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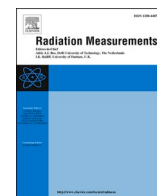
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Feasibility study of using earbuds and wireless headphones for retrospective dosimetry

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ABSTRACT

Luminescence dosimetry could be an essential tool in retrospective dosimetry for assessing an absorbed dose after a radiological overexposure. Mobile phone components could be useful proxies for measuring the amount of dose an individual has received. Different research groups have extensive experience in characterising different elements of mobile phones (i.e. electronic components, display or touch screen glass) for physical retrospective dosimetry. However, so far these techniques are frequently destructive and alternative materials need to be sought for further research on cheaper electronic devices.

Earbuds and wireless headphones have become quite popular and are often carried closely to the body or may be found in personal bags. These low-budget electronic devices might potentially be better accepted by the general population compared to high-price objects, such as an expensive smartphone.

On the circuit boards of these items, electronic components (SMDs) were found. The results of a dose recovery test after x-ray irradiation using a standardized luminescence measurement protocol developed for resistors extracted from mobile phones are presented. The estimated doses from the sampled SMDs were overestimated by a factor up to 2.1 following this initial experiment. Further investigations showed that the signal stability of some SMDs was significantly different from that of mobile phone resistors. The use of a fading correction specific to these SMDs improved the dose reconstruction results. Generally, these low-budget electronic devices are potentially suitable for dose assessment and an alternative fortuitous retrospective dosimeter.

1. Introduction

Over the past decade, the fear of an accident involving radiation sources or of a malevolent act by placing a hidden radioactive source in a crowded environment (e.g. public squares or means of mass transportation) has gradually increased. At the same time, there has been considerable interest in identifying potential fortuitous dosimeters from items carried by the general population that may be used for individual dose reconstruction in the case of a radiological accident (ICRU, 2019). Mobile phones contain materials that could be useful for measuring the amount of dose received by an individual. Different research groups have extensive experience in characterizing different components of mobile phones, such as electronic components (e.g. Inrig et al., 2008; Bassinet et al., 2014a; Mrozik et al., 2014a; Eakins et al., 2016; Lee et al., 2017; Geber-Bergstrand et al., 2018), display glass (e.g. Bassinet et al., 2014b; Discher and Woda, 2013; Mrozik et al., 2014b; Kim et al., 2019)

or touch screen glass (e.g. Discher et al., 2016; McKeever et al., 2017) using luminescence techniques for physical retrospective dosimetry. However, as these techniques are destructive to date, the phones can no longer work after use in a dose assessment, which is a major issue in terms of public acceptance due to the loss of the mobile phone and potential emotional damage. Alternative approaches should therefore be sought, and further research carried out. For example, the use of OSL from the protective back-glass of modern mobile phones with wireless charging capabilities has been suggested and a custom-made OSL reader has been built to perform the measurements without dismantling the phone (Sholom et al., 2020; Chandler et al., 2021; Sholom and McKeever, 2021). In addition, the use of TL from mobile phone protective glasses (Bassinet and Le Bris, 2020; Bassinet et al., 2022; Discher et al., 2023) has been investigated.

Earbuds and wireless headphones have also become quite popular and are often carried close to the body (i.e. from commuters in public

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transports) or may be found in personal bags. Giving up these low-budget electronic devices for dose estimation purposes might potentially be more acceptable to the general population than losing high-price objects, such as an expensive smartphone. Additionally, these devices neither store any personal data (contacts, notes, documents, etc.) nor personal pictures and can be replaced easily. The circuit boards of these items contain electronic components. Some earbuds and wireless headphones were irradiated with x-rays, and a dose recovery test was performed using a standardized OSL measurement protocol developed for resistors (Bassinnet et al., 2014a). The results are presented and discussed in this work.

2. Materials and methods

2.1. Samples

Two models of earbuds and one model of wireless headphones were selected for this feasibility study. Details of the devices are given in Table 1. These devices belong to a low budget price range and were bought in a popular store selling consumer electronics. Additionally, some reference surface-mounted device (SMD) resistors from a kit (TRU COMPONENTS, reference: TC-0402WGF2702TCE203, provider: CONRAD, 25 pcs) were used for comparison purpose.

2.2. Preparation of the electrical devices before the radiation exposure

The wireless headphones and the earbuds were equipped with TLDs (TLDs LiF:Mg,Cu,P chips (GR200A)) before their irradiation to get a well-defined dose for comparison. The location of the TLDs was selected to be as close as possible to the circuit board and its components (i.e. inside the charging case) during their irradiation. Additionally, some TLDs were attached on the surface of the devices to estimate the dose gradient due to (i) the increase of the source-sample distance and (ii) the absorption of the radiation by the material itself (i.e. battery). The locations of the TLDs are shown in the sketch in Fig. 1.

2.3. Irradiation facility and reference dosimeters

All samples were irradiated at IRSN in terms of air kerma using a linear accelerator (Elekta Synergy®) with a 4 MV photon beam (dose rate: ~ 2.8 Gy/min, homogenous area: 30×30 cm²). 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 samples and the table in order to ensure electronic equilibrium conditions during irradiations (Fig. 2). The nominal dose was set at 5.0 Gy to ensure measuring sufficient luminescence signals for an unknown number of SMD components of the investigated electrical devices. For irradiation under controlled conditions the earbuds were removed from their charging case and all samples were directly put on the PMMA plate (see Fig. 2 a). This realistic exposure scenario was chosen because the earbuds are located externally of the charging case in the user's ears and the case may be stored in a user's bag or pocket while the devices are in use.

2.4. Luminescence readers

At the Salzburg laboratory an automated reader Lexsyg Research made by Freiberg Instruments (Richter et al., 2013) was used for luminescence measurements. The reader is equipped with a built-in

Table 1
Details of the purchased devices.

No.	Brand name	Model	Price
1	Hama Bluetooth® Headphones "Freedom Lit"	184,084	<25 €
2	QCY T5 Pro earbuds	In1933	<25 €
3	Jlab Go Air Pop true wireless earbuds	Go Air Pop	<25 €

Sr-90/Y-90 beta source for laboratory irradiations, delivering a dose rate of ≈ 0.052 Gy/s, which is calibrated (air kerma) against a Cs-137 gamma source for Al₂O₃ material. The Research reader is equipped with an optical stimulation module containing three different stimulation wavelengths, however, in this study only the blue LEDs (458 ± 5 nm) with an optical power of 100 mW/cm² at the sample position were used. The luminescence signals are detected by a bi-alkali cathode photomultiplier tube Hamamatsu H7360-02. In order to block the blue stimulation light and thermal background, a combination of a glass filter (Hoya U340, 3 mm thickness) and an interference filter (Delta-BP 365/50 EX) is selected for BSL (blue stimulated luminescence) and TL measurements to record the signals in the UV detection window.

At IRSN TL measurements of the reference dosimeters were performed with a manual reader made by Fimel (Fontenay-aux-Roses, France).

2.5. Sample preparation

For dose reconstruction the SMD components are removed from the circuit board. The devices were opened under red light conditions in the laboratory with small screw drivers and opening picks to extract the electronic components of the circuit boards (see Fig. 3 a-c). Pliers were helpful to open the small earbuds. One should note that the indication LEDs of the earbuds lit up automatically when the earbuds are removed from their charging case and potentially bleach the luminescence signals. A solution is to cut the cable from the battery after opening the devices.

The electronic components on the circuit board were screened using a binocular. The suitable components were extracted from the board and fixed with a thin layer of silicone oil on the surface of the stainless-steel cup of the luminescence reader (see Fig. 3 d).

One cup was prepared for the Hama headphones, one cup for the earbuds (left and right earbuds to increase the number of SMD components) and one cup for the charging case for the QCY and Jlab samples, respectively. In Table 2 the extracted numbers of SMDs are summarized, which were fixed on a cup for the measurements.

2.6. Measurement protocols and data analysis

A standardized measurement protocol (Bassinnet et al., 2014a) was applied in this study. This protocol called "OSL with preheat" was developed using OSL of resistors extracted from the circuit board of mobile phones in the framework of the EU-FP7 MULTIBIODOSE project and tested in several interlaboratory comparisons for retrospective dosimetry and field tests in the framework of the EU-FP7 CATO project (Discher et al., 2021), the "European Radiation Dosimetry" (EURADOS) WG 10 and "Running the European Network for Biological Dosimetry and Retrospective Physical Dosimetry" (RENEB) network (Waldner et al., 2021), the "Korea retrospective dosimetry network" (KREDOS) group (Kim et al., 2022) and, more recently, again the RENEB network (Port et al., 2023). The OSL signals were measured at 100 °C for 30 s after a preheat up to 120 °C for 10 s. The calibration dose was approx. 5 Gy using the built-in beta source. The early background from 6 to 12 s was subtracted from initial OSL signals from 0 to 6 s and a macro spreadsheet of the EURADOS WG10 was used for analysis. A universal fading correction is included in this macro spreadsheet to account for OSL signal loss over time.

For an additional investigation of the SMDs TL signals were recorded by heating up the samples to 450 °C with a heating rate of 2 °C/s incl. a second TL measurement for thermal background correction.

The measurement of the TLDs was the following: preheat at 135 °C for 15 s, and heat up to 240 °C at a heating rate of 3 °C/s.

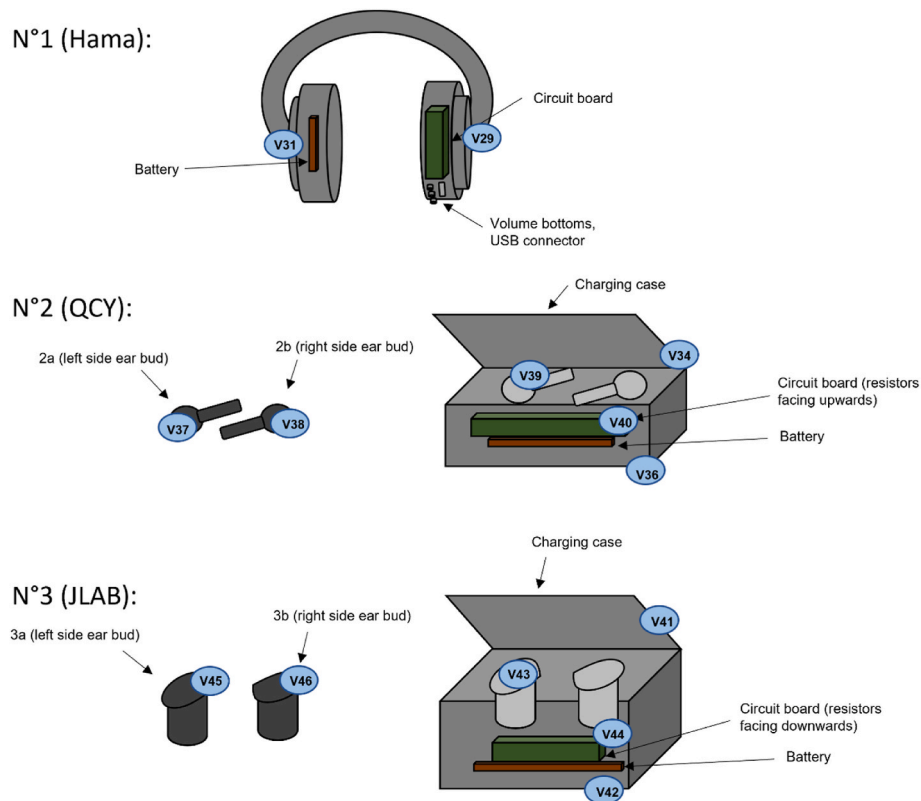


Fig. 1. Sketch with the location of the TLDs on the surface or inside the devices during the 5.0 Gy irradiation.

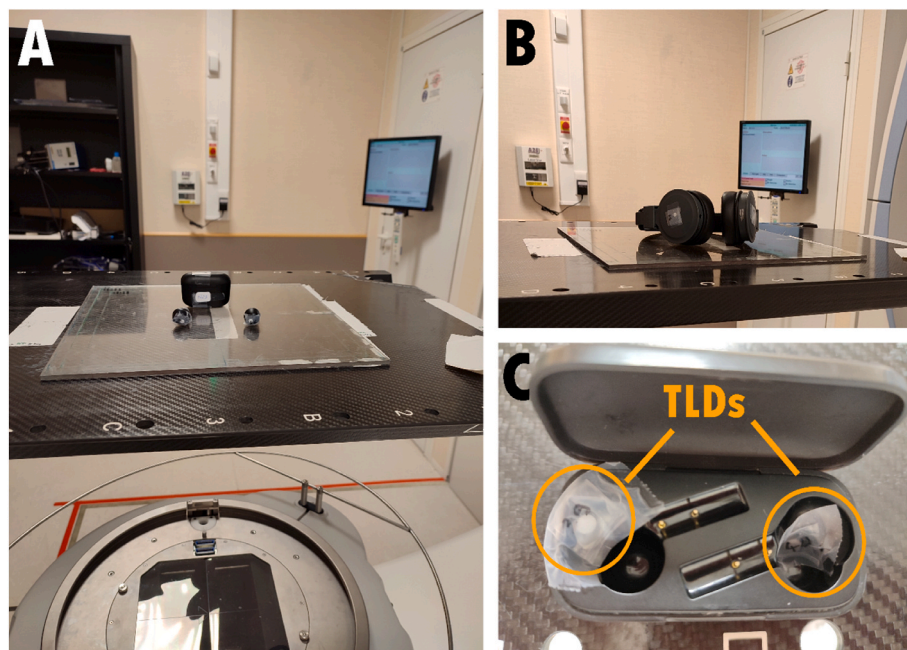


Fig. 2. Setup for irradiations using a linear accelerator: (a) Earbuds (removed from their charging case) and (b) wireless headphones on the PMMA plate; (c) position of the reference TLDs inside the charging case of the earbuds.

3. Results and discussion

3.1. Results of the TLDs readout

The TLD readouts are summarized in Table 3. The TLDs on the Hama headphones indicate a reference dose of 4.0 Gy on the left and right

speakers (centered position). The dose gradient (cover and bottom of the charging case) ranges from 3.9 to 4.8 Gy and from 3.7 to 5.0 Gy for the QCY and Jlab samples, respectively. The TLD readouts inside the case at the upper position and lower position range between 4.4 and 4.5 Gy for the QCY sample, and between 4.0 and 4.3 Gy for the Jlab sample. The reference doses of the removed earbuds of both samples, which were

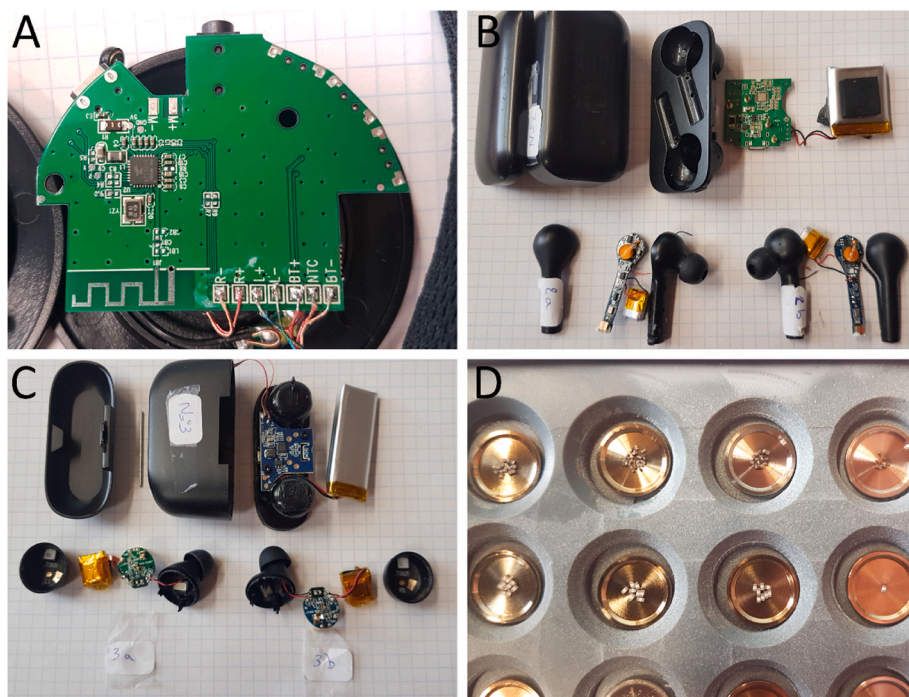


Fig. 3. (a) Circuit board of the Hama wireless headphones. Opened charging cases and earbuds of the QCY (b) and Jlab (c) models. On some of the printed circuit boards, the SMDs were labelled with the letter „R“ and „C“ along with a number. The SMD components with a dark-colored upper surface and white-colored lower surface which are identified as resistors were found on the position with a “R” letter. (d) Extracted SMDs from the devices and reference SMD resistors placed in the center of the measurement cup of the Lexsyg reader. The pictures were taken under white light after the measurements.

Table 2
Details of the extracted number of SMD components from the devices and reference SMD resistors of a kit.

Brand name	Cup No.	SMDs identified as resistors	Remark
Hama Bluetooth® Headphones “Freedom Lit”	1	8 x 0402 sized components	Circuit board was located only on one side of the headphones (on the other side the battery is located)
QCY T5 Pro earbuds	2	Charging case: 7 x 0402 sized components	Bigger sized SMDs were found in the charging case, smaller sized SMDs were found in the earbuds
	3	Both earbuds: 20 x 0201 sized components	
Jlab Go Air Pop true wireless earbuds	4	Charging case: 5 x 0402 sized components	Both earbuds: 6 x 0201 sized components
	5	Both earbuds: 6 x 0201 sized components	
Reference SMD resistors	6	8 x 0402 sized components	Three identical cups were prepared and on one cup only a single SMD resistor was fixed
	7	8 x 0402 sized components	
	8	8 x 0402 sized components	
	9	1 x 0402 sized components	

placed directly on the PMMA plate, are between 4.5 and 4.6 Gy.

In general, the TLDs readout fit to the expected radiation field due to source-sample distance and absorption.

3.2. Reconstructed dose of the SMD components

3.2.1. Preliminary dose estimation

After a delay time of 5 and 6 days (due to shipping and sample preparation) the sampled SMDs from the devices and the reference resistors from the kit were measured with the standardized protocol (see section 2.6) and analyzed using the template spreadsheet. The results

are shown in Table 3 in comparison to the TLD doses.

Using the universal fading correction factor of the macro spreadsheet template, the estimated doses of the reference SMD resistors were in good agreement with the reference TLD doses, while the estimated doses of the sampled SMDs were overestimated by a factor up to 2.1. Further analysis and experiments were carried out to explain these results.

3.2.2. Additional investigations

The BSL decay curves of the sampled SMD components indicate a much higher background level, compared to the reference SMD resistors (see Fig. 4 a). An investigation of the TL signals of the SMD components was carried out by a TL measurement up to 450 °C (Fig. 4 b). Expected TL peaks (ca. 75 °C and 150 °C) for resistors are observed (Lee et al., 2017) and in the temperature range between 200 °C and 350 °C a difference of the TL intensities is discovered. This could be due to the presence of other types of components, such as inductors.

Due to these differences in the OSL decay and TL glow curves of the sampled SMD components versus the SMD resistors from the kit, the BSL signal fading was checked for each cup. Cycles of beta irradiation (ca. 5 Gy) and BSL readouts after different storage times (from 1 h to 13 days) were carried out. The cups were not moved but stored on the sample wheel in the reader. After each readout step a calibration measurement was conducted immediately after irradiation (storage time $t < 2$ min) to calculate the fading factor F.

In Fig. 5 the fading of the BSL signals of the sampled SMD components (except for components of the QCY case) indicates a significantly different signal stability compared to the reference SMD resistors (cup 6 to cup 9). The fading factors of reference SMD resistors are in good agreement with the universal fading factors F and their 1σ uncertainty, calculated from the fading correction formula given in the macro spreadsheet template. The lower fading rate of the sampled components could again suggest the presence of other types of components on the cups.

Generally, possible explanations of the differences comparing the TL glow curves, the OSL decay curves and the fading characteristics may be the lack of cleaning of the sampled SMDs or a misclassification of the SMD components. The analysis of their composition and its comparison with that of components from the kit or extracted from mobile phones

Table 3

Dose readout of the TLDs as reference values for the comparison. The locations on or inside the devices are shown in Fig. 1. In addition, the results of the reconstructed doses using the universal fading correction factor are added.

No.	Brand name	Location	TLD code	TLD dose/reference dose (Gy)	Cup No.	Reconstructed dose (Gy)
1	Hama Bluetooth® Headphones “Freedom Lit”	In the center of left speaker	V29	4.0 ± 0.2	1	6.7 ± 1.0
		In the center of right speaker	V31	4.0 ± 0.2		
2	QCY T5 Pro earbuds	Left earbud	V37	4.6 ± 0.2	2	8.5 ± 1.2
		Right earbud	V38	4.5 ± 0.2		
		On the lid case	V34	3.9 ± 0.2	3	4.4 ± 0.7
		Inside case, upper position	V39	4.4 ± 0.2		
		Inside case, lower position	V40	4.5 ± 0.2		
3	Jlab Go Air Pop true wireless earbuds	Left earbud	V45	4.5 ± 0.2	4	8.5 ± 1.2
		Right earbud	V46	4.6 ± 0.2		
		On the lid case	V41	3.7 ± 0.2	5	9.0 ± 1.4
		Inside case, upper position	V43	4.0 ± 0.2		
		Inside case, lower position	V44	4.3 ± 0.2		
		Under the case	V42	5.0 ± 0.3		
4	Reference SMD resistors			5.0 ± 0.3	6	4.6 ± 0.7
				5.0 ± 0.3	7	4.1 ± 0.6
				5.0 ± 0.3	8	4.2 ± 0.6
				5.0 ± 0.3	9	4.4 ± 0.8

could provide information.

3.2.3. Results of the dose reconstruction using individual fading correction

The results of the reconstructed doses are depicted in Fig. 6 using individual fading factors for correction. The logarithmic fitting of the fading data used are depicted in Fig. A1 in the Appendix including the

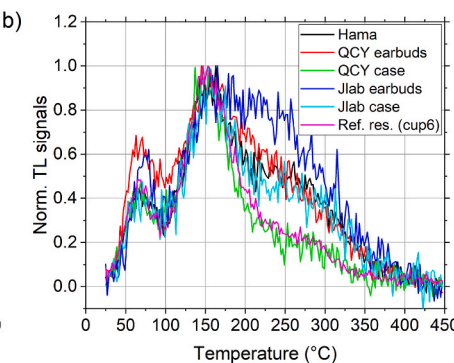
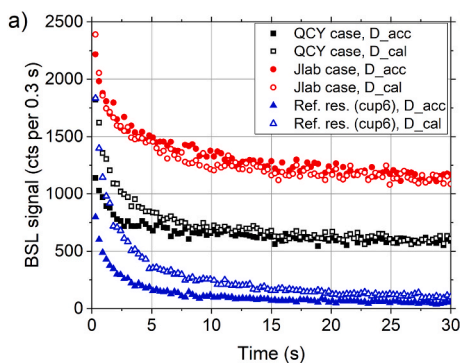


Fig. 4. (a) Selected decay curves of the sampled SMD components and the SMD resistors of the kit. The faded “accident” BSL signals are shown as solid symbols and the signals for calibration (ca. 5 Gy beta dose) as open symbols. A higher background level is observed for the sampled SMDs compared to the reference SMD resistors. (b) TL signals of the SMDs normalized to the maximum intensity for comparison purposes. Most of the sampled SMDs (except QCY case) indicate a stronger TL signal at higher temperatures (>200 °C) compared to the reference SMDs.

fitting parameters (Table A). The uncertainties were calculated from the combination of the error estimation due to counting statistics for the instrument signal and the uncertainty resulting from logarithmic fitting of the fading curves to the experimental data in Fig. 5.

For comparison the reference dose values of the TLDs are included. The TLD doses on the left and right earbuds are shown, as well as both TLDs doses at the lower positions (inside the charging case and on the bottom of the case), because it is the closest position to the circuit board and its components.

In general, the given “accident” dose of 5.0 Gy was reconstructed in an acceptable range and the reconstructed doses vary between 5.0 and 6.9 Gy of the earbuds and wireless headphones. However, there is a trend that these estimated doses are higher than the corresponding TLD values, especially for the “Jlab case” sample. The individual fading correction improves the accuracy of the reconstructed doses (in average an overestimation factor of 1.3) compared to the universal fading correction.

4. Conclusions

This study proves that the dose reconstruction using earbuds and wireless headphones for retrospective dosimetry is possible. In general, it can be stated that these low-budget electronic devices are potentially suitable for dose assessment and an alternative fortuitous retrospective

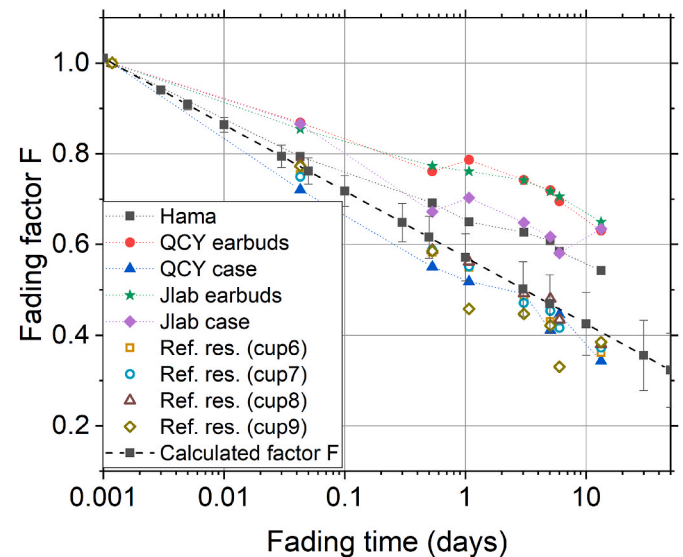


Fig. 5. Fading factor of the sampled SMD components (symbols are connected by dotted lines for sake of clarity), reference SMD resistors (open symbols) and calculated universal fading factor F of the macro spreadsheet template (square symbol with dashed line) and its 1 σ uncertainty.

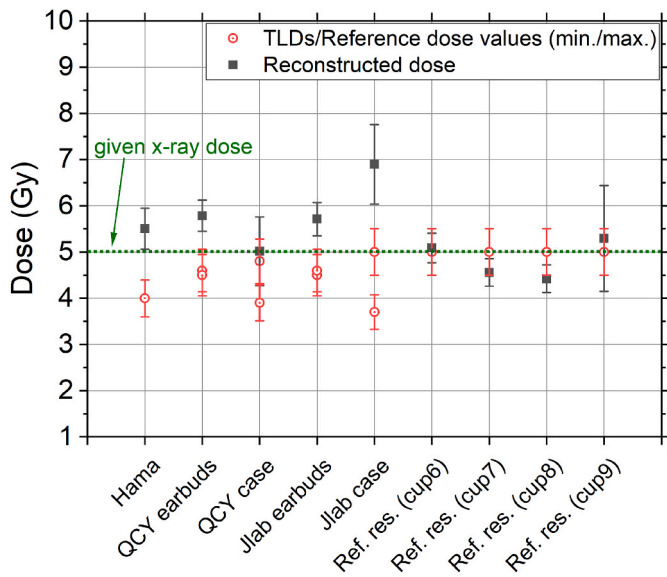


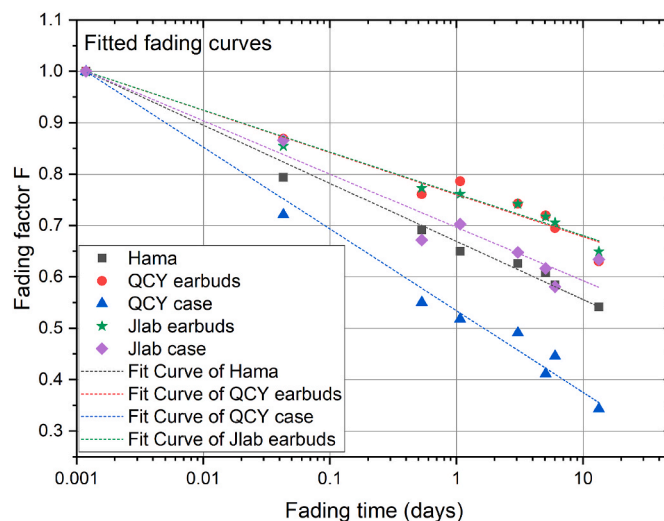
Fig. 6. Results of the reconstructed doses in comparison with the dose values of the TLD doses. A 2σ uncertainty of the reconstructed doses and the TLDs is displayed as error bars.

dosimeter, for a multi-method approach, combining different materials and techniques. Additionally, the doses from different locations could be reconstructed (multi-location dose assessment) and possibly provide some additional information about the radiation exposure scenario, i.e. the case of the earbuds was transported in a bag (lower position on a person’s torso) and the earbuds were worn in the ears at head level. In case of a dose assessment after a radiological incident the use of low-budget electronic devices might potentially be better accepted by the general population compared to high-price objects, such as an expensive smartphone. Additionally, these devices neither store any personal data (contacts, notes, documents, etc.) nor personal pictures and can be replaced easily.

The present study focused mainly on the feasibility of applying the

APPENDIX

The data of Fig. 5 was used to calculate the fading functions using a ln function which was applied in the EURADOS WG10 macro spreadsheet and mentioned in Bassinet et al. (2014). The goodness of the fit (R^2 values) and the plotting parameter are included (see Table A).



A1. Logarithmic fitted fading curves of the sampled SMD components..

existing knowledge, i.e. the measurement protocol for SMDs in mobile phones, and the expertise, i.e. the methods for material testing and better fading correction, to SMDs from other electronic devices. This would be a real case in an accident scenario where there is limited time to test all dosimetric properties of specific materials and where further validation and analysis of the results is required. Clearly, the discrepancies between the materials tested and the resistances in the published data indicate the need for further investigation, which will be addressed in future studies. There is also a need to study and estimate the number of electronic components available in several models of earbuds and wireless headphones, to improve the sampling of components to avoid any misidentification, and to repeat the irradiation test with a dose value in the relevant ranges for triage (i.e., triages levels of <1 Gy; 1–2 Gy and >2 Gy).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Michael Discher reports financial support was provided by National Research Foundation of Korea and by Austrian Federal Ministry of Education Science and Research.

Data availability

Data will be made available on request.

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Table A
Parameters of the fit.

Model	User specific ln function				
Equation	Fading factor $F=(1-Kappa*\ln(x))/(1-Kappa*\ln(0.001180556))$ [x=> fading time in days]				
Sample	Hama	QCY earbuds	QCY case	Jlab earbuds	Jlab case
Parameter Kappa	0.07334 ± 0.00177	0.0468 ± 0.00196	0.12924 ± 0.00452	0.04636 ± 0.00128	0.06463 ± 0.00352
R ² value	0.98879	0.96198	0.98537	0.98183	0.94555

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