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A TL study of protective glasses of mobile phones for retrospective dosimetry

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ABSTRACT

Several studies have shown that certain components of mobile phones, such as electronic components, display or touch screen glass, are suitable as emergency dosimeters in case of radiological incidents. However, so far the methods are frequently destructive and in case of a dose assessment the mobile phone will be destroyed. In order to overcome this problem, alternative materials need to be sought and further research is necessary. Building on results of a previous study, we further investigated protective glasses in this work, which have become an alternative material for dose reconstruction. Protective glasses are easy to sample and cheap, have become very popular to protect the surface of phones, can be easily replaced without complete destruction of an expensive smartphone, thus a dose assessment method based on this material will potentially find much greater public acceptance. The aim of this study was to optimize the detection window by systematically investigating the radiation-induced TL signals and intrinsic zero dose signals. Using two selected detection windows, the long-term and optical stability of the TL signals were investigated. The set of nine different protective glass samples studied fell into two groups with different fading and optical bleaching characteristics. Further research is necessary in order to reduce the zero dose signal, to reinvestigate the dosimetric properties and to verify the final protocol using a realistic irradiation test.

1. Introduction

In the field of medicine, industry and research there is an increasing risk of accidental over-exposure of operators and civilians to ionizing radiation. In addition, attention is given by authorities and institutions of emergency preparedness to the possible scenario of an intentional radiological attack with a possible high number of exposed people. In such an event, the dosimetric triage is extremely important to minimize public panic, identify the people with high exposures and to distinguish them from the lower and non-exposed. Emerging methods of physical retrospective dosimetry could play an important role here, complementing the more established biological dosimetry assays [1,2].

The focus of a collaboration research project called ProGlaDos, is to develop new tools for assessing an absorbed dose after a radiological overexposure. Generally, mobile phones are carried closely to the body and could be useful proxies for measuring the amount of dose an individual has received as personal dosimeters are usually not available. There are many studies in which different elements of mobile phones (i.e. electronic components on the circuit board, display or touch screen glass) have been characterized for physical retrospective dosimetry. Regarding luminescence techniques, thermoluminescence (TL), optically stimulated luminescence (OSL), thermally assisted OSL (Ta-OSL) and phototransferred thermoluminescence (PTTL) methods have been used to determine the absorbed dose of touch screen glasses [3–5] and display glasses of modern mobile phones [6–12]. However, so far these techniques are frequently destructive. This implies that, in case of a dose assessment, the phones can no longer be used, which is a major issue in terms of the acceptance within the population due to the destructive loss of the mobile phone and potential emotional damage. In order to overcome this problem, alternative materials need to be sought and further research is necessary.

One approach to implement a non-destructive dose-reconstruction method was proposed by Sholom et al. [13] by applying the OSL method on the external protective back-glass, which can be found on the back of some modern phones. In a first step the authors investigated pulsed OSL using an optical fiber and in a second step built a custom-made OSL

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Table 1
Representative samples of protective glasses used in this study.

Sample ID	General information		
	Brand/ product name	Type of glass according to product description	Protective glass for mobile phone model
P4	ZAGG	Invisible shield glass+	Samsung Galaxy J7
P6	Otter Box	Alpha Glass	Apple iPhone 6 Plus, 6S Plus, 7 Plus, 8 Plus
P7	Belkin	ScreenforceTM, Tempered Curve	Samsung Galaxy S9
P11	Mobilis		Apple iPhone 5, 5S, 5C, SE
P16	Belkin	Screenforce InvisiGlass UltraTM (Accessory Glass 2 by Corning)	Apple iPhone 6 Plus, 6s Plus
P17	Belkin	Screenforce InvisiGlass UltraTM	Apple iPhone Xs/X
P28	Belkin	n.a.	Samsung Galaxy A3
P32	Mobilis	n.a.	Samsung Galaxy J3
P34	Uniformatic	n.a.	Samsung Galaxy Xcover 4

reader [14] that could accommodate the entire phone, measuring the back glass with CW-OSL. A dose recovery test proved the usability of this approach and the estimated doses were in good agreement with the corresponding nominal values.

Another approach is to use protective glasses, which are easy to sample and cheap, have become very popular to protect the display screen surface of phones and can be easily replaced without complete destruction of an expensive smartphone, thus finding much greater public acceptance. Bassinet and Le Bris [15] first indicated the potential of this kind of glass, by showing that it is sensitive to ionizing radiation and could be an alternative fortuitous retrospective dosimeter. However, the authors discovered low sensitivity of some glass samples, when measured using a wideband blue glass filter combination and they suggested to optimize the detection window in order to adapt the measurement protocol.

This paper deals with a selection of different protective glass samples which were systematically investigated in order to optimize the parameters of the TL measurements (mainly the filter combination/ detection window) and subsequently analysed. The final goal is to develop a robust measurement protocol which will be tested by realistic dose recovery tests within the ProGlaDos research project.

2. Materials and methods

A representative selection of protective glass samples was chosen, covering a number of different brands and manufacturers. Information on the glass samples and the internal sample IDs are summarized in Table 1.

The prepared glass aliquots were cleaned by ethanol and subsequently cut into pieces of approx. 5 × 5 mm^2, suitable for fitting into the stainless steel cups of the luminescence reader. If necessary, the aliquots were annealed to 450 °C and held for a few tens of seconds to erase any intrinsic TL signals.

For the measurements an automated reader Lexsyg Research made by Freiberg Instruments [16] was used, including a built-in Sr-90/Y-90 beta source (norm. activity of 1.51 GBq) which delivers a dose rate of ≈0.058 Gy/s for laboratory irradiations (calibrated against a standard Cs-137 gamma source). The luminescence signals were detected with a bialkali cathode photomultiplier tube Hamamatsu H7360-02. An automated filter changer unit is available which consists of two programmable filter wheels equipped with glass and interference filters in order to select the required detection window (see Table 2 for details).

All TL measurements were performed in a N_2 atmosphere. The heating rate was always set to 2 °C/s and the maximal readout temperature to either 420 or 450 °C, depending on the filter combination. A second TL measurement was always carried out for thermal background subtraction. For the analysis, the thermal BG corrected TL signals were integrated between 150 and 250 °C. For the bleaching test, the blue LEDs (548 ± 5 nm) of the reader were used, delivering an optical power of 100 mW/cm^2 at the sample position.

Table 2
Filter combinations for optimization of the detection window.

No.	Name of filter combination	Filter name	Center wavelength and full width at half maximum (FWHM) according to datasheet of the filters	Detection window
1	TL - 340 nm	Schott KG3 (3 mm) + AHF-BrightLine HC340/26 Interference	340 nm, FWHM = 30.2 nm	UV/blue detection window
2	TL - 365 nm	Schott KG3 (3 mm) + Delta-BP 365/50 EX Interference	365 nm, FWHM = 50 nm	
3	TL - 410 nm	Schott KG3 (3 mm) + AHF-BrightLine HC 414/46 Interference	414 nm, FWHM = 50 nm	
4	TL - 475 nm	Schott KG3 (3 mm) + AHF-BrightLine HC 475/50 Interference	475 nm, FWHM = 55.7 nm	
5	TL - 575 nm	Schott KG3 (3 mm) + AHF-BrightLine HC 575/25 Interference	575 nm, FWHM = 31.3 nm	Yellow/red detection window
6	TL - 620 nm	Schott KG3 (3 mm) + AHF-ET Bandpass 620/ 60 Interference	620 nm, FWHM = 60 nm	
7	TL - wideband blue	Schott BG39 + Schott BG 25 + Schott KG3	400 nm, FWHM* = 100 nm	
8	TL - wideband KG3	Schott KG3 (6 mm)	490 nm, FWHM* = 300 nm	
9	TL - HoyaU340 + 365 nm	Hoya U-340 (2.5 mm) + Delta-BP 365/ 50 EX Interference	350 nm, FWHM* = 35 nm	

FWHM*: The FWHM is manually calculated by the total transmission of the filter combination using filters' datasheets and filters' thickness.

3. Results and discussions

3.1. Variation of the detection filter

Glass and interference filters are helpful to optimize the detection window of a TL measurement. In this part of the study, one aliquot was used per protective glass sample. All aliquots were first annealed to delete any intrinsic signals and then irradiated with ca. 5 Gy. TL measurements were then carried out using different filter combinations of the detection unit of the reader, as given in Table 2, and the radiation-induced TL signals (RIS) recorded. Representative TL glow curves of three selected samples (P4, P16 and P28) are depicted in Fig. 1 a-f.

For a qualitative comparison three protective glass samples are selected and further discussed. It is obvious in Fig. 1 a-c that the TL

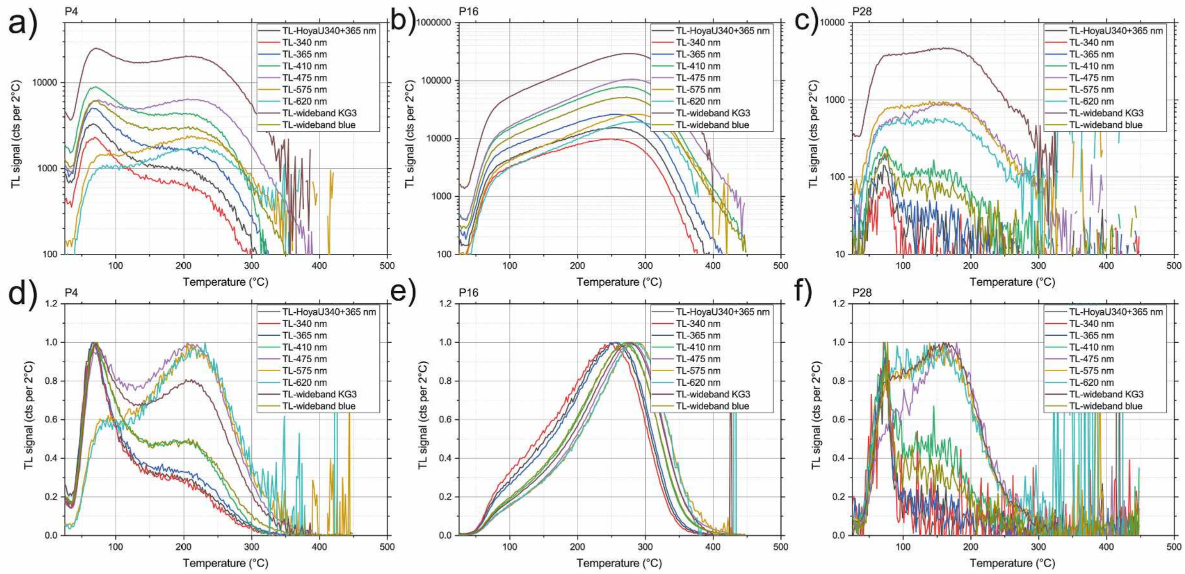

Fig. 1. a–f: TL glow curves of three selected samples (P4, P16 and P28) using different detection windows. For each sample, one single aliquot was used and all nine filter combinations were tested. For irradiation the same dose (ca. 5 Gy) was applied. (a–c) The curves are shown in a lin-log scale for sake of clarity. (d–f) The normalized TL glow curves are shown. The glow curves are normalized to the first TL peak intensity for sake of clarity.

Table 3
Normalized RIS values (integral 150–250 °C) for the nine protective glass samples.

Filter	P4	P6	P7	P11	P16	P17	P28	P32	P34
TL - 340 nm	0.7	0.6	0.5	0.7	0.7	0.7	0.5	0.6	0.5
TL - HoyaU340 + 365 nm	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
TL - 365 nm	1.7	1.9	1.8	1.7	1.6	1.6	1.6	1.7	1.8
TL - 410 nm	4.4	6.0	5.9	4.5	4.2	4.2	6.0	4.4	6.2
TL - 475 nm	6.4	14.4	11.7	6.6	5.0	5.0	59.6	5.0	12.2
TL - 575 nm	2.3	9.9	7.1	2.6	1.2	1.2	58.1	1.7	6.3
TL - 620 nm	1.7	6.3	4.6	2.0	0.9	0.9	34.1	1.4	4.1
TL - wideband blue	3.1	3.9	3.9	3.1	2.8	2.8	4.0	3.0	3.9
TL - wideband KG3	20.4	59.7	46.2	21.3	14.9	14.9	298.4	17.1	43.4

signal intensity and the glow curve shape depend strongly on the filter combination used. The highest TL signals are obtained using the TL-wideband KG3 filter combination. For sample P4 the choice of the detection window influences the relative intensities of both observed peaks. The lower-temperature peak is higher in the UV/blue detection window compared to the peak around 220 °C. In the yellow/red detection window the case is reversed. Sample P16 indicates a slight temperature shift of the TL maximum intensity depending on the used detection window. In the UV/blue detection window the peak is around 250 °C, compared to the peak around 290 °C measured with the yellow/red detection window. For sample P28 the choice of the detection window is very crucial: in the UV/blue detection window the TL signal is very weak, however, the TL signal in the yellow/red detection window is sufficient for dose reconstruction. Generally, TL emission spectra measurements are more favorable to verify the observations above in order to further optimize the detection window. However, spectral measurements using a CCD camera are often at least an order of magnitude less sensitive than PMT measurements, and therefore are restricted to investigations in the higher dose range up to hundreds of Gy or even kGy [10]. With the method used here, signals can be studied in a dose range directly relevant for accident dosimetry.

3.2. Comparison of the integrated RIS signals

The obtained TL signals of the nine protective glass samples were integrated between 150 and 250 °C (see also section 3.3). For a quantitative comparison the RIS signals using the different detection windows were normalized to the UV filter combination (TL - HoyaU340 + 365 nm, number 9 in Table 2), which represents one of the most available filter combination of commercial luminescence readers. The ratios are displayed in Table 3 and visualized in Fig. 2.

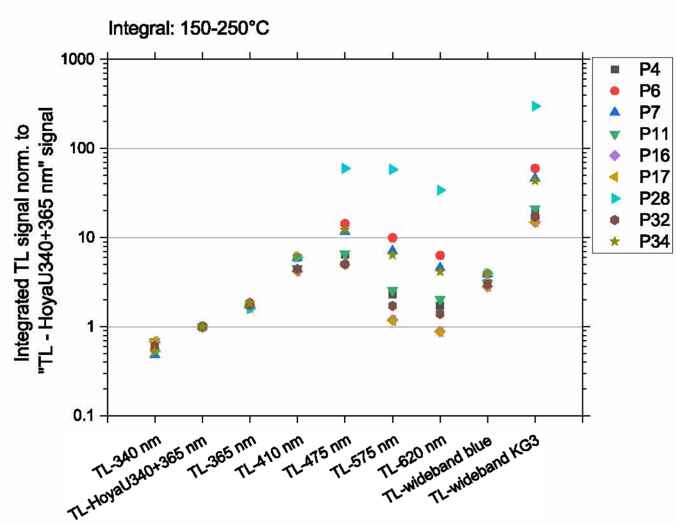

Fig. 2. Quantitative comparison of the RIS using the different filter combinations of the reader. For each protective glass sample one aliquot was used and the detection window was varied.

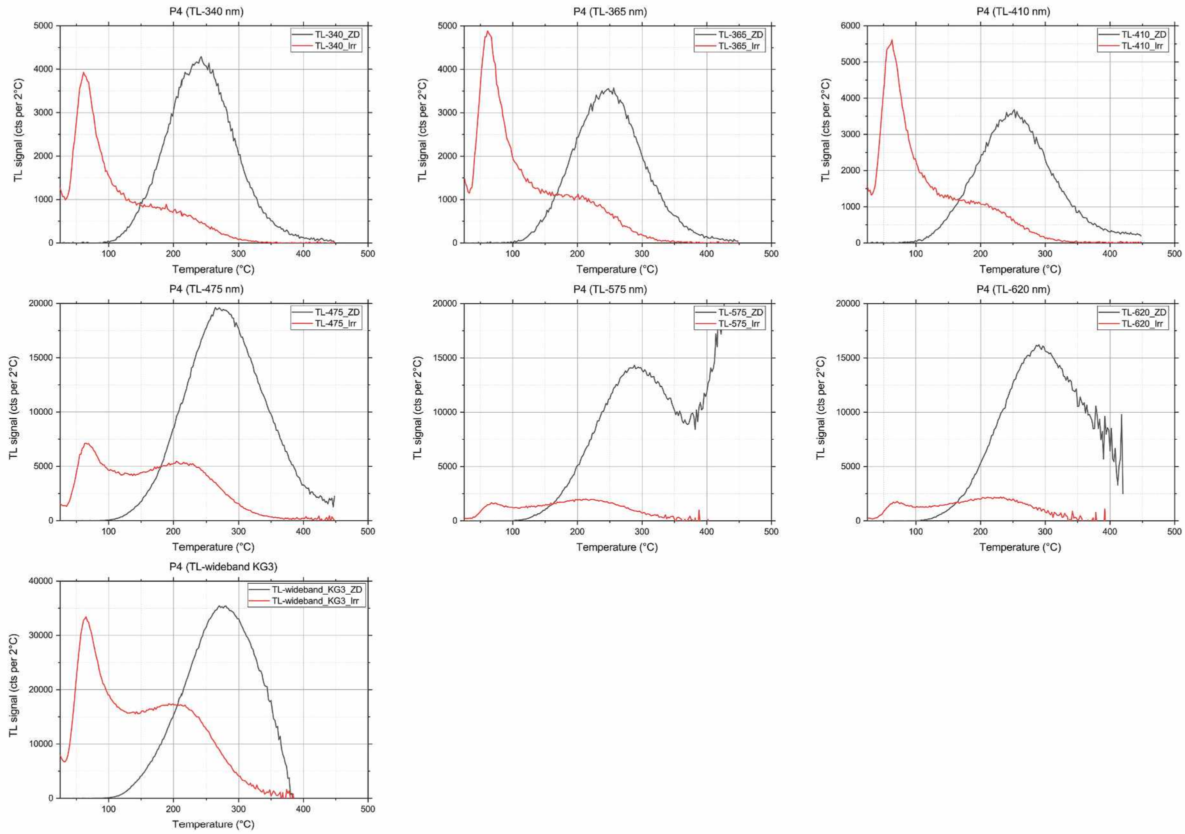

Fig. 3. Comparison of the zero dose (ZD) and radiation induced TL signals using different detection windows. For each filter combination an unused glass sample was used. First, the intrinsic zero dose was measured and afterwards the radiation induced TL signal after ca. 5 Gy irradiation was recorded.

Table 4
Calculation of the zero doses of the different protective glass samples.

	Calculated zero doses (Gy)								
	Integral 150–250 °C								
Filter	**P4**	**P6**	**P7**	**P11**	**P16**	**P17**	**P28**	**P32**	**P34**
TL - 340 nm	20.07	0.01	20.38	0.15	0.89	0.49	35.41	0.87	−0.22
TL - 365 nm	11.19	0.03	23.18	0.12	0.69	0.41	48.30	0.53	0.13
TL - 410 nm	11.61	0.24	37.05	0.13	0.76	0.35	0.95	0.81	0.26
TL - 475 nm	8.86	0.11	17.47	0.10	0.79	0.38	8.12	1.27	0.43
TL - 575 nm	14.80	0.01	10.13	0.07	0.92	0.42	13.49	1.22	0.16
TL - 620 nm	14.75	0.04	10.24	0.07	0.96	0.47	19.01	1.01	0.30
TL - wideband KG3	4.93	0.93	14.80	0.19	0.31	0.30	12.52	0.86	0.15

The ratios in Fig. 2 indicate the signal gain of several orders of magnitude when using different detection windows for measurement of the TL signal. Generally, the TL-wideband KG3 combination increases the signal by a factor >10 compared to the UV filter combination. The choice of the detection filter significantly impacts the sensitivity and therefore the detection limit of the method.

3.3. *Investigation of the zero dose signals*

Even if the protective glass sample has not been exposed to ionizing radiation, a non-radiation induced signal is observed which is called zero dose signal. It overlaps with the radiation induced signal, limits the useable integration range and consequently increases the detection limit [12]. Unexposed glass samples were used for this study and the zero dose signals recorded using seven selected filter combinations of the reader. As an example, the glow curves of sample P4 are shown in Fig. 3. The glow curves of the other samples are given in the supplement (Figs. S1–S8).

Compared to the other investigated protective glass samples, sample P4 shows one of the strongest intrinsic zero dose signals. However, the choice of the detection window is crucial in order to suppress the impact of the disruptive TL signal, which would overestimate the reconstructed dose.

In order to have a quantitative comparison, the zero doses were calculated in the temperature interval 150–250 °C, results are shown in Table 4.

The calculated zero doses vary depending on the filter combination used. However, the results in Table 4 indicate that a single detection window does not exist, which gives the lowest apparent dose due to the zero dose signal for all investigated protective glass samples. Generally, the TL-wideband KG3 filter indicates reasonable results and may be generally recommended. As the zero-dose signal can be measured only once, seven fresh aliquots were needed from each glass sample. These were cut from neighboring positions to minimize any possible effect of a non-homogeneous distribution of zero dose signals across the glass surface.

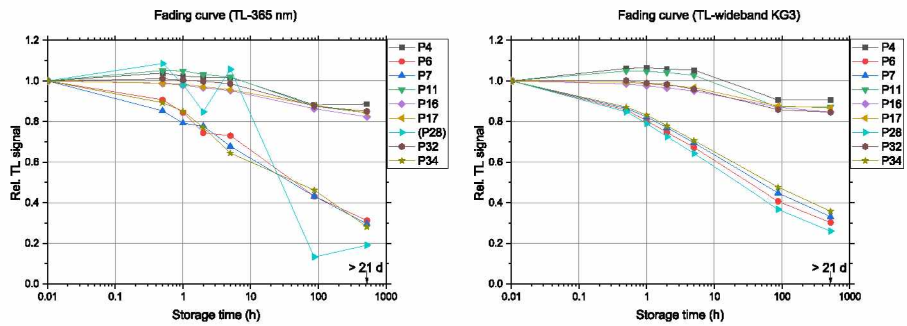

Fig. 4. Fading curves of two selected detection windows.

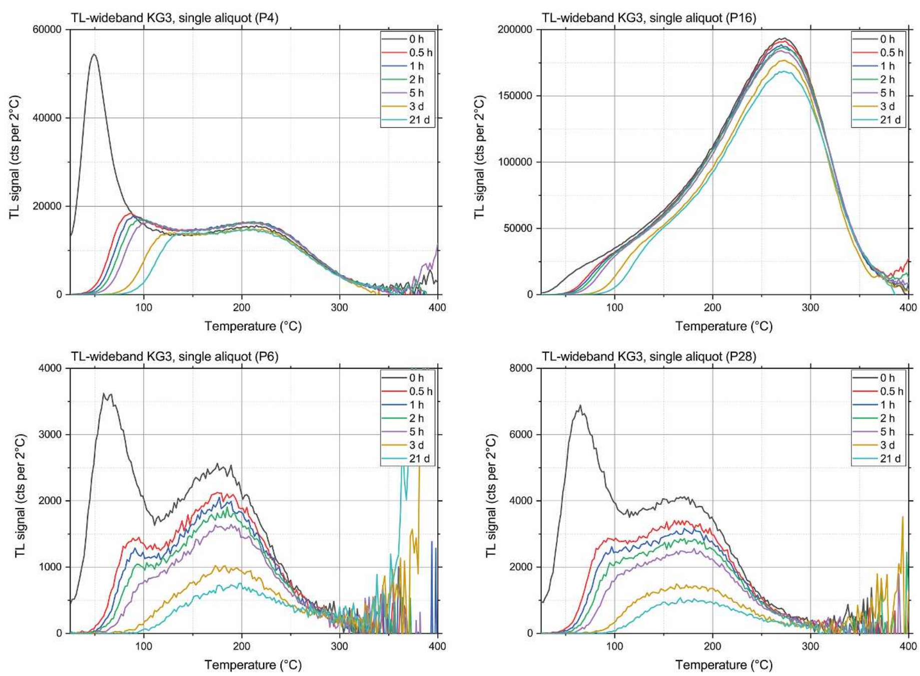

Fig. 5. TL glow curve measured using the TL-wideband filter combination (KG3) after different storage times.

More investigations are necessary to reduce the zero dose signals. For instance, mechanical or chemical pre-treatment of display and touchscreen glasses of mobile phones has been shown to reduce the zero dose signal per unit mass significantly while not affecting the radiation-induced signal per unit mass at the same time [5,9,12,17]. Chemical pre-treatment was also successfully applied in the initial study on protective glasses [15].

3.4. Fading study

For the fading study one single aliquot was used for each protective glass sample. The aliquots were always irradiated with the same dose (ca. 5 Gy), stored in dark and at ambient temperatures and the readouts were performed after different storage times. The fading curves were obtained by normalizing the integrated signals (150–250 °C) to the shortest storage time (a few seconds delay between end of irradiation

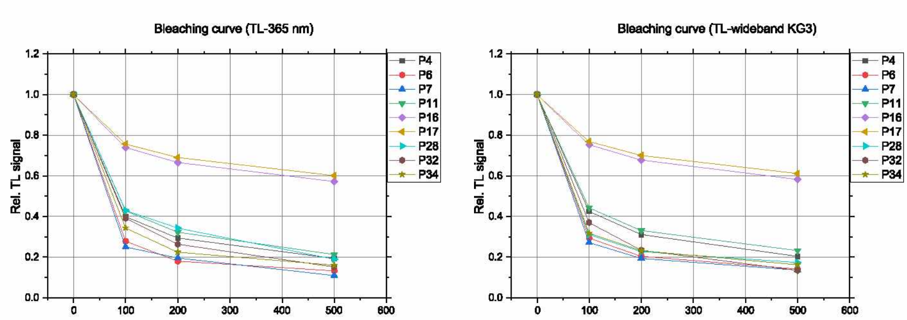

Fig. 6. Bleaching curves of two selected detection windows.

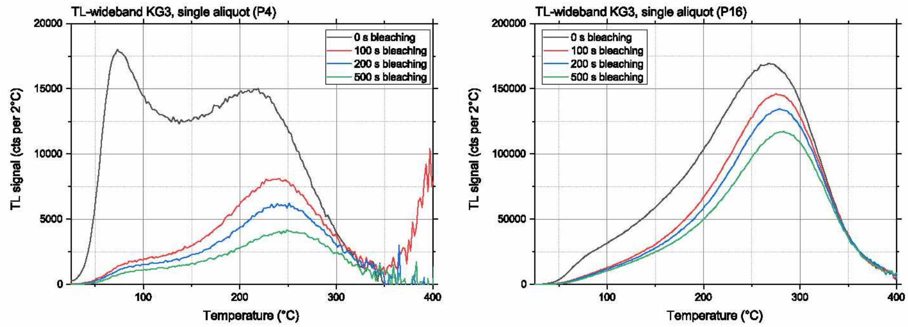

Fig. 7. TL glow curve measured using the TL-wideband filter after different bleaching times.

and readout).

In Fig. 4 the fading curves up to a storage time of 21 days of two selected detection windows are shown. Firstly, fading characteristic appears to be similar for both detection windows and seems to be independent of the choice of filters. Secondly, the signal fading of the investigated protective glasses can be divided into two groups: Samples P4, P11, P16, P17 and P32 indicate a signal loss of about 10–18% after 21 days of storage and samples P6, P7, P28 and P34 indicate a signal loss of about 65–74%.

In Fig. 5 the TL glow curves of the two groups with different fading characteristic, measured in the TL-wideband detection window, are depicted. The rapid decay of the lower temperature components of the TL signal is observed.

3.5. *Bleaching study*

The signal bleaching study on the protective glass samples was carried out using the strong blue LEDs of the reader (maximal optical power of 100 mW/cm^2) and again one single aliquot each sample. The aliquots were always irradiated with the same dose (ca. 5 Gy), bleached at ambient temperatures and the readouts were performed with a constant time difference between end of irradiation and start of the TL readout. In this way it was ensured that a possible additional signal loss during bleaching due to signal fading was the same for all measurements. The bleaching curves were obtained by normalizing the integrated signals (150–250 °C) to the unbleached TL signal.

In Fig. 6 the bleaching curves up to a bleaching time of 500 s for two selected detection windows are shown. Similar to the fading study, the bleaching characteristic appears to be similar for both detection windows and seems to be independent of the choice of filters. However, samples can be divided into two groups according to the degree of bleaching: Samples P16 and P17 indicate a signal loss of about 40% and seem to be less sensitive to bleaching than samples P4, P6, P7, P11, P28, P32 and P34, which indicate a signal loss of about 77–89% after 500 s of bleaching with blue LEDs.

In Fig. 7 the TL glow curves, measured in the TL-wideband detection window, of the two groups are depicted. The strong reduction of the lower temperature components of the TL signal is observed, resulting in an isolation of harder-to-bleach component(s) of the TL glow curve. Similar to display glasses the protective glasses are exposed to internal (back light illumination of the screen) and external light sources (i.e. sun light), which will have an effect on the reconstructed dose. The extend of light exposure between radiation exposure and measurement is usually unknown and thus difficult to correct for, therefore dose reconstruction should ideally be carried out on TL signals, which are as optically stable as possible. In addition, optical bleaching has the potential effect of isolating a thermally more stable TL signal as well, as compared to the unbleached samples (Fig. 5).

4. Conclusions and outlook of the research project

In this study protective glasses, which are fixed on the screen of a mobile phone, were investigated as fortuitous dosimeters using different sets of detection filters. TL signals were recorded using nine different combinations of glass filter and interference filter in order to select the optimum detection window. It was shown that the choice of filter combination impacts the TL glow curve shapes (i.e. the relative intensities of observed peaks) and the sensitivity, which varied by more than two orders of magnitude. The latter is also directly linked to the signal detection limit.

The choice of the detection window also affected the ratio of zero dose to radiation induced signal, which influences the achievable dose detection limit. No single detection window could be found which worked optimally for all samples but the use of the wideband filter combination (KG3) seemed to be a reasonable compromise and is recommended at this stage of investigations on protective glasses.

Two important dosimetric properties, the long-term and optical stability of the TL signals, were studied using two selected detection windows. Both the fading curves and the bleaching rates appeared to be independent of the choice of filters and for both properties samples could be divided into two groups with different rates. While samples which were less bleachable also showed a higher long-term stability, the opposite was not true for all samples. The TL pre-bleaching is recommended because usually the extend of light exposure is unknown and optical bleaching has the additional effect of isolating a more stable TL signal (hard-to-bleach components).

Further research is necessary in order to reduce the zero dose signal (i.e. chemical treatment of the glass samples) and is presented in a follow-up study [18]. In addition, dosimetric properties (such as the long-term and optical stability, reproducibility, dose response) have to be reinvestigated with a final protocol. In the end, a realistic irradiation test is necessary to prove the robustness of the dose reconstruction and to compare it with other dose reconstruction methods.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.omx.2023.100233.

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