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Retrospective radiation dosimetry using OSL of electronic components: Results of an inter-laboratory comparison

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HIGHLIGHTS

- Resistors in mobile phones could function as reliable fortuitous dosimeters in case of a large scale radiological accident.
- Two OSL protocols were validated by an inter-laboratory comparison.
- It is feasible to set up a network of laboratories so as to increase the measurement capacity.

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ABSTRACT

In the framework of the EU-FP7 MULTIBIODOSE project, two protocols using OSL of resistors removed from the circuit board of mobile phones were developed with the aim to use the resistors as fortuitous dosimeters in the event of a large scale radiological accident. This paper presents the results of an inter-laboratory comparison carried out under the umbrella of EURADOS. The two aims of this exercise were the validation of the MULTIBIODOSE protocols by a large number of laboratories and the dissemination of the method with the objective of preparing the basis for a network that could increase Europe's response capacity in the case of a mass casualty radiological emergency. Twelve institutes from eleven European countries and one institute from the USA, with various degrees of expertise in OSL dosimetry, took part in the OSL inter-laboratory comparison. Generally, a good agreement within uncertainties was observed between estimated and nominal doses.

1. Introduction

In the event of a large scale radiological accident, a rapid and accurate retrospective dose assessment of individuals potentially overexposed is needed (Alexander et al., 2007). Mobile phones are

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carried by a large part of the population and are thus potentially useful objects, because some of their components may be able to function as individual fortuitous dosimeters. In the framework of the EU-FP7 MULTIBIODOSE project, several assays have been developed to discriminate the "worried well" from those individuals exposed to potentially harmful doses of radiation, and to categorize the potential victims into those who have experienced low, intermediate or high exposures. To this end a study was implemented with display glass and resistors found on the circuit boards of mobile phones using Electron Paramagnetic Resonance (EPR) and Optically Stimulated Luminescence (OSL), respectively. The procedures were validated by an internal blind test among the three project partners (HMGU, IRSN and ISS). An intercomparison on a larger scale involving laboratories external to the project was carried out under the umbrella of EURADOS. The two aims of this exercise were the validation of the MULTIBIODOSE protocols by a large number of laboratories and the dissemination of the method with the objective of establishing a network of laboratories that could increase Europe's capacity to respond to a mass exposure radiological emergency. Results of the OSL inter-laboratory comparison will be reported in this paper, whereas the EPR results can be found in Fattibene et al. (in press).

Twelve institutes from eleven European countries and one institute from the USA took part in the OSL inter-laboratory comparison. Two OSL protocols optimized by the three project partners (Woda et al., in preparation) were tested. The circuit board of a mobile phone contains a variety of electronic components (resistors, inductors, capacitors, etc.). Most of these components contain a substrate that is sensitive to ionizing radiation, such that OSL is detectable from exposed materials (Inrig et al., 2008; Bassinet et al., 2010; Woda et al., 2010; Fiedler and Woda, 2011; Ekendahl and Judas, 2012; Pascu et al., 2013). Resistors were selected to establish the protocols because of their high degree of availability, radiation sensitivity and signal stability with time. With the first protocol ("*fast-mode*" protocol), no preheat process is performed on the sample, so that measurements are much faster. This protocol could be suitable for a first triage in a mass casualty radiological emergency. In the second protocol ("*full-mode*" protocol), a preheat of the sample aims to make the signal more stable. The procedure is slower but higher precision is expected. In principle this protocol should be more appropriate for an accurate dose-assessment process.

2. Materials and methods

During a two-day preparatory meeting organized at IRSN, the participants were trained on the various steps of the procedure and especially on resistor identification, making use of the physical appearance of the devices such as the black cover layer and the white ceramic substrate underneath. Only one participant did not attend the training.

The participants received three mobile phones irradiated with a ^{60}Co source at IRSN. The doses (air kerma) fall within three triage dose ranges: $<$1 Gy (low dose), 1–2 Gy (medium/intermediate dose) and $>$2 Gy (high dose). Nominal doses were 0.3, 1.7 and 3.3 Gy, but they were unknown to the participants. The general experimental procedure involved removing resistors from the exposed phones, to prepare groups of them for analysis. For each of the 3 unknown doses, laboratories had to provide OSL results from at least two groups, each containing about ten resistors; one group had to be measured using the "fast-mode" protocol (OSL acquisition at room temperature for 30 s) and one had to be measured using the "full-mode" protocol (preheat: 10 s at 120 °C, OSL measurement at 100 °C for 30 s). Some labs measured two aliquots per protocol, the first one as soon as possible after irradiation, the second one about 20 days after irradiation.

Irradiated phones were disassembled and the circuit boards and components removed by the participants under red light. The resistors were removed using screwdrivers, scalpels, or utility knives. Resistors were put on sample holders ("cups") previously sprayed with silicone oil. For both protocols, a first measurement was performed at some time after the irradiation to obtain the signal related to the unknown dose (the so-called "accident" signal); then a calibration dose (5 Gy) was delivered by each participant to the sample and the resulting OSL was recorded (the "calibration" signal). OSL measurements were performed using Riso TL/OSL readers equipped with a blue light source (470 $\pm$ 30 nm). Most readers were equipped with an internal beta ^{90}Sr/^{90}Y source but some participants used an external gamma source (^{137}Cs or ^{60}Co) to deliver the calibration dose. Each built-in source was calibrated against the ^{60}Co source at IRSN by providing 3 cups of resistors irradiated at a known dose (6 Gy) to the participants. In each laboratory a dose conversion factor was obtained by comparing the OSL signal of the samples irradiated at IRSN with the OSL signal obtained from the same samples after re-irradiating them to the same dose using the laboratory's built-in source, with the time delays between the exposure and signal acquisition identical in each case. OSL signal from resistors is unstable with time. It decreases with time after irradiation (fading). In this way, the same fading effect applies to both measurements and a direct comparison of OSL signals is possible. The conversion factor was then applied for the determination of the unknown doses during the inter-comparison.

An analysis template was provided to the participants in order to calculate the signal intensities (integration windows of 0–6 s for signal and 6–12 s for background, respectively), uncorrected dose according to the procedure described in the previous paragraph, dose corrected for fading (fading correction factor depending on the time between the first irradiation and the first readout), and the related error. The fading correction factors (Woda et al., in preparation) were derived from two fading curves (one for each protocol) calculated by the three MULTIBIODOSE project partners (HMGU, IRSN and ISS). Uncertainties were calculated from the combination of the error estimation due to counting statistics for the instrument signal and background and the uncertainty resulting from fitting of the fading curves to the experimental data. For the purpose of triage categorization, the approach used in the biodosimetry intercomparisons was adopted and only the numerical value of the measured dose considered, without the uncertainty, in order to see whether the result falls into the correct category (i.e. dose range). On the other hand, uncertainties were taken into account in the evaluation of the dose assessment capapilities of the method.

3. Results and discussion

3.1. The "fast-mode" protocol

3.1.1. Triage categorization

Measured doses provided by each participating laboratory for the three triage dose ranges using the "fast-mode" protocol are shown in Fig. 1. They are plotted against the nominal doses. In cases where one laboratory reported two results for the same nominal dose (see above), both measured doses are considered and plotted individually. Considering all results, correct identification of the actual triage dose range was obtained in 87.5% of the cases (35 out of 40). The fraction of misclassification into the respective lower category is of about 7.5% (3 out of 40) and into the respective higher category about 5% (2 out of 40). Considering the three doses separately, correct identification of the triage category ($<$1 Gy, 1–2 Gy and $>$2 Gy) was achieved for all samples (11 out of 11) for the lowest dose, for 7 out of 11 for the medium dose and for 17 out of 18 of samples for the highest dose.

Although it is unrealistic to expect that, in a triage situation, multiple laboratories will use multiple assays and operational methods to estimate doses for the same individual, for validation purposes it is interesting to see the triage categorization results when the full data set is used. The mean values of the measured doses are reported in Table 1. From this table, it is evident that the mean values of the measured doses are correctly categorized in the 3 triage dose ranges considered here.

Table 1
Mean values of the doses measured by all the participants of the OSL intercomparison using the "fast-mode" protocol per triage category.

Triage category (Gy)	Nominal dose (Gy)	Mean measured dose (Gy)	Standard deviation (Gy)
<1	0.3	0.25	0.15
1–2	1.7	1.41	0.46
>2	3.3	3.30	0.95

3.1.2. Dose assessment

Considering the dose assessment, in Fig. 2 doses measured by each participant are shown with error bars representing 1 SD. Within a 95% confidence interval, for the highest dose (3.3 Gy) 11 out of 12 laboratories were able to assess the nominal dose, for the medium dose (1.7 Gy) a correct assessment was done by 9 out of 11 and for the lowest dose (0.3 Gy) 10 out of 11 laboratories provided a correct assessment within 2 SD. Note that one participant (ID 9) did not provide results for the medium and low doses using the "fast-mode" protocol.

In two cases (participants ID 6 and 12), the lowest nominal dose was below the detection limit, which was roughly estimated from the signal response to the calibration dose and the background noise level at 0.3 and 0.5 Gy for the respective laboratories. Although a dose assessment was thus not possible, the correct triage categorization could still be inferred, as the maximum possible undetectable dose cannot be higher than the detection limit.

For the medium dose, the underestimation by participants 2 and 5 was shown to be due to the fact that the actual fading rate for these two samples was significantly higher than the general fading curve predicts.

Within 95% confidence interval, no participant tends to systematically overestimate or underestimate the dose with respect to the actual value for the three doses.

3.2. The "full-mode" protocol

3.2.1. Triage categorization

In Fig. 3 measured doses provided by each participating laboratory using the "full-mode" protocol are plotted against the nominal doses. In cases where one laboratory reported two results for the same nominal dose, both measured doses are reported. Considering all results, a correct identification of the actual triage dose range was obtained in 90.5% of the cases (38 out of 42). The fraction of misclassification into the respective lower category is about 2.4% (1 out of 42) and into the respective higher category about 7.1% (3 out of 42). Considering the 3 doses separately, a correct identification of the triage category was given for 11 samples out of 12 for the lowest dose, for 9 out of 12 for the medium dose and for 100% of samples (18 out of 18) for the highest dose.

In order to estimate the triage categorization results when the "full-mode" protocol is used, the mean values of the measured doses are reported in Table 2. For each triage dose range considered here, the mean values of the measured doses are correctly categorized.

3.2.2. Dose assessment

Considering the dose assessment, in Fig. 4 doses measured by each participant are shown with error bars representing 1 SD. For the "full-mode" protocol for the highest dose (3.3 Gy) 10 out of 12 laboratories were able to assess the nominal doses within a 95% confidence interval, for the lowest dose (0.3 Gy) 7 out of 12 laboratories provided a correct assessment within uncertainty, and for the medium dose (1.7 Gy) a correct assessment was done by 8 out of 12.

Similar to the fast mode protocol, the lowest nominal dose was below the detection limit for two laboratories (ID 4 and 12), which was roughly estimated at 1.4 Gy and 0.6 Gy, respectively. Furthermore, for participant 4, the medium dose was also below the detection limit, which in this case roughly corresponded to 10.4 Gy. The unusually high detection limits for participant 4, especially in

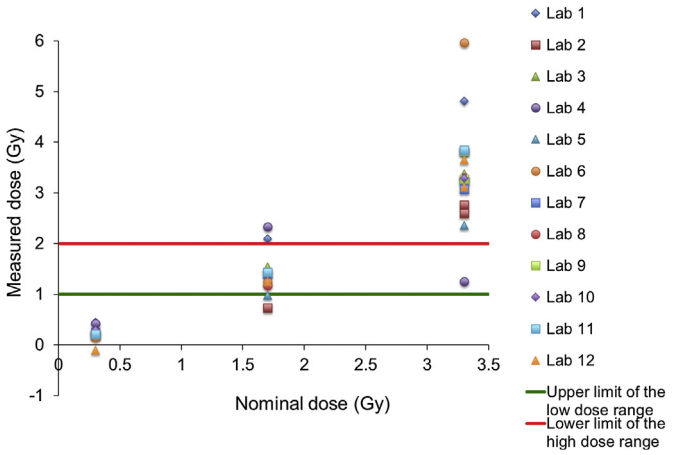

Fig. 1. Scatterplot of doses measured by the 12 participants using the "fast-mode" protocol against the nominal doses (0.3 Gy, 1.7 Gy and 3.3 Gy). The green and red lines represent the upper limit of the low dose triage category and the lower limit of the high dose triage category, respectively. In cases where one laboratory reported two results for the same nominal dose both measured doses are reported.

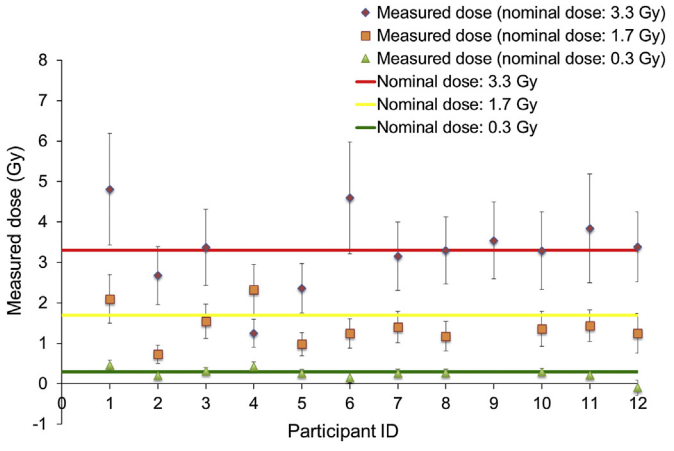

Fig. 2. Scatterplot of doses measured by the 12 laboratories using the "fast-mode" protocol against the participant ID. The green, yellow and red lines represent the 3 values of the nominal doses: 0.3 Gy (green), 1.7 Gy (yellow) and 3.3 Gy (red) respectively. Error bars (1 SD) for each measured dose are also shown. In cases where one laboratory reported more than one result the mean value between the provided doses are reported.

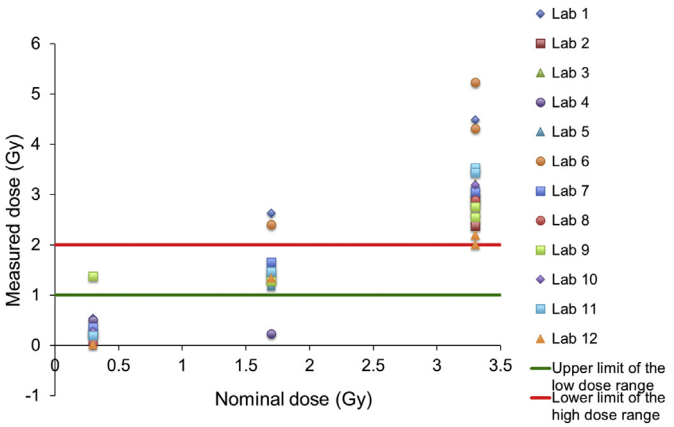

Fig. 3. Scatterplot of doses measured by the 12 participants using the "full-mode" protocol against the nominal doses 0.3 Gy, 1.7 Gy and 3.3 Gy. The green and red lines represent the upper limit of the low dose triage category and the lower limit of the high dose triage category, respectively. In cases where one laboratory reported two results for the same nominal dose both measured doses are plotted.

Table 2
Mean values of the doses measured by all the participants of the OSL intercomparison using the "full-mode" protocol per triage category.

Triage category (Gy)	Nominal dose (Gy)	Mean measured dose (Gy)	Standard deviation (Gy)
<1	0.3	0.36	0.36
1–2	1.7	1.50	0.60
>2	3.3	3.17	0.77

the case of the medium dose, is due to the fact that different electronic components other than the alumina rich resistors were sampled, with considerably lower sensitivity. This also explains the strong underestimation in the case of the medium dose (Fig. 4) and the underestimation of the high dose value in case of the "fast mode" protocol (Fig. 2). Note that the participant did not attend the training. One lab (ID 9) measured almost the same dose with the "full-mode" protocol for both phones irradiated with the low and

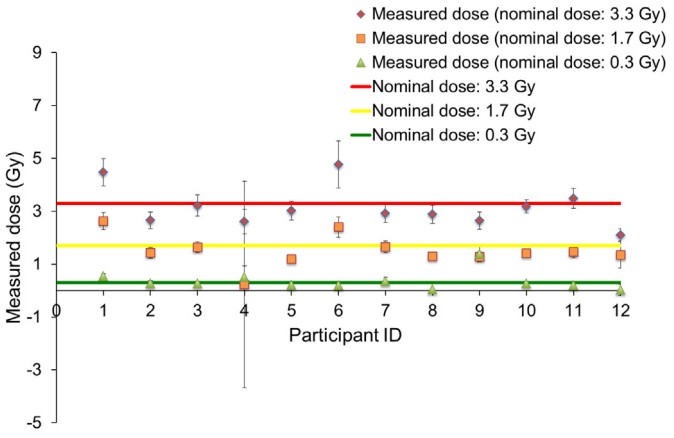

Fig. 4. Scatterplot of doses measured by the 12 laboratories using the "full-mode" protocol against the participant ID. The green, yellow and red lines represent the 3 values of the nominal doses: 0.3 Gy (green), 1.7 Gy (yellow) and 3.3 Gy (red) respectively. Error bars (1 SD) for each measured dose are also shown. In cases where one laboratory reported more than one result the mean value between the provided doses are reported.

medium dose. The OSL decay curve and signal intensities for both samples were almost equal. This implies that either this participant received by accident two phones of identical dose or that the same phone was accidentally sampled twice. As no results were reported for the low and medium dose with the fast mode protocol, the reasons for the odd results cannot be fully identified. The systematic deviances introduced by the results from two participants for the "full-mode" protocol explains the apparent larger standard deviation for the low and medium nominal dose, as compared to the results from the "fast-mode" protocol.

4. Conclusions

The inter-laboratory comparison using OSL of electronic components was carried out using two different protocols: a "fast-mode" protocol and a "full-mode" protocol. With the "fast-mode" protocol no preheat process is performed on the sample, so that measurements are much faster. In the "full-mode" protocol a preheat process on the sample aims to make the signal more stable and higher precision is expected. The ability of the two protocols to identify the correct triage dose range and to assess the actual simulated accident dose delivered to the sample was evaluated for three different doses delivered to mobile phones: a low dose (<1 Gy), a medium dose (1–2 Gy) and a high dose (>2 Gy). In about 90% of cases a correct identification of the triage category and agreement within uncertainty with the nominal dose was achieved, only for the dose assessment using the "full-mode" protocol, the percentage of agreement was lower, about 70%. The main reasons for outliers could be identified as: sampling of wrong components, possible sample mix-up and non-adequate fading correction. By chance this lead to more severe outliers during the application of the "full-mode protocol", therefore the possible higher precision of this protocol could not be demonstrated here. The source of error due to misidentification of electronic components on the circuit board only applied to one participant that couldn't attend the preparatory meeting and stresses the importance of a hands-on training. If this is guaranteed, then the method seems to promising for emergency dosimetry and to be readily transferable to any dosimetry laboratory with suitable equipment in order to increase the measurement capacity in case of a large scale radiological accident.

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