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Proposal of method dosimetry to realize in-vivo measurements in skin surface brachytherapy

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Abstract

Introduction: Skin surface brachytherapy is a highly targeted radiation therapy used for treating superficial malignancies, offering precise dose delivery with minimal impact on surrounding healthy tissues. However, in-vivo dose verification remains a critical challenge in brachytherapy. Thermoluminescent dosimeters (TLDs) provide a promising solution for increased precision of dose delivery to cancer patients. This study proposes a TLD-based method to assess radiation exposure during skin surface brachytherapy, with a particular focus on TLDs calibration process and validation leading to the opportunity to reduce dose of radiosensitive structures such as the lens of the eye.

Materials and Methods: TL detectors were calibrated using both an *Iridium-192 (^{192}Ir) source* and a *6 MV photon beam*, incorporating correction factors to enhance measurement accuracy. During measurements, TLDs were positioned on the skin surface of the anthropomorphic head phantom to absolute point dose measurements. The measured TLD doses were compared with treatment planning system (TPS) calculations to validate the proposed method. Additionally a specific analysis was conducted to compare the radiation exposure of the eye lens with and without the use of a protective eye shield with use of the anthropomorphic head phantom.

Results: TLDs response to a uniform radiation dose were within the range of ±10% of the mean. For the method of calibration used 6MV photons from medical linear accelerator, a value 3% for the energy correction factor was applied to account for the difference in sensitivity of the TLDs in ^{192}Ir and 6MV. For both calibration methods, with used appropriate calibration factors, obtained dose values for the anthropomorphic head phantom were within ±5% of the TPS dose values. The use of a lead shield placed in the phantom's eye socket reduced the dose to the eye lens by up to 20%.

Conclusions: The developed TLD dosimetry method provides a precise and reliable approach for in-vivo dose verification in skin surface brachytherapy. By integrating calibrated TLD-based measurements, the correct implementation of radiotherapy plans can be verified. The study also confirms the protective efficacy of an eye shield in minimizing radiation exposure to the lens, reinforcing the importance of shielding strategies in clinical practice. Further validation and clinical implementation will contribute to improved patient safety and therapeutic outcomes in brachytherapy.

Keywords: HDR brachytherapy, in-vivo dosimetry, TLD, calibration, medical exposure, radiotherapy

Introduction

The demand for radiotherapy treatment is steadily increasing in Poland, as evidenced by the steadily increasing number of patients treated with radiotherapy. In 2023, 105 890 patients received radiation therapy (of which 12 843 were brachytherapy patients), 6% more than in 2022[1]. Brachytherapy (BT) is the most common choice in treating skin cancers whose surgical treatment would result in serious cosmetic defects. This would subsequently lead to the need for reconstructive surgery[2-4]. Using ^{192}Ir sources in high dose-rate (HDR) remotely afterloaded brachytherapy treatments is a practice in clinical skin surface brachytherapy[5-7]. In surface HDR brachytherapy, where three-dimensional (3D) printed boluses are increasingly common, some radiosensitive organs near the surface may absorb significant dose[8].

Accuracy of brachytherapy treatment depends on a few steps. These procedures are done manually which indicates potential risk. Lack of precision in source placement, anatomical changes in patient's face or not correct physical parameters of the source can lead to differences between real dose in therapy and dose simulated via treatment plan. Currently,

Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

dosimetry verification of treatment is not routinely available, which may result with systematics, unintentional errors[6]. An important part of this clinical treatment process is to verify that the treatment is carried out as prescribed. Together with other treatment verification tools used in brachytherapy, in vivo, dosimetry constitutes a part of the treatment plan quality assurance. It is a suitable measurement method both to monitor treatment delivery and to detect potential errors early in the course of treatment. Moreover, it is important to not forget, that this kind of treatment gives opportunity to irradiate large surfaces with reasonably minimum exposure, which indicate low probability receiving unfavourable local post-radiation complications.

Tanderup et al. in their paper summarize the types and characteristics of dosimeters that can be used in in vivo dosimetry[7]. One of the systems which was included are thermoluminescence detectors (TLDs). TLDs are commonly used in radiotherapy, in particular lithium fluoride doped with traces of magnesium and titanium (LiF:Mg, Ti) TLDs are useful for those applications in which small detectors with high sensitivity are required[9]. This characteristic is desirable in brachytherapy to record the dose to critical organs or for in vivo dose verification for areas of high dose gradients[10]. The disadvantages of the TL detectors are long time to prepare system (anilation, calibration) and lack of real time readout[11].

The current interest in TLDs based in vivo dosimetry in brachytherapy is mainly from the research point of view, and is not yet routine clinical use, but TLD equipment needed for in vivo dosimetry such as readers, annealing ovens and dosimeters are increasingly available in radiotherapy hospitals in developing countries[10].

This work aims to show how TLDs can be used for detecting differences in doses, especially for critical regions. The paper will present a full description of the procedure, starting from the selection of detectors used in the research, through the detector preparation process (i.e. their thermal treatment, calibration using a therapeutic source (^{192}Ir) and using a linear accelerator and determination of optimal conditions for working with the detectors).

Materials and Methods

The TLD-100 (LiF:Mg,Ti)

All measurements were made with, type TLD-100 standard-sized chips 3.2×3.2×0.9 mm^3 , thermoluminescent dosimeters of lithium-fluoride doped with magnesium and titanium (Harshaw, Thermo Fisher Scientific Inc., Waltham, MA). Before the detector exposure process, an anilization procedure was carried out. The detectors were annealed for 1 hour at 400°C in MagmaTherm MT1105-E4 chamber, then cooled to room temperature (20°C) using an aluminum plate and then annealed again for 2 hours at 100°C in SUP-18W oven[12]. After exposure, the detectors were subjected to post-exposure anilization at 100°C for 10 minutes. The response of the detectors is carried out through the process of annealing the detectors in a laboratory material reader. In this research, Reader Analyser RA'04 manufactured by the Polish company Mikrolab was used. Read-out was performed in analyser mode using a heating rate of 10°C/s up to a maximum temperature of 280°C which was maintained for 20 s. The TL-light was integrated from 80°C upward and during the 20 s at 280°C (total integration time was 40 s)[11]. **Figure 1** shows a sample light curve obtained in the reading process.

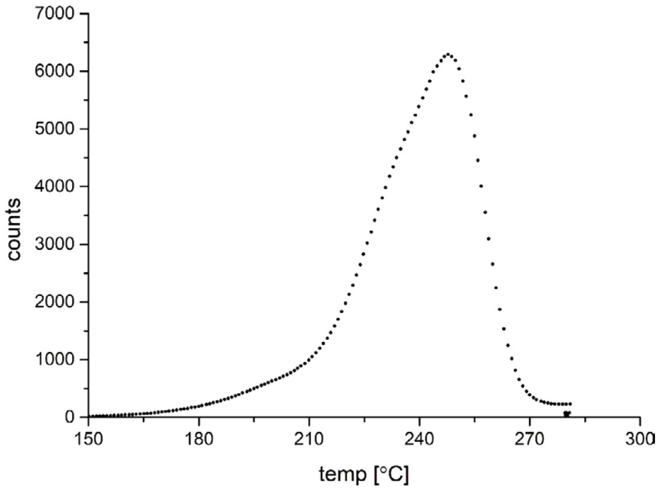

Figure 1. Glow curve obtained in analyser mode for dose 2 Gy.

Uniformity of detector response

For a group of 60 detectors, the distribution of values obtained for a group of detectors was verified, and the signal mean value and standard deviation were determined. For this purpose, the detectors were irradiated at the same time in a water equivalent RW3 slab phantom (IBA Dosimetry GmbH, Germany) with a uniform dose of 2Gy using a linear accelerator with 6 MV photon static beam and then their signal was registered in the reader according to the given procedure. This made it possible to select detectors with similar responses to the radiation field. According to IEC 61066, the uniformity of a batch of detectors should show the relationship[13]:

$$\frac{N_{\max} - N_{\min}}{N_{\min}} < 0.3, \qquad (1)$$

where:
N_{max} – maximum counts value for the batch,
N_{min} – minimum counts value for the batch.

Therefore, for further measurements, it was decided to select detectors that fall within the dose response range:

$$N_{AVG} - 2\sigma \le N \le N_{AVG} + 2\sigma, \qquad (2)$$

Where:
N_{AVG} – the average value of the number of counts for the whole group of detectors,
N – the number of counts of a given detector,
σ – standard deviation value,
which means that the response of a single detector is in the range of N_{AVG} ±10%.

Calibration of detectors

In vivo dosimetry should be characterized by a relatively simple and rapid measurement and reading methodology. That is why the authors of this paper decided to develop a single calibration factor for the entire group of TLD detectors. Two methods of TLD calibration were applied using 6MV photon beam and ^{192}Ir source. Calibration of the TLD with a megavoltage source compared to a 192Ir source enables a uniform radiation dose field to be produced on a flat surface, allowing several TL detectors to be irradiated with the same dose in a single exposure. However, this method has the disadvantage of introducing an energy correction factorThe detector calibration process was carried out as described in the following sections. The exposed detectors were read under the conditions described, and the average count values obtained for radiation doses of 0.5, 1, 2, 4 and 6 Gy were used to determine the calibration curves.

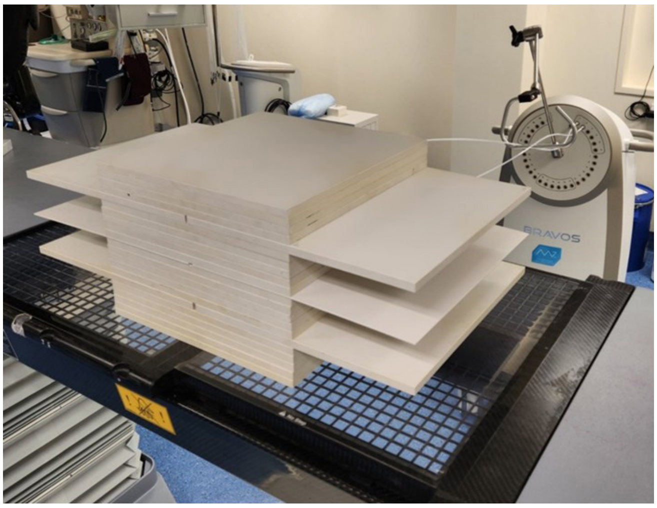

Figure 2. RW3 slab phantom used to calibration TLDs with ^{192}Ir HDR source.

Irradiation with linear accelerator for 6 MV photon beam

The detectors were irradiated in a water equivalent RW3 slab phantom (IBA Dosimetry GmbH, Germany) at a depth 10 cm and distance 90 cm from the source to surface phantom for a 6 MV photon beam with flattening filter (WFF) in static field size of 10×10 cm^2.

Five groups of dosimeters, each containing four TLDs, were exposed to different doses ranging from 0.5 to 6 Gy. The steps were 0.5 Gy for doses between 0.5 and 1 Gy, 1 Gy for doses between 1 and 2 Gy, and 2 Gy for doses between 2 and 6 Gy. Four dosimeters were not exposed to radiation and were used to compensate for the background signal.The monitor units (MU) needed to deliver the prescribed dose in above mentioned irradiation conditions were calculated by Eclipse treatment planning system. To control the accelerator operation, before the irradiation TLDs, the beam output (Gy/MU) was verified using a Dose One electrometer (IBA Dosimetry GmbH, Germany) with Farmer-type ionization chamber (IBA Dosimetry GmbH, Germany) placed in the PMMA phantom, according with our internal quality control procedure for a weekly machine output check.

Irradiation with 192Ir HDR source

The Bravos™ afterloader high dose rate 192Ir brachytherapy source (Varian, A Siemens Healthineers Company) was used to irradiation TL dosimeters in RW3 slab phantom.

The central axis of the two opposite catheters was placed at 50 mm from the TLDs. The design of the calibration phantom is shown in **Figure 2**.

Dwelling times and positions of the single ^{192}Ir source were planned in BrachyVision treatment planning system (Eclipse ver. 16.1, Varian, A Siemens Healthineers Company) to deliver the prescribed dose values to the specific volume, where the TLDs were placed. The plans were designed to produce *the* largest possible volume of uniform dose for the following values: 0.5, 1, 2, 4, and 6 Gy. Similar to the case of irradiation with a linear accelerator, the phantom was irradiated with five groups of dosimeters, each containing four TLDs. Four dosimeters were not exposed and used to measure the background signal. In this work independently, an HDR 1000 Plus ionization chamber (Standard Imaging Inc, Middleton WI) was used to compare the reference air kerma rate (RAKR) for the ^{192}Ir source provided by the manufacturer. This quality control procedure is necessary not only to verify the calibration provided by the manufacturer, but also to ensure traceability to international standards[14].

Verification of in-vivo dosimetry system

The comparison of dose values between calculation in BrachyVision with measurement by TLDs was verified using anthropomorphic CIRS phantom (CIRS Inc., Norfolk, VA, USA) consisting of adult head made with tissue-equivalent epoxy resins and optimized TLD locations.

In this study, which was based on CT images, the target volume was defined and a 3D-printed HDR surface brachytherapy applicator (3D bolus) was created (**Figure 3**). The catheter paths/channels and thickness of the bolus was created in 3D Slicer software to efficiently cover the target volume. After the

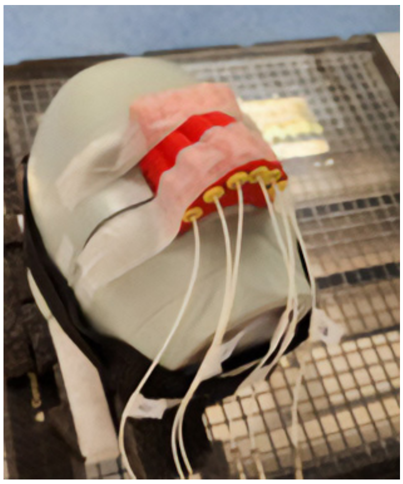

Figure 3. Head of the CIRS anthropomorphic phantom with a 3D bolus mounted on it.

surface applicator was printed with polylactic acid (PLA) material, the CT images of the head phantom with the applicator on the surface of the phantom was acquired and transferred to the BrachyVision TPS to generate a treatment plan with optimal radiation dose to deliver 4Gy to the irradiation target, minimizing the dose reaching surrounding healthy structure at the same time. The described process was as similar as possible to clinical situations .

The comparison of dose values between calculation in BrachyVision with measurement by TLDs was defined as:

$$\frac{D_{TLD} - D_{TPS}}{D_{TPS}} \cdot 100\% \quad (3)$$

where D_{TPS} is TPS calculated dose and D_{TLD} is the dose determined from TLD reading, using anthropomorphic CIRS phantom (CIRS Inc., Norfolk, VA, USA) consisting of adult head made with tissue-equivalent epoxy resins and optimized TLD locations as shown in **Figure 4**. The procedure was carried out 2 times and the average values obtained for a given detector were compared with the values obtained from the TPS system.

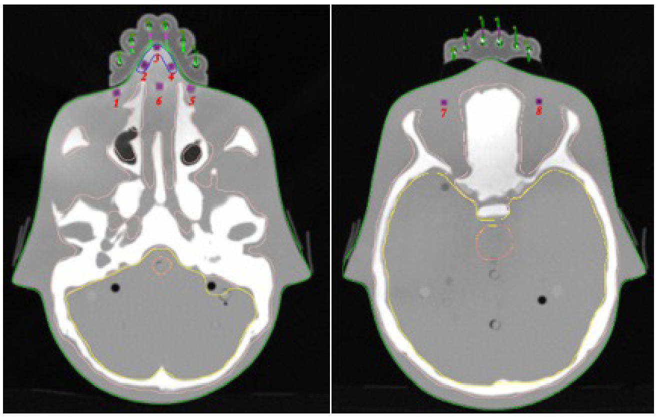

Figure 4. Position of measurement points in CIRS head phantom.

The uncertainty in determining the dose for TLD-100 detectors ranged from 4.6% to 6.1%. The uncertainty budget also included reading uncertainty (0.5%) and geometric uncertainty related to the detector position (2%). Calculated combined standard uncertainty (k=1) for the entire system averaged 5.4%.

This study also verified the dose deposited near the lens of the eye under the lead shield using TLDs placed in the phantom. The eye shield is made of 4 mm thick lead and placed on the patient's eye socket. The treatment planning system does not consider the above configuration with lead shield, and therefore there is no way to determine the value of the dose deposited on the lens of the eye in such a geometrical arrangement. The authors of the study decided to use the proposed dosimetry system to compare the value of the dose the patient would receive in both cases, i.e. without and with the shield installed.

Results

Figure 5 graphically shows the results obtained from the test of uniform detector response to a 2 Gy dose.

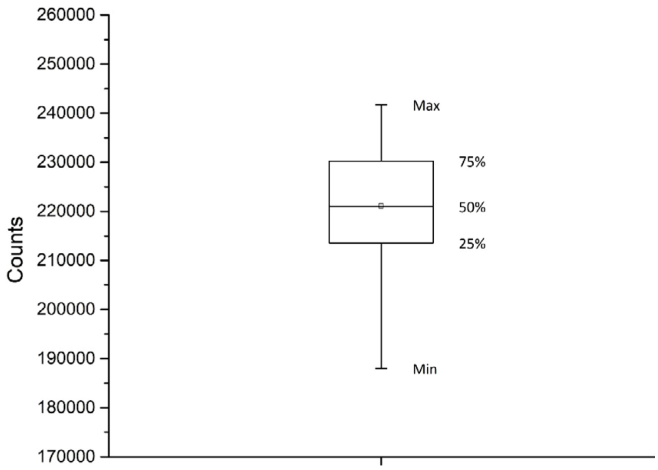

Figure 5. Counts obtained for 60 TLD-100 type detectors.

The homogeneity result obtained using formula (1) for the batch of detectors was 0.29. Applying the methodology proposed by formula (2) resulted in 59 out of 60 detectors being qualified for further measurements, while the homogeneity result for the batch thus determined was 0.19.

Detector's calibration

For calibrations in the range from 0.5 to 6 Gy, a polynomial fit was applied using a polynomial of degree 2. The obtained curves are shown in grey in the **Figure 6**.

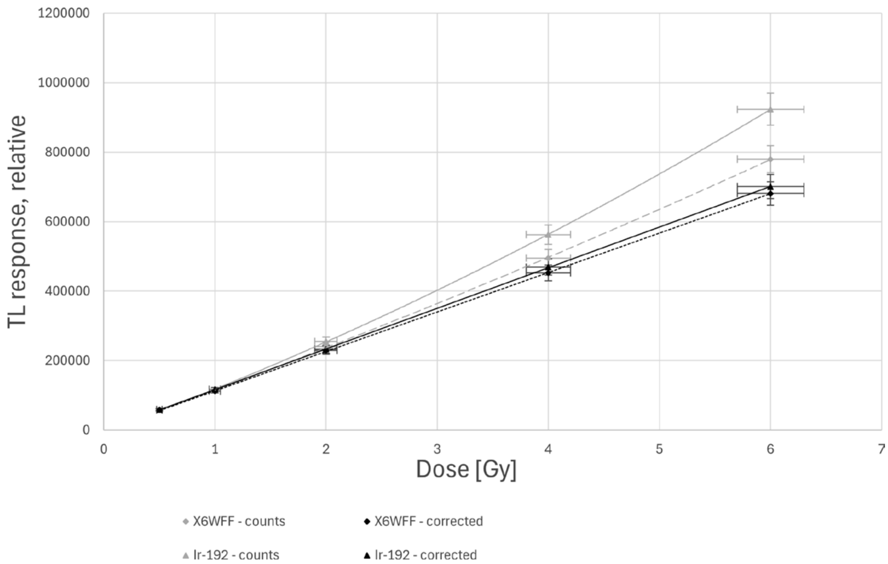

Figure 6. Calibration curves obtained for both radiation sources. Grey indicates curves obtained, black indicates curves with correction factor included.

The light output of TLD-100 is linearly related to dose up to approximately 1 Gy, but after that, it becomes supralinear (**Figure 6**) For doses of 0.5 Gy and 1 Gy, the mean dose value obtained using the calibration factors at both 6 MV and ^{192}Ir calibrations coincided with the values from the therapeutic plan. The relative differences were at most 5%. A significant difference appears for doses above 2 Gy.

The correction was established by plotting the TL reading against dose for TLD-100 both for irradiation with linear accelerator for 6 MV photon beam and ^{192}Ir HDR source, as in **Figure 6.**

In in-vivo dosimetry for HDR surface brachytherapy, when only used calibration method for linear accelerator with 6 MV WFF beam, the dose value on the base the TL response for ^{192}Ir source, we can obtain by the following formula:

$$D_{192Ir} = \frac{k_{corr}(x_{X6WFF}) \cdot x_{X6WFF}}{k_{ECF} \cdot a_{X6WFF}}, \quad (3)$$

where a_{X6WFF} is coefficient of linear expansion for calibration with linear accelerator (**Figure 6**), k_{ECF} is energy correction factor and x_{X6WFF} can be calculated on the base TL response x_{X192Ir} for ^{192}Ir source:

$$x_{X6WFF} = a \cdot x_{192Ir} + b, \quad (4)$$

where *a* and *b* are the parameters of a curve fitted to correlate the TLD response obtained from exposure to a 6MV photon beam with the response measured for a ^{192}Ir source (with values 0.848 and 25189, respectively).

The value of k_{corr} is equal 1 for doses ≤ 1 Gy, but after that, the correction for supralinear response will need to be used . The factor k_{ECF} in the equation 3 is determined by the quotient of a_{192Ir}/a_{X6WFF} and is equal 1.03. Although the observed ~3% over-response is consistent with an energy dependence of LiF:Mg,Ti TLDs when calibrated in a 6 MV beam and measured in a ^{192}Ir field, previous work has attributed this effect to differences in a linear energy transfer (LET) distribution of secondary electrons produced by the different photon spectra; in particular Tedgren et al.[15,16] noted an increased detector response of 3% – 4% when using TLD-100 dosimeters calibrated in a ^{137}Cs beam for measurements in a ^{192}Ir beam and recommended LET-dependent correction factors for LiF:Mg,Ti detectors.

In vivo measurement

Verification of the proposed in vivo dosimetry system was realized using an anthropomorphic phantom. The obtained results are shown in the **Table 1**.

The relative difference in the values obtained from the TPS ranged from 0.2% to 5.0% for a dose of 3.2 Gy and a dose of 5.6 Gy, respectively. It is worth noting that the maximum value of the difference is achieved for the maximum dose value from TPS.

Nevertheless, one can see very good agreement between the results obtained and the doses simulated in the treatment plan. It should be remembered, of course, that precise detector placement is extremely important for brachytherapy measurements, which was possible with phantom measurements.

A comparison of the exposure of the lens of the eye when using an eye shield made of 4 mm thick lead was made in the same configuration as shown above, adding the mentioned shield. The measurement was carried out 3 times. The averaged values for measurement points 1 and 2, i.e. points at which the dose to the eye lens was measured, are shown in the **Figure 7**.

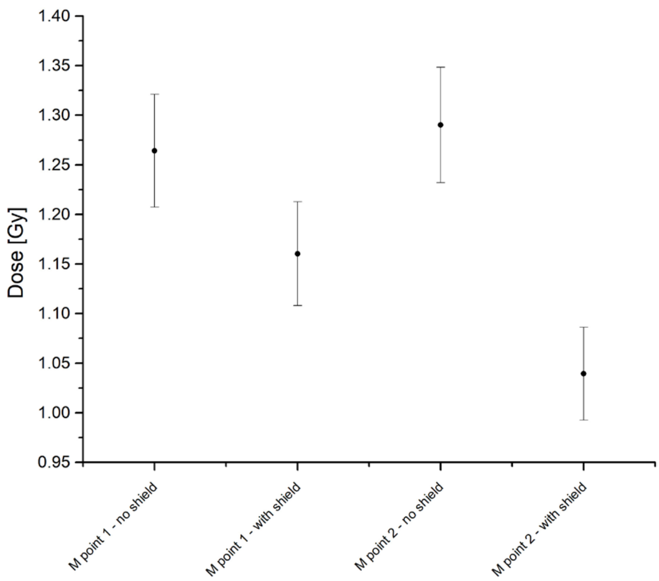

Figure 7. Dose values obtained in measurements on an anthropomorphic phantom taking into account the solid shield in the eye socket. The measurement error bars represent the combined measurement uncertainty budget (k=1).

For the geometry that did not include the lead shield on the eye, the TLD detectors recorded dose values of 1.27 and 1.28 Gy for measurement point 1 and 2, respectively. For the measurement with the shield values of 1.16 and 1.04 Gy were obtained for measurement point 1 and 2.

Table 1. Dose values were recorded with TLD detectors. The average dose from * denotes the use of the calibration factor obtained with the ^{192}Ir source, the value denoted ** are the doses obtained from calibration for 6MV including the correction factor.

Measuring point (according to fig. 5)	1	2	3	4	5	6	7	8
Dose values from TPS including ±5% measurement tolerance[6] [Gy].	3.07 - 3.40	5.20 - 5.75	5.35 - 5.91	4.96 - 5.48	2.43 - 2.68	2.71 - 3.00	1.22 - 1.35	1.23 - 1.36
Average dose values from TLD detectors* [Gy].	3.23	5.33	5.35	5.26	2.6	2.87	1.27	1.29
Average dose values from TLD detectors** [Gy].	3.22	5.34	5.35	5.28	2.59	2.86	1.28	1.3
Calculated combined standard uncertainty of the TLD dose (k=1) [%].	5.0%	6.3%	6.4%	6.4%	4.8%	4.9%	4.6%	4.6%
Expanded uncertainty for TLD dose (k=2)	10.1%	12.7%	12.9%	12.9%	9.5%	9.9%	9.2%	9.2%

Conclusion

Detectors whose response to a uniform radiation dose falls within the range $N_{AVG} \pm 2\sigma$ were deemed suitable for in vivo measurements in brachytherapy. This selection criterion aligns with the requirements of formula (1) in the IEC 61066 standard, enabling the use of a single calibration factor for the entire detector batch.

Calibration of the TLDs to measure absorbed dose to water had been done in a clinical 6 MV photon beam and the noted overestimate of the absorbed doses to water in the ^{192}Ir beam is consistent with the results of a previous investigation [15,16] The results of this work simply demonstrate that there exists an increased detector response by 3% for TLD-100 in clinical ^{192}Ir beams relative to the high energy photon beams (6 MV).

The results of measurements using an anthropomorphic phantom demonstrated, the effectiveness of the proposed in vivo dosimetry system to be used in clinical. The relative differences between the dosimetry results and the values from the TPS plan ranged from 1% to 5%, with an average measurement uncertainty for TLD detectors of 5.4%.

Additionally, the introduction of a lead shield in the eye socket reduced lens dose by up to 20%, suggesting a practical protective measure in clinical treatments.

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