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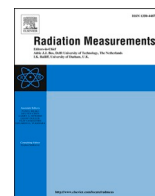
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OSL signal of electronic components from portable radios for radiation accident dosimetry

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ABSTRACT

The portable radio (hand-held device) is the preferred means of communication for the first responders from the homeland security forces and is systematically carried during intervention. This electronic device could therefore be a good candidate as a possible fortuitous dosimeter to estimate the dose received by the members of these security forces in the event of a radiological accident. For this purpose, the dosimetric properties of electronic components extracted from the circuit board of portable radios used by a French specialised intervention unit were investigated using the OSL technique. The dosimetric properties of such electronic components were compared to those of resistors extracted from mobile phones to determine whether an OSL protocol developed for mobile phone resistors could be applied also to these electronic components. The OSL dosimetric properties were generally similar and the results of a dose recovery test using these components removed from a portable radio were in good agreement with the nominal dose. Further experiments showed the importance of knowing the storage temperature conditions of these devices to accurately estimate the dose in case of a radiological accident.

1. Introduction

When a radiological accident occurs, the dose absorbed by the victims must be assessed quickly and accurately to select an appropriate medical treatment. In emergency situations where radiological risk has not been immediately identified, first responders from the homeland security forces are rarely equipped with a personal dosimeter. In the absence of conventional dosimetric data, materials found on or near the first responders could be used as fortuitous retrospective dosimeters to estimate the dose received (ICRU, 2019).

Mobile phones are carried by a large part of the population, and these electronic devices could therefore be good candidates as emergency dosimeters for the general public. Thus, the dosimetric properties of mobile phone materials have been extensively studied, especially using the techniques of thermoluminescence (TL) and optically stimulated luminescence (OSL). The investigations focused mainly on electronic components (notably resistors or inductors) mounted on the surface of their circuit board (e.g. Inrig et al., 2008; Bassinet et al., 2010a; Eken-dahl and Judas, 2012; Lee et al., 2017; Mrozik et al., 2014a; Eakins et al., 2016; Ademola and Woda, 2017; Bassinet et al., 2017; Geber-Bergstrand et al., 2018), and display glass (e.g. Bassinet et al., 2010b; Discher and

Woda, 2013; Discher et al., 2013; Bassinet et al., 2014a; Mrozik et al., 2014b; Kim et al., 2019). Measurement protocols have been developed for these materials. For example, with regards to resistors, two protocols (namely the “fast-mode” protocol and the “full-mode” protocol) using OSL signal of these alumina-rich components were developed in the framework of the EU-FP7 MULTIBIODOSE project and validated in an interlaboratory comparison (Bassinet et al., 2014b) organized within the European Radiation Dosimetry Working Group 10 (EURADOS WG10) on retrospective dosimetry. Since then, they have been used in several interlaboratory comparisons and field tests (Discher et al., 2021; Waldner et al., 2021; Kim et al., 2022; Port et al., 2023).

For the first responders from the homeland security forces, the preferred means of communication is the portable radio. This hand-held device is systematically carried on the front of the bullet-proof jacket during intervention and could be a fortuitous dosimeter of choice if containing electronic components with similar dosimetric properties as previously investigated electronic components in mobile telephones.

In this work, portable radios used by a French specialised intervention unit were studied. The resistors in mobile phones can be identified by their black coating and white ceramic substrate underneath (Bassinet et al., 2014b). Many components with these characteristics and of

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different sizes were observed on the circuit boards of the portable radios investigated, but only one specific type, with the largest number of items available, was studied. In order to check whether an OSL protocol developed for mobile phone resistors could be applied to this component type, its main dosimetric properties e.g. measurement reproducibility, dose response, signal stability, were investigated by OSL and compared to those of resistors extracted from mobile phones. These results, as well as those of a dose recovery test, are presented. In addition, portable radios may be subjected to various constraints when used on the field and in particular the temperature which can vary considerably. The influence of this parameter on the OSL signal is also discussed.

2. Materials and methods

2.1. Electronic components

Several models of portable radios (brand: MOTOROLA, product line: MTS/XTS) used by a French specialised intervention unit were investigated.

The radios were opened using a screwdriver to isolate the circuit boards. The type of component studied, with a black coating and white ceramic substrate underneath, was available in more than 100 samples in each of the portable radios and was larger in size than the resistors (type 0402) typically found in mobile phones (Fig. 1). These components were extracted from the circuit boards using scalpels or utility knives, similar to the procedure for extracting mobile phone resistors (Bassinet et al., 2014b). They were then cleaned with acetone (ultrasonic bath, 10 min, twice) to remove any glue used during manufacturing process, as well as any other dust or substances (such as salt) deposited when the radios are used in degraded operational environments. The electronic components were put on cups previously cleaned with acetone in an ultrasonic bath for 10 min (twice) and with distilled water for 10 min, then sprayed with silicon oil prior to measurement.

2.2. Measurement parameters

The protocol tested on electronic components in this study is the “full-mode” protocol developed in the framework of the EU-FP7 MULTIBIODOSE project using OSL from mobile phone resistors (Bassinet et al., 2014b). The OSL signals are measured at 100 °C for 30 s after a preheat of 120 °C during 10 s. To calculate the OSL signal intensity from the OSL decay curve, the integral between 6 and 12 s (background signal) is subtracted from the integral between 1 and 6 s.

A calibration dose (D_{cal} , 5 Gy) is delivered after measuring the “accident” signal (S_{acc}) and the resulting “calibration” signal (S_{cal}) is recorded. The data are then analysed, and the dose estimated using a



Fig. 1. A cup of five electronic components from a portable radio investigated in this study (on the left) and a cup of ten resistors (type 0402) from a mobile phone (on the right).

fading correction factor to correct for the loss of OSL signal over time after irradiation. A universal fading correction was calculated for resistors as part of the MULTIBIODOSE project, then implemented in a EURADOS WG10 template provided to participants in intercomparisons. The fading correction factor $F_{mobile\ phone}$ is given in equation (1). In this equation, t_{acc} is the time (in days) between accident and OSL measurement of the resulting accident signal and t_{cal} is the time (in days) between calibration and OSL measurement of the resulting calibration signal. Finally, the corrected dose D is estimated using equation (2).

$$F_{mobile\ phone} = (1 - 0.11 \ln(t_{acc})) / (1 - 0.11 \ln(t_{cal})) \quad (1)$$

$$D = \frac{S_{acc} D_{cal}}{S_{cal} F_{mobile\ phone}} \quad (2)$$

2.3. Luminescence reader used to perform luminescence measurements on electronic components

Luminescence measurements of the electronic components were performed with an automated Freiberg Instruments lexyg smart system (Richter et al., 2015), equipped with a bi-alkaline Hamamatsu H7360-02 photomultiplier tube. OSL measurements were taken using the blue LEDs (458 ± 5 nm) of the reader with an optical power of 90 mW cm^{-2} at the sample position for all experiments. Luminescence signals were detected through a set of filters composed of one Hoya U-340 large band glass filter and one Delta BP 365/50 EX interference filter.

For comparison purposes and dosimetric characterisation, additional TL measurements on cups of electronic components extracted from portable radios and on cups of resistors extracted from mobile phones were also carried out with the lexyg smart system and the same filter combination. The materials were previously annealed by a TL measurement up to 400 °C to remove any zero-dose signal and the TL measurements were performed under nitrogen atmosphere at a heating rate of 2 °C.s^{-1} up to 400 °C. A second reading with the same parameters was taken to subtract the thermal background.

The luminescence reader is equipped with a built-in beta source ($^{90}\text{Sr}/^{90}\text{Y}$). All irradiations of electronic component cups were carried out using this source. It was calibrated in terms of air kerma from OSL measurements of resistors from a kit (TRU COMPONENTS, type: SMD resistor 0402, references: TC-0402WGF2702TCE203 and TC-0402WGF1301TCE203, provider: CONRAD) irradiated at the IRSN’s linear accelerator (Elekta Synergy® Platform, 6 MV). The dose rate of the beta source was $\approx 57 \text{ mGy s}^{-1}$. OSL measurements using electronic components extracted from radios were also performed and a good agreement with this value was obtained. All luminescence measurements were taken directly after irradiation, except for the fading study.

2.4. Dose recovery test

For a dose recovery test, a portable radio was irradiated to a nominal dose of 1 Gy (“accident” dose) in terms of air kerma with the IRSN linear accelerator (Elekta Synergy® Platform, 6 MV, dose rate: 5.5 Gy min^{-1} , homogenous area: $30 \times 30 \text{ cm}^2$). The gantry was at 180°, with the beam oriented from bottom to up, and a 5 mm thick polymethylmethacrylate (PMMA) plate was placed between the portable radio and the table in order to ensure electronic equilibrium conditions during irradiation (Fig. 2a). The portable radio is systematically carried on the front of the bullet-proof jacket during intervention. The battery is located at the rear of the device, with the electronic components between the front of the portable radio and the battery. In this experiment, the front of the portable radio was placed on the table.

For reference dosimetry, TL dosimeters (LiF:Mg,Cu,P chips (GR200A)) were annealed at 240 °C for 10 min with a Fimel oven (Fontenay-aux-Roses, France). Five TL dosimeters were attached on the front of the radio and five were similarly fixed on its back (Fig. 2b) before its irradiation in order to estimate any dose gradient due to the

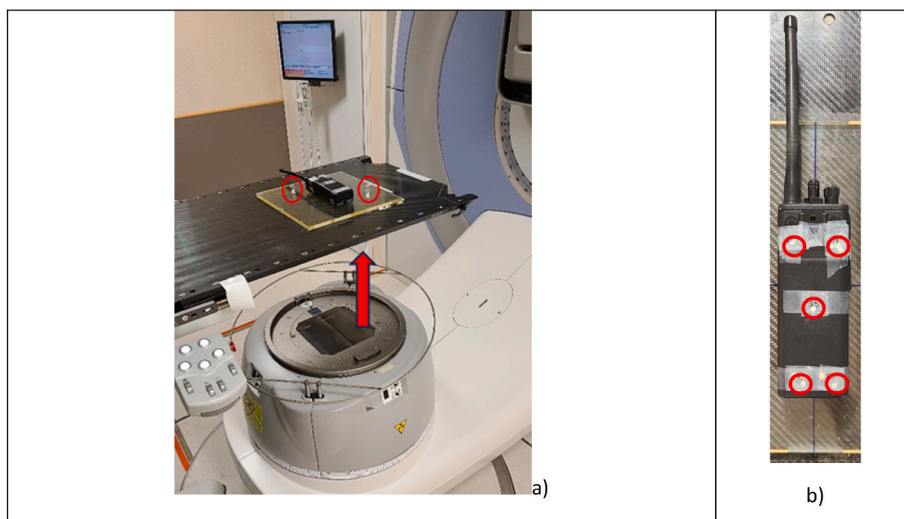


Fig. 2. Irradiation of a portable radio for a dose recovery test. (a) Setup for irradiation using a linear accelerator. The red arrow indicates the direction of the beam and the red circles the position of the TL dosimeters on the table. The front of the radio is in contact with the plate that is placed on the table to ensure electronic equilibrium conditions, (b) Back of the portable radio with the location of the five TL dosimeters (red circles).

source-dosimeter distance and absorption of the radiation by the materials of the portable radio. Two TL dosimeters were also put on the table next to the portable radio. TL measurements of the reference dosimeters were performed with a Fimel manual reader (Fontenay-aux-Roses, France) equipped with a blue filter (415 nm). The TL dosimeters were preheated from room temperature (~ 20 °C) to 135 °C using a heating rate of 6 °C. s^{-1} . This temperature (135 °C) was held constant for 15 s. The TL dosimeters were then heated up to 240 °C using a heating rate of 3 °C. s^{-1} .

After irradiation, the following steps were performed under red light to avoid any loss of luminescence signal. The radio was opened a few hours after irradiation, and electronic components of interest extracted from an electronic card. Ten cups of five electronic components each were prepared. They were divided into two groups of five cups. The “full-mode” protocol was used to estimate the dose. The “accident” signal was measured one day after irradiation for the cups in the first group, and seven days after irradiation for those in the second group. From irradiation to measurement, the portable radio and then the cups of electronic components were stored at room temperature.

2.5. Influence of the storage temperature on the OSL signal

When portable radios are used on the field, they can be exposed to different temperature ranges. To study the influence of the storage temperature on the OSL signal, cups of electronic components were irradiated at 5 Gy and stored at different temperatures for different times. A programmable oven (PTW-TLDO) and a fridge (Liebherr Economy) and its freezer compartment were used to investigate four storage temperatures corresponding to different specific situations. The temperatures and possible corresponding exposure situations are given in Table 1. Temperature loggers were used to monitor temperature

Table 1
Scenarios and experimental details.

Temperature (°C)	Type of intervention	Device used for sample storage
−8	In mountain areas or in winter	Freezer compartment of the fridge
5	In mountain areas or in winter	Fridge
50	In desert areas	Oven
80	Behind a windshield of a vehicle parked in direct sunlight	Oven

throughout the experiments. Mean temperatures were -8 °C, 5 °C, 50 °C and 80 °C. For each temperature, three storage times (1 h, 4 h and 8 h) were studied. These durations were chosen in line with those of standard interventions in the field. Three unused cups of five electronic components, from a different portable radio for each cup, were used per temperature and per storage time.

When returning from an intervention, the portable radios are put away and stored at room temperature. After exposure to a specific temperature within this experiment, the cups were also stored at room temperature (~ 20 °C) and their remaining OSL signal was taken 24 h after irradiation for each cup, regardless of the scenario. This signal was normalized to that of a test-dose (5 Gy) taken prior to the exposure scenario to avoid any effect of the temperature on components. Each cup had been stored at room temperature before this measurement using the same delay between irradiation and measurement (24 h) to avoid any fading effect.

3. Results and discussion

3.1. Dosimetric properties

The chemical composition of the electronic components extracted from portable radios, that is directly related to the dosimetric properties, was not available to ensure they were indeed resistors. In addition, Discher et al. (2023) found electronic components in “ear buds” and wireless headphones with a black coating and white ceramic substrate underneath, like mobile phone resistors, but with different dosimetric properties. It was therefore necessary to ensure that the OSL protocol developed for mobile phone resistors could be applied to the electronic components from portable radios. Comparison of the TL glow curve of electronic components removed from portable radios with that of mobile phone resistors, as well as that of their main OSL dosimetric properties, was used as a means of verifying the type of component sampled.

3.1.1. TL glow curves

The radiation-induced TL signals of electronic components extracted from portable radios were compared to those of resistors extracted from mobile phones. With this aim, aliquots of five electronic components from portable radios and aliquots of ten resistors (type 0402) from mobile phones were prepared and annealed by a TL measurement up to 400 °C to remove any zero-dose signal. Then, they were irradiated with a dose of 5 Gy. Fig. 3 depicts examples of recorded radiation-induced TL

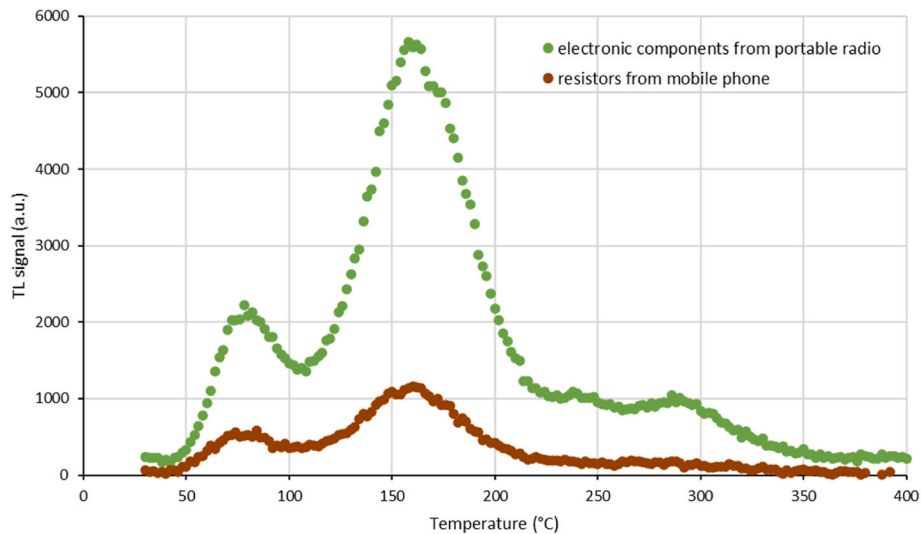


Fig. 3. Radiation-induced TL signals recorded for a cup of five electronic components extracted from a portable radio and a cup of ten resistors (type 0402) extracted from a mobile phone immediately after irradiation (dose: 5 Gy). They were previously annealed by a TL measurement.

signals. For both devices, the shape of the TL glow curve is similar, with two main peaks appearing at ~ 80 °C and ~ 160 °C respectively.

3.1.2. Reproducibility of the radiation-induced OSL signal

A good reproducibility of the radiation-induced OSL signal with repetition of the cycles “irradiation - measurement” was generally observed for mobile phone resistors (ICRU, 2019). After having previously checked that the zero-dose OSL signal was negligible (results not shown), the measurement reproducibility of the radiation-induced OSL signal was investigated for aliquots of electronic components from portable radios. Firstly, three doses (0.5 Gy, 1 Gy and 5 Gy) were studied using a stimulation time of 30 s. Examples of results are shown in Fig. 4a. An aliquot of five unused electronic components from a portable radio was used for each dose. After ten cycles, the sensitivity change was very low for the two lowest doses as it remained $<2\%$ and $<5\%$ for 0.5 Gy and 1 Gy respectively, but it reached 24% for the dose of 5 Gy. As only one calibration point of 5 Gy is used in the “full-mode” protocol, a limited impact on the estimated dose is expected. However, this could result in non-linear dose-response curves given that several cycles with increasing doses are used for this type of study, for example.

Transfer from the deep, slow-to-empty traps into traps that

contribute to the OSL signal is a hypothesis to explain the apparent sensitivity changes (Sholom and McKeever, 2016). Increasing the stimulation time could help to stabilize the sensitivity, as shown by Beerten et al. (2009) and Sholom and McKeever (2016) in OSL studies of a ceramic resonator from an USB flash drive and integrated circuits from mobile phones, respectively. Thus, the measurement reproducibility of the radiation-induced OSL signal was investigated for aliquots of electronic components using longer stimulation times (100 s, 300 s, 500 s and 700 s) for a dose of 5 Gy. An aliquot of five unused electronic components from the same portable radio was used for each stimulation time. Fig. 4b shows that the sensitivity change is reduced when increasing the stimulation time. For specific studies (investigation of dose response, stability of the radiation-induced OSL signal and influence of the storage temperature on the OSL signal, see sections 3.1.3, 3.1.4 and 3.3), a 500 s stimulation time was used as a compromise to minimize both measurement time and sensitivity change.

3.1.3. Dose response of the radiation-induced OSL signal

The dose response of the radiation-induced OSL signal for electronic components from portable radios was studied from 0 Gy up to 20 Gy. The results obtained for four cups of electronic components extracted

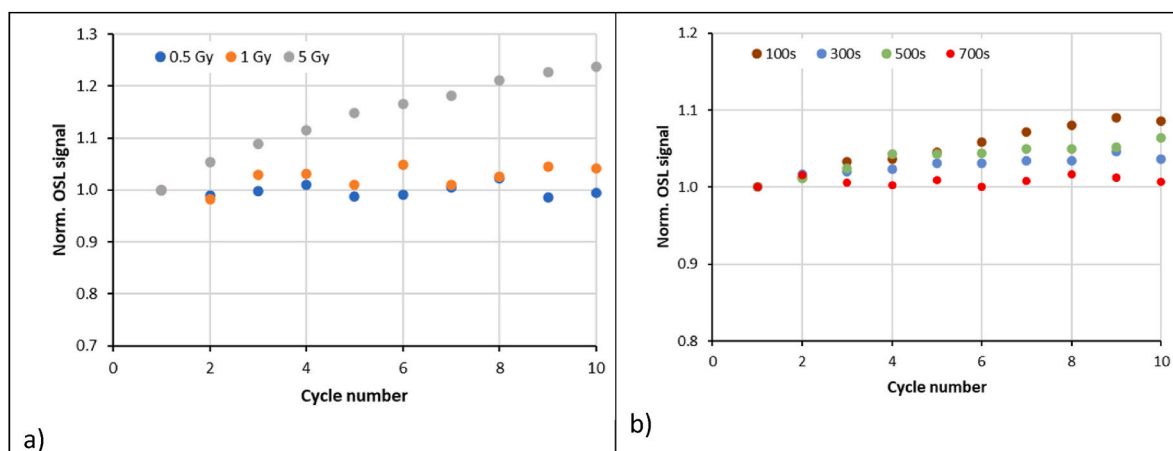


Fig. 4. Reproducibility of the radiation-induced OSL signal of electronic components extracted from portable radios with repetition of the cycles “irradiation - measurement”. Data are normalized to the first cycle. (a) aliquots of electronic components irradiated to 0.5 Gy, 1 Gy and 5 Gy, stimulation time: 30s, five unused electronic components per aliquot, (b) aliquots of electronic components irradiated to 5 Gy, stimulation time: 100 s, 300 s, 500 s and 700 s, five unused electronic components per aliquot.

from different portable radios are presented in Fig. 5. The dose-response curve was linear over this dose range, as found for mobile phone resistors (ICRU, 2019). The difference in slope of the dose response curves shows the variability in sensitivity between the electronic components from different radios ($\sim 20\%$). The variability was lower for aliquots of electronic components extracted from the same radio. For example, the variability between five aliquots of five electronic components extracted from another radio and irradiated to 5 Gy was only $\sim 8\%$.

3.1.4. Stability of the radiation-induced OSL signal

The fading of the radiation-induced OSL signal of electronic components extracted from portable radios was studied for storage periods of up to ~ 120 days. Ten aliquots of five electronic components, from a different portable radio for each cup, were used. Results are presented in Fig. 6. The variability between aliquots was $<15\%$ (1 standard deviation). The average fading correction factor $F_{\text{portable radio}}$ obtained from these data is given in equation (3), where t_{acc} is the time (in days) between exposure (accident dose) and OSL measurement of the resulting accident signal and t_{cal} is the time (in days) between the calibration dose and OSL measurement of the resulting calibration signal. This results in a fading correction factor slightly higher for electronic components from portable radios than for mobile phone resistors (see equation (1)), due to their slightly higher signal stability.

The following example illustrates this conclusion. In a realistic case, t_{acc} could be three days. For a laboratory responsible for estimating the dose received by a portable radio and using a luminescence reader not equipped with a source, the time between irradiation using a calibration source placed in another building and the OSL measurement could be 30 min. In this case, $t_{\text{cal}} = 0.021$ days. The fading correction factor $F_{\text{portable radio}}$ obtained from these data is 0.669. For a mobile phone, the fading correction factor $F_{\text{mobile phone}}$ would be 0.617, using the same values for t_{acc} and t_{cal} .

$$F_{\text{portable radio}} = (1 - 0.09 \ln(t_{\text{acc}})) / (1 - 0.09 \ln(t_{\text{cal}})) \quad (3)$$

3.2. Dose recovery test on a portable radio irradiated and stored under well-controlled conditions

The results of the reference dosimetry are presented in Table 2. There is a good agreement with the applied dose for the TL dosimeters put on the table. The dose estimated with the TL dosimeters put on the face of the radio in contact with the table is $\sim 10\%$ higher than the expected 1 Gy due to backscattered radiation. The dose estimated with the TL dosimeters placed on the face of the radio that was not in contact with the

table is lower, partly due to the higher source-dosimeter distance, but mainly due to the absorption of radiation by the materials in the portable radio (i.e. internal components and battery).

Regarding the electronic components from the portable radio, the doses measured for both groups of aliquots (Table 3) are in a good agreement with the reference dosimetry and the nominal dose.

3.3. Influence of the storage temperature on the OSL signal

The effect of the storage temperature of irradiated electronic component cups on the OSL signal was investigated. The results of these experiments are shown in Fig. 7. A storage temperature of -8°C or 5°C had no significant effect on the remaining OSL signal, whatever the storage duration. For a storage temperature of 50°C for 8 h, a slight decrease in the remaining OSL signal ($\sim 5\%$) was observed. When the cups were stored at 80°C for 1 h, the loss of signal was $\sim 12\%$ and increased with storage time. This could lead to an underestimation of the estimated dose in the event of a radiological accident.

When a radiological accident occurs, this highlights the importance of having information on the temperature to which a portable radio has been exposed on site, and then up to the measurements, when a dose assessment is required. Van Hoey et al. (2021) performed fading measurements on resistors eight days after irradiation and storage at -10°C , 17°C and 40°C and they also showed that increasing the storage temperature enhances the signal fading.

For these experiments, the test-dose had been taken prior to the exposure scenario to avoid any effect of the temperature on components. It should be noted that a test-dose can only be administered after the accident signal has been measured in the event of a radiological accident. Further experiments should be carried out to check if there are any effects on the signal to ensure this method could be applied in the event of an accident.

It should also be noted that for practical reasons of the present experiments the irradiations were carried out at room temperature. In case of a radiological accident, the irradiation itself could occur at a higher or lower temperature, how that may influence the OSL signal should also be investigated.

4. Conclusions

Main OSL dosimetric properties of electronic components extracted from portable radios used by a French specialised intervention unit were investigated using the measurement parameters of an OSL protocol developed for mobile phone resistors. The dosimetric properties of the

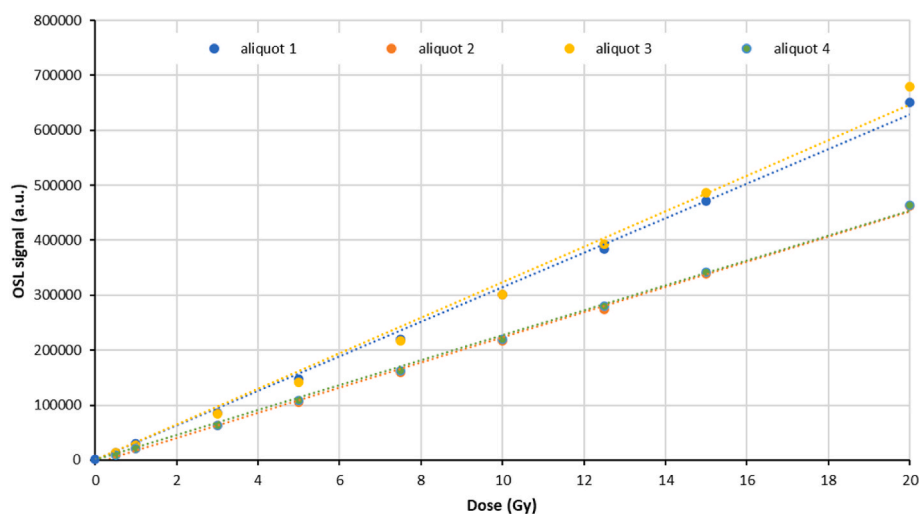


Fig. 5. Dose-response curves of radiation-induced OSL signals obtained for four aliquots of electronic components from different portable radios (five unused electronic components from the same radio per aliquot, electronic components from a different portable radio for each aliquot).

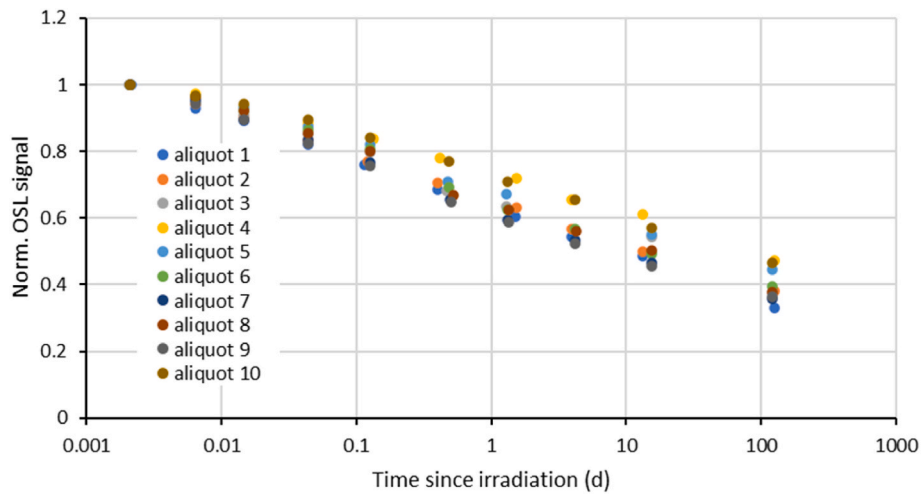


Fig. 6. Stability of the radiation-induced OSL signal for ten aliquots of electronic components from different portable radios (five unused electronic components per cup, dose: 5 Gy, study at room temperature (~20 °C)).

Table 2

Results of reference dosimetry associated to a dose recovery test (nominal dose: 1 Gy).

TLD position	#TLDs	Mean measured dose ± SD (Gy)
On the table	2	0.99 ± 0.08
On the radio, face in contact with the table	5	1.11 ± 0.01
On the radio, opposite face	5	0.74 ± 0.06

Table 3

Results of a dose recovery test using electronic components from a portable radio (nominal dose: 1 Gy). The average measured dose (five electronic components per cup) and standard deviation (SD) of five cups were determined for 1 day and 7 days delay between irradiation and measurement.

Delay between irradiation and measurement (d)	1	7
Mean measured dose ± SD (Gy)	1.16 ± 0.04	1.14 ± 0.06

electronic components studied were generally similar to those of resistors from mobile phones. The OSL protocol was successfully applied to recover a dose received by a portable radio. In the event of a radiation accident, portable radios could be used as fortuitous dosimeters with some considerations.

This study highlighted the importance of having information on the ambient storage conditions of a portable radio for radiation accident dosimetry, given that exposing a portable radio to high temperatures over a long period could indeed lead to an underestimation of the dose.

Further investigations are still needed. In particular, other models of portable radios used by other first responders and in other army units, as well as new models of portable radios that are or will be available on the market, should be investigated to ensure the relevance of using the suggested OSL protocol for radiation dose assessments.

CRedit authorship contribution statement

Simon Fleuriot: Methodology, Investigation, Formal analysis, Writing – review & editing. **Céline Bassinet:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

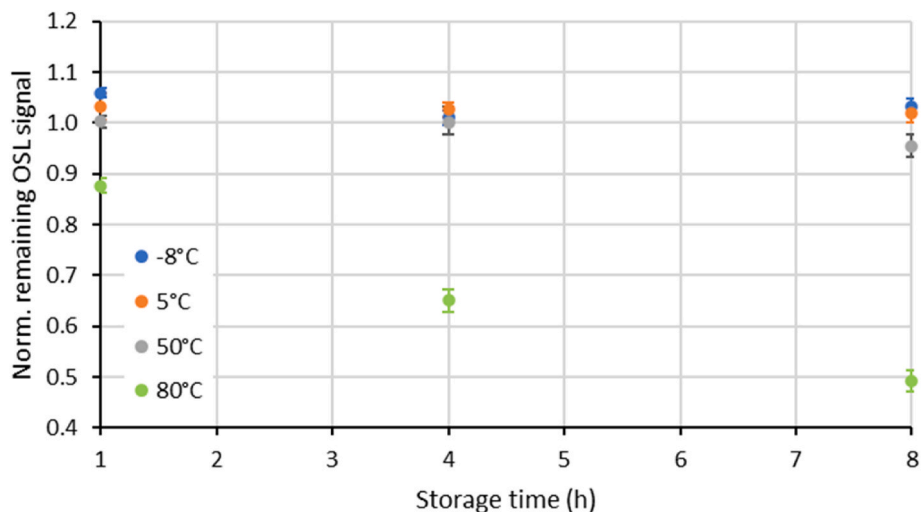


Fig. 7. Effect of the storage temperature on the OSL signal. Remaining OSL signal was normalized to a test-dose (mean of three cups per temperature and per duration, 1 SD).

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.

Data availability

Data will be made available on request.

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