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Ancient TL

Beta dose rate reduction for the built-in ^{90}Sr/ ^{90}Y sources of Risø TL/OSL automated readers

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Abstract

Environmental dosimetry requires measuring doses, which are often below the range accessible with the commonly used built-in β-source of Risø TL/OSL readers. Al_2O_3:C Luxel® dosimeters were used to investigate irradiation cross-talk and attenuators as means to reduce the dose rate of the source. Irradiation cross-talk was found to be highly effective in reducing the dose rate but was not reproducible and resulted in dose recovery deviations of up to 80%. Four attenuator materials (PTFE, microscope coverslip glass, wine glass, and ABS plastic) were investigated with regard to their dose reduction capabilities. All materials resulted in good dose recovery results and allow building a standard reference dose response curve. Microscope cover glass reduces the dose rate by a factor of 3 for each 1 mm thickness. The material is transparent and does not have to be removed during measurement and is therefore recommended as attenuator of choice for dose rate reduction.

Keywords: Dose rate reduction, Risø source, Al_2O_3:C, OSL, Attenuators

1. Introduction

Al_2O_3:C dosimeters have become one of the most widely used luminescence dosimeters for environmental dose-rate assessment. The appeal of this dosimeter stems from its high sensitivity to radiation and linear behavior over a wide dose range from µGy to several Gy (Akselrod et al., 1990; Yukihara & McKeever, 2008). Al_2O_3:C has been used in various studies for retrospective dosimetry (McKeever et al., 1995; Bøtter-Jensen et al., 2000; Discher et al., 2021) and measurement of β dose rates to natural sediments (Göksu et al., 1999; Burbidge & Duller, 2003; Kalchgruber et al., 2002; Kalchgruber & Wagner, 2006; Durcan et al., 2015; Smedley et al., 2020). To determine the environmental dose absorbed by the dosimeters during burial, the signal is first measured in the laboratory, followed by irradiation of dosimeters for calibration (Kalchgruber & Wagner, 2006). A common instrument for this measurement and subsequent irradiation is the Risø TL/OSL-DA reader. The reader is often equipped with a 1.48 GBq ^{90}Sr/ ^{90}Y β-source, that delivers a dose rate of the order of 100 mGy/s to a sample when the source is open. Considering that signals from Al_2O_3:C dosimeters are very bright a dose rate of this magnitude can easily saturate the photomultiplier tube (PMT) of the reader after a few seconds of irradiation. The light reaching the PMT can be reduced by using an aperture. Alternatively, on can or correct for the dead time loss that causes saturation, in which case, there is a risk, however, of damaging the PMT. Furthermore, environmental radiation is classified under low level background radiation and dose-rates are typically less than 100 µGy/s (Burbidge & Duller, 2003). In routine environmental beta dose-rate assessment, dosimeters are buried for a period of few weeks to a year (Kalchgruber & Wagner, 2006). The cumulative absorbed dose measured even after a year has been reported to be comparable to the dose obtained after a 1s irradiation from the β-source of the reader (Kalchgruber et al. (2002)). Such short irradiation times are however not recommended since the rotating nature of the irradiation unit introduces a time offset and thus adds uncertainty to the given dose (Markey et al., 1997). Although Al_2O_3:C shows a linear behavior from µGy to few Gy it is not recommended to use larger irradiation times and to extrapolate the dose response to lower doses. Extrapolation is well known to lead to large errors in dose recovery, due to the relatively large impact of

the uncertainty in the intercept fitting parameter.

To reduce the dose rate of the beta source, Burbidge & Duller (2003) used bremsstrahlung radiation that is produced by beta particles from the source in closed position. This option greatly reduced the dose rate to about (0.687 ± 0.003) μGy/s at the dosimeter position and is therefore an effective method for assessing very low doses in the range of 10 μGy to about 1 mGy. However, when the goal is to assess medium doses ~ 1 – 100 mGy, bremsstrahlung requires long exposure times under the closed source; for example, it will take 4 hours to obtain a dose of 10 mGy. Such long exposure times are often not feasible when instrument time is limited. Additionally, this leakage radiation was reported to be maximum at a position different from the position directly under the source (see Fig.1) and asymmetric due to the asymmetric scattering of radiation (Kalchgruber et al., 2002). The radiation affects more than a quarter of all positions on the turntable and additional positions are impacted are impacted by leakage radiation from the alpha source for readers which have an alpha source installed as well. Consequently, it is only practical to irradiate and analyze one or two dosimeters at a time.

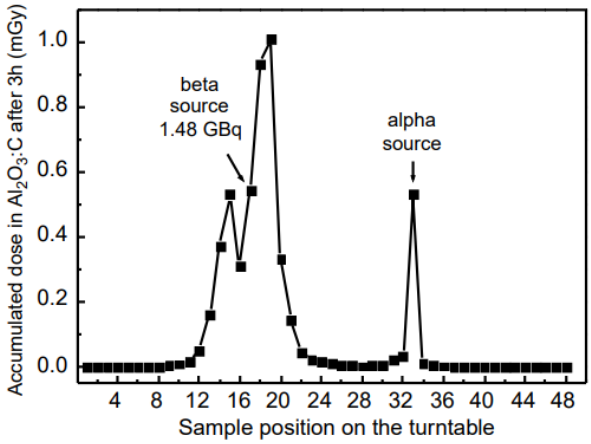

Figure 1. Accumulated dose due to leakage radiation in 3 h at various carousel positions in a Risø TL/OSL-DA-15 reader measured with Al_2O_3:C dosimeters, with both beta and alpha sources installed. The position underneath the beta source indicated on the plot is not the position of maximum dose. The position under the alpha source is also a hotspot as indicated on the plot (Fig. 4. from Kalchgruber et al. (2002))

Other options offered by the manufacturer include purchasing a second, weaker source or the reduction of dose rate by increasing source-sample distance using a separately sold dose rate kit. The kit consist of an aluminum filter, a brass ring and an aluminum spacer that can reduce the dose rate by a factor of ~ 10. However, this dose rate kit requires removing the built-in source from the irradiator for installation. The radiation safety regulations in many institutions require that a radiation safety officer perform this kind of procedure and thus might not be feasible if inserting or removing the kit is required several times a week.

A third option is the use of irradiation cross-talk. Irradiation cross-talk is defined as radiation exposure to dosimeters in the vicinity but not directly under the irradiation source, when the source is open. This effect has been investigated by various authors for quartz and Al_2O_3:C dosimeters and has been shown to be in the range of 0.006 – 0.25 % of the direct dose rate, depending on the specific reader and the irradiated sample (Bøtter-Jensen et al., 2000; Kalchgruber et al., 2002; Bray et al., 2002; Thomsen et al., 2006). Yet another option for dose rate reduction, which to our knowledge has not been investigated in detail, involves placing an attenuator directly on top of the dosimeter.

This paper investigates the latter two options of reducing the dose rate of the built-in β-source of the Risø reader: i) irradiation crosstalk and ii) attenuators. The major limitation with the absorber is the small distance between the bottom of the cup and the lid. This distance which can range from ~ 1.8 – 2.5 mm is reader specific. To this end, different materials of different thicknesses were investigated to arrive at the best option for the attenuator. The overall goal is to build a reference dose response curve that can be used for dose assessment of dosimeters buried in sediment for several weeks to a year.

2. Materials and methods

2.1. Dosimeters

The dosimeters used in this work are the Al_2O_3:C Luxel® dosimetry tapes cut into 6.0 mm diameter round pieces using a hole puncher (Fig.2). The Luxel® tapes are produced by Landauer Inc. and consist of 20 - 90 µm Al2O3:C grains sandwiched between two polyester sheets, resulting in a thickness of about 0.3 mm (Akselrod et al., 2000; Bøtter-Jensen et al., 2003). Prior to use, the dosimeters were bleached for 8-12 hours with light from a halogen lamp filtered with a Schott FSQ-GG-495 colored glass long-pass filter (thickness 3.0 mm) as recommended by Sawakuchi et al. (2008) to remove any background signal accumulated during storage and transport, if applicable. Between irradiation and measurement, the dosimeters were handled in a dark room with subdued red light for visibility and to prevent any bright light from resetting the dosimeters and placed in stainless steel cups.

2.2. Attenuators

Attenuators of different materials were investigated in this work as a way of reducing the dose rate of the β-source of the Risø reader. Four different attenuator materials were tested for their effect on the dose rate:

- a 10 mm diameter disk of clear glass, type “Libbey midtown white wine glass” produced by LIBBEY GLASS. The thickness of the disk is 1.4 mm and its density is 2.27 g/cm^3.
- two sets of round coverslips (microscope cover glass, density 2.42 g/cm^3), 12 mm diameter and 8 mm diameter respectively. Six of the 12 mm coverslips were stacked to get a thickness of 1.4 mm (including the

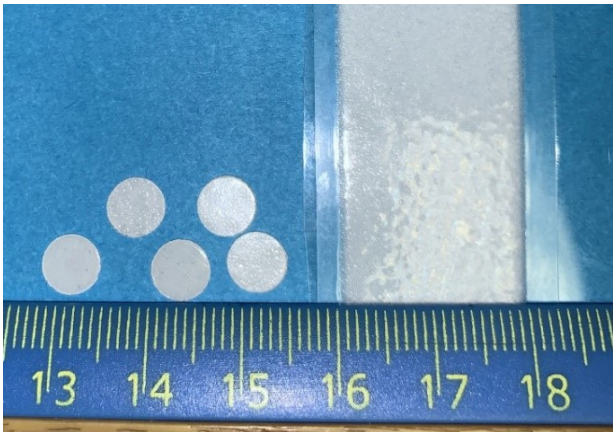

Figure 2. OSL Luxel® round punch-out and tape. The round punch-out was obtained by using a hole punch on the tape. The thickness of the dosimeter is 0.3 mm and diameter is 6.0 mm.

transparent tape used to hold the stack together). The actual thickness of the stack without the tape is 1.2 mm. Similarly, ten 8 mm coverslips were stacked to get a thickness of 1.9 mm and held together by glass glue. The use of a tape was not feasible in this case because of the smaller diameter. The coverslips are produced by BIPEE, China.

- Acrylonitrile-Butadiene-Styrene (ABS) (density: 1.17 g/cm^3) disks, 8.2 mm diameter with a recess of diameter 6.3 mm and depth 0.3 mm to hold the Luxel dosimeter (Fig. 5c). The thickness of the disk at the rim is 1.8 mm and 1.5 mm above the dosimeter in the recess. The material is produced and sold in the form of rods by US Plastic Corp®. Lima, OH.

- Teflon® (natural virgin PTFE, density 2.20 g/cm^3) disks with 8.2 mm diameter and thicknesses of 1.4 mm and 1.9 mm respectively. Teflon is produced in the form of rods by ePlastic®, San Diego, CA.

Photos of all the attenuators are shown in Fig. 4. The wine glass disk and the 12 mm diameter microscope coverslip glass stack were placed on top of the sample cup as shown in Fig. 3 (left) and 5a, leaving a small air gap of ∼0.4 mm between attenuator and dosimeter. The maximum total height of the combination is about 2.3 mm, which is the allowable distance between the bottom of the cup and the lid for this specific model of Risø reader. The 8-mm cover glass, and the ABS and Teflon disks were in direct contact with the dosimeters (Figs. 3b and 5b, c).

2.3. Irradiation and readout equipment

All measurements were performed with a Risø TL/OSL-DA-20 automated reader produced by DTU Physics, Denmark. The reader is equipped with a built-in nominal 1.48 GBq ^{90}Sr/ ^{90}Y source with a beryllium window located between the irradiator and the measurement chamber, which acts as a vacuum interface for the measurement chamber (Markey et al., 1997). The dose rate to Al_2O_3:C Luxel® in the position directly under the source is 72.7 mGy/s (±3%). Green LEDs (at 525 nm, 68 mW/cm^2) were chosen for optical stimulation of the dosimeters. Due to the high sensitivity of Al_2O_3:C, a 10 mm aperture was used in combination with 7.5 mm thick U-340 filters (transmission 340 ± 40 nm) in front of the PMT to reduce the possibility of over-saturation. The dosimeters were placed on stainless steel cups mounted on a turntable with 48 sample positions. Only every 5th position was used to prevent radiation crosstalk from affecting the dosimeters.

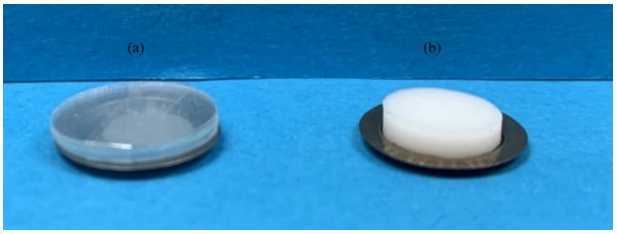

Figure 3. Absorber and sample cup combinations: (a) 12 mm diameter microscope coverslip glass stack on top of the sample cup with a dosimeter and (b) 1.9 mm PTFE disk placed inside the sample cup directly on top of the dosimeter.

2.4. General read-out procedure

The measurement procedure is as follows. Irradiation steps varied with experiment and are described in detail below.

1. Irradiation with beta source:
   (a) indirect irradiation using cross talk (see section 3.1)
   (b) direct irradiation, with or without attenuator (see section 3.2)
2. Remove attenuator, where applicable
3. OSL with green diodes for 500 s at 30°C, record one data point every 1s; signal S
4. Test dose irradiation
   (a) indirect irradiation using cross talk (see section 3.1)
   (b) direct irradiation, without attenuator (see section 3.2)
5. OSL with green diodes for 500 s at 30°C, record one data point every 1s; signal S_T

The test dose accounts for variation in parameters such as dosimeter sensitivity, dosimeter mass, and equipment sensitivity (Murray & Wintle, 2000; Yukihara et al., 2005). OSL intensity was obtained from the integrated signal of the first 10 s of stimulation, and the background from the last 10 s of stimulation. The test-dose corrected signal S/S_T and its uncertainty is calculated for each dosimeter. Each dosimeter is only used once.

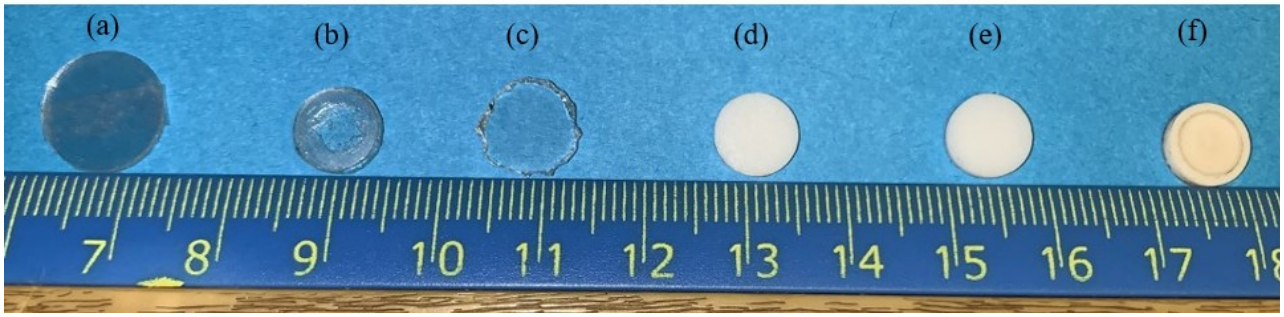

Figure 4. Absorber materials used in this study. From the left, (a) microscope coverslip glass stack (diameter = 12 mm, thickness = 1.4 mm), (b) microscope coverslip glass stack (diameter = 8 mm, thickness = 1.9 mm), (c) wine glass disk (diameter = 10 mm, thickness = 1.4 mm), (d) PTFE disk (diameter = 8.2 mm, thickness = 1.4 mm), (e) PTFE disk (diameter = 8.2 mm, thickness = 1.9 mm), and (f) ABS disk (diameter = 8.2 mm, thickness = 1.8 mm, also showing the 0.3 mm recess for the dosimeter).

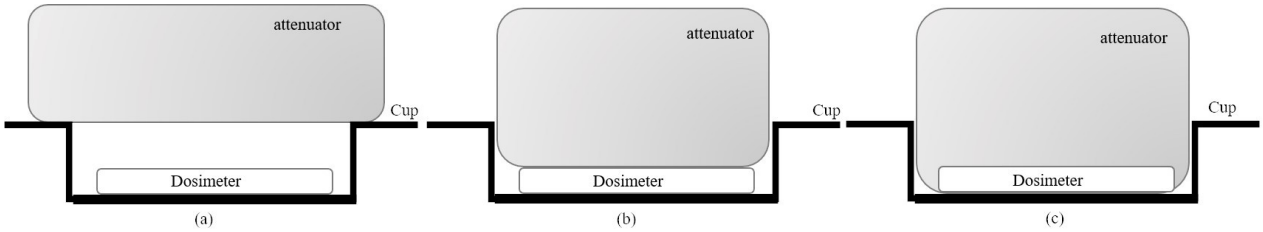

Figure 5. Three Configurations of sample cup-dosimeter-attenuator combination. Configuration (a) was used for the 12mm diameter coverslip glass stacks and the 10 mm diameter wine glass, since their diameters exceed the 8.3 mm diameter of the recess in the sample cup. Configuration (b) was used for the PTFE disks and the 8 mm diameter coverslip stack, and (c) was used for the ABS disk with recess.

3. Results

3.1. Indirect irradiation with radiation cross-talk

3.1.1 Estimation of cross-talk dose-rate

In our first set of experiments, we investigated the use of next-position irradiation ("cross-talk") as described by Kalchgruber et al. (2002), as a method of extending the range of the dose-response curve to low doses in the μGy region. No attenuators were used for this set of experiments. The position adjacent to each dosimeter was irradiated with specific doses ranging from 200 – 3000 s (3 dosimeters per dose point) and subsequently implementing the readout procedure described in section 2.4 using a test dose of 250 s, also via cross-talk. A linear fit was used to determine the resulting dose response. In a second step, 3 separate dosimeters were irradiated directly for 1 s. Their 250 s indirect test-dose corrected signal was compared to the dose response. The cross-talk irradiation time equivalent to 1 s direct irradiation was determined to be 2078 s (±8%) (see Fig. 6). In other words, the cross-talk dose rate of the Risø reader is about 0.05% that of direct irradiation.

3.1.2 Effect of dosimeter positioning on reproducibility

The purpose of dose-response curves is generally for dose recovery. For environmental dosimetry the dosimeters are irradiated during burial and the test-dose corrected signal is then compared to an established dose response curve to determine the absorbed dose. Radiation cross-talk changes considerably between adjacent positions (Fig. 1). Dosimeters buried in sediments and then placed in the reader for measurement might not all be in exact same position on the cup. There is also the possibility of random shift in the position of the dosimeter in the cup during measurement procedure. To test the impact of positioning on our results, 3 dosimeters were irradiated with cross-talk doses of 250 s, 450 s and 800 s

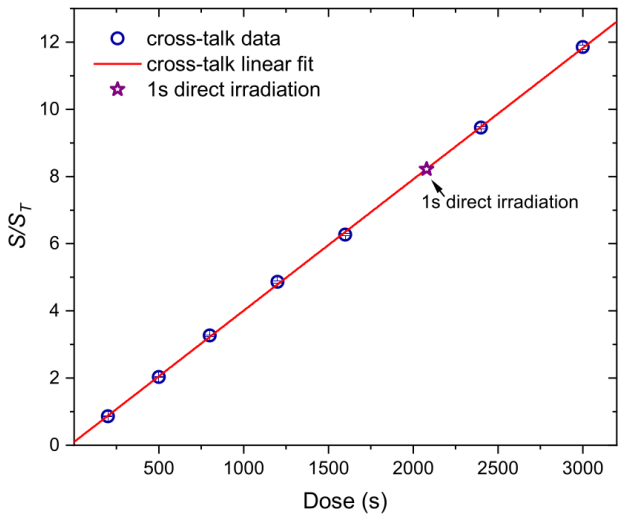

Figure 6. Reference dose–response curve of Al_2O_3:C dosimeter built up with the β-source of the Risø reader (Risø TL/OSL-DA-20) using cross-talk for indirect irradiation. The red line indicates the linear fit of the irradiation cross-talk S/S_T vs. equivalent dose data while the purple star symbol represents the 1s direct irradiation data.

Protocol	Known Dose (s)	Recovered Dose (s)	Recovery Ratio
Dosimeter "stayed in reader" between irradiation and measurement	250	254 (± 4%)	1.016
	450	455 (± 2%)	1.011
	800	802 (± 2%)	1.003
Dosimeter removed, stored for 4h between irradiation and measurement	250	107 (± 9%)	0.428
	450	585 (± 2%)	1.300
	800	1483 (± 1%)	1.854

Table 1. Accuracy of dose recovery when dosimeters remain in the reader after irradiation, versus brief removal and re-insertion of dosimeters.

respectively. The three dosimeters were read immediately without opening the reader using the readout procedure. Another set of 3 dosimeters, used to mimic external irradiation, were removed from the reader subsequent to irradiation and stored for 4 hours in a dark room to simulate transport and storage, before they were read using the readout procedure. The doses recovered from these dosimeters using the dose response curve were compared to the known doses and results are given in Table 1

Table 1 shows that the measurement procedure is suitable for recovering doses with a precision of better than 2%, and that random shifts during measurement have little impact on the results. For the dosimeters that were removed from the reader and stored for 4 hours, measured doses show large deviations up to 85%. Yukihara & McKeever (2006), reported that UV emission from Al_2O_3:C increases with the time elapsed between irradiation and measurement. In order to remove the effect of wait time, a similar test, but with an equal wait time of 5 min for all dosimeters was conducted. In this test, 10 dosimeters were irradiated with radiation cross-talk for 500 s and the signal was measured using the readout procedure, including test-dose application via cross-talk. For 5 out of the 10 dosimeters, the reader was not opened, but there was a 5 min delay between irradiation and measurement. The other set of 5 dosimeters was irradiated in the reader, removed and stored for 5 minutes, before signal measurement and test-dose correction. For each of the two sets, consisting of 5 dosimeters each, the average recovered dose and its standard error was calculated. The relative standard error for dosimeters removed from the reader is about 19% compared to 0.6% when there was no removal of the dosimeter, again showing that removal of dosimeters from the reader has a significant impact on the reproducibility and accuracy of dose recovery.

3.1.3 Summary of cross-talk results

Table 1 shows that our recovered doses differ from the known dose by about 30 – 85% when the dosimeter is removed from the reader and stored for 4 hours before measurement, compared to 2 – 4% for dosimeters that remained in reader throughout irradiation and measurement with no wait time in between. For the latter, it is impossible to isolate what part of this deviation is due to removal of the dosimeters and what part is due to increase in UV signal with time after irradiation. According to Yukihara & McKeever (2006), the UV signal increase after 4 hours is about 33%. While this can explain some of the deviation seen, it is important to mention that for the 250 s irradiation, the recovered dose was about 57% less than the known dose. This cannot be explained by the UV effect. Additionally, the test by Yukihara & McKeever (2006) that showed the increase of UV signal with measurement time after irradiation was performed with 20 Gy. We do not know if this effect also occurs for very low doses like those measured here and to what extent. Furthermore, our second test eliminated effects of wait-time, but it also showed poor reproducibility when the dosimeters were removed, further indicating that removal of the dosimeter introduces some variability to the result

3.2. Dose rate reduction using attenuators

In a second set of experiments the dose-rate of the source was reduced by placing the absorber materials described in section 2.2 between source and dosimeter. For this set of experiments direct irradiation was used as opposed to the cross-talk used above. Unless otherwise noted, the attenuators used for this investigation are the 1.9 mm PTFE disk, 1.2 mm microscope coverslip glass stack, 1.4 mm wine glass disk and the 1.8 mm ABS plastic disk.

3.2.1 Dose rate reduction factor and reproducibility

To measure the amount by which the attenuator reduces the dose rate, i.e. the "dose rate reduction factor," a dosimeter was exposed to a fixed dose of 10 s without the attenuator and then the readout procedure as described in section 2.4 was performed with a test-dose of 4 s (given without the attenuator) to obtain (S_1/S_T). In a second step, the same dosimeter was irradiated with the attenuator inserted for (S_2/S_T). The ratio $k = (S_1/S_T)/(S_2/S_T)$ corresponds to the *dose rate reduction factor* of a specific attenuator used, where S_1 represents the signal from exposure without the attenuator ma-

Attenuator description	k	$k_t(mm^{-1})$
10 mm diameter, 1.4 mm thick Wine Glass disk	4.11 ± 0.04	2.94 ± 0.04
12 mm diameter, 1.2 mm thick Microscope Coverslip stack	3.61 ± 0.03	3.02 ± 0.04
8.2 mm diameter, 1.4 mm thick PTFE disk	3.34 ± 0.04	2.39 ± 0.03
8.2 mm diameter, 1.5 mm thick ABS plastic disk	2.07 ± 0.04	1.38 ± 0.03
8.2 mm diameter, 1.9 mm thick PTFE disk	5.33 ± 0.07	2.81 ± 0.04
8 mm diameter, 1.9 mm thick Microscope Coverslip stack	5.97 ± 0.10	3.14 ± 0.06

Table 2. Dose rate reduction factors k for the absorber materials investigated. The mean was calculated from 6 dosimeters per attenuator material, the uncertainties represent the standard error. k_t is the dose reduction factor per thickness

terial, where S_1 represents the signal from exposure without the attenuator and S_2 represents the signal from exposure with the attenuator. The results for the various attenuators is presented in Table 2. For easier comparison the reduction factor per 1 mm thickness, k_t is listed as well

To test reproducibility in absorber placement, for each absorber material 10 dosimeters were irradiated for 10 s. The same absorber stack was used in each case to eliminate possible variation between stacks of the same material. The test dose corrected signals, normalized to the average value for each material are presented in Fig 7. Table 3 lists relative standard deviations for all materials, including experiments without absorber and results for an experiment with 10 different coverslip stacks.

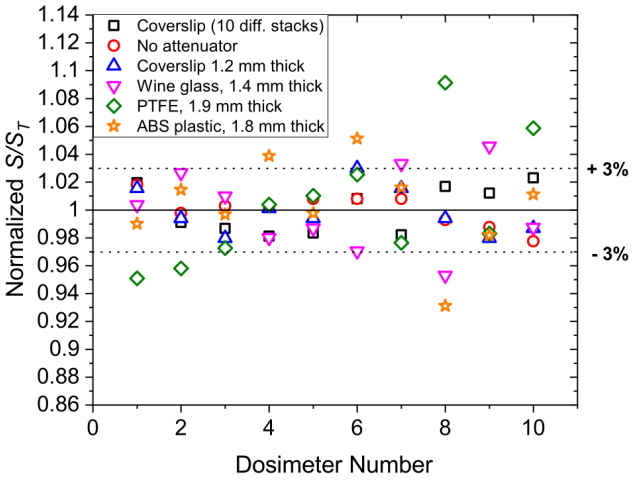

Figure 7. Absorber reproducibility. The same absorber stack was used for 10 dosimeters per material. Test dose corrected signals were normalized to the average value for each material. For comparison, data obtained without absorber and data obtained with 10 different coverslip stacks are shown as well. The normalization line (bold line) and the ±3% spread from the mean lines (dotted lines) are also indicated

Attenuator description	$\frac{\sigma}{\mu}(\%)$
PTFE, 1.9 mm	1.4
Coverslip 1.2mm thick	0.6
Wine glass, 1.4 mm	0.9
ABS plastic, 1.8 mm	1.0
No attenuator	0.4
Coverslip (10 different stacks)	0.5

Table 3. Absorber reproducibility. Relative standard deviations for 10 dosimeters per material. Data obtained without absorber and data obtained with 10 different coverslip stacks are shown as well.

3.2.2 Dose response/Calibration curve and dose recovery

The overall goal of this study is to use the built-in source of the Risø reader to build a dose response that will be used as reference curve for externally irradiated dosimeters. Dose response curves for the different attenuators were built, by exposing three dosimeters per given dose to 10 different doses in the range 1 – 100 s (with attenuators). The actual dose given to each dosimeter will depend on the attenuator used. Attenuators were removed after irradiation and before measurement, since some of the attenuators are opaque. Dose responses for uncorrected and test-dose corrected signals are shown in Fig. 8. Yukihara et al. (2005) and Akselrod et al. (2000), reported linearity only for the uncorrected dose response in this dose range. In our case, both responses are linear in this dose range. Although, the corrected dose response shows a better linearity compared to the uncorrected dose response.

The accuracy in dose determination using the dose response curves in Fig. 8 was assessed by giving known doses to 4 dosimeters each (with the attenuator in place), then measuring the dose as if the dosimeters had absorbed an unknown burial dose. Doses were recovered based on S/S_T values and also the uncorrected S values. The recovered dose is then compared to the known dose using dose recovery ratio. The dose recovery results are presented in Table 4.

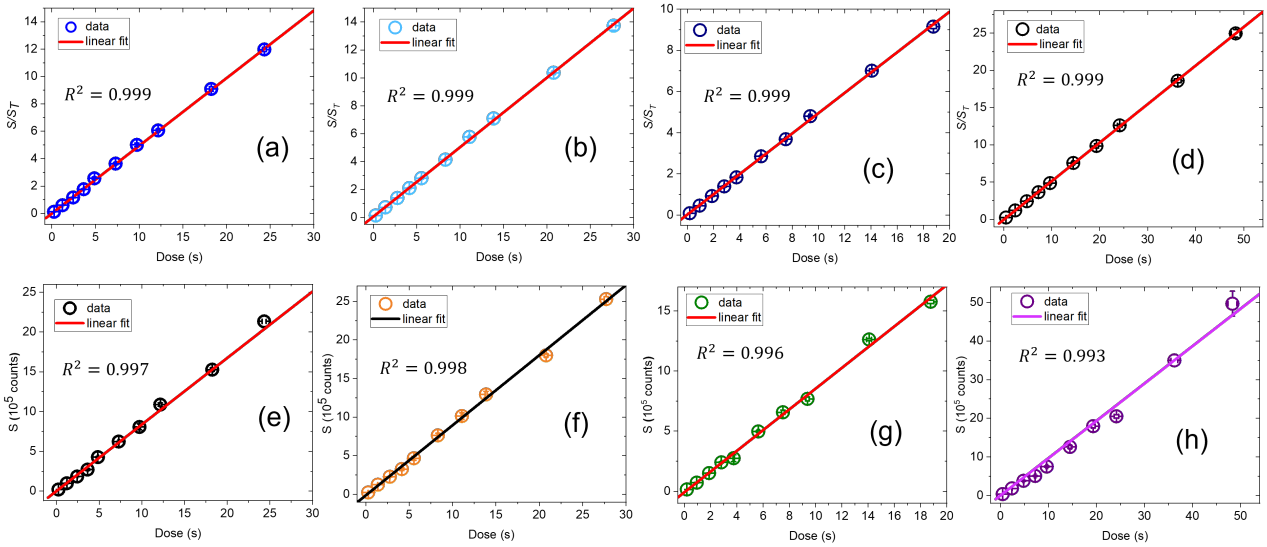

Figure 8. Test dose corrected (upper row) and uncorrected (lower row) dose responses of Al_2O_3:C irradiated with wine glass attenuator (a and e), microscope coverslip glass (b and f) PTFE (c and g) and ABS (d and h). Each data point represents the average and standard error for 3 dosimeters.The adjusted R^2 is also represented to show the goodness of the fit

Attenuator	**Known Dose (s)**	**test-dose corrected**		**uncorrected**	
		Recovered dose (s)	**Recovery Ratio**	**Recovered dose (s)**	**Recovery Ratio**
PTFE	8	8.30 ± 0.06	1.04	7.83 ± 0.10	0.98
	17	17.97 ± 0.12	1.06	17.57 ± 0.23	1.03
	43	44.84 ± 0.28	1.04	40.62 ± 0.53	0.95
	77	81.59 ± 0.51	1.06	78.07 ± 1.01	1.01
Coverslip glass	8	8.18 ± 0.05	1.02	7.50 ± 0.08	0.94
	17	17.22 ± 0.10	1.01	15.62 ± 0.16	0.92
	43	44.36 ± 0.25	1.03	44.16 ± 0.45	1.03
	77	73.81 ± 0.42	0.96	68.87 ± 0.70	0.89
ABS plastic	8	7.88 ± 0.03	0.99	7.14 ± 0.18	0.89
	17	16.90 ± 0.07	0.99	15.20 ± 0.38	0.89
	43	42.02 ± 0.16	0.98	38.88 ± 0.96	0.90
	77	76.35 ± 0.29	0.99	78.64 ± 1.95	1.02
Wine glass	8	7.65 ± 0.05	0.96	6.50 ± 0.078	0.81
	17	16.63 ± 0.10	0.98	15.64 ± 0.16	0.92
	43	42.91 ± 0.24	1.00	44.52 ± 0.46	1.04
	77	74.95 ± 0.43	0.97	67.87 ± 0.69	0.88

Table 4. Summary of dose recovery for irradiation with attenuator. Average recovery ratios for the test-dose corrected data are (1.05 ± 0.01)for PTFE, (1.01 ± 0.02) for coverslip glass, (1.01 ± 0.02) for ABS, and (0.98 ± 0.01) for wine glass.

The goal is to compare externally irradiated dosimeters with the calibration curves. It was therefore imperative to test if calibration curves built with attenuators can be used to recover doses administered without an attenuator. 12 dosimeters were irradiated without attenuator to assess if the attenuator itself influences the dose recovery. It is important to note that the test dose in the readout procedure must be the same as the test dose in the readout procedure used to build the dose response curve. Using the known dose reduction factors (see Table 2) and the test-dose corrected dose response curves (Fig. 8), measured and given doses were compared (Table 5).

Known Dose (s)	PTFE		coverslip glass		wine glass		ABS plastic	
	Recovered dose (s)	Recovery ratio	Recovered dose (s)	Recovery ratio	Recovered dose (s)	Recovery ratio	Recovered dose (s)	Recovery ratio
1	1.00 ± 0.02	1.00	0.95 ± 0.02	0.95	0.97 ± 0.02	0.97	0.97 ± 0.06	0.97
2	2.08 ± 0.04	1.04	1.98 ± 0.04	0.99	2.03 ± 0.03	1.02	2.01 ± 0.13	1.01
3	3.20 ± 0.06	1.07	3.05 ± 0.06	1.02	3.12 ± 0.05	1.04	3.1 ± 0.2	1.03
4	4.22 ± 0.07	1.06	4.02 ± 0.08	1.01	4.12 ± 0.07	1.03	4.1 ± 0.3	1.02
5	5.33 ± 0.09	1.07	5.07 ± 0.10	1.01	5.19 ± 0.08	1.04	5.15 ± 0.33	1.03
6	6.26 ± 0.11	1.04	5.96 ± 0.12	0.99	6.10 ± 0.10	1.02	6.06 ± 0.38	1.01
7	7.41 ± 0.13	1.06	7.04 ± 0.14	1.01	7.22 ± 0.12	1.03	7.17 ± 0.45	1.02
8	8.45 ± 0.15	1.06	8.03 ± 0.16	1.00	8.23 ± 0.13	1.03	8.17 ± 0.52	1.02
9	9.76 ± 0.17	1.08	9.28 ± 0.18	1.03	9.51 ± 0.15	1.06	9.44 ± 0.60	1.05
10	10.63 ± 0.19	1.06	10.11 ± 0.20	1.01	10.36 ± 0.17	1.04	10.29 ± 0.65	1.03
11	11.74 ± 0.21	1.07	11.16 ± 0.22	1.01	11.44 ± 0.18	1.04	11.35 ± 0.72	1.03
12	12.67 ± 0.22	1.06	12.05 ± 0.24	1.00	12.35 ± 0.20	1.03	12.26 ± 0.78	1.02

Table 5. Dose recovery results for dosimeters irradiated without attenuator using the dose-response curves in Fig 8, produced from the S/ST data for irradiation with attenuators. The average recovery ratios are (1.05 ± 0.01) for PTFE, (1.00 ± 0.01) for coverslip glass, (1.03 ± 0.02) for wine glass, and (1.02 ± 0.01) for ABS plastic.

4. Discussion

4.1. Dose rate reduction using irradiation cross-talk

The irradiation cross-talk on the position adjacent to the irradiated position as measured here is about 0.05% of the direct dose. This is a little higher than the 0.04% reported by Kalchgruber et al. (2002) for Al_2O_3:C dosimeters and 8 times higher than the 0.006% reported by Bray et al. (2002) for quartz discs. But it is about 3 times lower than the 0.17% reported by Bøtter-Jensen et al. (2000) for quartz coarse grain. This result confirms previous observation by Kalchgruber et al. (2002) that values of cross-talk depend on the individual reader, the sample holder and the dosimeter material used.

Dose recovery tests resulted in excellent agreement between given and measured dose, when the reader remained closed between irradiation and measurement (Table 1). However, Table 1 also illustrates that a reference dose response built with irradiation cross-talk is not suitable for externally irradiated dosimeters. When dosimeters are removed from the reader between irradiation and measurement, recovered doses deviate 50-80% from the expected values. Recovered doses were well below and also well above the expected values.

This high variability in measurement response is suspected to be partly due to the increase in UV luminescence signal with time of measurement after irradiation that was reported by Yukihara & McKeever (2006), due to the 4-hour wait period before the dosimeter was read, which was done to simulate external exposure of the dosimeters. However, even this effect doesn't fully explain the huge deviation observed as can be seen from the the 19% compared to 0.6% reproducibility observed for the case where the dosimeters were taken out of the reader before measurement compared to when they were not even when the wait time before measurement were the same. Similar variation has been reported by Vargas (2011). She reported a 9% relative standard deviation for a reproducibility test on a single dosimeter that underwent twelve 1.26 Gy irradiation/measurement cycles when the reader is opened, and the dosimeter is exposed to room light from a weak red bulb between irradiation and measurement. Our result for a similar test using 10 dosimeters yielded a reproducibility of 1%. Vargas also reported high variability for a fading test where the dosimeter was taken out of the reader and kept in a dark case for a period before measurement. She concluded that this effect is due to change in the position of the dosimeter on the cup from one irradiation-measurement cycle to another (Vargas, 2011).

It can be argued that in the case of cross-talk, where scattered radiation is used, the dose has a significant dependence on the exact position of the dosimeter in the sample holder. We therefore recommend that irradiation crosstalk, when considered as an option for dose rate reduction, should be tested for reproducibility and dose recoverability first.

4.2. Dose rate reduction using attenuators

Dose rate reduction with attenuators depends as expected on the density and thickness of the material (Table 2). The microscope coverslip glass stack provides the highest dose rate reduction per thickness at a factor of 3 per mm, followed by the wine glass, then the PTFE. The lowest dose rate reduction per thickness is that of the ABS rod which also has the lowest density among the materials investigated. The microscope coverslips and wine glass have the additional advantage of being transparent compared to the PTFE and ABS disks that are opaque. A transparent attenuator will

allow OSL measurements to be conducted without opening the reader to remove the attenuator before measurement. i.e., measurement will be automatic, requiring no user intervention until completion. Additionally, the microscope coverslip glass is the cheapest material investigated (US$10 for a pack of 100).

Reproducibility test for all attenuators presented in Fig.7. shows that 83% of the S/S_T values are within $\pm$ 3% of the mean. The overall relative standard error of the distribution is 0.5%. Yukihara et al. (2005) reported 0.7% for Luxel® dosimeters, and Burbidge & Duller (2003) reported 2.1% for Al_2O_3:C chips. This proves that the use of the attenuator doesn't introduce any substantial uncertainty to the measurement process. The relative standard error when a single coverslip stack was used for 10 dosimeters and when 10 different coverslip stacks were used are 0.6% and 0.5% respectively. The average thickness of the 10 coverslip stacks was calculated to be (1.40 $\pm$ 0.02) mm. This indicates that the coverslip stacks exhibit uniform response, even though there might be a slight nonuniformity in the glue used to bind the slips into a stack.

Attenuators allowed building a dose response for lower doses than usually accessible with the most commonly used built-in source. Dose response of Al_2O_3:C dosimeters is more linear and accurate for all attenuator materials when test-dose corrected signals were used compared to when the uncorrected signal was used, as evident from the dose recovery result in Tables 4 and 5. The results in Table 4 indicate that on average, the dose response curve based on the test-dose normalized signal S/S_T yields better dose recovery results than that based on the uncorrected signal S. On average, the dose recovery ratios of doses recovered using S/S_T data is 1.00 ± 0.01 with a maximum of 1.05 $\pm$ 0.01 (for PTFE) compared to 0.94 $\pm$ 0.02 with a maximum of 0.91 $\pm$ 0.05 (for wine glass) for the uncorrected signals. Dose responses from S/S_T data have a slightly higher adjusted R^2 value (0.999) than those of the S data (0.993 – 0.998). Additionally, the use of a test-dose for Al_2O_3:C Luxel® corrects for sensitivity variations between dosimeters, when they are punched out from the same Luxel® strip. Dose recovery from direct irradiation, yielded promising results as well. A higher deviation was generally seen for the PTFE attenuator. On average, the dose recovery ratio for the direct irradiation are 1.05 $\pm$ 0.01 for PTFE, 1.00 $\pm$ 0.01 for microscope coverslip, 1.03 $\pm$ 0.01 for wine glass, and 1.02 $\pm$ 0.01 for ABS plastic.

5. Conclusion

Irradiation crosstalk and attenuators were investigated as methods for reducing the dose rate of the built-in β-source of the Risø TL/OSL reader. For the Risø TL/OSL system used in this study, the irradiation crosstalk dose rate is about 0.05% of the value for direct irradiation. While, it was possible to extend the dose range to lower doses, dose recovery tests for dosimeters removed and re-inserted in the reader resulted in deviations of 50 – 80%. One possible explanation was attributed to an increase in UV luminescence with measurement time after irradiation. Another possible reason for the large deviations is a change in the position of the dosimeter on the cup during handling of the carousel which led to the conclusion that response to cross-talk irradiation might be sensitive to dosimeter position. However, more tests need to be performed to quantify the positional dependence of cross-talk irradiation.

The use of low-cost attenuator materials, though limited in thickness, provides a cheap and reliable alternative for dose rate reduction for the Risø TL/OSL reader. Four attenuator materials were investigated: PTFE, microscope coverslip glass, wine glass and ABS plastic. All materials resulted in good dose recovery results and allowed building a standard reference dose response. Microscope cover glass reduces the dose rate by a factor of 3 for each 1 mm thickness. The material is transparent and does not have to be removed during measurement and is therefore recommended as attenuator of choice for dose rate reduction.

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Reviewer

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