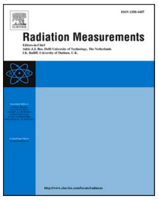
Radiation Measurements 196 (2026) 107717

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas



Retrospective dosimetry based on red Thermoluminescence (RTL) of a single resistor from mobile phones

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ARTICLE INFO

Keywords:
Retrospective dosimetry
Red thermoluminescence
Resistors from mobile phones

ABSTRACT

In the framework of the European Project CONFIDENCE („COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs"), the dosimetric properties of alumina (Al_2O_3) substrates of surface-mount resistors placed on mobile phone circuit boards were used to further develop a new retrospective dosimetry method. Resistors showed a strong emission due to the Cr^{3+} emission at a wavelength of 695 nm, thus enabling Thermoluminescence (TL) measurements in the red detection window (RTL). The resulting strong increase in sensitivity, as compared to the earlier protocols in TL and OSL with either blue or UV light detection, allowed to establish a new protocol which is optimized for the low-dose region (10-100 mGy) and is based only on a single resistor. The single resistor can be potentially replaced, leaving the phone intact. Possible parameters affecting the precision of the method such as confounding signals intrinsic to the material (zero-dose), signal loss with time (anomalous fading), and uncertainty related to the instrumentation were explored. Irradiation trials on intact smartphones demonstrated that dose assessment down to 20 mGy and 40 mGy is possible at the single resistor level, for measurements up to several days and 30 days after exposure, respectively.

1. Introduction

In case of a radiological emergency, people would not be equipped with proper devices for ionising radiation monitoring and conventional methods for assessing the accident dose would not be available (ICRU, 2002). Therefore, ideal targets for retrospective dosimetry techniques might be all those personal items that, for their dosimetric properties, can be used as fortuitous dosimeters when meeting specific requirements (Woda et al., 2012). In the last ten years investigations focused on common objects worn or kept close to the body in everyday life, such as clothes made of various types of fibers, cigarettes, banknotes and coins (Sholom and Mckeever, 2014; Sholom et al., 2011), as well as portable electronic devices (Fleuriot and Bassinet, 2024; Discher et al., 2023; ICRU, 2019; Beerten et al., 2009). The latter represent a valuable and challenging source of information, since the electronic components placed on the circuit boards, like inductors and surface mount resistors (SMRs) contain Aluminum oxide (Al_2O_3) or alumina substrate. Luminescence properties of alumina have been largely investigated with optically stimulated luminescence (OSL), reaching a certain level of maturity and standardization (Bassinet et al., 2014). Especially for resistors, different protocols to prepare and measure the samples are nowadays well known, and inter-laboratory comparisons on reconstructing pre-delivered unknown low doses (<1 Gy), medium doses (1–2 Gy) and high doses (>2 Gy) succeeded in about 90% of cases (Bassinet et al., 2014). OSL readout from resistors was also largely proved to be reliable in terms of sensitivity, low intrinsic background and homogeneity of fading characteristics (Geber-Bergstrand et al., 2018; Bassinet et al., 2014; Mrozik et al., 2014b; Ekendahl and Judas, 2012; Beerten et al., 2011; Inrig et al., 2008). On the contrary, only few studies have examined in depth the usability of Thermoluminescence (TL) (Panda et al., 2025; Lee et al., 2024; Mesterházy et al., 2012; Beerten et al., 2009; Beerten and Vanhavere, 2008) on such of electronic components. This lack of knowledge might have an impact on all those national radiation protection agencies, which have only ordinary TL readers available, not equipped with specific optical stimulation units. Moreover, previous investigations on the TL signals from resistors usually referred to measurements in the UV or blue detection window from a multi-component approach. Target of the measurements are groups of up to ten resistors for a sufficient sensitivity (Ademola and Woda, 2017). One of the limitations of this method lies in the fact that the phone will

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https://doi.org/10.1016/j.radmeas.2026.107717
Received 6 August 2025; Received in revised form 17 April 2026; Accepted 8 May 2026
Available online 9 May 2026

be broken and, consequently, the procedure might be generally not well accepted by the population. Furthermore, another drawback is related to the construction tendency of more modern phones that encompass fewer and fewer resistors to sample.

In a recent study Woda and Discher (2026) tried to potentially overcome the mentioned issues by investigating the luminescence emission of the resistors in a new detection window (Red Thermoluminescence – RTL). Detailed spectral studies in the same work and also by Lee et al. (2017) have demonstrated that the TL signal, irradiated with 1 kGy (Lee et al., 2017) or 0.1 kGy (Woda and Discher, 2026) has emission bands at 330 nm, 420 nm, attributed to oxygen vacancy centers (F+ and F centers) and a strong emission in the red (695 nm). The latter emission, which in un-doped Al_2O_3 had been attributed to the trace impurity of trivalent chromium Cr^{3+} ions (Kusuma et al., 2019) surpasses in intensity the other emissions by two orders of magnitude. Preliminary investigations of the dosimetric properties the Cr^{3+} emission in Woda and Discher (2026) showed a linear dose response for the dosimetric peak at 185 °C but also a minor but significant dose overestimation of around 7% in a dose recovery test under idealized conditions. This was ascribed to a reduction in sensitivity by the continuous cycles of dosing and measurement, which warranted further investigation. The theoretical detection limit on thermally annealed samples using 4-10 resistors was estimated to be below 1 mGy but the existence of zero dose (intrinsic background dose) signals in unexposed samples increased this value to around 10 mGy. The added value of using red TL of resistors for dose assessment, compared to TL in the blue wavelength range or OSL, was thus not necessarily seen to be able to decrease the detection limit but to be able to decrease the number of resistors, while maintaining a comparable level of sensitivity.

In the present study this idea was followed up to develop for the first time a new measurement protocol on a single resistor type “0402” (sizes 1 mm × 0.5 mm x 0.35 mm), thus with the potentiality to be non-destructive. A sampling procedure on a single component might allow its replacement after measurement, thus leaving the phone operational and not damaged. Hence, the issue of general acceptability of the method by the public is taken into account. The use of a single (resistors) detector for dose measurement implies a number of specific issues, such as variability of zero dose signals and variability of fading rate at the single resistor level that must be addressed for a reliable application. Furthermore, the reason for the observed de-sensitization of the red TL with measurement cycles and ways to overcome this by improvement in the sample preparation protocol were investigated. Finally, the reconstruction of individual doses with RTL technique was optimized in the low dose-range (10 – 100 mGy), to cover a dose range typical for the external exposure of the population following a nuclear emergency and validated in a number of trial irradiations using intact smartphones.

2. Materials and methods

The surface mount resistor type “0402” were extracted from electronic circuit boards of different phone models and brands. Except for a preliminary investigation on the cleaning procedure carried out in white light, the sample preparation was entirely executed in dark room conditions, under subdued light, to avoid any light-induced transfer of charges from deep traps into the dosimetric trap (Beerten et al., 2009). After the extraction, the samples were cleaned and, with the ceramic side facing upwards, placed in stainless steel cups (ø = 10 mm) sprayed lightly with silicon oil to ensure that the component do not move or fall off in the process of movement. The RTL measurements were carried out with the Hamamatsu H7421-40 photomultiplier tube (PMT) of the “LEXSYG Research” luminescence reader developed by Freiburg Instruments. The PMT offers a high sensitivity in wavelength from 300 nm to 720 nm, and the detection of the red light emission was further optimized by using the detector in combination with a glass short pass filter Schott KG3 (3 mm thickness) and a long pass filter type Schott OG 570 (3 mm thickness). TL measurements were performed in a nitrogen atmosphere to minimize the risk of oxidation of the heating plate and the sample itself. For a heating rate of 2 °C s^{-1}, the RTL glow curve shows three peaks at around 80-100 °C, 180 °C and 330 °C (Fig. 1). Only the 180 °C peak is useable for dosimetric purposes (Woda and Discher, 2026). In order to remove the lower temperature TL peak, which can also be detected in the blue wavelength range (Woda et al., 2010; Beerten et al., 2009), samples were treated with a preheat at 120 °C for 10 s with a heating rate of 2 °C s^{-1}. The same heating rate was used for the TL glow curves, from which signals were determined by integrating the curves from 125 °C to 180 °C.

For the dose response, fading study and the assessment of eventual confounding factors influencing the dose assessment protocol with RTL (e.g. instrument offset, background correction), samples were irradiated with the built-in β-source of $^{90}Sr/^{90}Yr$ of the luminescence reader. Trial irradiations on intact phones were carried out with the ^{137}Cs gamma source Amersham Buchler OB20 of the radiation facilities of the Helmholtz Zentrum München (HMGU). Phones were irradiated free in air in air kerma reference conditions, with the display glass facing the source and with a 2 mm thick Perspex plate placed in front of the phones for build-up. Samples were located at 1-m distance with respect to the source and irradiated with doses from 20 mGy up to 5 Gy (air kerma values). After irradiations, the phones were disassembled in the laboratory (under dark room conditions), and resistors were extracted, cleaned, dried and measured at different times after the exposures, from a few hours to almost one month later.

The same ^{137}Cs source was also used to calibrate the built-in $^{90}Sr/^{90}Y$ β-source of the Lexsyg reader using resistor substrates from a sample kit (AGL Technology GmbH), which were irradiated in kerma reference conditions with a dose of 1 Gy. Samples were measured one day after gamma irradiation, then irradiated with the beta source of the reader, stored again for one day and measured again. In this way, RTL signal loss due to fading (see section 3.6) cancels out. This gave a dose rate for resistors of (19.4 ± 0.7) mGy s^{-1} for a reference date of 01/06/2019.

When calculating the dose from a calibration curve, the error attributed to the dose was generally assessed by choosing the uncertainties from either the weighted or unweighted linear fit to the calibration curve data, depending on which approach provided the larger uncertainty value in order to provide a conservative estimate.

3. Results and discussion

3.1. Sample preparation procedure

The cleaning efficiency of 20 min acetone procedure described in Ademola and Woda (2017) and also used in Woda and Discher (2026) was tested by evaluating the reproducibility of the RTL signals. Samples targeted were resistors extracted from circuit boards, possibly characterized by the presence of soldering mask residuals, and resistors from a commercially available sample kit from AGL Technology GmbH, adhesive free. The sample preparation was performed under condition of normal white light. Several cycles of irradiations either at 1 Gy or 400 mGy and subsequent RTL measurements were performed. A systematic and continuous decrease in sensitivity was observed, as shown in Fig. 2 (left and right panel).

The decrease in sensitivity was more pronounced for samples extracted from the phones (up to 10%), compared to the samples taken from the kit, and is attributed to a possible ineffectiveness of the cleaning procedure. Therefore, other two substances commonly used in printed circuit boards cleaning and rework were considered: Methyl Ethyl Ketone (MEK) and propanol. In addition, in order to reduce the most pronounced sensitivity change (5-6%) after the first readout possibly due to a phototransfer effect (Ademola and Woda, 2017; Woda et al., 2012), the sample preparation was performed in subdued red light conditions. Results are reported in Fig. 3.

Cleaning the samples in an ultrasonic bath for about 20 min with propanol resulted in the least decrease in sensitivity during the repeated

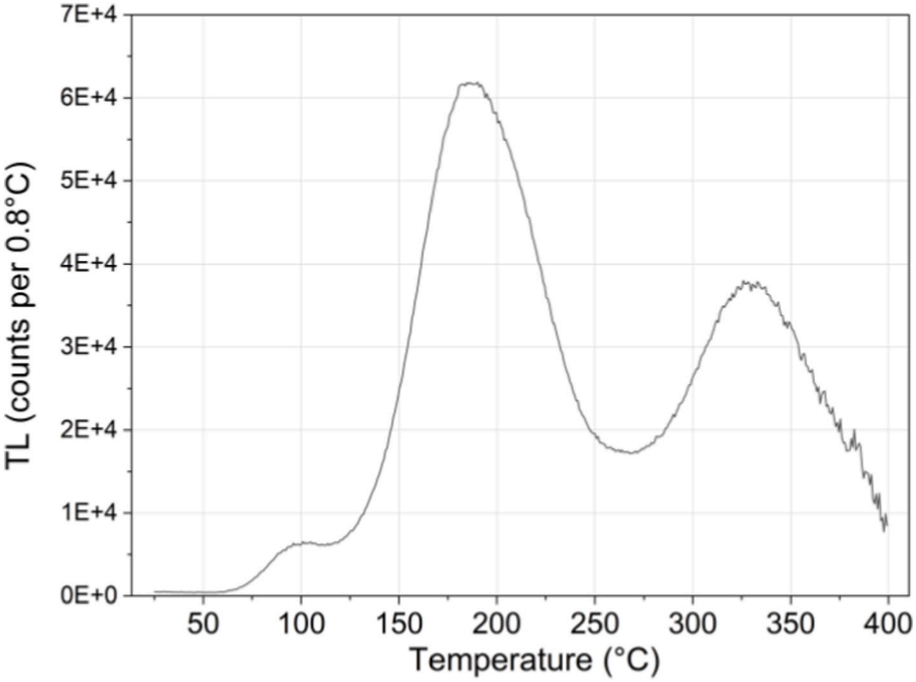

Fig. 1. Example RTL glow curve of a set of 10 resistors, taken from a Samsung Galaxy3 and irradiated with 0.9 Gy. The sample was pre-annealed (by a similar TL run up to 400 °C) prior to irradiation, thus eliminating any pre-existing initial zero dose signals (see also section 3.5).

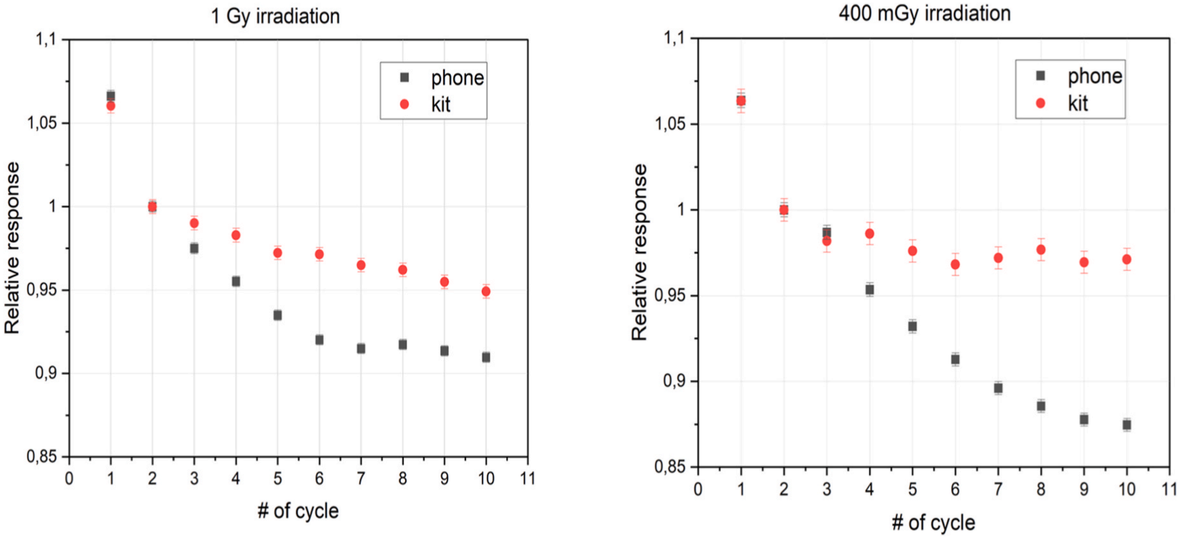

Fig. 2. Change in RTL signal sensitivity with repetition of the cycles "irradiation - RTL signal measurement" performed on resistors extracted from phones (black dataset) and from commercial sets (red dataset). The applied dose was 1 Gy (left panel) and 400 mGy (right panel) and data are normalized to the second cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cycles of irradiation and RTL measurements, but didn't eliminate the effect. From literature, studies on other materials such as quartz highlighted how changes in sensitivity might also be attributed to the maximum readout temperature of the luminescence signal (Zhi-Young et al., 2000). The RTL measurement protocol was thus further modified by lowering the readout temperature of the TL signal from a previous value of 400 °C down to 350 °C. Fig. 4 illustrates the results of the protocol assessed for single resistors, with the combination of the subdued redlight conditions during all the phases of sample preparations, the cleaning procedure with propanol and the RTL signal read out to a maximum temperature of 350 °C.

The first signal read out still shows a variation in sensitivity in the order of 2%, but the subsequent cycles are constant within the assessed standard deviations. Any possible minor variations observed from the 7th cycle on, might be ascribed to internal processes occurring in the material.

3.2. Dose response

A first evaluation of the RTL protocol was performed through several dose recovery tests using single resistors extracted from the circuit board of Samsung phone model of 2011. For those tests, the built-in beta source of the reader was used for irradiation with both, the doses to be reconstructed and the calibration doses. Results of the reconstructed doses are reported in Table 1.

Individual errors on doses were calculated from both the scatter of

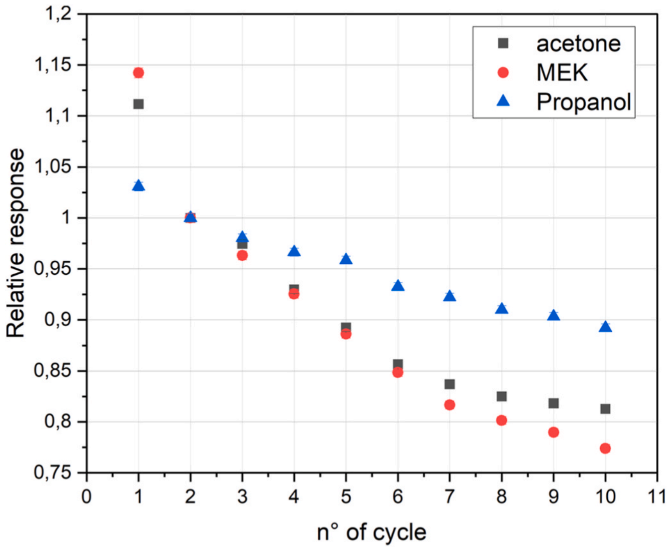

Fig. 3. Change in RTL signal sensitivity with repetition of the cycles “irradiation - RTL signal measurement” performed on resistors extracted from phones and cleaned with different solvents: acetone (black squares), Methyl Ethyl Ketone (MEK - red dots) and propanol (blue triangles). The applied dose was 1 Gy. Data are normalized to the second cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

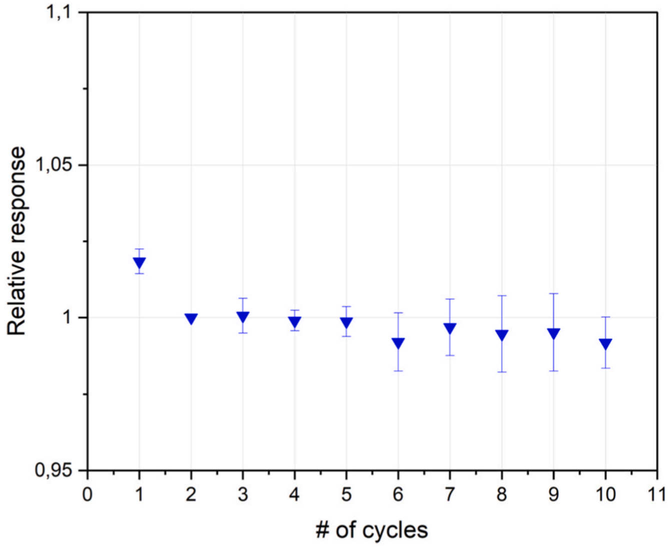

Fig. 4. Reproducibility test performed after preparing extracted resistors in subdued redlight conditions, cleaned with propanol and read out by heating the samples up to T = 350 °C. Samples were irradiated at 1 Gy. Error bars represent standard deviations from three sets of data. Data are normalized to the second cycle.

Table 1
Doses reconstructed with RTL measurement on single resistor. Errors (1 σ) are assessed by choosing the larger value provided by weighted and unweighted linear fits.

Given Dose [mGy]	Recovered dose [mGy]
1200	1170.4 ± 3.4
500	533.6 ± 6.2
200	216.5 ± 5.6
120	123.9 ± 6.6
80	85.7 ± 2.4
60	86.8 ± 3.9
40	50.7 ± 3.2

Table 2
Zero doses of resistors sampled from three different parts of the circuit board of a Samsung Galaxy Trend Plus. Errors are quoted at the one sigma level. Results below detection limit (DL) are commented with “<DL”.

Position	Zero dose [mGy]	Comment
top	2.4 ± 2.4	< DL
	1.0 ± 3.4	< DL
	3.0 ± 3.8	< DL
	5.9 ± 4.8	< DL
	5.7 ± 3.4	< DL
	10.4 ± 5.1	< DL
	73.4 ± 2.5	
middle	1.1 ± 3.6	< DL
	1.6 ± 5.3	< DL
	−3.9 ± 3.5	< DL
	−1.1 ± 5.0	< DL
	0.7 ± 2.8	< DL
down	−2.2 ± 5.2	< DL
	3.8 ± 4.0	< DL
	6.9 ± 3.6	< DL
	60.9 ± 3.1	

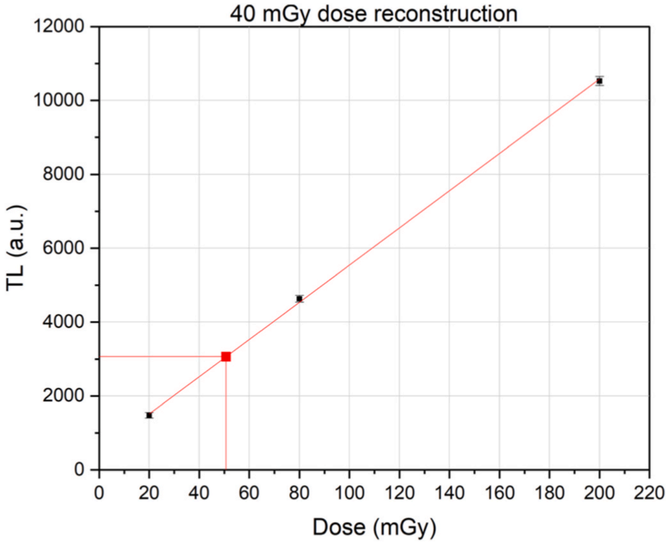

Fig. 5. Example of calibration curve for reconstructing the 40 mGy dose shown in Table 1. The red square symbol denotes the RTL signal after irradiation with the dose to be reconstructed, black square symbols the RTL signals after irradiation with the calibration doses. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

the data with respect to the calibration curve and by the error propagation of the parameters of the linear fit. An example of a calibration curve is given in Fig. 5.

For the dose region from 1.2 Gy down to 80 mGy (see Table 1), the average difference between nominal and given doses is 3.8%. In contrast, for the lowest two doses tested (40 and 60 mGy), the deviation increases up to ~50% or, in absolute terms, to ~25 mGy. The comparison of the calculated errors with the observed deviation in Table 1 implies that the true uncertainties are underestimated. In the following sections, additional effects that were not taken into account and can influence the recovered doses are described and evaluated in a sequential manner. The results are then considered in the final measurement protocol, which is then validated in the trial irradiations on intact phones.

3.3. Offset time of the beta source

In order to optimize the RTL measurement protocol for the dose assessment of low doses with one resistor, the origin of a possible confounding effect was investigated. The built-in calibration beta source of the luminescence reader is characterized by a dose-rate of approximately 20 mGy s^{-1}, therefore low doses of 20, 40, and 60 mGy are equivalent to short irradiation times of 1, 2 and 3 s respectively. However, the mechanical action of opening/closing the beta source is not instantaneous: the circularly arranged ^{90}Sr/^{90}Y source capsules are “opened up” by the shutter in a step-by-step process. Thus, the sample might already be exposed before counting of the “irradiation time” starts. The additional dose due to such an offset time of the beta source intrinsic to the instrumentation was evaluated and taken into account in the dose reconstructions with the RTL technique. Specifically, the irradiation time offset of the reader was estimated following the methodology described in Kalchgruber et al. (2002), as the intercept of the calibration curves for very short irradiation times (e.g. 1, 2, 3 s), by carrying out experiments on both resistors from commercially available kits and crystalline dosimeters made of Al_2O_3:C (TLD-500). An illustrative example is shown in Fig. 6. Overall, an average value of (0.27 ± 0.11) s was assessed, corresponding to an offset dose of (5.2 ± 2.2) mGy, for a reference data of 01/06/2019. This dose is not large but can be an effect, when reconstructing doses below about 50 mGy. With respect to the results in Table 1, consideration of the offset dose will actually increase the deviation between measured and given dose to ~30 mGy for the two lowest dose points.

3.4. Background assessment

By analyzing the initial dark current counts of the PM tube of the reader from several RTL glow curves, a non-constant signal baseline after background correction was noticed. As depicted in Fig. 7, counts showed to be higher than zero on average in the temperature region where no radiation induced signal is expected, in a real case application mimicking a corresponding accident dose. This implies that the background could not be fully removed by subtracting the second measurement from the first one, thus leading to a positive bias likely relevant for low dose reconstruction.

The observed deviations might be attributed to the fixed operational mode of the Photomultiplier Tube of the luminescence reader, which cools down to −20 °C before and warms up to room temperature after every measurement. Such an instrumentation-specific aspect might have a stronger effect, as compared to higher doses, when recovering low dose signals especially later in time (~ one month later) but can also explain, at least partly, the dose overestimation in section 3.2. Therefore, a modified background correction is introduced. In addition to the initial procedure of subtracting from the first TL signal a second one performed on the same sample, the average of the counts recorded in the first 95 channels (from 25 °C to 100 °C) of the first readout is further subtracted.

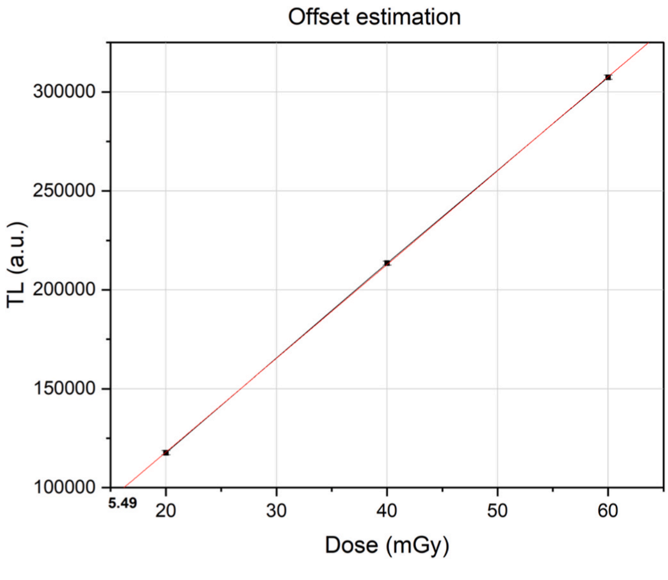

Fig. 6. Illustrative example of the offset time reconstruction. The calibration curve is related to irradiations on a TLD-500.

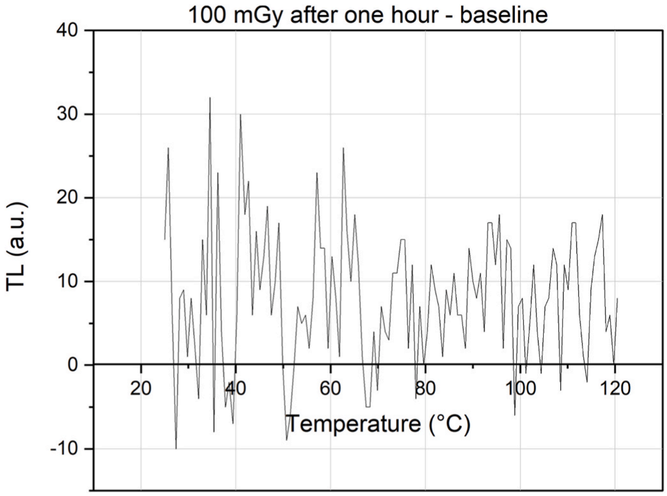

Fig. 7. Detail of the fluctuating baseline of a background corrected RTL glow curve of a resistor measured 1 h after irradiation of an intact phone with 100 mGy. Shown is the measurement region up to 120 °C, where no radiation induced signal is present, due to the preheat. Negative counts are due to the process of background correction described above.

3.5. Zero dose signal

One of the dosimetric properties of the alumina substrates of resistors is the existence of a strong native signal measured in unexposed samples, the so called “zero dose” signal. The latter was observed for the first time by Beerten et al. (2009), and further reported by Ademola and Woda (2017) and Woda and Discher (2026). A possible explanation for the presence of such a signal has been attributed to the black overcoat made up of 75% epoxy resin possibly cured by UV light during resistors production (Ademola and Woda, 2017). The UV treatment might cause the formation of electron-hole pairs in the ceramic substrate and thus lead to the formation of latent TL signals (Woda and Spöttl, 2009). The zero dose signal is most pronounced in the high temperature range (250°C-400 °C) of the TL glow curve (see Fig. 8) but for some samples also extends into the lower temperature range (see also Fig. 7 in Woda and Discher (2026) and Fig. 2 (a) in Ademola and Woda (2017)).

The presence of the zero dose signal could affect the measurement protocol developed within this work, especially at low doses, through interference into the signal integration interval. Moreover, the upper limit of 10 mGy for the zero dose was assessed in Woda and Discher (2026) on multiple resistor samples. If the relative intensity of the zero-dose signal is not homogeneously distributed among the resistors in a phone, sampling at a single resistor level could result in accidently picking a component characterized by a high intrinsic background signal. This is illustrated by the example zero dose glow curves of Fig. 8. Evaluation of the distribution of zero doses within the same phone model and between different phone models was therefore carried out. The homogeneity of zero doses among components extracted from different positions of the same circuit board was assessed on a Samsung Galaxy Trend Plus. A total of 16 samples were extracted from the top, middle and bottom part of the circuit board, depending on the availability of components in those parts. The zero doses were calculated

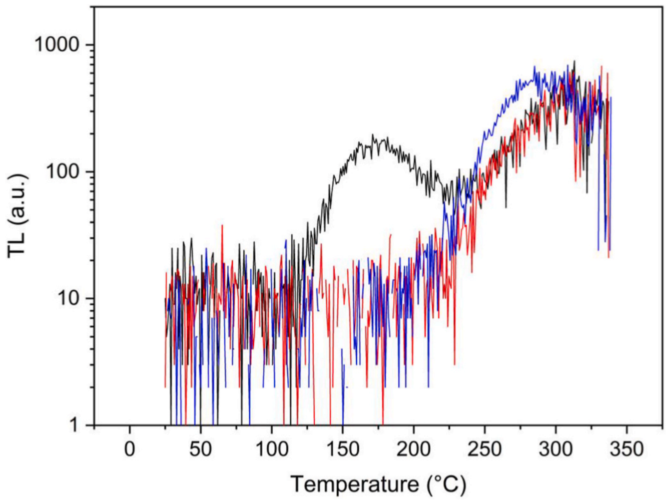

Fig. 8. Glow curves of four unexposed single resistors, taken from a Samsung Galaxy Trend Plus (see also Table 2). All resistor samples show a peak of the zero dose signal between about 280 and 300 °C, but only one sample also a signal in the integration region of the dosimetric signal (125-180 °C). This additional peak is similar in shape to the dosimetric signal, as was also observed in Ademola and Woda (2017).

from the intercepts on the x-axis of the calibration curves, while the errors were estimated from the unweighted linear fits. The modified background subtraction of section 3.4 was applied and the offset value of (5.2 ± 2.2) mGy, reported in section 3.3, added to all zero doses.

Overall, two samples showed a zero dose significantly different from zero with values of (73.4 ± 2.5) mGy and (60.9 ± 3.1) mGy. For the remaining 14 samples the difference between measured dose and zero was statistically not significant and therefore can be considered to be below detection limit. Furthermore, zero doses from resistors extracted from four different phones were also evaluated. For this, other 22 samples in total were picked from a ZTE Blade L5, a NOKIA 5250, a Samsung Galaxy Fame and a HUAWEI. Results were in line with the previous experiment, with all measured doses not being significantly different from zero. If the weighted standard deviation of all non-significant dose results from all phones is calculated, a value of $\sigma = 4.1$ mGy is obtained. A simple estimation of the overall detection limit can then be derived by taking three times this value (~12 mGy). Therefore, for 36 out of 38 investigated single resistor samples, possible zero doses were below the detection limit and thus considered negligible. On the other hand, a (rough) probability of ~5% (2/38) for sampling a resistor with significant zero dose can be estimated. This makes it somewhat unlikely that both low dose points in Table 1 were affected by this property. Also, the measured significant zero doses are ~61 and 73 mGy, which is a factor of two to three higher than the average dose overestimation in Table 1. While the occurrence of significant zero doses is probably not an issue for the experiment in section 3.2, the possibility of sampling resistors with a strong native signal cannot be fully excluded in any dose measurement or real accident scenario. Thus, the retrospective dosimetry method using a single resistor developed within this work might not be considered as a standalone method but as a part of a multi-technique approach. The advantage of combining different dose measurement techniques to increase robustness in the dose assessment has been demonstrated in a previous field test (Discher et al., 2021).

3.6. Fading

The dose recovery test in section 3.2 was carried out under idealized conditions, with readout of the simulated accident dose taking place immediately after irradiation. In the majority of cases of accidental or emergency exposures dose assessment will take place days or even weeks after the accident (ICRU, 2019). Hence, the knowledge of how the signal fades with time is crucial for a proper dose reconstruction. The TL dosimetric signal from resistors has been observed to be subject to a pronounced fading with time (Beerten et al., 2009). The origin of the time-dependent loss of signal is the phenomena of anomalous fading, that can be explained by a quantum-mechanical tunneling model (Huntley and Lamothe, 2001). For electronic components the functional relationship between intensity and time since irradiation is described by the following equation (Huntley and Lamothe, 2001):

$$I = I_c\left[1-\frac{g}{100}\log_{10}\left(\frac{t}{t_c}\right)\right] \tag{1}$$

Where I_c is the intensity of luminescence at some time t_c, and g is the percent decrease in intensity per decade (i.e. per tenfold increase in t/t_C). A fading experiment was performed on 11 resistors of type 0402 and eight samples type 0201 (sizes 0.6 x 0.3 × 0.26 mm) extracted from circuit boards. Samples were first annealed by a TL run up to 400 °C to erase any native signal, irradiated with a beta dose of 1 Gy and then stored at room temperature in the dark for periods ranging from 5 min up to four weeks before the RTL measurement. As an example, Fig. 9 displays the decay curves of two resistors extracted from a Samsung Fame model.

Using the same value for $t_c = 8.3\,h$ as in previous publications (Ademola and Woda, 2017; Inrig et al., 2008) an average value and standard deviation for the percent decreases per decade g of 17.54 ± 2.74 was observed for all samples (Fig. 10). This is consistent with previous blue TL study reporting a value of $g = 17.63$ for an integration window 125°C-200 °C (Ademola and Woda, 2017). The value of 20.7, found when measuring five resistors from one smartphone with red TL (Woda and Discher, 2026) also lies in the range of calculated values.

From the calculation of g, a fading correction factor and relative error for the finally recovered dose were calculated following the EURADOS review paper on uncertainty assessments (Ainsbury et al., 2018). From Eq. (1) and introducing $k = \frac{g}{100}\ln(10^{-1})$:

$$I = I_c\left[1-k\ln\left(\frac{t}{t_c}\right)\right] \tag{2}$$

The fading correction factor can be calculated as follows:

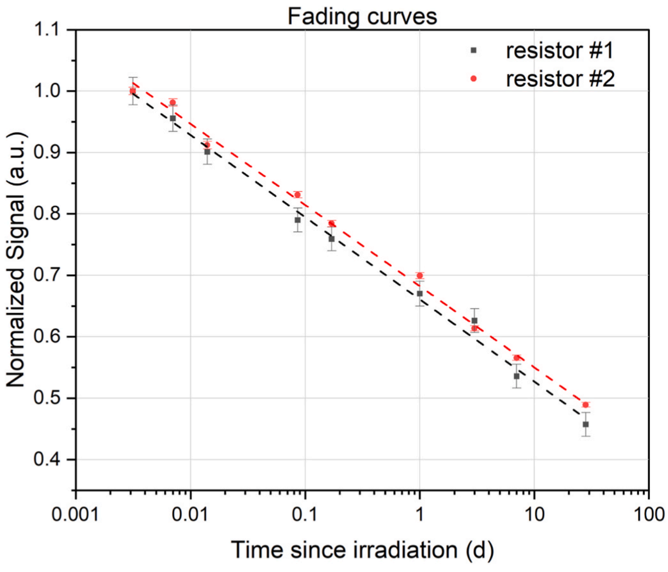

Fig. 9. Fading of RTL signals of two resistors for different storage time at room temperature. The lines were obtained by fitting Eq. (1). For $t_c = 8.3$ h g values of 17.61 ± 1.02 and 18.64 ± 1.15 were obtained.

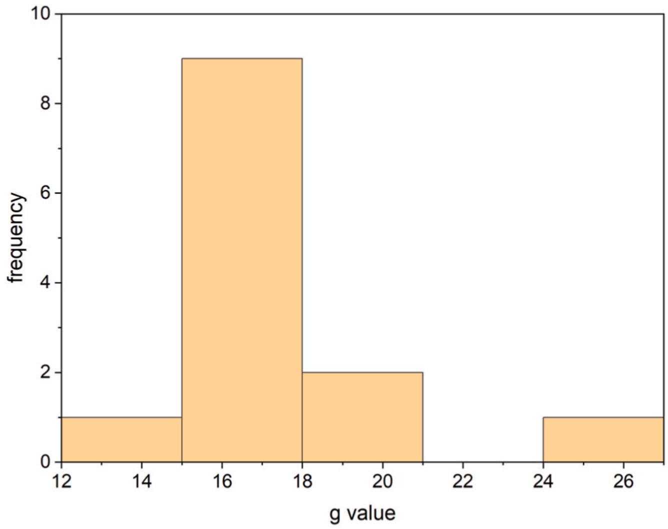

Fig. 10. Distribution of g values among all samples.

$$F = \frac{I(t_{acc})}{I(t_{cal})} = \frac{1 - k\,ln\left(\frac{t_{acc}}{t_c}\right)}{1 - k\,ln\left(\frac{t_{cal}}{t_c}\right)} \tag{3}$$

Where $I\,(t_{acc})$ is the signal measured after the time of the accidental exposure t_{acc}, and $I\,(t_{cal})$ is the signal obtained from a given calibration dose for a certain time t_{cal}. The fading correction factor and its relative error calculated specifically for the RTL signal, are taken into account in the dose recovery tests performed after irradiation on intact phones.

3.7. RTL measurement protocol

The assessed dosimetric properties of single resistors led to the following RTL measurement protocol, tailored to the specific measurement conditions of the Lexsyg Resarch Reader.

1. Extraction of resistors under subdued redlight conditions and cleaning in an ultrasonic bath with propanol for about 20 min
2. RTL measurements with a preheat at 120 °C for 10 s and a TL readout up to 350 °C using a heating rate of 2 °C s^{-1}
3. Modified background correction, performing first the “normal” background subtraction and then additionally subtracting the average counts of the 25 °C to 100 °C temperature interval of the first readout
4. Measurement of a calibration curve with several (e.g. three) dose calibration points, similar to Fig. 5. Calculation of the uncorrected accident dose D_{TL} from the linear fit (with intercept) to the calibration data.
5. Calculation of the corrected dose $D_{TL,C}$ via:

$$D_{TL,C} = \frac{D_{TL}}{F} + D_{offset} \tag{4}$$

Where F is the fading correction factor and D_{offset} is the dose due to the offset time of the beta source. The error in $D_{TL,C}$ is derived from the error of D_{TL}, and the standard deviations of D_{offset} and F.

3.8. Irradiations of intact phones

The RTL measurement protocol on a single resistor was evaluated by application for recovering doses in trial irradiations of intact mobile phones. Different phone models were irradiated at the radiation facility of the Helmholtz Zentrum München, described in section 2, and measured at different times after the exposures, from a few hours to almost one month later. For the purpose of illustration, results are first shown in Fig. 11 for the RTL protocol without step 3 (modified background correction).

Good agreement between recovered and given doses is seen for doses of 100 mGy and above, while an overestimation between 10 and 40 mGy is observed for lower doses, with the largest discrepancies occurring for doses recovered after one month of storage. Re-introducing the modified background correction (step 3) into the protocol significantly improves the performance of the dose assessment method for low doses, now giving good agreement between recovered and given doses over the entire dose range (Fig. 12).

Limitations of the method arose when recovering the lowest dose of 20 mGy after the longest period of time of one month. In this case, the recovered dose was not statistically different from the detection limit (~12 mGy immediately after irradiation, ~24 mGy after 30 days, see also Fig. 9).

4. Conclusions

In this work, a new retrospective dosimetry protocol based on red thermoluminescence (RTL) from surface-mounted resistors in mobile phones was developed and evaluated, with the aim of reconstructing low-level external gamma exposures relevant to large-scale radiological emergencies. The Cr^{3+}-related RTL emission at 695 nm exhibited high signal intensity, enabling dose assessments at the single-resistor level—offering a minimally destructive approach that may allow the original device to remain functional after analysis.

The complete protocol was optimized for the Lexsyg Research reader and includes sample extraction and cleaning under subdued red light, RTL signal integration after preheating and a modified background correction to account for non-constant PMT baselines. Additional corrections addressing the offset dose from the beta source and signal fading ($g = 17.54 \pm 2.74$ % per decade) were integrated into the dose reconstruction algorithm. Furthermore, a systematic assessment of the zero-dose signals in resistors across various phone models revealed that significant native signals were present in only ~5% of components, indicating a generally low probability of interference in single-resistor sampling.

Trial irradiations of intact phones with ^{137}Cs gamma radiation confirmed the method's applicability: doses ≥40 mGy could be reliably reconstructed up to one month post-irradiation, with uncertainties ranging from ~10% shortly after exposure to ~25% at 30 days. For the

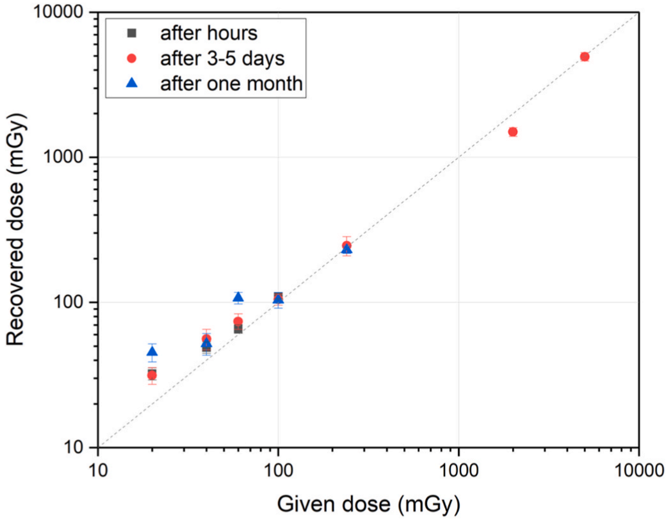

Fig. 11. Results of trial irradiations on intact phones. Given doses are recovered with the RTL measurement protocol without step 3 after different storage times.

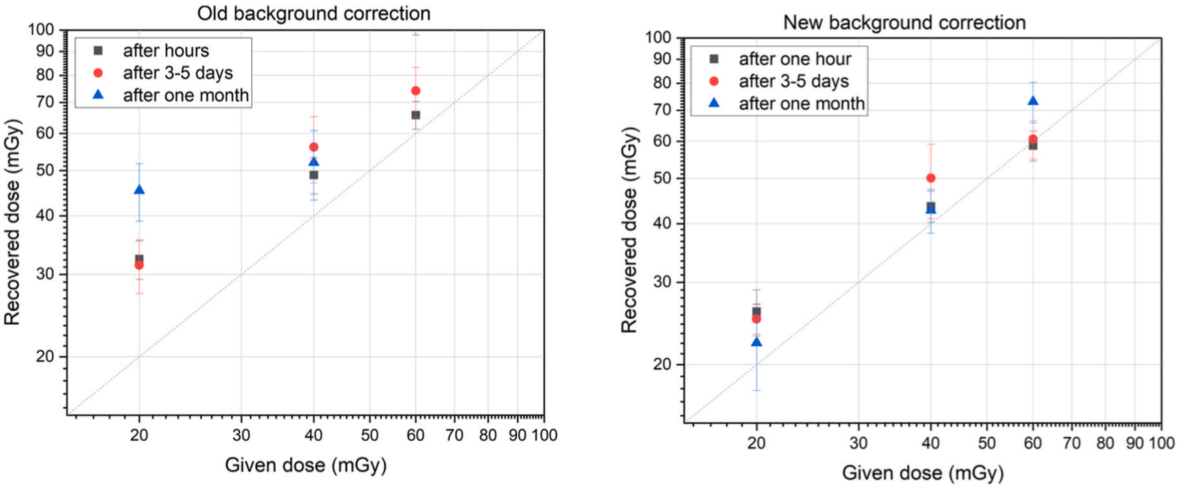

Fig. 12. Comparison of the results of trial irradiations on intact phones after different storage times: on the left panel data are referred to the "normal" background correction (same as in Fig. 11), whereas data on the right panel are assessed with the modified background correction.

lowest tested dose of 20 mGy, the reconstructed signal approached the system's detection limit, suggesting a lower practical threshold for reliable dose assessment under real-world conditions.

Overall, the RTL-based single-resistor approach provides a sensitive and semi-non-destructive method suitable for emergency retrospective dosimetry. While it may not serve as a standalone technique due to limitations in detection threshold and component variability, it is well-suited for integration into multi-technique strategies for large-scale individual dose assessment in radiological or nuclear incidents.

CRediT authorship contribution statement

Alessia Mafodda: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft. **Clemens Woda:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research leading to these results was carried out within the CONFIDENCE project that was part of CONCERT ("European Concerted Programme on Radiation Protection Research"). The CONCERT project has received funding from the Horizon 2020 - EURATOM Programme for Research and Innovation (2014-2020) under grant agreement No. 662287.

Data availability

Data will be made available on request.

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