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PII: S0969-806X(18)31414-2
DOI: https://doi.org/10.1016/j.radphyschem.2019.04.047
Reference: RPC 8297

To appear in: Radiation Physics and Chemistry

Received Date: 15 December 2018
Revised Date: 18 April 2019
Accepted Date: 20 April 2019


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Thermoluminescence Characterization of Smartphone Screen for Retrospective Accident Dosimetry

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Abstract

With increasing use of ionizing radiation and associated nuclear materials, concern arises regarding the possibility of harm from unplanned events, both to the surrounding environment as well as to its inhabitants; the Three Mile Island, Chernobyl and Fukushima Daiichi nuclear power plant incidents come to mind. Retrospective dosimetry can provide estimation of the radiation dose received from such accidents, the information allowing appropriate remedial measures to be formulated. In the affected area a number of objects can be applied as natural dosimeters. Given that the mobile phone is a device used by a large fraction of the population, investigation has been made of the suitability of the phone screen for retrospective dosimetry. Samples of five brands of phone screen were studied (Iphone, Sony, Samsung, Asus and Xiomi), investigating key thermoluminescence (TL) properties, including TL dose response, glow curves, reproducibility and long-term stability of the TL signal. Within the γ-radiation dose range up to 10 Gy, these parameters show the Iphone screen to offer best use as a suitable material for retrospective dosimetry. Reconstruction of absorbed dose is possible for a period of up to four weeks post-incident. One proviso concerns the ability to adequately correct for TL signal loss during this time.

Keywords: Phone screen, TL dosimetric properties, Iphone screen, Low fading, Retrospective dosimeter.

1. Introduction

In the event of a radiation incident involving exposure to large number of individuals, a reliable and significant technique is crucial in estimating the absorbed dose received by the recipients. As an example, accurate dose estimation provides essential information regarding resource mobilisation, triage and medical management of affected individuals included, a matter invariably arising after nuclear or radiological events (Inrig, Godfrey-smith, & Larsson, 2010). Materials chosen for particular retrospective dosimetry should have high

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radiation sensitivity (in particular good sensitivity to low doses), as well as satisfying specific requirements for emergency dosimetry such as fast sample preparation and reliable measurements (Discher & Woda, 2013). In addition, it must be a relatively common and easily utilised medium, ubiquitously available as a fortuitous dosimeter in response to large scale emergency situations, personal belongings carried close to the body being of particular interest (Discher & Woda, 2013).

Over the past four decades luminescence techniques have been employed in estimating doses to exposed population, use being made of ceramic materials found in the environment (Bøtter-Jensen, 1997; Ademola & Woda, 2017). Among the promising techniques successfully utilised for accurate estimation of absorbed doses can be included electron paramagnetic resonance (EPR), optically stimulated luminescence (OSL) and thermoluminescence (TL). In regard to retrospective dosimetry, TL has been suggested to offer superiority over OSL and EPR due to its capability of measuring a broader spectrum of the light signal and significantly lower fading in use of the signal from higher-temperature glow peaks (Bailiff et al., 2016; Lee et al., 2017). Consequently, since the 1950s thermally stimulated luminescence has been widely used to measure ionizing radiation doses (Bailiff et al., 1996; Godfrey-Smith & Haskell, 1993).

The TL method has utilized a variety of personal objects as fortuitous dosimeters, one proposal being for use of the glass displays of mobile phones. Given that the mobile phone is typically carried close to the body it is of interest as an emergency dosimeter, with Discher & Woda (2013), Discher et al. (2013), Mrozik, et al., (2017) and Bassinet et al., (2010) having examined mobile phone glass samples irradiated to gamma-ray doses up to 100 Gy. Signal stability and effects of storage conditions have been studied, relatively fast fading being found, with post irradiation decrease of TL signal of ~ 40% following 24 hours storage in the dark. Discher et al., (2013) have shown improvements to result from concentrated hydrofluoric acid etching of the glass surface, leading to a factor of four gain in the lower detection limit, corresponding to approximately 80 mGy. Thus said, the origin of the intrinsic background signal is not yet understood. Moreover, detailed studies of the utility of the phone screen within the lower dose range are still highly limited.

With the foregoing in mind, present study seeks to add further crucial information in the 1 to 10 Gy dose region, aiming to firmly establish the glass-based radiation sensor for retrospective dosimetry. In this, five different types of mobile phone screen have been investigated, those of the manufacturers: Sony, Xiaomi, Iphone, Samsung and Asus, evaluating several key TL material properties required for dosimetric purpose including TL glow curves, dose response, reproducibility and long-term stability of the TL signal. Comparison has been made against that of TLD-100, one of the more sensitive commercially available LiF-based TL media.
2. Experimental details

In this study, five different brands of smartphone screen glass were examined; Iphone (Iphone 5S), Sony (Xperia Z5), Samsung (Galaxy 6), Asus (Zenfone 5) and Xiomi (Redmi 6). The displays were first mechanically extracted from the smartphones and all plastic film removed. The pixel coloured-layer fixed to the front side of the glass was removed through use of a scalpel. Subsequently, the glass samples were cleaned with ethanol and then cut into pieces using a diamond-cutter, each of approximate size $5 \times 5 \, \text{mm}^2$, suitable for fitting into the sample planchette cup of the TL reader. Each sample was weighed using an electronic balance.

![Preparation of a typical phone screen sample of approximate size $5 \times 5\, \text{mm}^2$, (a) showing a part of the intact screen and (b) an example sample.](image)

Figure 1. Preparation of a typical phone screen sample of approximate size $5 \times 5\, \text{mm}^2$, (a) showing a part of the intact screen and (b) an example sample.

Irradiated glass phone screen were investigated using a conventional Gammacell-220 $^{60}$Co, mean energy 1.25 MeV (the source being located in the Department of Physics, University of Malaya). The response of the glass phone screens have been compared against that of TLD-100 chips (Thermo Fisher Scientific Inc, Waltham, MA, USA), the latter being of dimension $3.2 \times 3.2 \times 0.89 \, \text{mm}^3$ and mean mass 23.4 mg. Following irradiation, the samples were then immediately retained inside a black box in order to avoid light exposure during storage.

Readout was carried out 24 h post irradiation, use being made of a Harshaw 3500 TL reader (USA) supported by WinREMS software. The time-temperature profile (TTP) was set to provide for a preheat temperature of 50 °C, heating rate of 10 °C/s and maximum temperature for data acquisition of 400 °C. A slow flow of nitrogen gas was supplied during the read out
process to inhibit sample oxidation. For each sample, the TL yield was normalized to its mass.

3. Results and discussion

3.1 Effective atomic number

The strength of photon interaction in a given material is greatly influenced by its effective atomic number \((Z_{eff})\), a single valued representation of the multi-element composition. A further, less powerful influencing factor is the material density. To calculate the \(Z_{eff}\) of the studied materials, a Field Emission Scanning Electron Microscope with energy dispersive X-ray (EDX) capability was used. The elemental chemical compositions obtained via EDX analyses of the phone screen samples are summarized in Table 1. It is interesting to observe that the Si content of the screen materials of several of the brands (Iphone, Sony and Asus) is extremely low while the C content is far more striking. The reason is attributed to developments in the touch-sensitive technology together with improved physico-mechanical properties, of the screen, several other chemical elements being brought into play. Use of a thin layer of carbon ensures the desired electrical conductivity while reducing the overall stress. Literature points to the use of C from 2010 as an alternative to indium tin oxide (ITO) in fabrication of low-cost touch screens (https://www.fraunhofer.de/en/press/research-news/2011/january/Touchscreen_Made_of_Carbon.html), the latter also blocking between 10-30% of the light from the display screen, reducing clarity and brightness (https://www.azonano.com/article.aspx?ArticleID=3176). In addition, indium is an expensive and rare material, with natural supplies likely to run out in just a few years. Note is also made that electronics manufacturers are investing heavily in materials such as nanowires and graphene, actively developing manufacturing processes and products that take advantage of their properties (https://newatlas.com/low-cost-carbon-nanotube-touchscreen/17715/).

Table 1. Respective results of samples using EDX analysis. The presented values in Table 1 are from the average of at least two EDX spectra for each type of sample, and in each spectrum the results were obtained from 3-5 iterations.

<table>
<thead>
<tr>
<th></th>
<th>Iphone</th>
<th>Sony</th>
<th>Asus</th>
<th>Samsung</th>
<th>Xioi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (%)</td>
<td>Atomic (%)</td>
<td>Weight (%)</td>
<td>Atomic (%)</td>
<td>Weight (%)</td>
<td>Atomic (%)</td>
</tr>
<tr>
<td>C</td>
<td>65.18</td>
<td>73.82</td>
<td>50.88</td>
<td>59.78</td>
<td>55.87</td>
</tr>
<tr>
<td>N</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>O</td>
<td>29.30</td>
<td>24.89</td>
<td>40.95</td>
<td>36.11</td>
<td>34.39</td>
</tr>
<tr>
<td>Na</td>
<td>0.17</td>
<td>0.10</td>
<td>0.04</td>
<td>0.02</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>-</td>
<td>0.97</td>
<td>0.92</td>
<td>0.60</td>
<td>0.32</td>
</tr>
<tr>
<td>Cu</td>
<td>5.22</td>
<td>0.62</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Si</td>
<td>0.15</td>
<td>0.07</td>
<td>5.56</td>
<td>2.80</td>
<td>1.66</td>
</tr>
<tr>
<td>In</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mg</td>
<td>-</td>
<td>0.40</td>
<td>0.25</td>
<td>0.19</td>
<td>0.11</td>
</tr>
<tr>
<td>Ca</td>
<td>-</td>
<td>0.41</td>
<td>0.15</td>
<td>5.59</td>
<td>1.26</td>
</tr>
<tr>
<td>Mo</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zn</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.72</td>
</tr>
<tr>
<td>K</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For a mixture of elements, the effective atomic number \((Z_{eff})\) are calculated using the Mayneord equation (Khan, 2010), as follows:
\[
Z_{\text{eff}} = \left( a_1 Z_1^{2.94} + a_2 Z_2^{2.94} + a_3 Z_3^{2.94} + \ldots + a_n Z_n^{2.94} \right)^{\frac{1}{2.94}}
\] (1)

where \( a_1, a_2, \ldots a_n \) are the fractional contribution of each element to the total number of electrons in the mixture, the latter calculated as follows:

\[
N_e = \frac{N_A Z}{A_w} (W_i)
\] (2)

where \( N_A \) is the Avogadro number, \( A_w \) is the atomic weight, \( W_i \) is the fractional weight, and \( Z \) is the atomic weight of the element. By calculating the number of electrons per gram, as in Eq. 2, \( Z_{\text{eff}} \) can be determined using Eq. 1. In the context of radiation protection it is favourable for a dosimeter to be tissue equivalent (\( Z_{\text{eff}} = 7.14 \)) (Cossio et al., 2012), TLD-100 being particularly so with an effective atomic number, \( Z_{\text{eff}} \) of 8.2 (Gonzalez et al. 2007). Given that, as shown in Table 2, all five sample types are not soft-tissue equivalent, the need for calibration for dose deposition in tissue arises (Hashim et al., 2014).

**Table 2.** Respective effective atomic number of phone screen samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Effective atomic number, ( Z_{\text{eff}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iphone</td>
<td>12.0</td>
</tr>
<tr>
<td>Sony</td>
<td>8.1</td>
</tr>
<tr>
<td>Asus</td>
<td>10.6</td>
</tr>
<tr>
<td>Samsung</td>
<td>13.6</td>
</tr>
<tr>
<td>Xioami</td>
<td>20.0</td>
</tr>
</tbody>
</table>

### 3.2 Annealing study

Thermal annealing has been conducted to erase any irradiation memory from the dosimetric material, important in restoring the material to initial conditions prior to first irradiation, further to stabilize the trap structure (Furetta, 2003). In Fig. 2, investigation has been made of the best annealing temperature (threshold temperature) to erase any effect of previous irradiation of Iphone screen sample, providing a representation of all the measured screen samples. The most favourable choice is the one in which the TL residual signal is practically the same as background. The samples were initially irradiated to a dose of 1 Gy of gamma-rays. As a control measure following one hour of annealing, with the samples remaining in the furnace, additional thermal stress has been avoided by allowing the samples to cool down naturally over a period of 24 h (Hashim et al., 2014).

Following irradiation, the samples were then annealed over temperatures from 100 °C to 500 °C, in increments of 100 °C for a constant annealing time of one hour. The measurements were recorded by averaging three repeated sample readings using the Harshaw 3500 TLD reader. Based on results such as that shown in Fig. 2, it was observed that the residual TL response decreased with temperature and at 400 °C the value of residual TL response trended towards a constant values, approaching that of background. Therefore, 400 °C was chosen as
the threshold temperature, $T_c$ and considered the best temperature to erase all previous irradiation memory.

![Figure 2](image-url)  
**Figure 2.** Residual TL response of Iphone screen sample annealed from 100 °C to 400 °C. $T_c$ is the threshold value where the temperature starts to constant at 400 °C at 1 hour.

### 3.3 TL glow curve

Figure 3 shows the glow curves of all phone screen samples irradiated to 10 Gy of gamma-rays, providing a representation of all the measured samples. The area under the curve represents the number of electrons released from traps and thus by association the radiation energy deposited, while the peak height is indicative of the maximum number of electrons traps released (Hashim et al 2015; Nawi et al 2015). During the thermal stimulation process the electrons are released from their traps, TL response increasing with radiation dose as in Fig. 4 later. From Fig. 4, it is clear that the resultant glow curve is composed of a broad, dominant peak with a maximum between 330°C to 360°C, the integrated area indicating the particular sensitivity to the amount of absorbed dose. The general structure of the TL glow curve remains unchanged in repeat cycles of annealing and irradiation at various doses.
Figure 3. The glow curve of samples irradiated to 10 Gy of gamma-rays.

3.4 TL dose response

TL dose response is defined as the functional dependence of the intensity of the measured TL signal upon absorbed dose (Furetta, 2003). The linearity of the TL response over a wide dose range is one of the important characteristics for the ideal dosimeter. Figures 4 (a) and (b) show the TL dose response of the phone screen samples compared against TLD-100, irradiated to gamma-rays to deliver doses up to 10 Gy. Each point represents the mean of three repeated measurements, normalized to sample mass, with error bars of one standard deviation. Overall, the dose response of the phone screen samples were all below that of TLD-100, all with good linearity.

TL gradients are shown in Table 3, Iphone showing the greatest TL response, followed by Sony, Asus, Samsung and Xiaomi. Specifically, the TL response of Iphone, Sony, Asus and Samsung have been found to be respectively ~0.06, ~0.05, ~0.03 and ~0.03 that of TLD-100. It is noted that Xiaomi sample shows marginal degradation of response with dose.
Figure 4. (a) TL dose response of the phone screen samples compared against TLD-100; (b) expanded view of the TL dose response of the phone screen samples. (Note: in some cases the error bars are smaller than the data points).

Table 3. Gradient of respective phone screen samples in comparison with TLD-100, referring to the dose response graph of Fig. 4.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Gradient (nC/g.Gy)</th>
<th>Ratio gradient of sample to TLD-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLD-100</td>
<td>191539</td>
<td>-</td>
</tr>
<tr>
<td>Iphone</td>
<td>10961</td>
<td>0.06</td>
</tr>
<tr>
<td>Sony</td>
<td>9148.5</td>
<td>0.05</td>
</tr>
<tr>
<td>Asus</td>
<td>5774</td>
<td>0.03</td>
</tr>
<tr>
<td>Samsung</td>
<td>5616.4</td>
<td>0.03</td>
</tr>
<tr>
<td>Xiomi</td>
<td>-141.25</td>
<td>nil</td>
</tr>
</tbody>
</table>
3.5 TL sensitivity and linearity index

The sensitivity of the TL dosimeter, defined as TL yield per unit dose per unit mass of sample (Alyahyawi et al., 2017), is an important characteristic in representing material response. In the present study, the TL sensitivity is expressed as the TL yield (measured in nC) per unit mass of dosimeter and per unit dose (g⁻¹.Gy⁻¹). The mean readings of three dosimeters were taken at each point. Figure 5 shows that of TLD-100 and phone screen samples. In specific terms, the TL response for an absorbed dose of 1 Gy, for TLD-100 and the Iphone, Sony, Asus, Samsung phone screen were 180µC/Gy.g, 11µC/Gy.g, 9µC/Gy.g, 5.8µC/Gy.g, 5.7µC/Gy.g. It is noted that the Xiomi sample is practically insensitive, giving an approximate zero TL value to irradiation.

Figure 5. Sensitivities of all samples at 1Gy, the inset provides an expanded view of phone screen response.

Figure 6 illustrates the Linearity Index, $f(D)$ against dose for the Iphone sample, evaluated using relation (1), measuring the deviation from linearity of TL:

$$f(D) = \frac{F(D)/D}{F(D_0)/D_0}$$

(1)

where $F(D)$ is the TL response corresponding to dose $D$, $F(D_0)$ is the TL response measured at low dose $D_0$. Linearity of response is exhibited at $f(D) = 1$, being sublinear when $f(D) < 1$ and supralinear for $f(D) > 1$. Based on Fig. 6, Iphone sample data points show sublinear behaviour at doses above 2 Gy, below this the sample clustering close to a value of $f(D) = 1$. 

Figure 5. Sensitivities of all samples at 1Gy, the inset provides an expanded view of phone screen response.
Figure 6. Plot of linearity index, $f(D)$ against dose for Iphone sample.

3.6 Reproducibility

Results of reproducibility of the Iphone samples in 5 cycles of irradiation are as shown in Fig. 7. Stability of sample influences on TL response shows there to be a small deviation compared to the first cycle, in the range 3, 10, 11, 10 %, the Iphone samples being seen to be a good candidate for use as a retrospective dosimeter.

Figure 7. 5-cycles of reproducibility study of Iphone sample irradiated to a dose of 1Gy
3.7 Fading

The response of TL dosimeters typically exhibit changes during storage, both before and after irradiation. The fractional loss of TL signal in a dosimeter over period of time is referred to as fading (Bilski et al., 2013). Temperature and time of storage are dominant fading factors, the traps of lower entrapment energy fading to a greater degree than the more energetic ones, a result of the higher transition probabilities, contributing to larger errors in dose assessment (Sasho Nikolovski, Nikolovska, Velevska, & Velev, 2010). Figure 8 shows the natural log of TL signal over a period of 28 days, representative of the residual signal for Iphone samples (considered the most sensitive sample type) when irradiated to 1 Gy of gamma-rays. In the case of fading, the readout at “day zero” was carried out immediately following irradiation. As can be seen from the graph, a rapid decrease in signal intensity is observed during the first day post irradiation, the signal loss decreasing subsequently, a result of the more stable deeper TL traps. Overall, over the 28 days of study, an approximate 70% loss in TL signal strength is seen compared to the initial value, giving a mean loss in TL response for the Iphone sample of some 4% per day, with a decay factor of -0.0388. By using this fitting equation, it is possible to reconstruct the initial dose.

![Figure 8](image.png)

**Figure 8.** Fading over a period of 28 days; residual signal of Iphone sample post-irradiation to a dose of 1 Gy.
4. Conclusion

The study has demonstrated the potential of commercially available representative brands of phone screen samples for accident dosimetry. Key thermoluminescence properties including the effective atomic number, annealing, dose linearity, reproducibility and fading were investigated with gamma radiation doses of up to 10 Gy. Among the materials investigated the Iphone screen sample is seen to offer the most promising for retrospective dosimetry purposes, with greater TL responses, a well-defined glow curve peak and near linear TL response in the dose range up to 10 Gy. TL yield reproducibility for the Iphone sample over five repeat cycles show a small deviation compared to the first cycle, in range of 3, 10, 11 and 10 %. Over 28 days post-irradiation, the rate of fading of the Iphone screen sample has been found to be approximately 4% per day, being promising for retrospective dosimetry purposes.

Acknowledgement
The authors would like to acknowledge to the Sunway University for funding of this research through the grant no.: INT-2018-SHMS-CRS-02.

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Low-cost touchscreens made with carbon nanotubes <https://newatlas.com/low-cost-carbon-
nanotube-touchscreen/17715/; Accessed date: April 18, 2019


Highlights

- Popular brands of phone screen samples were studied for retrospective dosimetry.
- Iphone screen shows good sensitivity to $\gamma$-ray and suitable TL dosimetric properties.
- Dose reconstruction can be impaired by fading which depends on several factors.
- Iphone shows a fading rate of $\sim 3\%/d$ which is promising for retrospective dosimetry.