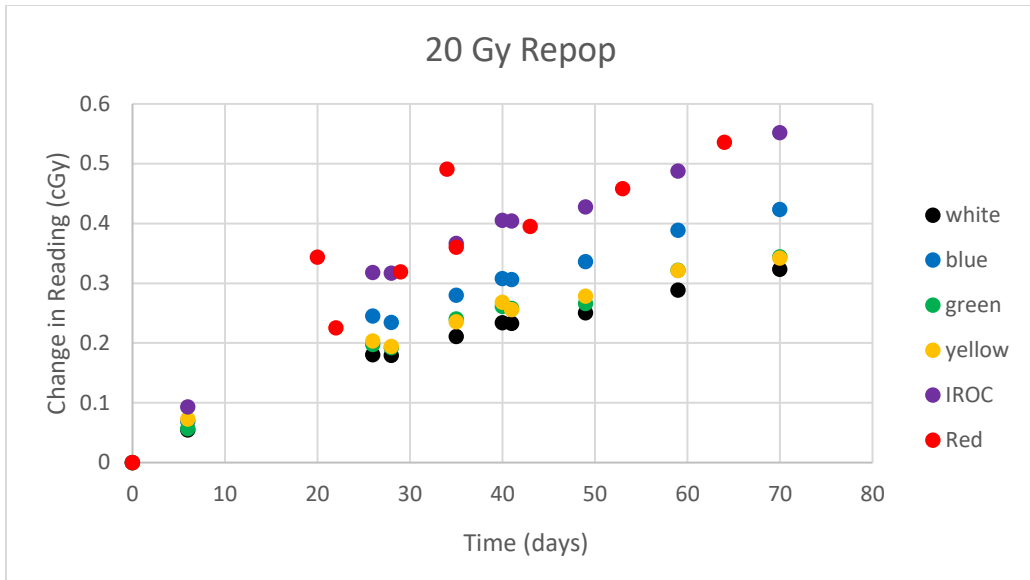


Figure 40: Change in OSLD signal at 20 Gy for varying optical bleaching colors

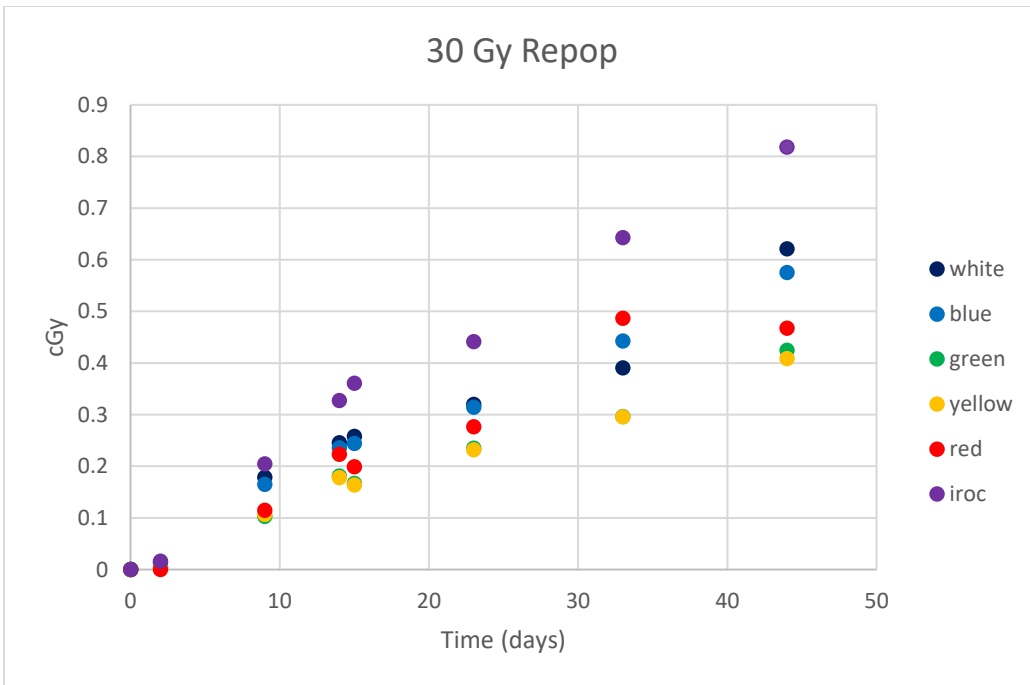


Figure 41: Change in OSLD signal at 30 Gy for varying optical bleaching colors

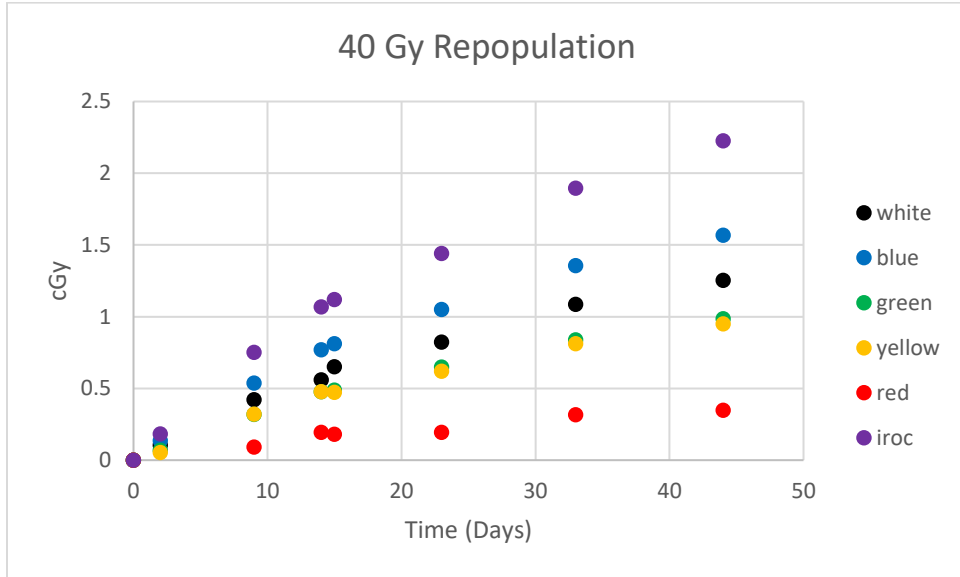


Figure 42: Change in OSLD signal at 40 Gy for varying optical bleaching colors

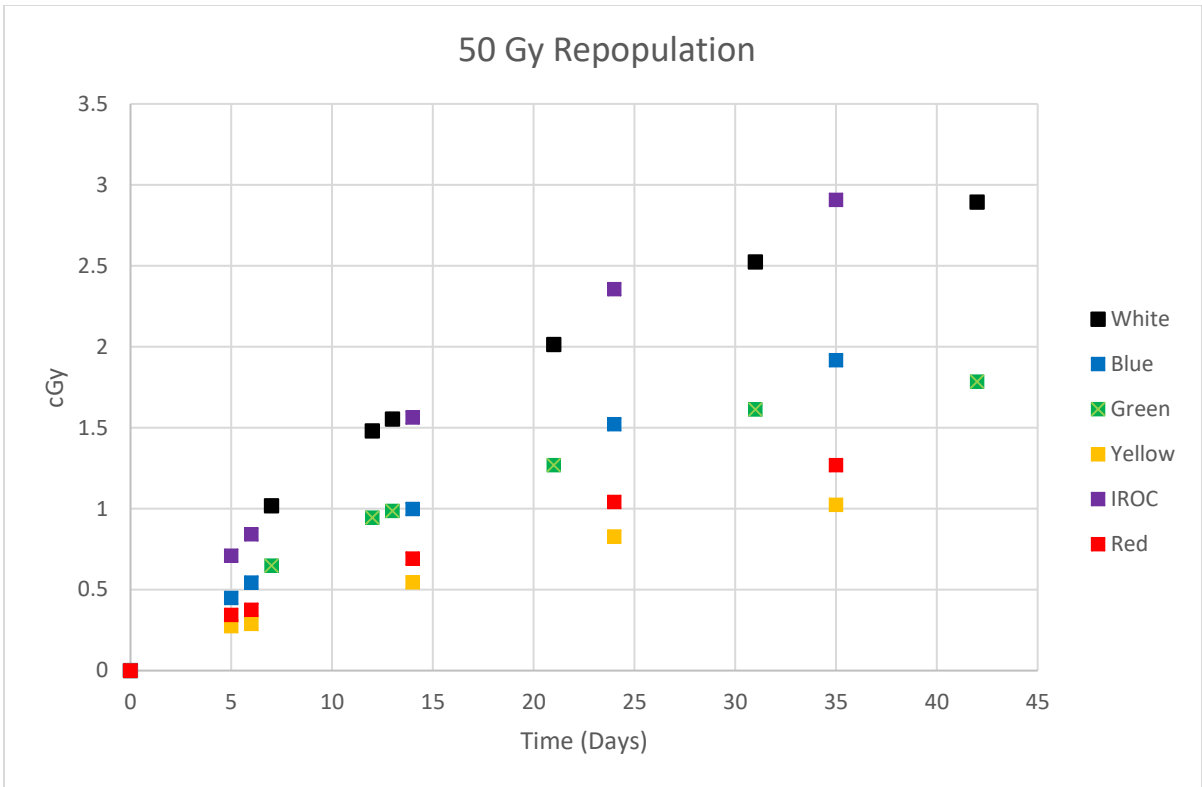


Figure 43: Change in OSLD Signal at 40 Gy for varying bleaching colors

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