Introduction of optically stimulated luminescence based postal audits for radiation protection level dosimetry at Secondary Standard Dosimetry Laboratories

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HIGHLIGHTS

- OSL dosimeters were commissioned for the audit system at radiation protection level.
- OSLDs showed good reproducibility and low signal fading.
- OSLD based audits for radiation protection calibrations have been successfully established.

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ABSTRACT

The IAEA has introduced an Optically Stimulated Luminescence Dosimetry (OSLD) system to conduct postal audits to Secondary Standard Dosimetry Laboratories (SSDLs) for radiation protection level. The audit independently checks $^{137}$Cs radiation protection air kerma calibrations provided by the SSDLs. The OSLD system has replaced the previously used TLD based audit for radiation protection.

The OSLD system used in the audit consists of nanoDot dosimeters and MicroSTARii reader (Landauer, IL, USA). Prior to introducing the audit service, an extensive commissioning process quantified the dosimeter reading reproducibility, signal depletion and fading, linearity of response to air kerma, individual sensitivities of OSLDs and optical annealing procedure for the dosimeters. In an audit run, the participating SSDLs are supplied with two dosimeter sets consisting of two lightweight holders each preloaded with two OSLDs. The participants are asked to irradiate them with 5 mGy air kerma free in air, following their standard laboratory procedures. The OSLDs returned to the IAEA are evaluated by the IAEA Dosimetry Laboratory.

The OSLDs demonstrated acceptable reading reproducibility of 1.75% and a signal depletion of 0.25% per readout. The OSLDs signal fading resulted in a signal decrease of 2.1% in the period from eight days to over 160 days post irradiation. A relative expanded ($k=2$) uncertainty of the OSLD determined air kerma was estimated to 3.08%. In two audit runs in 2015–2016, 29 SSDLs participated. The average ratio of the air kerma measured by the IAEA to the air kerma stated by the SSDL was 0.998 and the standard deviation of the distribution of results was 1.8%. All participants except one had results within the acceptance limits of ±7%. One laboratory with the result outside the acceptance limit was invited to a follow-up procedure with the aim to resolve the discrepancy.

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1. Introduction

Traceability to the International Measurement System is essential to maintain confidence and accuracy in radiation measurements. To assist in effective dissemination of dosimetry standards to IAEA Member States, the IAEA established, jointly with the World Health Organisation (WHO), the Network of Secondary
OSLDs are 0.2 mm thick and 4 mm active diameter plastic disks encapsulated in a 10 × 10 × 2 mm³ light-tight plastic case. The active component of the OSLD can be opened by the reader mechanism during the dosimeter reading process or it can be opened manually for optical annealing purposes. To ensure OSLDs are not exposed to light they are stored in light tight boxes.

Each dosimeter is labelled with a unique serial number and a barcode that automates the readout process and facilitates subsequent data manipulation and record keeping. At DOL, OSLDs are read with two MicroSTARii readers using Pulsed Optically Stimulated Luminescence (POSIL) technique (McKeever and Akselrod, 1999) and operating in an automatic light power stimulation mode. The reader's optical engine consists of a light emitting diode (LED), a photo-multiplier tube (PMT) for recording the generated luminescence, optical filtration components that allow for effective spatial separation of the stimulation light from the luminescence light, and a photodiode.

The recommended warm up time of the reader is 60 min after which a two-step internal daily consistency check is done, firstly with an empty OSLD reader drawer to check the intrinsic noise, PMT and diode counts, and afterwards the control OSLD readings are done to assess the reader stability.

OSLD readouts are saved in the computer's internal database, together with the relevant information about the reading parameters. Upon finalising the reading session, the readings are exported and related air kerma calculations are done with spreadsheet programs.

2.2. Irradiation unit, setup and dosimetry equipment

All OSLDs irradiations, performed at the Dosimetry Laboratory, were done with the photon beam from the 137Cs source in the OB 85 irradiator (STS Buchler, Germany). At the distance of 2 m from the source, the central 15 cm diameter part of the beam has less than ±0.3% nonuniformity. The air kerma rate at the reference point of the radiation protection level 137Cs gamma beam is regularly measured with a DOL reference standard ionization chamber (LS-01 connected to a Keithley 6517 electrometer) calibrated at BIPM.

To enable simultaneous irradiation of the larger number of OSLDs and increase the efficiency during the OSLD characterisation process, a square PVC foam holder, with dimensions 11 × 11 × 0.5 cm³, was designed to accommodate 25 OSLDs.

The holder with OSLDs, was always positioned during irradiation with its reference point at 2 m distance, using the calibration bench, a laser beam defining the central beam axis and a telescope.

2.3. OSLD system commissioning

During the commissioning process, a series of measurements were carried out to determine the reading reproducibility, signal depletion per readout, signal fading, linearity of response, individual dosimeter's sensitivity correction factors and optical annealing procedure.

2.3.1. Reading uncertainty and system reproducibility

The reproducibility of the OSL system was evaluated from readings of 200 dosimeters irradiated with 5 mGy air kerma. They were read by three different operators and with two readers. The reading reproducibility of individual OSLDs was estimated as the mean value of relative experimental standard deviations (SD) calculated from 5 consecutive readings for each OSLD. The reproducibility of the OSLD system was expressed as the relative SD of all mean readings of 200 dosimeters. For the uncertainty budget estimation of the air kerma derived for OSLD readings, the average value of the standard deviations of the mean, determined from 5 OSLD readings, was calculated as the standard reading uncertainty.

2.3.2. Signal depletion

Optical stimulation of the OSLD empties only a fraction of the trapped charge from the dosimeter. As multiple readouts were used to estimate the signal after the irradiation, the signal depletion...
correction factor was experimentally determined. In two sets of measurements, eight OSLDs irradiated to 5 mGy air kerma were read one hundred times in sequence. After each five consecutive readings of an OSLD, the reader’s drawer was opened, dosimeter removed from the drawer and inserted again for the next reading, thus replicating the procedure carried out during the actual reading of the audit participant dosimeters. The depletion of the OSLD signal per reading was obtained as an average value of the slopes of the linear functions fitted to the normalised successive readings of OSLDs.

2.3.3. Signal fading

The spontaneous decrease of the OSLD signal with time after the irradiation was measured with twenty OSLDs irradiated with 5 mGy air kerma. Although readings started right after the irradiation, for the audit purposes the most important is the evaluation of long-term fading. The fading function, characterising the change in the signal with time, was obtained as a fit of a power function to the measured data determined from the regular readings in laboratory conditions, in the period of over 160 days.

2.3.4. OSLD sensitivity correction factor (SCF)

An individual dosimeter sensitivity correction factor (SCF) is defined as the ratio of the sum of average readings for OSLDs irradiated in a group \((n = 25)\) and the individual average reading of the OSLD under consideration. It accounts for individual differences in sensitivity. The readings are corrected for the depletion and average background. Prior to each audit run, the SCF values were re-evaluated; the dosimeters annealed, irradiated and the new SCFs were calculated.

2.3.5. Linearity

The linearity of the OSLDs response to air kerma was tested in the range from 1 mGy to 10 mGy. For each air kerma value of 1, 3, 5, 7 and 10 mGy, ten OSLDs were irradiated.

2.3.6. Optical annealing

OSLDs can be optically annealed to deplete the trapped electrons/holes by exposing them to light. The annealing was performed in the custom made optical annealing cabinet, based on the parallel rows of light emitting diodes (LED) attached to the top and bottom of the cabinet. Uniform illumination is achieved with a glass shelf in the mid-position of the cabinet on which the opened dosimeters can be placed. Four OSLDs irradiated to 1.5 and 10 mGy air kerma were read out to estimate the relative signal decrease as a function of the accumulated time to light exposure. In that process, irradiated OSLDs were opened and exposed to light in the cabinet for a predefined time, then closed and read to record the residual signal.

2.3.7. Air kerma calculation algorithm

The air kerma measured by the audit participant OSLD, \(K_{air(SSDL)/OSLD}\), was calculated from the following equation:

\[
K_{air(SSDL)/OSLD} = (M - B_s) \cdot N_k \cdot SCF \cdot \left(\frac{f_{fad}^r}{f_{fad}^p}\right)
\]  

where \(M\) is an average value of the OSLD signal from five readings, \(B_s\) is the correction for travel background radiation (Background Sent), \(N_k\) is the average OSLD calibration factor, SCF is the sensitivity correction factor and the last factor is the fading correction factor defined as a ratio of the values of fading functions for the reference \((f_{fad}^r)\) and the participant \((f_{fad}^p)\) dosimeter. The average calibration factor was calculated from the readings of six reference dosimeters for each readout session consisting of three participant dosimeter sets according to the equation:

\[
N_R = \left(\frac{1}{n}\right) \sum K_{air}^r \frac{R_i - B_l}{SCF}
\]  

where \(n\) is the number of reference OSLDs, \(K_{air}^r\) the reference air kerma of 5 mGy, \(R_i\) is the average reading of a reference dosimeter, \(B_l\) is the average background radiation count (Lab Background) recorded by the dosimeters which were kept together with reference dosimeters in the lead shielding after irradiation at DOL. All readings used for calculating quantities in equations (1) and (2) were corrected for depletion.

2.4. Dosimetry system uncertainty estimation

A combined uncertainty of the IAEA OSLDs measurement of the air kerma consists of the following uncertainty components related to: (i) the reference air kerma measured by the ionisation chamber at the DOL, (ii) the OSLD system calibration and (iii) the evaluation of the audit participant’s OSLD.

The uncertainty in determination of the air kerma at a point of irradiation of OSLDs has its origin mainly in the uncertainty of the DOL standard ionisation chamber calibration. In addition, the chamber positioning and readout value contribute to the uncertainty.

The second source that contributes to the uncertainty is the readout of the OSL dosimeters. A standard uncertainty (Type A) was estimated from the evaluation of distributions of 5 readouts done during commissioning. This value was used for the assessment of uncertainty associated with the OSLD calibration as well as the one associated with the readout of participants’ dosimeters. The similar statistical analysis of repeated measurement cycles was carried out to determine the uncertainty components of the SCF for individual OSLDs, travel background counts for OSLDs sent to the participants (Background Sent) and OSLDs kept in the laboratory (Lab Background). The uncertainty of the fading correction factor was calculated by assuming that a distribution of typical delays for reference and participant OSLDs is similar to the delays known from a large number of previous TLD audit evaluations. The parameters of a power function fit to experimental fading data and their uncertainties were used to calculate the uncertainty in the fading correction. The mean of the distribution of fading correction uncertainties, calculated from the distribution of typical delays for reference and participant OSLDs, was taken as the uncertainty in the fading correction. The evaluation of the uncertainties is based on the Guide to the Expression of Uncertainty in Measurement (JCGM 100:2008, 2008).

2.5. OSLD air kerma audit

The OSLD postal dose audit service for radiation protection available to the SSDLs in IAEA Member States, similarly to TLD audits, operates in annual runs forming a cycle of three years to cover all SSDLs having radiation protection level service. A dosimeter set for the SSDL consists of two lightweight PVC foam standard holders, with dimensions \(5 \times 3 \times 0.5\) cm\(^3\), each preloaded with two non-irradiated OSLDs, and two separate OSLDs to record environmental conditions during the transport and storage of the set. The holder can be easily fixed by a clamping device and positioned at a calibration distance free in air.

The participating SSDL also receive the irradiation instructions and data sheets to be filled in. The participants are asked to measure the air kerma rate at a calibration point, following their routine procedure, calculate the time to deliver 5 mGy at the calibration point and to irradiate the holders in air with OSLDs with 5 mGy air.
kerma. On receipt of irradiated OSLDs, they are stored in a lead safe and evaluated within 2–3 weeks by the IAEA Dosimetry Laboratory. Quality control checks are essential in providing a high level of quality of the audit service. During each audit run, the dosimeter sets are also sent to the PSDLs for irradiation to independently check the OSLD system performance. The SSDLs with results outside the acceptance limits of 7% are contacted with the aim of resolving the discrepancies, then also invited to participate again in the next audit run.

3. Results

3.1. Commissioning results

The OSLD reading reproducibility, estimated as the mean value of the distribution of experimental standard deviations (SD) of the mean values (n = 600 per reader), calculated from 5 readouts was 1.75%, and the standard reading uncertainty was 0.78% (k = 1).

In a batch of 200 OSLDs, the calculated SCFs varied from 0.893 to 1.069. The average value was 1.001 with a SD equal to 2.8% and the mean SCFs obtained with two readers were not significantly different (t-test, p < 0.05). Average SCF values obtained from three reading sessions and with two readers, were used in calculating the air kerma delivered to the dosimeters.

From the two sets of signal depletion measurements, performed prior to each audit run in 2015–2016, it was determined that each OSLD reading depletes the signal by 0.25% (Fig. 1).

The signal fading, determined from the consecutive readout sessions and normalised to the 8th day, was 2.1% after 160 days (Fig. 2).

As expected, no presence of non-linearity in the response to air kerma was observed in the range 1–10 mGy (Fig. 3).

About 20 min of light exposure in the annealing cabinet was necessary to decrease the signal of OSLDs irradiated with 5 mGy to the background signal level of less than 0.5% of the initial value. For OSLDs irradiated with 1 and 10 mGy, the exposure times to reach the background signal were 12 and 30 min, respectively.

3.2. Uncertainty budget

The analysis of the uncertainty for the measurement of the air kerma using OSLDs is shown in Table 1. The relative expanded (k = 2) uncertainty is 3.08%.

In previous audits with TLDs and the manual Harshaw 3500 TLD reader, the relative expanded (k = 2) uncertainty in the measurement of the air kerma was 3.4% (Pernicka et al., 2002).

3.3. Audit service results

The results of OSLD runs in 2015–2016 are depicted in Fig. 4. It shows the results of the ratio of the IAEA measured air kerma with the OSLD to the air kerma stated by the SSDL, $\frac{K_{\text{air}}(\text{IAEA})}{K_{\text{air}}(\text{SSDL})}\text{OSLD}$, for 29 SSDLs. One deviation outside the acceptance limits of 7% was observed and the follow-up process is underway. The mean ratio $\frac{K_{\text{air}}(\text{IAEA})}{K_{\text{air}}(\text{SSDL})}\text{OSLD}$ was 0.998 and the SD of the distribution of results was 1.8% excluding outlying results, while the mean ratio of the PSDL stated to the IAEA measured air kerma, $\frac{K_{\text{air}}(\text{PSDL})}{K_{\text{air}}(\text{IAEA})}\text{OSLD}$ for 5 PSDLs was 1.001 and the SD was 1.0%.

In the period 1999–2013, 294 $^{137}$Cs and 16 $^{60}$Co beam checks with a TLD system were carried out for SSDLs. The mean ratio of the

![Fig. 1. Signal depletion per readout over 100 readouts determined from the linear function fit to the normalised signal. Readings were recorded using the same procedure as in the audit measurements; the OSLD was inserted into the drawer, read five times, taken out and repositioned for the next readout.](image1)

![Fig. 2. Signal fading function determined as a fit of a power function to the experimentally measured response over 160 days. Each point is a mean value of twenty OSLDs and error bars represent the standard uncertainties in the reading of these dosimeters.](image2)

![Fig. 3. Air kerma response of OSLDs in the range 1–10 mGy. Each point is a mean value of ten OSLDs.](image3)
TLD measured air kerma at the IAEA to the air kerma stated by the SSDL, \( K_{\text{air(IAEA)}}/K_{\text{air(SSDL)}} \), for this period was 1.000 and the SD was 4.3% (Fig. 5).

When only TLD results (N = 289) within the acceptance limits of 7% are taken into account, the mean ratio is 1.001 and the SD is 2.6%.

During the same period, the PSDLs performed 30 reference irradiations of TLDs. These irradiations, used as an external check of the performance of the TLD system, resulted in the mean ratio \( K_{\text{air(PSDL)}}/K_{\text{air(IAEA)}} \) of 1.001 and the SD of 1.4%.

The audit results showed reduced SD of the distribution of ratios of the stated to the measured air kerma, from 2.7% in the initial 5-year period to 2.0% in the period 2009–2013, and 1.8% in the last two years of OSLD service. Similarly, the number of outlying results dropped from 13 in the first 5-year period to only 2 in the last 5 years of TLD audit service and 1 in OSLD audits in 2015–16.

4. Conclusions

A novel postal OSLD audit service at the radiation protection level has been successfully established to verify the \(^{137}\text{Cs}\) air kerma calibrations carried out by SSDLs. It replaced the TLD service that had been maintained for 15 years. The OSLD system has proven to be a reliable and practical system for remote postal air kerma audits. The reading of dosimeters and record keeping are simple and well implemented in the system, enabling thus the rapid audit data processing. OSLDs have shown acceptable reproducibility, low signal fading and linear response to air kerma. The methodology presented is applicable to air kerma calibration checks free in air and additional investigations would be required for its potential use for measurements on phantoms.

The results of the OSLD audit runs carried out in 2015–2016 show that all participating institutions, except one, are within the acceptance limits of ±7%, and therefore, in the future the reduction of ±7% acceptance limits might be considered.

From the retrospective analysis of the TLD and OSLD audit results it is evident that better accuracy has gradually been achieved during the course of time. Reduction in the number of outlying audit results and the reduced SD of the distribution of ratios of the stated to the measured air kerma values are observed when initial 5-years results are compared with the latest results.

References


