Introduction of a Single Chip TLD System for Patient Dosimetry

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Abstract. A thermoluminescence dosimetry system with single detector chips was developed for patient dosimetry applications. LiF:Mg,Cu,P detector chips, dosimetry protocol, calibration, and dose calculation were prepared for measurements inside phantoms for determining organ and effective doses in medical diagnostic examinations. The first step was optimizing the readout time-temperature-profile for reaching a well resolved dosimetric peak and stability of the glow curves. A number of parameters was varied for the optimization process, e.g. preheating and heating rate. Individual chip sensitivities, residual dose and dose linearity were studied for establishing a reliable and accurate TL dosimetry system.

KEYWORDS: patient dosimetry, thermoluminescence, TLD, single chips, glow curve, calibration.

1. Introduction

Detailed knowledge about patient dose accumulation during medical exposure is of increasing importance especially since the introduction of the European Council Directive 97/43/EURATOM [1]. A TL (thermoluminescence) dosimetry system with single detector chips is being developed mainly for new or special patient dosimetry applications. A number of TL chips is positioned inside anthropomorphic phantoms for determining organ and resulting effective dose values. First applications are planned for diagnostic radiology examinations with new 3D dental imaging scanners.

LiF:Mg,Cu,P detector material has been selected for medical dosimetry applications due to a number of reasons, especially due to its dose detection accuracy and dose linearity in the typical diagnostic dose range up to several tens of mGy. Higher accuracy may be achieved by special treatments or higher dose levels as in radiotherapy TL dosimetry [2].

The main work of introducing a new single chip TL system was optimizing the readout parameters for reaching a number of goals such as stability of the readout glow curves.

2. Materials and Methods

2.1 Detector Chips and TL Reader

TLD-700H detector chips (from Thermo Fisher Scientific) of 3.2 x 3.2 x 0.89 mm size are read out in a Harshaw 3500 manual TL reader with planchet heating system and WinREMS readout software. TLD-700H detector material (\(^7\)LiF:Mg,Cu,P) has properties well suited for a number of medical diagnostic dosimetry applications, e.g.

\begin{itemize}
  \item small sizes for measurements inside phantoms
  \item tissue equivalence for detecting tissue and organ dose
  \item improved sensitivity compared to standard materials such as TLD-100
  \item independence of dose rate for pulsed radiation fields
\end{itemize}

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Two groups with 20 and 140 chips were used for testing purposes and for measurement purposes, respectively. TL light is detected by a photomultiplier tube positioned close to the heated detector chip. Glow curves represent detected light signals as a function of readout time. Two important requirements for optimizing the dosimetry protocol were:

- long term stability in glow curve shapes
- total readout time less than 3 hours

The main glow curve peak, referred to as peak 4 for this TL material, has to be fully visible and well resolved in the glow curve. The requirement of total readout times less than three hours allow “fast” measurements within half a day following the protocol steps:

- oven annealing
- irradiation (except background chips)
- simultaneous calibration irradiation (only calibration chips)
- oven pre-readout tempering
- readout (including empty readouts, test chip readouts, QC noise and reference light readouts)

### 2.2 Readout Time-Temperature-Profile

The TTP (Time-Temperature-Profile) defines the readout temperature as a function of readout time. The TTP consists of a preheating phase, a linear heating phase up to the maximum readout temperature and a final constant readout period at the maximum temperature. The following five parameters are describing the TTP:

- preheating temperature (°C)
- preheating time (s) at the preheating temperature
- heating rate (°C/s)
- maximum readout temperature (°C)
- total readout time (s)

The recording of the glow curve starts directly after the preheating phase at the preheat temperature. The actual heating time is defined by the ratio of temperature increase up to the maximum readout temperature and the heating rate. The remaining readout time at the maximum temperature is determined by the difference of the total readout time and the heating time. This final phase is important for the chips to reach the adjusted maximum temperature and to achieve a complete readout the TL signal of the main dosimetric peak 4.

### 2.3 Glow Curve Optimization

The main goals of the optimization process were achieving long-term stability in glow curve shape and reproducible TL signals. The following parameters were investigated with varying parameter values close to manufacturer or literature recommendations:

- annealing process, recommended 240°C for 10 min
- pre-readout tempering, recommended approx. 100°C for 10 or 20 min
- preheating temperature, varied between 135°C and 165°C
- preheating time, varied between 5 s and 20 s
- heating rate, varied 5°C/s to 30°C/s

The maximum temperature was set close to the recommended 240°C limit for this TL detector material avoiding sensitivity loss. The total readout time depends mainly on the heating rate and was set accordingly to get a full readout of main peak 4. Time intervals between annealing, i.e. zeroing of the TL chips, and readout are typically between half a day and one day. Fading effects are therefore expected to be negligible.
2.4 Individual Chip Sensitivity

Differences in individual chip sensitivities of a production batch are mainly caused by differences in chip masses. \( k_i \) (individual chip sensitivity correction factor) measurements are carried out regularly for determining long term changes in chip sensitivities. All detector chips are irradiated under reference conditions (1 mGy \(^{137}\text{Cs} \) free-air calibration) and \( k_i \) values are calculated as ratios of the average TL signal to the individual TL signal.

2.5 Dose Determination

Dose calculation is based on summing up the whole glow curve resulting in a single TL signal value. This simple analysis is possible due to a number of reasons, especially due to the stability of main peak 4, due to the low signal tails at the beginning and end of the glow curves and due to the stabilization of peak 3 which showed the biggest variations during the optimization process. Extracting only peak 4 signal values by simple glow curve analyses showed no significant improvements in calculated dose values. The dosimetry model for determining dose \( D_i \) of chip number \( i \) is based on a simple linear equation:

\[
D_i = N \cdot k_Q \cdot (k_i \cdot TL_i - TL_{bg})
\]

Individual chip signals \( TL_i \) are \( k_i \) sensitivity corrected and have an average background signal value \( TL_{bg} \) of a group of unirradiated background chips subtracted from them. Typically a number of measurement chips are positioned together allowing the determination of a mean dose value \( D \) and a related standard deviation of the mean. At least ten percent of the chips are used as calibration chips for determining the current readout calibration factor \( N \). The group of calibration chips are irradiated at reference conditions in a \(^{137}\text{Cs} \) free-air calibration facility at 1 mGy air kerma. Finally the appropriate \( k_Q \) quality correction factor has to be applied. A set of \( k_Q \) values will be determined at the secondary standards dosimetry laboratory Seibersdorf in diagnostic reference X-ray radiation fields free-in-air and in-phantom.

3. Results

3.1 Final TTP

The final Time-Temperature-Profile can be described by the parameter set 135/10/5/245/26.7, i.e. a preheating phase at 135°C for 10 s, a linear heating phase with 5°C/s heating rate up to the maximum readout temperature of 245°C with a total readout time for the glow curve of 26.7 s. Examples of glow curves can be seen e.g. in figure 5 for a single chip calibrated with a constant dose of 1 mGy. Temperature shifts in the glow curves may depend on the thermal contact and heat transfer between planchet and chip. It has to be noted that the displayed temperature is not equal to the real chip temperature but close to the planchet temperature.

3.2 Variation of Parameters

One goal of the optimization of glow curve structure was to reduce peak 3 compared to the main peak (peak 4). Additionally peak 3 should be as stable as possible, i.e. the ratio of peak 3 to peak 4 maximum should not vary due to small variations in measurement parameters. At the beginning of the optimization process peak 3 magnitude was up to one half of main peak magnitude for TTPs similar to the final one.

3.2.1 Annealing

Annealing at 240°C for 10 minutes is recommended in literature. The manufacturer recommends oven annealing only after dose applications above certain limits. Zeroing may be done by individual readout
cycles but result in longer preparation times. To study the influence of the annealing process on the reproducibility of glow curves, chips with and without annealing have to be compared over longer time periods.

As in routine radiation protection dosimetry, TL detectors are stabilized before readout by a pre-readout oven tempering process at about 100°C for 10 or 20 minutes. The results of this tempering process were investigated. As expected, the influences were quite small for glow curves with preheating temperatures above 135°C. In figure 1, glow curves without any preheating are compared.

**Figure 1:** Comparison of glow curves with and without pre-readout tempering (tempering was at 100°C for 10 minutes). Both glow curves are without a preheating phase i.e. starting from room temperature. The glow curve “no pre-readout tempering” clearly shows peaks 2, 3, and 4 from left to right i.e. from lower to higher readout temperatures.

3.2.2 Preheating

Glow curves without preheat may show pronounced low temperature peaks 2 and 3 depending on the time interval between irradiation and readout due to different fading characteristics of the peaks. A drawback of preheated glow curves is that signal information at low temperatures is not visible e.g. irregularities due to dirt effects. Preheat temperatures were varied between 135 and 165°C. The applied preheat temperature should not reduce the main peak but only reduce the lower temperature peaks. Preheat time has to be long enough not to produce any changes at the beginning of the glow curve. Further increase of the preheat time should not change the glow curve. Preheat times were varied between 5 and 20 s.

Preheating temperatures below 135°C resulted in no differences in the glow curves but in longer readout times per chip, e.g. 50 s instead of 26.7 s at 5°C/s heating rate without preheating. Preheating shows a better resolved, i.e. broader peak 4. Finally, a preheating phase at 135°C preheat temperature and 10 s preheat time was chosen, similar to the manufacturer’s recommendations.

3.2.3 Heating Rate

Increasing the heating rate allows faster readout times but results in increasing variations of temperature shifts of the glow curves. Heating rates were varied between 5 and 25 °C/s. Lower rates were not considered because of too long total readout times. Figure 5 shows temperature shifts for the final heating rate of 5°C/s. Higher heating rates produce glow curves with narrower peak shapes resulting in unwanted overlaps of peak 3 and peak 4, as can be seen in figure 2.
Figure 2: Comparison of glow curves with heating rates of 5, 15, and 25°C/s. Curves are peak maximum normalized. Original curves have similar areas because of similar applied dose values.

3.3 Second Readout Residual

The residual signal can be determined as the ratio of the second readout TL signal to first readout TL signal. Irradiations at different dose levels showed residuals in the range of 1 to 2%. Increasing residuals, up to 8%, were measured below 100 μGy down to the lower detection limit of about 10 μGy. Individual second readout signals were not taken into account for dose determination because dose linearity calculations showed no improvement compared to subtracting an average background signal. Therefore, for each measurement a group of background chips (typically 20% of all chips) is used. Additionally, the performance of the annealing cycle for removing all residual TL signals, especially at higher dose levels, is necessary.

Figure 3: Glow curve examples of 1 mGy and 0.1 mGy 137Cs irradiation and their second readouts immediately after the first readout glow curves.

3.4 $k_i$ Correction Factors

Five $k_i$ (individual chip sensitivity correction) experiments are currently being carried out. All $k_i$ values of this production batch are between 0.93 and 1.30. Standard deviations of individual chips vary between 0.2% and 2.3%. The average standard deviation of the 140 chips in these five measurements
is 1.1%. It has to be noted that differences between consecutive \( k_i \) values for a given chip are up to 8%. Typically, an increase in \( k_i \) is followed by a decrease and vice versa. Therefore it is important to use average sensitivity correction factors instead of current values. No criteria are currently applied to remove chips with high \( k_i \) values, fluctuating behaviour or long term drifts. Frequency of \( k_i \) measurements is now increased for faster identification of problems in the chip sensitivities.

3.5 Dose and its Uncertainty

Relative standard deviations for investigated dose levels (between 10 µGy and 30 mGy) are on average 1.1%, varying between 0.4% and 1.9%. These fluctuations are similar to the fluctuations in the \( k_i \) values and are therefore inherent to the accuracy of the TL dosimetry method. Techniques may be introduced to reduce this uncertainty contribution, e.g. to eliminate chips with obvious instabilities in their \( k_i \) history. Currently no criteria are applied, because the accuracy achieved is sufficient for most diagnostic applications. The only statistical test which is taken into account is to remove outliers whose values are more than three times off the standard deviation. At least three chips should be grouped together at a measurement point to get statistically trustable results. Dose dependent coefficients of variation values (relative standard deviations determined during the linearity experiment) may be applied for estimating statistical uncertainties of measurements with low number of detectors. A detailed uncertainty analysis based on the dose model of equation (1) is currently under development. The biggest contribution is expected to result from the energy response of the TL detector material in the range of diagnostic X-ray energies. Narrow filtered X-ray radiation showed energy responses up to 20% below the reference quality of \(^{137}\)Cs radiation (662 keV). Precise values of energy correction factors \( k_Q \) have to be determined for diagnostic X-ray radiation fields, a single correction factor for photon energies up to 150 keV may be useful. The total measurement uncertainty is expected to be within 10% at 95% confidence level.

3.6 Calibration

Calibration chips are handled similarly to the other chips. Calibration chips’ readouts are distributed over the whole readout process to get the best average calibration factor taking possible drifts of the reader into account. It has been shown that there is a tendency of decreasing signal output over typical readout periods of about two hours taking the warm-up phase of the reader as well as empty and test chip readouts into account. Readouts of the linearity experiment presented in figure 4 show linear decreases of signals of about 1 to 2%.

Figure 4: TL readout signals of 90 individual chips irradiated in a linearity test between 3 µGy and 30 mGy. Linear interpolations are shown at 10 and 30 mGy readouts over 4 hour total readout time. Second readouts are carried out but not shown here.
A time dependent calibration function may be introduced for high accuracy measurements such as in radiotherapy applications. In our dosimetry system the small drift in the calibration procedure will be taken into account in the uncertainty of the average calibration factor. Figure 5 shows the glow curves of a single chip after a number of 1 mGy $^{137}$Cs irradiations over a 7-month period. Glow curve shapes are almost identical proving stability of the dosimetry parameters over the time. Temperature shifts can be seen for the single chip over a number of readouts similar to different chips over a single readout. Shifts may depend on the precise chip positioning inside the reader, but may not influence the TL signal which corresponds to the area under the glow curve.

Typical standard deviations of 10 calibration chips are close to 2%. Differences in TL signals of individual calibration chips are well below 2%. These fluctuations have not to be taken into account in the uncertainty analysis because calibration factors are calculated for each individual measurement experiment. It has to be mentioned that the calibration factor shows no long term drift up to now. Sensitivity changes due to inappropriate readout parameters such as a too high maximum temperature can therefore be excluded. It seems possible to use an average calibration factor without too large an increase in uncertainty, thus avoiding efforts to irradiate calibration chips at the $^{137}$Cs nuclide facility at the very same time as the measurement chips.

**Figure 5:** Comparison of uncorrected glow curves of chip number #1 which was used as a calibration chip (1 mGy $^{137}$Cs) for a number of measurements.

### 3.7 Dose Linearity

Linearity of measured dose was investigated in the typical dose range of diagnostic applications. Ten chips were irradiated together at air kerma values up to several tens of mGy in a $^{137}$Cs calibration field. The mean value of unirradiated background chips was subtracted. Variations of dose values were within 1% for dose levels greater than 100 µGy. Differences of determined low dose values compared to applied doses were 3%, 4%, and 10% for 30 µGy, 10µGy and 3 µGy, respectively. Lowest doses in this linearity study are close to the background level of unirradiated chips of about 2.4 µGy ($^{137}$Cs equivalent). (a) is chosen from the four listed possibilities of taking non-linearity into account:

1. (a) no linearity correction is applied, a relative uncertainty contribution due to non-linearity of up to 4%/Sqrt(10) at the lower dose limit of 10 µGy is taken into account
2. (b) a non-linearity correction factor may be applied in the dose formula (1) depending on the measured dose, e.g. at 10 µGy equal 1/1.04=0.96
3. (c) a background correction may be introduced, the optimized background dose value for this readout is 2.7 µGy resulting in a background correction factor of 1.12
4. (d) individual glow curves may be corrected by subtracting zero-dose glow curves or by applying computerized glow curve deconvolution.
Figure 6: Linearity graph relating measured dose to dose applied at the $^{137}$Cs facility. Details in differences to the ideal linear dose dependence may not be visible due to the logarithmic scaling.

Figure 7: Examples of glow curves from the linearity experiment normalized to 1 mGy. Dose levels are between 3 and 300 µGy (upper figure) and 0.3 and 30 mGy (lower figure). Temperature shifts are corrected in these presentations for better comparability. Glow curves at lower doses show increasing signal contributions outside main peak 4.
4. Applications

Detailed patient dose measurements are planned in different digital volume tomographs which are now introduced for 3D imaging of patient’s jaws and teeth in dental practice in Austria. First free-air and in-phantom measurements were carried out in the rotating X-ray cone beam fields using adult patient examination settings [3]. The phantom positions were like the one of patients inside the scanner, see figure 8. Free-air exposure resulted in a mean air kerma values of about 4 mGy for a single scan. Phantom measurements revealed absorbed dose to water values of about 3 to 6 mGy depending on the position inside the phantom. Differences between ionisation chamber measurements and TL dose results were within several percent. Future experiments will include organ dose measurements with an anthropomorphic phantom. Studies of different volume tomographs and alternative examination devices such as panoramic units and CTs are planned comparing organ and resulting effective doses.

Figure 8: Adult head sized phantoms positioned inside a digital volume tomograph, cylindrical PMMA calibration phantom (left) and Rando-Alderson head phantom borrowed from IAEA (right).

REFERENCES

