DOSIMETRIC CHARACTERISATION OF THE NANODOT OPTICALLY STIMULATED LUMINESCENT DOSIMETER FOR USE IN NATIONAL ELECTRON BEAM DOSIMETRY AUDIT SERVICES FOR RADIOTHERAPY FACILITIES

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ABSTRACT: The Malaysian Nuclear Agency's secondary standard dosimetry laboratory (SSDL) aims to establish a national dosimetry audit service for radiotherapy facilities. For this purpose, a nanoDot optically stimulated luminescent dosimeter (OSLD) was selected as the transfer dosimeter for the audit program. The study aims to establish the basic dosimetric characteristics and associated correction factors of nanoDot OSLD for use in electron beam dosimetry audits. An investigation of the dosimetric characteristics of the nanoDot, comprising the sensitivity correction factor (SCF), dose-response linearity, beam energy dependency, signal depletion per readout, and signal fading when subjected to electron beams, was conducted. A preliminary electron beam dosimetry audit using nanoDot OSLD was performed for two radiotherapy facilities under both reference and non-reference conditions. The measurement uncertainty of the absorbed dose for the nanoDot OSLD was also estimated. The mean SCF of the 91 nanoDot OSLD was 1.001 ± 0.25%. The dose-response curves for the 6 MeV and 9 MeV beams exhibited linear characteristics, with a determination coefficient of 0.9982 for the dose range of 50–300 cGy. However, a high energy dependency was observed at 12 MeV, resulting in a deviation of 4.08% compared to that at 6 MeV. The nanoDot signal decreased by 0.03% after 100 readouts and faded by 3.20% at 70 days post-irradiation. It is noteworthy that all audit results from the six electron beams were in compliance with the tolerance limit of ± 5%, with mean dose deviations of -1.66% ± 0.81% and -1.37% ± 0.65% for the reference and non-reference conditions, respectively. The combined uncertainty was estimated to be ± 1.41% (coverage factor, k = 1). National electron beam dosimetry audits using nanoDot OSLD can now be implemented as a regular service.

KEYWORDS: *radiotherapy dosimetry audit; electron beam; optically stimulated luminescent dosimeter; nanoDot OSLD.*

1.0 INTRODUCTION

Safe and effective radiotherapy relies on the accuracy of dose delivery to the target volume in the patient, which is typically within ± 5% of the prescribed dose at a 95% confidence level, as recommended by the International Commission on Radiation Units and Measurements (ICRU)[1]. Any errors in radiotherapy dosimetry can lead to radiation injuries and severe complications [2]. To prevent such errors, dosimetry audits are conducted at the national or international level as part of the quality assurance program (QAP) in radiotherapy. These audits have been successful in identifying errors, providing support for identifying the sources of errors, and rectifying them [3], [4]. The audit also serves as an early error detection mechanism, which is essential for taking prompt corrective action to safeguard patients from potential harm. This practice will improve dosimetry practices and reduce the likelihood of errors occurring, ultimately affecting patient health [5]. According to D. Van Der

Merve [6], an independent dosimetry audit should be performed for every new installation and regularly. This is crucial because dosimetry audits provide medical physicists with confidence in applying new radiotherapy modalities and techniques [7].

In keeping with the International Atomic Energy Agency (IAEA) guidelines, Malaysian radiotherapy facilities have actively participated in IAEA/World Health Organization (WHO) postal radiotherapy dosimetry audits since 2011, with a focus on assessing the absorbed dose of water from photon beams under reference conditions [8]. Presently, there are 35 radiotherapy centres in the country, comprising seven government hospitals and 28 private facilities [9]. One government-funded radiotherapy service was provided through a contract with a private institution. In total, 93 radiotherapy modalities are available, including 57 medical linear accelerators (linac), 19 brachytherapy, 7 intra-operative radiotherapy (IORT), 5 tomotherapy, 3 gamma knife, and 2 cyberknife [10]. On average, seven radiotherapy centres in Malaysia participate in the IAEA audit annually, with the highest participation reaching 12 centres in 2022. The IAEA audit results from 2011 to 2022 found that out of 202 beams checked, the majority (93%) were satisfied with an acceptance limit of ±5%, except for 13 photon beams (6%) and three electron beams (2%) [11]. Despite the low failure rate, this situation poses a severe risk of radiation injuries and, in extreme cases, death if not addressed promptly. Until recently, no national remote dosimetry audits had been conducted in Malaysia, as a national dosimetry audit network (DAN) has not yet been established. An international review of remote dosimetry audits indicated that electron beams are more susceptible to errors than photon beams [12], [13]. In 2021, the International Atomic Energy Agency (IAEA) initiated the Electron Audit Service for its member states, with one facility from Malaysia participating [14]. Therefore, establishing a national dosimetry audit for electron beams is crucial because of insufficient access to radiotherapy centres for IAEA audits, as priority is given to new linac installations.

Generally, electron remote dosimetry audits are limited to the measurement of the electron beam output under reference conditions [15], [16], with some additional parameters tested for on-site audits [17], [18], [19]. For this purpose, various detectors have been employed, including alanine, ionisation chambers, and radio photoluminescent glass dosimeters (RPLD). Each dosimeter has exclusive advantages; however, the nanoDot optically stimulated luminescent dosimeter (OSLD), one of the most versatile dosimetry systems with great dosimetric characteristics and convenience of use for a large-scale audit, is preferable for remote dosimetry audits [20], [21]. Several studies have described the dosimetric characteristics of nanoDot OSLD for radiotherapy dosimetry applications [22], [23], [24], [25]. However, this study is the first to present the establishment of dosimetric characteristics and their associated correction factors for nanoDot OSLDs for remote radiotherapy dosimetry audits using electron beams for reference and non-reference conditions. These characteristics include (i) dosimeter sensitivity, (ii) dose-response linearity, (iii) beam energy dependency, (iv) signal depletion, (v) signal fading, and (vi) readout reproducibility. This was followed by the fabrication and testing of the newly fabricated nanoDot OSLD holder for electron beam audit, implementation of a preliminary dosimetry audit for electron beams in reference and non-reference conditions, and relevant measurement uncertainty of the absorbed dose from nanoDot OSLD.

2.0 METHODOLOGY

2.1 NanoDot optically stimulated luminescence dosimetry system

This study utilized a nanoDot optically stimulated luminescence (OSL) dosimetry system procured from Landauer Inc. (Gleenwood, USA). The nanoDot OSL material was made of Aluminum Oxide doped with Carbon (Al_2O_3:C) and has a thickness of 0.12 cm and a diameter of 0.5 cm. It is encased in a 1 cm × 1 cm × 0.18 cm light-tight plastic case with a mass density of 1.03 g/cm^3 to protect it from light-induced signal fading. The OSL material in the disc can easily slide out of its plastic casing during the readout and optical bleaching processes. The nanoDot was read using an InLight MicroStar system installed with MicroStar software version 4.3. During the readout process, the OSL material was exposed to green light (540 nm wavelength). This process triggered the dosimeter to emit blue light with a wavelength of 430 nm, and the light signals were counted using a photomultiplier tube (PMT). The OSL signals were then converted to the actual absorbed dose in Gray by multiplying with the relevant correction factors.

To minimise errors due to accumulative background signals, pre-irradiation OSL signals were recorded by reading the nanoDot within one day before irradiation. Between the irradiation and readout periods, the nanoDots were kept in a closed cabinet at room temperature to minimise sensitivity and optical fading [26]. The nanoDots can be read 10 min post-irradiation to allow stabilisation of the OSL signals [27], [28]; however, in this study, the irradiated nanoDots were read not earlier than 24 h after irradiation to acquire post-irradiation OSL signals. When necessary, the net OSL signal was calculated by subtracting the pre- and post-irradiation signals. At least three nanoDots were used for all measurements, which were read more than five times sequentially to provide reliable mean values and a smaller margin of error.

2.2 Optical annealer

The OSL signals were bleached using an light emission diode (LED) X-ray illuminator (MST-4000, Minston, China). The annealer was made of a 20 W LED light panel with a luminance of 5500 cd/m^2. This optical bleaching process requires manual sliding of the OSL disc out of the plastic case. The OSL disc was continuously exposed to light from the optical annealer for at least three days until the residual signal was nearly identical to the background signals (< 200 counts). Background subtraction was not performed if the background signals were minimal compared to the OSL signals (> 100,000 counts).

2.3 Electron beam irradiation using a linac

A linac Novalis Tx linear accelerator (Varian Medical Systems, Palo Alto, CA, USA) at the University Malaya Medical Centre (UMMC) was used to establish the dosimetric characteristics and relevant correction factors of the nanoDot subject to electron beams. To minimise the air gap during irradiation, the nanoDot was placed inside a polymethyl methacrylate (PMMA) slab phantom with dimensions of 30 cm × 30 cm × 0.7 cm that was designed with a slot to accommodate the nanoDot tightly. A 10 cm thick solid water phantom (type 457, Gammex RMI, USA) with dimensions of 30 cm × 30 cm was placed below the PMMA slab phantom to provide a full-scatter condition. The nanoDots were irradiated at the intended dose, delivered at a rate of 400 cGy/min at 100 cm source-surface distance (SSD) with a 10 cm × 10 cm field size at scaled depth in a PMMA slab phantom, Z_{PMMA} for 6 and 9 MeV electron beams. Considering the density of the PMMA slab phantom, ρ_{PMMA} of 1.19 g/cm^3 and depth scaling factor, C_{PMMA} of 0.941 [29], the Z_{PMMA} and measurement depth equivalent in water, Z_{water} was estimated as presented in Table 1. These experimental setups were the same for all dosimetric measurements unless otherwise mentioned.

Table 1: Measurement setup of nanoDot in PMMA slab phantom for electron beam irradiation.

Beam energy (MeV)	6	9
Beam quality, $R_{50,water}$ (cm)	2.47	3.68
Reference depth in water, Z_{ref} (g/cm^2)	1.38	2.11
Measurement depth in PMMA, $Z_{measured}$ (cm)	1.05	1.50
Scaled depth in PMMA, Z_{PMMA} (g/cm^2)	1.25	1.79
Measurement depth equivalent in water, Z_{water} (g/cm^2)	1.18	1.68
Percentage depth dose, PDD (%)	99.65	99.36

To determine the calibration coefficient, the nanodots were calibrated in terms of the absorbed dose to water under reference conditions in 6 and 9 MeV beams. A calibrated 0.4 cm^3 plane parallel ionisation chamber, type PPC40 (IBA Dosimetry GmbH, Germany), connected to a PTW Unidos E electrometer, type T10009 (PTW Freiburg, Germany), was used to measure the absorbed dose to water. The absorbed dose to water was determined according to IAEA's Technical Report Series (TRS) No. 398 [29]. Detailed procedures are discussed in Abdullah et al.(2023). The calibration coefficient of the nanoDot OSLD dosimetry system was calculated as the ratio of the absorbed dose in water measured using an ionisation chamber, in cGy, and the corrected OSL readings of the nanoDot, in nC.

2.4 Dosimetric characteristics and relevant correction factors

2.4.1 NanoDot sensitivity correction factor

The inhomogeneous composition of the OSL material in the nanoDot produced variability in the sensitivity required for the individual sensitivity correction factor (SCF). In this study, 93 nanoDots were examined for their SCFs. Before irradiation, the pre-irradiation signal (initial background) was measured for each nanoDot. The nanoDots were then irradiated with 50 cGy under conditions of 20 cm × 20 cm field size (FS) and 100 cm SSD for a 6 MeV electron beam. A 0.5 cm bolus and a 1.0 cm slab phantom were placed above the nanoDots to provide a flat beam at the reference depth of 1.5 cm. After removing the outliers (nanoDots whose background corrected signal was outside three times the standard deviation), the SCF was calculated by taking the ratio of the average net OSL signal of all nanoDots and the net OSL signal of each nanoDot. The data were further assessed using a one-sample t-test using IBM SPSS Statistics Version 29.

2.4.2 Linearity of dose with OSL signal

To investigate the OSL signal response as a dose function, three nanoDots were irradiated for each planned dose within 50–300 cGy at 25 cGy intervals for both 6 MeV and 9 MeV beams. The linearity curves of the OSL signals against dose were plotted with linear functions fitted to the data to obtain the determination coefficients (R^2). The corresponding dose-response linearity correction factor, k_{lin} for each beam energy was calculated as the ratio of the OSL signal at 100 cGy to other doses. A graph of k_{lin} versus dose was plotted, with the linear functions fitted to the data to obtain a linear equation model. Finally, simple linear regression statistical tests were conducted to predict the value of k_{lin} based on the dose for each beam energy.

2.4.3 Beam energy dependency

The beam energy dependency of nanoDots was quantified for the most commonly used radiotherapy treatment beams: 6, 9, and 12 MeV. The nanoDots were irradiated under the reference conditions using a fabricated PMMA OSLD holder (Figure 1) following TRS-398 [29]. The energy correction factors, k_{energy} were subsequently determined based on the ratio of the OSL signal emitted by the nanoDots in a 6 MeV beam relative to the other beams.

2.4.4 Signal depletion per readout

The OSL signal in the nanoDot could be read repeatedly, but with partial signal loss. To study the signal depletion per readout, the nanoDots were exposed to 200 cGy with 6 MeV and 9 MeV beams. Without repositioning the nanoDot in the reader, signal depletion of nanoDot was observed by reading the nanoDots 100 times successively with a 10-second reading cycle. A graph of the signal depletion versus the sequential reading number was plotted, and a linear function was fitted to the data.

2.4.5 Signal fading over time

The decay in the OSL signal as a function of time post-irradiation was assessed by exposing the nanoDots to 200 cGy with 6 MeV and 9 MeV beams. A total of 17 nanoDots were prepared, of which 15 nanoDots were exposed to the corresponding beams, and the remaining dosimeters were used for background radiation monitoring. The first OSL reading was taken 24 h after irradiation to allow for decay of the phosphorescence signals observed immediately after irradiation [31]. The irradiated nanoDots were then read once per week for ten weeks. Simultaneously, two control nanoDots were read to monitor the accumulated background radiation. Each data point was corrected using a signal depletion correction factor and accumulated background radiation. A graph of the normalised OSL signal against days post-irradiation was plotted. A logarithmic function was fitted to the data, and the standard uncertainty was calculated.

2.4.6 Reproducibility of OSL readout and dosimeter

The reproducibility of the OSL readout was evaluated by randomly taking five nanoDots and delivering them at 200 cGy with 6 MeV and 9 MeV beams. The standard uncertainty provided by each dosimeter for various numbers of readings was compared to determine the readout reproducibility. In this study, the nanoDots were reused multiple times after bleaching as opposed to a single use. Therefore, the dosimeter reproducibility after long-term reuse of nanoDots was evaluated. To test this, the SCF for all nanoDots, except for four nanoDots used for the long-term stability of the OSL reader, was determined again following the method described in 2.4.1. A paired sample t-test was used to evaluate the differences in the data of old and new SCF for statistical significance.

2.4.7 Fabrication and test of nanoDot OSLD holder for remote dosimetry audit

The OSLD holder for the electron beam dosimetry audit was fabricated using PMMA with a density of 1.190 g/cm^3. The complete set of holders consisted of a stand, nanoDot OSLD disc, rod spacers, ring spacers, and screws (Figure 1). The stand was fabricated following the IAEA TLD standard stand [32] with a lead base to provide weight in water. The OSLD disc was designed with a 10 mm × 10 mm × 2 mm groove to fit into a single nanoDot and a watertight lid. Various ring spacer thicknesses (1, 2, and 10 mm) were used to adjust the irradiation depth of the nanoDots to correspond to the beam energy used. Two metal screws were used to open the nanodot disc lid. The scatter influence of the fabricated holder was investigated experimentally using the EBT 3 film by comparing the results to the IAEA standard holder for beams with energies of 6, 9, and 12 MeV.

2.5 OSL reader stability

The OSL reader was warmed for 30 min to ensure system stability before use. Following this, the readers' performance was monitored according to the established measurement standards. The measurement includes dark counts from the PMT tube (DRK), count calibration using a built-in Carbon-14 (^{14}C) radioactive source (CAL), and beam intensity from the LED. The measurement standard results were checked to ensure that they were within the specified limits for the DRK (less than 30 counts), CAL, and LED (within ± 10% of the average value). Additionally, a quality control (QC) test using standard nanoDots irradiated with a Srontium-90 beta source (^{90}Sr) was performed to determine the long-term stability of the reader.

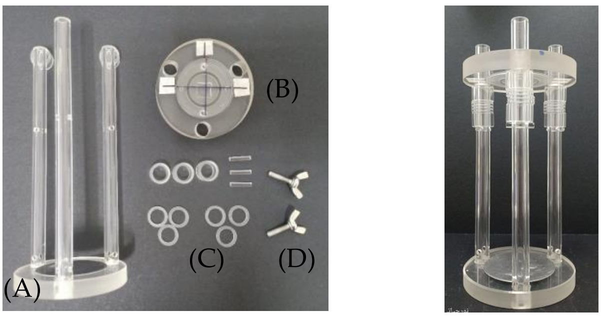

Figure 1*:* The PMMA OSLD holder for the electron beam audit. It consists of (A) a stand; (B) an nanoDot OSLD disc; (C) rod and ring spacers; (D) screws.

2.6 Preliminary dosimetry audit of electron beams

The primary objective of the dosimetry audits was to assess the accuracy of the absorbed dose delivered by the linac for electron beams under both reference and non-reference conditions. The audits involved six electron beams produced from four linacs at two radiotherapy centres. Prior to the audit, each centre received a set of instructions and materials including the irradiation procedure and form, a specified quantity of nanoDots for each beam (eight for irradiation and one for control), and a fabricated OSLD holder set. The centres were requested to irradiate the nanoDot in a water phantom using an OSLD holder at an absorbed dose of 100 cGy for the following conditions: (i) reference condition as defined by TRS 398, and (ii) non-reference condition at the beam's central axis with FS of 6 cm × 6 cm, 10 cm × 10 cm, and 15 cm × 20 cm at a depth of maximum dose, Z_{max} and SSD greater than 105 cm.

The measured absorbed dose (D) was calculated from the OSL signals using the following equation:

$$D = M \times SCF \times N \times k_{lin} \times k_{energy} \times k_{fade} \times k_{holder} \quad (1)$$

where M is the mean of the net OSL signals from the two nanoDots, SCF is the nanoDot sensitivity correction factor, N is the dosimetry system calibration coefficient of 0.001712 cGy ± 0.82%, k_{lin} is the dose-response linearity correction factor, k_{energy} is the energy correction factor, k_{fade} is the fading correction factor, and k_{holder} is the holder correction factor.

The audit results were expressed as the percentage deviation between the dose delivered by the radiotherapy centres and the absorbed dose measured from the nanoDots.

2.7 Estimation of measurement uncertainty

In accordance with Equation 1, an uncertainty analysis of the measured absorbed dose from nanoDots was carried out utilising the guidelines outlined in the "Guide to the expression of uncertainty in measurement" [33]. The sources of uncertainty and the corresponding numerical values of the random (Type A) and systematic (Type B) uncertainties were determined. The total combined standard uncertainty was calculated by summing the Type A and Type B uncertainties using a quadratic method.

3.0 RESULTS AND DISCUSSION

2.8 Establishment of dosimetric characteristics and correction factors

2.8.1 Sensitivity correction factor of nanoDot

Figure 2 shows the distribution of the SCFs of nanoDots subjected to a 6 MeV electron beam. After eliminating the two outliers, the SCFs ranged from 0.946 to 1.060, with a mean of 1.001 ± 0.25%. The nanoDots used in this study were obtained from the manufacturer and were pre-screened to ± 5% uniformity of sensitivity; however, the results revealed that 86 (94%) nanoDots were within this range. These findings are comparable with the published data by Retna Ponmalar et al. (2017), who reported the SCF distribution between 0.90 and 1.07, with 90% of the 200 nanoDots falling within that acceptance limit. Another study reported that 97% of 1000 nanoDots were within the acceptable limit, and the SCF distribution was between 0.930 and 1.134 [22]. These results help to justify that instead of using the SCFs provided by the manufacturer that were irradiated with Cesium-137 (^{137}Cs), users should determine the SCF experimentally for their applications. To minimise the uncertainty due to SCFs, selected nanoDots with sensitivities of ± 5% (ICRU 24, 1976) and ± 3% were subsequently utilised in the dosimetric characteristic study and electron beam dosimetry audit. Five nanoDots with SCF outside the acceptance limit were used for background radiation monitoring. Further analysis using a one-sample t-test was performed to assess whether the mean SCF in these nanoDots differed from the normal SCF, which was defined as 1.000. The assumption that the SCFs were normally distributed was met, as assessed by the Shapiro-Wilk test ($p = 0.811$). The mean SCF of 1.001, with a standard deviation of 0.024, was slightly higher than the normal SCF of 1.000; however, the difference was not statistically significant ($t(90) = 0.213$, $p = 0.831$). To achieve high dosimetry accuracy, SCF was required for each nanoDot in the following measurements.

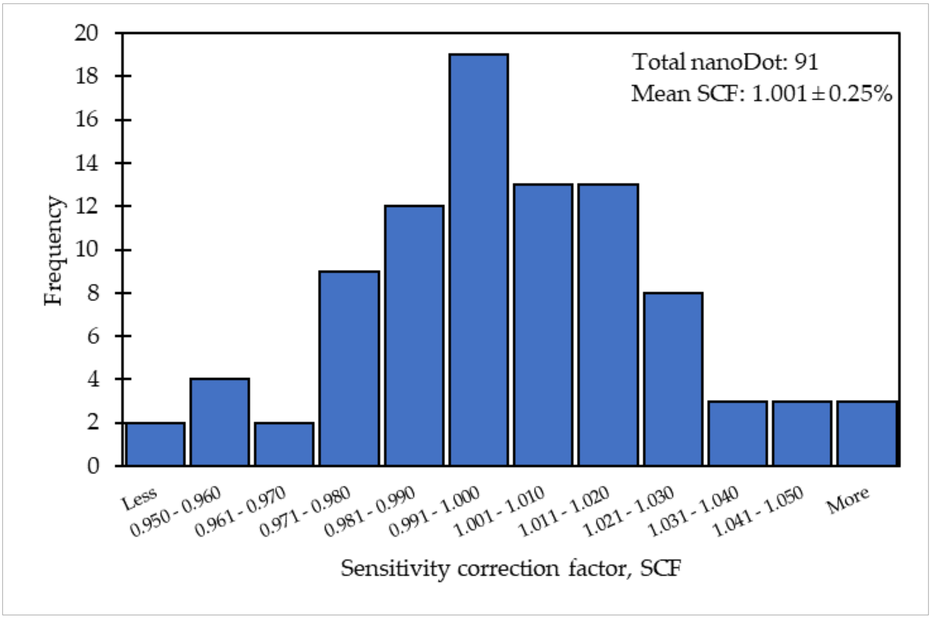

Figure 2: Histogram of the distribution of sensitivity correction factors of nanoDots subject to a 6 MeV electron beam.

2.8.2 Linearity of OSL signal with absorbed dose

The linearity of the OSL signal within a dose range of 50 cGy – 300 cGy for 6 MeV and 9 MeV was established. Overall, a gradual increase in the OSL signal was observed, with averages of 21.30% ± 4.49% and 20.80% ± 4.93% for each 25 cGy dose increment from 50 cGy – 300 cGy subject to the 6 MeV and 9 MeV beams, respectively. The results showed a linear OSL signal for the intended dose range, with an R^2 value of 0.9982 for both beams (Figure 3). Similar observations have been reported, in which the OSL signal was linear from 50 cGy – 300 cGy, with R^2 values ranging from 0.997 to 0.998 for 6 to 20 MeV beams [34]. According to previous studies, these results are comparable to those of photon beams, in which the OSL signal has a dose linearity of up to 400 cGy [35], [36], [37]. To obtain better accuracy in dose measurement, the values of k_{lin} over the dose range of 50 cGy to 200 cGy, normalised to 100 cGy, which is the reference dose used in the audit program, were determined (Figure 4). The k_{lin} values were 0.966 – 1.139 and 0.995 – 1.199 at 6 MeV and 9 MeV, respectively. From the SPSS output, the assumptions of a linear relationship between the absorbed dose and k_{lin} for each energy were met, as observed from the simple scatter plots. The linear regression models showed that there was a statistically significant difference between the absorbed dose and k_{lin} for 6 MeV and 9 MeV, with ($R^2 = 0.850$, $F(1,5) = 28.422$, $p = 0.003$) and ($R^2 = 0.646$, $F(1,5) = 9.134$, $p = 0.029$), respectively. These results indicate that the linear equations presented in Figure 4 must be applied to improve the accuracy of the dose calculation for the relevant nominal beam energies.

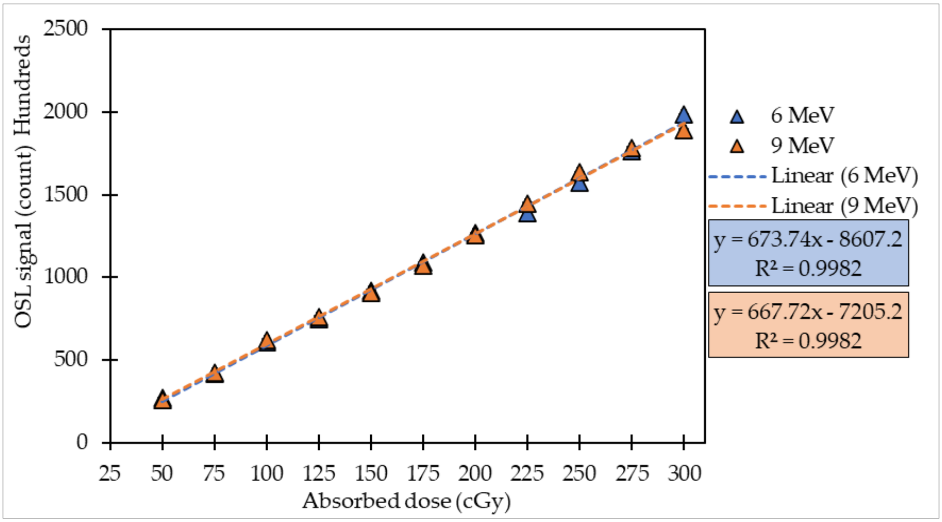

Figure 3: Linearity of the OSL signal for an absorbed dose range from 50 cGy – 300 cGy subjected to 6 MeV and 9 MeV electron beams. The dotted lines are linear function fits to the data, obtaining an R^2 of 0.9982 for both beams. The error bars were less than 955 counts, that is, smaller than the data points, so they do not appear in the graph.

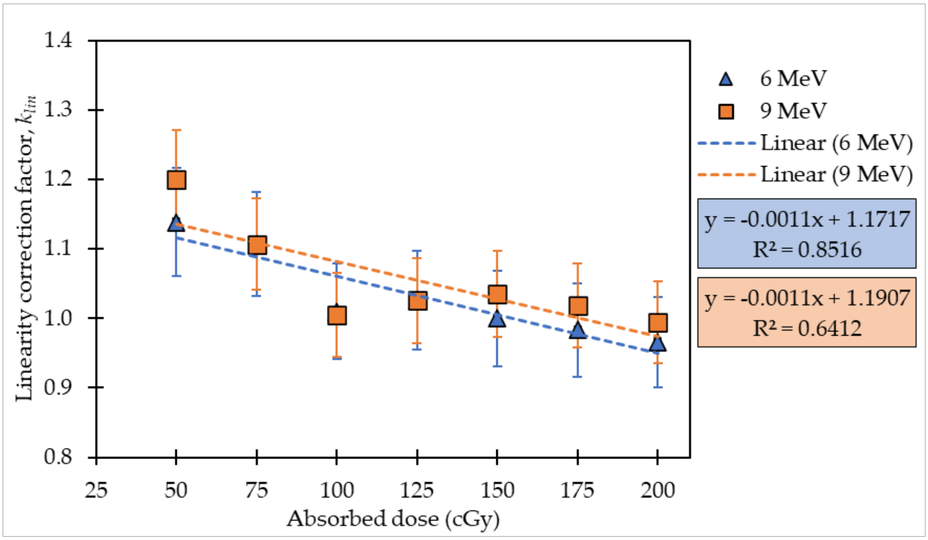

Figure 4: Linearity correction factors of nanoDots subjected to 6 MeV and 9 MeV electron beams for a dose range from 50 cGy – 200 cGy, normalised to 100 cGy. The dotted lines are linear functions that fit the data. Error bars represent standard uncertainty (k=1).

2.8.3 Beam energy dependency

The results for k_{energy} in comparison with those at 6 MeV are presented in Table 2. The nanoDot demonstrated high-energy dependency, particularly at a higher beam energy of 12 MeV, with a significant deviation of 4.08% compared to that at 6 MeV. This effect is precisely due to its non-tissue equivalent material (Al_2O_3:C) having a highly effective atomic number, Z_{eff} of 11.28, which makes it sensitive to different beam qualities. These findings are in line with those reported in the literature, where nanoDots exhibited a relative energy-dependent response for both photon and electron beams [23], [34], [38]. For radiotherapy dosimetry, the dosimetric material should have a Z_{eff} close to that of water or tissue (Z_{eff} = 7.4), and lithium fluoride doped with magnesium and titanium (LiF:Mg, Ti) with Z_{eff} ~ 8.2, is commonly used for this reason [39], [40]. However, the non-tissue equivalent of nanoDot is not an issue in radiotherapy dosimetry, as long as the k_{energy} for each beam energy is considered carefully in the dose calculation.

Table 2: Beam energy correction factor, k_{energy} in comparison with the 6 MeV beam.

Nominal electron beam energy (MeV)	Beam quality, R_{50} (cm)	k_{energy} in comparison with 6 MeV
6	2.47	1.000 ± 0.004
9	3.68	1.013 ± 0.005
12	5.02	1.041 ± 0.003

2.8.4 OSL signal depletion

After 100 consecutive readings, small signal reductions of 6 MeV and 9 MeV were observed for a dose of 200 cGy, with a similar value of 0.03% per reading (Figure *5*). These results indicate that the depletion rates were independent of the beam energy. In contrast, Ponmalar et al. (2017) reported a slight difference in the depletion rate of energy from 6 MeV to 20 MeV, where the percentage reduction in the signal for the same dose was 0.04% and 0.05% after 200 readings, respectively. The results are also comparable to previous findings by Dunn et al. (2013) and Wesolowska et al. (2017), where a signal depletion of 0.03% and 0.04% per reading in response to photon beams was reported. Where applicable, the linear equations presented in Figure 5 were used to correct the repeated readings in the following measurements, especially for signal fading and long-term stability of the OSL reader studies.

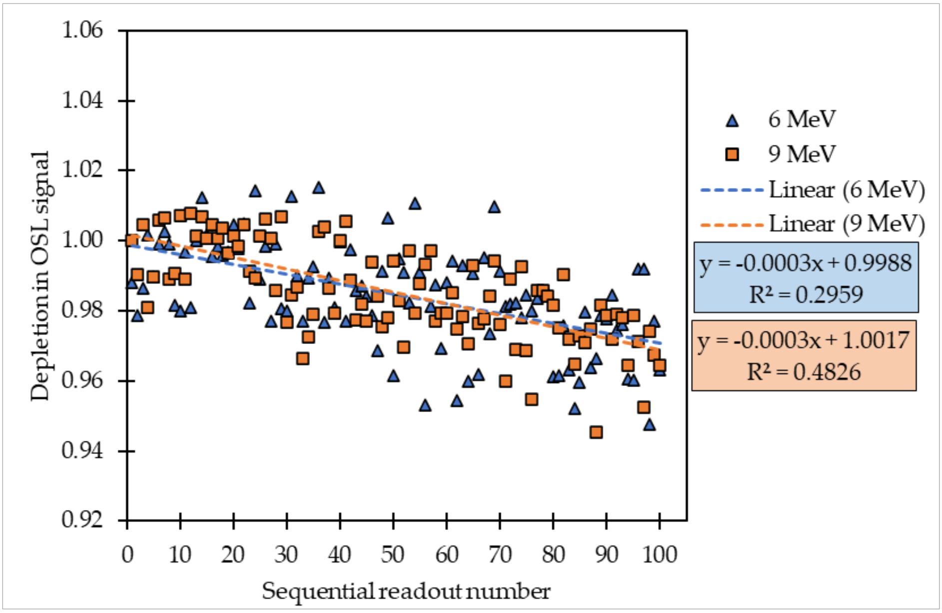

Figure 5: Signal depletion per readout for nanoDot subject to 6 MeV and 9 MeV beams. The dotted lines are linear functions that fit the data.

2.8.5 Signal fading over time

Figure 6 illustrates that OSL signal fading occurs logarithmically with time. The OSL signal fading was most noticeable within ten days of irradiation. After more time passes post-irradiation, the effect of OSL fading becomes more stable. The OSL fading exhibited a similar trend for all beams, regardless of the energy involved during irradiation. Over 70 days, the nanoDot signals exposed to 6 MeV and 9 MeV dropped by approximately 3.0% and 3.2%, respectively, with normalisation to day one post-irradiation. For comparison, the nanoDot fading reported by Dunn et al. (2013) was 3.5% six months after irradiation, normalised to the first day. Long-term fading of the OSL signal is an essential parameter in dosimetry audits, considering the one-month time frame required to complete the audit process. Therefore, a signal fading correction factor, k_{fading} (1/normalized OSL signal) should be applied in the dose calculation.

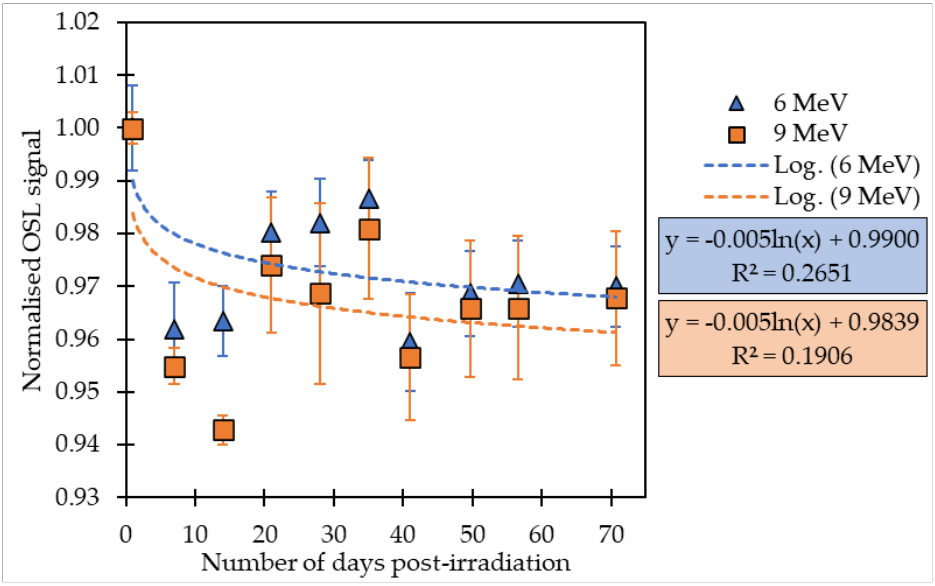

Figure 6: OSL signal loss over time normalised to day one post-irradiation of nanoDot subjected to electron beams with a constant absorbed dose of 200 cGy. The dotted lines are logarithm functions that fit the data. Error bars represent the standard uncertainty of 25 OSL readings, with the highest value of 0.017.

2.8.6 OSL readout and dosimeter reproducibility

The nanoDots showed consistent reproducibility for the readout and dosimeter. When the number of readings increased from 8 to 40, the readout reproducibility improved significantly, from 0.95% – to 0.51%. After five irradiation cycles, the dosimeter reproducibility was maintained at 0.72%. These results comply with the tolerance limit of ± 2% associated with a reliable dosimeter [41]. Overall, reproducibility can be better with multiple readings, and thus contributes to a smaller standard uncertainty of measurement. To achieve a standard uncertainty owing to a readout reproducibility of less than 1.0%, it is recommended to repeat the readings at least four times. In addition, the results of SCF reproducibility from a paired samples t-test demonstrated that there was no significant difference between old SCF (mean = 1.000, standard deviation = 0.023) and new SCF (mean = 1.002, standard deviation = 0.048); t(88) = -0.568, p = 0.572. Considering the changes in the nanoDot sensitivity after an accumulated dose limit of 10 Gy [26], [42], a new SCF should be implemented.

2.8.7 Holder correction factor

The result of the scattering influence showed no significant variation in response to the dose for the fabricated PMMA OSLD holder and IAEA TLD standard holder, with 0.29%, -0.32%, and 0.05% for the 6, 9, and 12 MeV beams, respectively. Therefore, the PMMA TLD holder correction factor, k_{holder} established by the IAEA was applied in the dose calculation. The k_{holder} for electron beams was calculated by Monte Carlo simulation and was essentially constant at 1.0019 ± 0.0008 for all 6 MeV – 20 MeV beams [32].

2.9 Stability of OSL reader

Throughout the study, the stability of the OSL reader was checked using the following parameters: The consistency of the dark current was (3.53 ± 0.25) counts, within the acceptance limit of less than 30 counts. The energy calibration and light intensity consistency from the LED were (4.21 ± 3.25) % and (1.68 ± 0.31) %, respectively, within the acceptable limit of ± 30%. The long-term stability of the OSL reader using standard nanoDots provided consistent data, with an average of − 0.85% and a standard uncertainty of 0.82%.

2.10 Preliminary audits for electron beams under reference and non-reference conditions

The results of the preliminary audit of the electron beams from the two radiotherapy centres are presented in Table 3. These results are well within the tolerance of ± 5%, as recommended in ICRU Report No. 24, except for two beams from Linac 2 for a non-reference condition of 6 cm × 6 cm FS. After the investigation, the cause of the deviation for Linac 2 was identified as a mistake in the positioning of the nanoDots at different irradiation depths. After follow-up irradiation, the results of Linac 2 were improved to 3.93% and 3.65% for 6 MeV and 8 MeV, respectively. Overall, the mean distribution of percentage deviations after follow-up irradiation was -1.66% ± 0.81% for the reference condition and -0.40% ± 1.49%, -2.92%

± -0.80%, and-0.80% ± 0.93% for the non-reference condition at 6 cm × 6 cm, 10 cm × 10 cm, and 15 cm × 20 cm FS, respectively.

Table 3: Preliminary audit results of electron beams for reference and non-reference conditions for first-round irradiation.

Linac	Nominaal beam energy (MeV)	Deviation of measured dose relative to delivered dose (%)			
		Reference condition	Non-Reference condition		
			6 cm × 6 cm	10 cm × 10 cm	15 cm × 20 cm
1	6	-1.79	-4.36	-4.18	-2.91
	9	-2.40	-0.52	-4.15	3.13
2	6	0.21	-44.32	-1.35	-0.46
	8	1.22	11.22	-0.15	-0.79
3	6	-3.60	-4.37	-4.10	-0.54
4	6	-3.59	-0.72	-3.59	-3.21

2.11 Measurement uncertainty

The combined standard uncertainty for determining the measured dose from the nanoDot is summarised in Table 4. The main source of uncertainty in this study arises from the ionisation chamber calibration (0.62%) and the stability of the OSL reader (0.47%). The combined standard uncertainty was 1.41% for a coverage factor, *k* of 1, which aligns with the findings of Wesolowska et al. (2017), who suggested a 1.46% combined standard uncertainty for photon beam audits. Conversely, Kumar et al. (2020) reported a much higher combined standard uncertainty of 3.3%.

Table 4:Combined standard uncertainties of measured absorbed doses from nanoDots.

Uncertainty component	Relative standard uncertainty (%)	
	Type A	Type B
Calibration of the nanodot OSLD dosimetry system		
Determination of absorbed dose from PPC 40 ionization chamber	-	0.62
Water phantom positioning during irradiation	-	0.04

Dosimeter positioning during irradiation	-	0.04
Dosimeter readout	0.26	-
Stability of OSL reader	0.47	-
Combined standard uncertainty (*k*=1)	**0.54**	**0.62**
Determination of the absorbed dose from nanodot OSLD		
Calibration coefficient of the nanodot OSLD dosimetry system	0.54	0.62
Dosimeter readout	0.26	-
Sensitivity correction factor	-	1.00
Stability of OSL reader	0.47	-
Dose-response linearity correction factor	0.07	-
Beam energy correction factor	0.03	-
Signal fading correction factor	0.05	-
Holder correction factor	0.08	-
Combined standard uncertainty (*k*=1)	**1.41**	-

4.0 CONCLUSIONS

A preliminary study was conducted to develop and evaluate a method for remote dosimetry auditing of electron beams under reference and non-reference conditions using a nanoDot OSLD dosimetry system. The dosimetry system performed admirably in terms of dosimeter sensitivity, readout reproducibility, and stability of the OSL reader. Additionally, correction factors were implemented for dose-response linearity, beam energy, signal fading, and a PMMA-fabricated OSLD holder to improve dose accuracy. With a coverage factor of *k*=1, the combined standard uncertainty of the dose measurement was 1.41%. The preliminary audit of electron beams from two radiotherapy centres showed percentage dose deviations within the ICRU Report No. 24 tolerance of ± 5%, except for three beams. There was a marked improvement in the dose deviation after subsequent irradiation. This pilot study laid the groundwork for the subsequent development and successful implementation of a method for conducting remote dosimetry audits of electron beams using nanoDots. Thus, it is now possible to conduct a national electron beam dosimetry audit on a regular basis.

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CONFLICT OF INTEREST STATEMENT

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