Thermoluminescent Dosimetry in Clinical kilovoltage Beams

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A research report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2010.

DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any University.

Sign:…….

AKPOCHAFOR MICHAEL ONORIODE

Date:……..

ABSTRACT

Aim: This study aimed at calibrating a new set of GR-200A thermoluminescent dosimeters (TLDs) in low and medium kilovoltage energy photon therapy beams and in a diagnostic beam of known beam quality, in order to determine their response and to establish if the same set of TLDs could be used across both environments for in-vivo dosimetry purposes.

Methods and Materials: A set of 20 TLDs was used for this study. An Oven type PCL_3 was used to anneal the TLDs. The response of the TLDs was read using the Reader type LTM manufactured by Harshaw Bicron, United State of America. Vacuum tweezers were used to transfer the TLDs at the time of measurements and calibration. TLDs were kept in a subdued ultra-violet environment between the annealing and irradiation process. TLDs were placed on a 30 x 30 x 17.6 cm^3 Polymethylmethacrylate (PMMA) phantom during irradiation. A calibrated Orthovoltage machine was used to deliver a known absorbed dose to the TLDs. A cylindrical ionization chamber (PTW 30001) and an electrometer (PTW 10008) were used to confirm the absorbed dose delivery of the orthovoltage machine at the time of measurement. Likewise, a calibrated LX40 radiotherapy Simulator was used to deliver a known diagnostic absorbed dose to the TLDs. A TM77334 ionization chamber was used similarly to confirm the absorbed dose. The TLDs were also irradiated on the PMMA phantom. The accepted variation in raw response of the individual TLDs from the average of the batch was compared and a deviation of less than ± 20 % was considered within tolerance. A 10 % tolerance was subsequently considered suitable for the measurement of absorbed dose.

Results: Of the 20 TLDs calibrated in the 95 kV_p therapy beam (3 mm Al half-value layer), 17 were within the accepted response level (i.e. ± 20 % deviation), 17 in the 180 kV_p therapy beam (1 mm Cu half-value layer), 16 in the 300 kV_p therapy beam (3 mm Cu half-value layer) and 15 in the diagnostic beam of 80 kV_p (2.97 mm Al half-value layer). 16 of the 17 TLDs were within ± 10 % dose tolerance at 95 kV_p whereas all the TLDs that were within the accepted response level at the 180 kV_p and 300 kV_p, were within the

± 10 % dose tolerance. 12 of the 15 TLDs at the diagnostic beam energy were within the ± 10 % dose tolerance. Three of the TLDs were therefore rejected at all energies.

Conclusion: The study concludes that the same set of GR-200A TLDs could be used across both kilovoltage therapy and diagnostic fluoroscopy environments for in-vivo dosimetry purposes if an accuracy of ± 10 % is considered acceptable, however a separate calibration needs to done at each beam quality. Individual dosimeters from a batch should be carefully identified and sorted during the calibration process prior to clinical use.

DEDICATION

To my mother Mrs Esther Akpochafor, the pillar of my success, my brothers Matthew Akpochafor and Ojiyovwi Omerhi and most importantly to God for guiding me through these years of study.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

DEFINITION OF TECHNICAL TERMS, ACRONYMS AND SYMBOLS

AAPM: American Association of Physicists in Medicine

Absorbed Dose: The energy absorbed per unit mass of the irradiated material[12].

Annealing: The thermal treatment needed to erase the irradiation memory from a TLD.

C: The unit of charge (coulombs)

Calibration: The determination of the response or reading of an instrument relative to a series of known radiation values over the range of the instrument.

cGy: Centi-gray (10^{-2} Gy)

CT: Computed Tomography

Dosimetry: The measurement of absorbed dose.

ECC: Element Calibration Coefficient

GR-200A: A Lithium Fluoride TLD doped with Magnesium, Copper, and Phosphorus.

Gy: The unit of absorbed dose (gray)

HVL: (Half-value layer) The thickness of an absorbing material (usually Al or Cu) necessary to reduce the air-kerma rate to 50 % of its original value in an X ray beam, in narrow beam conditions[19].

IAEA: International Atomic Energy Agency

In-vivo dosimetry: The process of determining the absorbed dose to a patient undergoing radiation treatment through the use of radiation detectors placed on the patient during treatment.

Irradiation: The exposure of matter to ionizing radiation.

kV: kilovoltage

MV: megavoltage

nC: nano-coulombs (10^{-9} C)

Phantom: A volume of material behaving in a manner similar to tissue with respect to the attenuation of radiation.

PTW: Physikalisch Technische Werkstätten

RCF: Reader Calibration Factor

SD: Standard Deviation

SSD: Source-Surface Distance

TL: Thermoluminescence

TLD: (Thermoluminescent dosimeter) crystalline materials that store absorbed energy on exposure to radiation and release it as visible light when exposed to heat.

TLD-100: A TLD of Lithium Fluoride doped with Magnesium and Titanium.

TLD-200: A TLD made up of Calcium fluoride.

WHO: World Health Organization

1.0 INTRODUCTION

When radiation is prescribed to a cancer patient, it is important that it is confirmed independently that the patient actually receives the dose prescribed. In the words of Peter Nette and Hans Svensson "In principle, a quality assurance programme should ensure that all patients treated with a curative aim receive the prescribed dose within a margin of about 5%"[1]. In-vivo dosimetry is a method to determine if the patient receives the actual dose prescribed.

At the Charlotte Maxeke Johannesburg Academic Hospital, GR200A and TLD-100 TLDs are used for in-vivo dosimetry of patients undergoing radiation treatment. These TLDs are calibrated and implemented clinically for the high-energy photon beams. No calibrations have been done yet for the low and medium energy photon therapy beams and therefore, the response of the TLDs in this range is unknown at this stage. No in-vivo dosimetry has been performed in diagnostic beams either.

In this study, GR-200A TLDs were calibrated in low and medium energy photon therapy beams and in a diagnostic beam of known beam quality, in order to determine their response and to establish if the same set of TLDs could be used across both kilovoltage environments for in-vivo dosimetry purposes.

1.1 Background

Radiation Oncology employs ionizing radiation in the treatment of cancerous cells. Two methods (teletherapy and brachytherapy) are used to deliver the ionizing radiation to the target volume. Teletherapy is a term used to describe treatments in which the source of radiation is distant from the patient[12]. Brachytherapy is a method of treatment in which radioactive sources are used to deliver radiation at a short distance by interstitial or surface applications[12]. A quality assurance programme ensures that all treatment facilities used in radiotherapy are properly checked for accuracy or consistency, that all radiation

facilities are functioning according to manufacturer's specification and it includes mechanical and dosimetric tests.

Dosimetry deals with methods for the quantitative determination of absorbed dose in a given medium by directly or indirectly ionizing radiation[18]. A dosimeter is the device or system that measures the absorbed dose either directly or indirectly[18]. In order for an instrument to function as a dosimeter, it must possess at least one physical property of the measured dosimetric quantity. Different types of dosimeters are used currently for the measurement of absorbed dose and these include ionization chambers, semiconductor dosimeters (e.g. diodes), film, alanine, gel, and thermoluminescent dosimeters. While some of these dosimeters are reusable (ionization chamber, TLDs, diodes) others are not (films, gels, and alanine)[18]. These dosimeters are calibrated from time to time to ensure consistency.

1.2 TLDs and their properties

1.2.1 Description of TLDs

Thermoluminescent dosimeters are crystalline materials that store absorbed energy from exposure to radiation and release it as visible light when exposed to heat. TLDs have been used widely for different studies (in-vivo, in-phantom and environmental) [14, 15, 17]. TLDs have the advantage of long-term stability[6, 13] and low cost of acquisition compared to other detectors such as diodes[11]. TLDs are used for in-vivo dosimetry primarily because of their small size. TL materials are available in various forms i.e. chips, ribbons, discs, rods and powder.

1.2.2 Interaction of radiation with TLDs

The interaction process between radiation and TLDs occurs in two stages. The processes' occurring within these two stages is diagrammatically shown in figure 1.

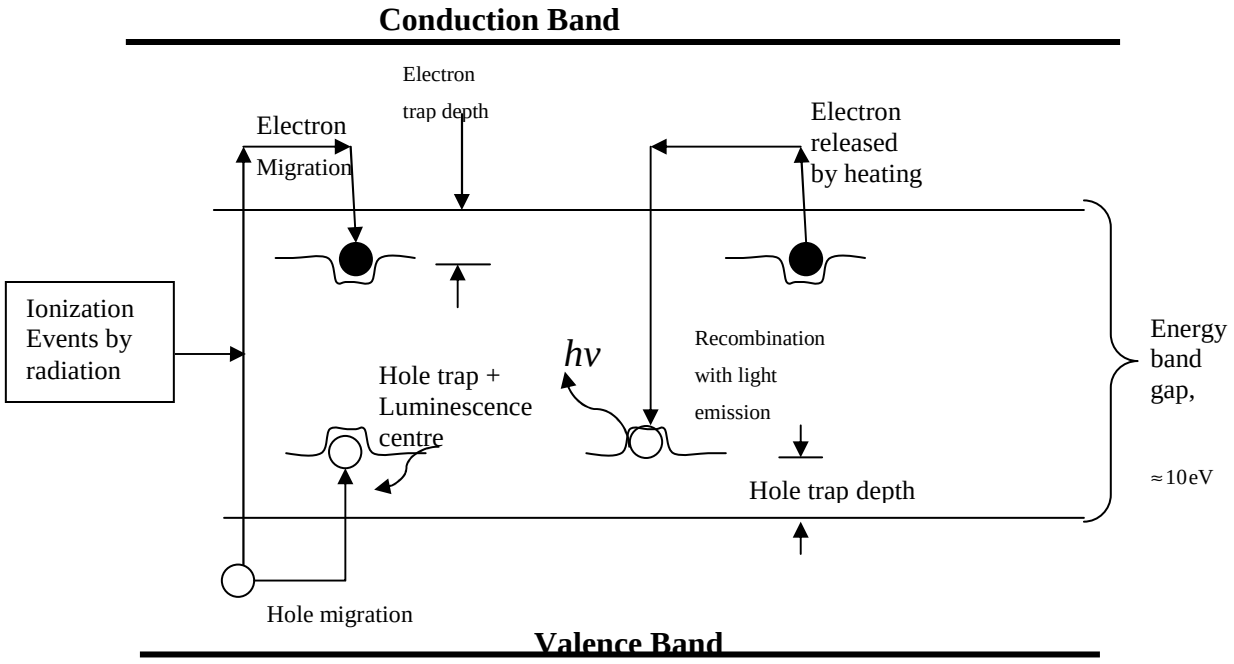

Figure 1: The energy-level diagram of the thermoluminescence process[21]

Irradiation stage: The ionization events triggered by irradiation begin with the elevation of electrons to the conduction band where they are trapped. The holes left behind migrate to hole traps, which are deep enough to prevent the escape of charge carriers (electrons and holes) for an extended period of time.

Thermoluminescence stage: At sufficient temperature the electrons are released from their traps to recombine with the holes accompanied by the release of light photons (thermoluminescence).

A glow curve is a plot of the total light emitted as a function of temperature. It contains several peaks, with each peak representing an intensity level. A sample of a glow curve is shown in figure 2.

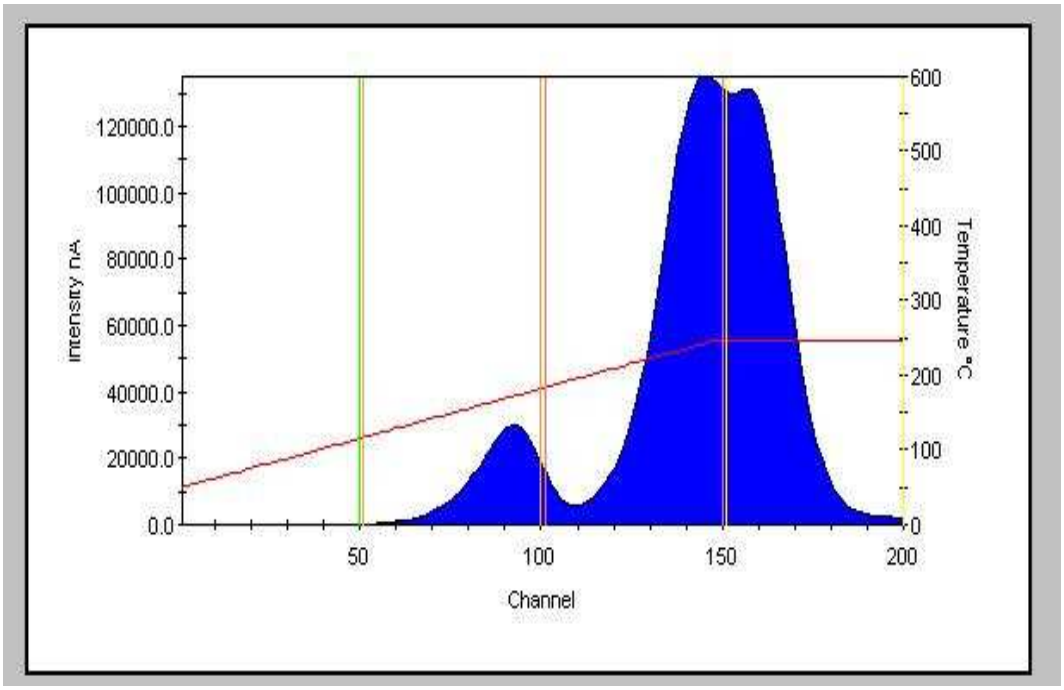

Figure 2: Sample of a glow curve[10]

1.2.3 Types of TL material

An important characteristic of TLDs is their applicability to different environments owing to the variety of TL materials available. Several materials have been used in the production of TLDs (e.g. LiF: Mg, Ti, LiF: Mg, Cu, P, $Li_2B_4O_7$: Mn, CaF_2: Mn, $Li_2B_4O_7$: Cu, Al_2O_3: C, $CaSO_4$: Dy, CaF_2: Dy) [8, 13]. Of these TL materials, the most commonly used ones are the lithium fluorides[2, 3, 5, 6].Table 1 shows different TL materials and their characteristics.

Table 1: Dosimetric characteristics of selected TL materials[13]

TL materials	**Form**	**Glow peak (˚C)**	**Emission maximum (nm)**	**Z_{eff}**	**Relative Sensitivity**	**Linear Range (Gy)**	**Fading**	**Annealing (Temperature and Time)**
LiF: Mg, Ti	Powder, chips, rods, discs.	210	425	8.14	1	5×10^{-5} to 1	< 5 % per year	400 ˚C, 1 h + 80˚C, 24 h
LiF: Mg, Ti, Na	Powder, discs.	220	400	8.14	0.50		N/A	500 ˚C, 0.5 h
LiF:Mg, Cu, P	Powder, discs, chips	232	310 (410)	8.14	15-30	10^{-6} to 12	< 5 % per year	240 ˚C, 10 min
$Li_2B_4O_7$: Mn	Powder	210	600	7.40	0.15-0.40	10^{-4} to 3	5 % in 2 months	300 ˚C, 15 min
Al_2O_3: C	Powder, discs	250	425	10.20	30	10^{-4} to 1	3 % per year	300 ˚C, 30 min
$CaSO_4$: Dy	Powder, discs	220	480 (570)	15.30	30-40	10^{-6} to 30	7-30 % in 6 months	400 ˚C, 1 h
CaF_2: Dy	Powder	200 (240)	480 (575)	16.30	16	10^{-5} to 10	25 % in 4 weeks	600 ˚C, 2 h
BeO	Discs.	180-220	330	7.13	0.70-3	10^{-4} to 0.50	7 % in 2 months	600 ˚C, 15 min

It can be observed from Table 1 that all lithium fluoride TLDs have the same effective atomic mass (Z_{eff}) and fading periods but differ in relative sensitivity. The LiF: Mg, Cu, P TLD is of the highest relative sensitivity and it is available in different shapes of different dimensions as shown in Table 2.

Table 2: A list of LiF: Mg, Cu, P TLDs and their technical specifications[8]

Part no.	Material	Type	Dimensions	Linear response
GR200A	LiF: Mg, Cu, P	Circular chips	4.5 mm diameter x 0.8 mm	1 x 10^{-6} to 12 Gy
GR200	LiF: Mg, Cu, P	Square chips	3.2 x 3.2 x 0.9 mm^3	1 x 10^{-6} to 12 Gy
GR200R4	LiF: Mg, Cu, P	Square micro rods	1 x 1 x 4 mm^3	1 x 10^{-6} to 12 Gy
GR200R1	LiF: Mg, Cu, P	micro cubes	1 x 1 x 1 mm^3	2 x 10^{-6} to 12 Gy
GR200P	LiF: Mg, Cu, P	Powder	80 to 200 10^{-6} m	1 x 10^{-6} to 12 Gy
GR200F	LiF: Mg, Cu, P	Film	4.5 mm diameter x 0.125 mm	1 x 10^{-6} to 12 Gy
GR206A	6- LiF: Mg, Cu, P	Circular chips	4.5 mm diameter x 0.8 mm	1 x 10^{-6} to 12 Gy
GR206P	6- LiF: Mg, Cu, P	Powder	80 to 200 10^{-6} m	1 x 10^{-6} to 12 Gy
GR207A	7- LiF: Mg, Cu, P	Circular chips	4.5 mm diameter x 0.8 mm	1 x 10^{-6} to 12 Gy
GR207P	7- LiF: Mg, Cu, P	Powder	80 to 200 10^{-6} m	1 x 10^{-6} to 12 Gy

1.3 Historical review of the calibration of TLDs

Different procedures have been employed in the handling and evaluating of TL materials [2,3,4,5]. Coudin and Marinello[3] calibrated a set of TLDs to be used for the measurement of back scatter factors, by irradiating $Li_2 B_4 O_7$: Cu TLDs in diagnostic beams of 20, 40, 70, 80 and 100 kV_p. The response measured by the TLDs was obtained from an automatic TLD reader FIMEL type PCL, based on isothermal heating kinetics. The results obtained were then compared to Monte Carlo calculated data (reference data). The advantage of their calibration technique lay in the energy range used for the irradiation of the TLDs. The TLDs were however not calibrated in kilovoltage therapy beams.

Nunn et al.[2] calibrated a set of TLDs (TLD-100) for brachytherapy by irradiating them with moderately filtered therapy X-ray beams (20-250 kV_p) and with a ^{60}Co source. The response obtained was compared to Monte Carlo calculated data. The study showed that there was poor agreement between the measured response and the Monte Carlo calculated

response using the mass-energy absorption coefficients of pure Lithium Fluoride. The study did not show if the set of TLDs could also be used in the diagnostic environment.

Perisinakis et al.[9] calibrated TLD – 100 and TLD – 200 TLDs to investigate the response of a pencil ionization chamber for the measurement of dose – width product (DWP) from diagnostic exposures. The TLD calibration was performed against a 3 cm^3 Radcal 2025 ionization chamber by simultaneously exposing the chamber and the TLDs to a 70 kV_p beam on a radiographic X-ray unit. The TLD signal was then measured using a Victoreen 2800 – M reader. Their report did not indicate how the 3 cm^3 Radcal 2025 ionization chamber had been calibrated. Their study concluded that the DWP values measured using the TLDs were up to 11 % less than the corresponding values determined using the pencil ionization chamber.

Daibes Figueroa et al.[4] gave a detailed calibration process for 90 TLD-100 TLDs used for mouse dosimetry with micro CT imaging. The TLDs were first calibrated using a Cs-137 reference check source. Of the 90 TLDs, only 24 TLDs had an 8 % sample-to-sample uniformity. Their study showed that there was a 40 % over response of the TLDs when they were calibrated using an X-ray source (diagnostic energy range). However, the type of TLD material may have influenced the over response as studies have shown that TLD-100 is not suited to low energy photon beam dosimetry[6, 7]. Duggan[6] compared the response of different TL materials in low energy photon therapy beams and showed that GR200A had a better response than TLD-100. Glenin[7] also showed in a separate report that GR200A releases 34 times more light than TLD-100 when calibrated in low energy photon therapy beams.

1.3.1 Factors affecting the response of TLDs

The following are some of the factors that may affect the response of TLDs in the measurement of absorbed dose.

- The response of TLDs varies from one material to another[8, 13].

- The fading period for TLDs differs between materials as indicated in Table 1 and this may affect the response of TLDs.
- Handling procedures[8] (such as keeping TLDs under subdued ultra-violet environment during measurement, use of vacuum tweezers for transferring TLDs), if not followed properly during calibration of TLDs, may affect response.
- Intrinsic response of the TLD reader may also affect the general response of the dosimeter[16, 20].
- The annealing used to prepare the TLDs for reuse may also influence the measurements as annealing regimes are different from one TL material to another[8].

TLD dosimetry is regarded as a 'black art' because to some, it produces excellent results with great accuracy but to others, all attempts seem to fail[11]. It is therefore necessary for each Radiotherapy centre to embark in a full dosimetric study for the calibration of TLDs before they are used clinically for in-vivo dosimetry.

1.4 Research objective

1. To calibrate a set of new GR200A TLDs (LiF: Mg, Cu, P) needed for in-vivo dosimetry in a range of kilovoltage therapy beams and in a diagnostic beam.
2. To compare the absorbed dose obtained from 4 different beam qualities to an independently confirmed reference dose.
3. To establish if the same set of TLDs could be used across both kilovoltage environments for in-vivo dosimetry purposes.

2.0 MATERIALS AND METHODS

2.1 Study materials

2.1.1 Detectors

20 TLDs manufactured by FIMEL, France were used for this study. The TLDs were in the form of circular chips with dimensions 4.5 mm diameter and 0.8 mm thickness. The TLDs were kept in a subdued ultra-violet environment during storage. The same set of TLDs was used for all the different energies. The 20 TLDs were used both as calibration dosimeters and field dosimeters. This TL material was chosen for this study because of its availability, its high response in low energy photon beams and its proven use in high-energy beams for clinical in-vivo dosimetry.[6, 7, 17]. The set of TLDs were arranged in an annealing pan prior to annealing for individual identification and then transferred to a plastic holder prior to irradiation to preserve the order of identification as shown in Figure 3.

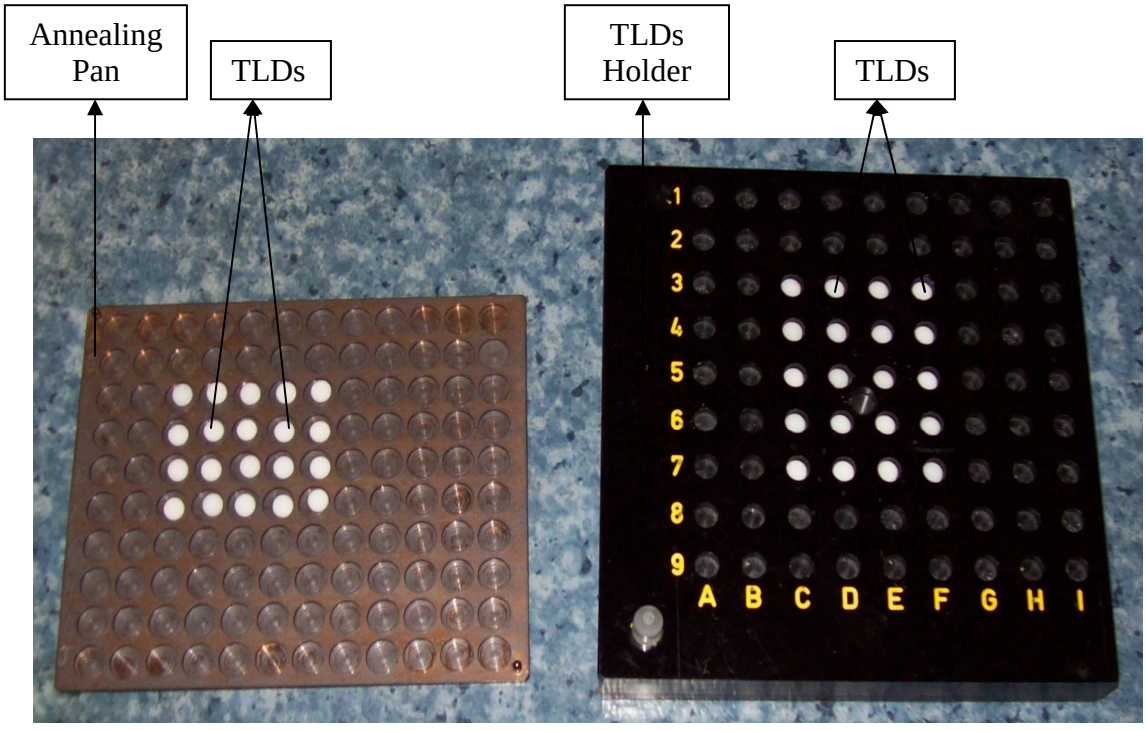

Figure 3: TLDs arranged in an annealing pan and in a plastic holder

A calibrated cylindrical ionization chamber (PTW 30001) and an electrometer (PTW 10008) were used to verify the output of the orthovoltage machine. The consistency of the ionization chamber was confirmed using a Strontium–90 check source. The ionization chamber and the electrometer used are shown in Figure 4. A calibrated TM77334 ionization chamber along with a T10008 electrometer was used to confirm the output of the radiotherapy simulator. The ionization chamber and the electrometer are also shown in Figure 4.

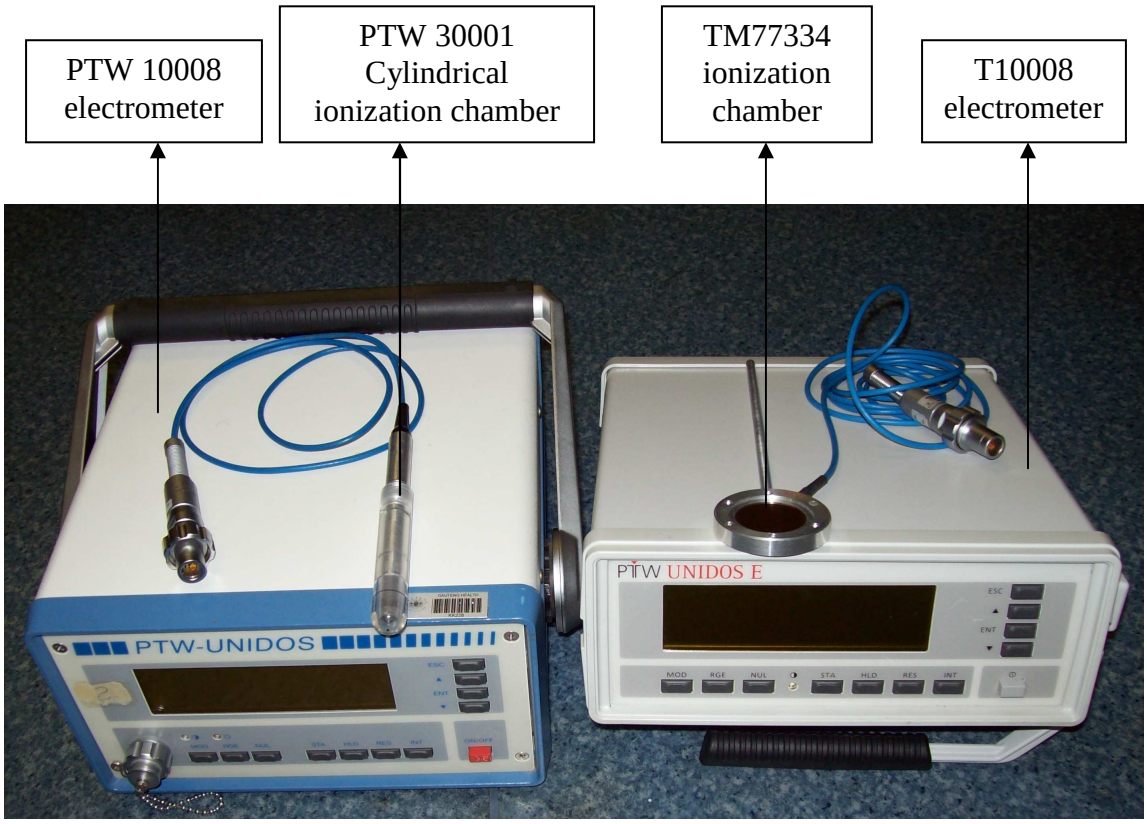

Figure 4: The PTW 10008 electrometer, PTW 30001 Cylindrical ionization chamber, TM77334 ionization chamber and T10008 electrometer that were used to confirm the output of the orthovoltage machine and the radiotherapy simulator respectively.

2.1.2 Annealing materials

A type PCL_3 Oven manufactured by PTW-Freiburg, Germany was used to anneal the TLDs. A photograph of the oven is shown in Figure 5. The parameters for the

Temperature Time Profile (TTP) were set as indicated in the TL Detector User manual[8] and are shown in Table 3. An appropriate TTP for the TL material being used was set according to the parameters shown in Table 3.

Figure 5: The Oven used to anneal the TLDs

Table 3: Parameters for the Temperature Time Profile.

Parameters	**GR200A**
Preheat Temperature	50 °C
Preheat Time	0 s
Acquire rate	10 °C/s
Acquire max. Temperature	245 °C
Acquire Time	26 s
Anneal Temperature	240 °C
Anneal Time	0 s

A Vacuum tweezer DYMAX 30 was used to transfer the TLDs during measurement and calibration. The Vacuum tweezer is shown in Figure 6.

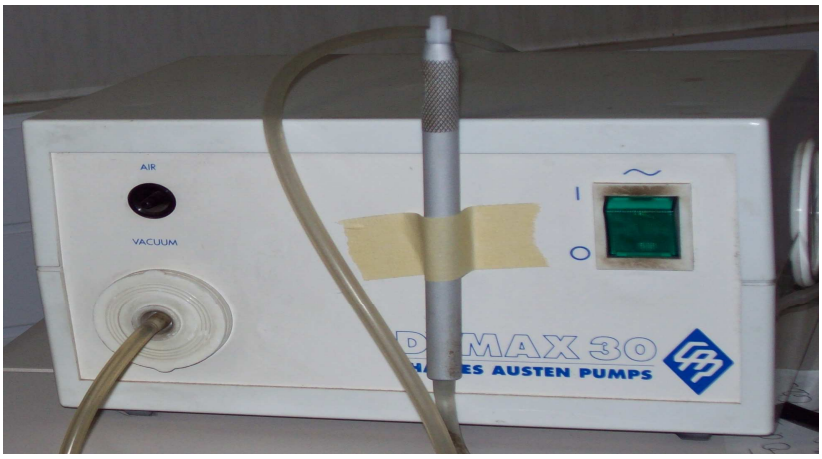

Figure 6: The Vacuum tweezer DYMAX 30 that was used to transfer the TLDs during measurement.

2.1.3 Reader

The response of the TLDs was read using the Reader type LTM. The automatic mode of the reader was used during readout. The Element Correction Coefficient (ECC) determines the response range of the TLDs and is generated as follows[10]:

$$ECC = \langle Q \rangle \div Q_i \quad \text{.....(1)}$$

Where,

$\langle Q \rangle$ is the average charge integral of the TLDs and

Q_i is the individual charge integral of the TLDs

The ECC range was set between 0.90 Gy to 1.10 Gy[10] (i.e. ± 10 % deviation) for the calibration dosimeters and between 0.80 Gy to 1.20 Gy[10] (i.e. ±20 % deviation) for the field dosimeters during the experimental process. The Reader was calibrated by selecting the set of TLDs that were within the ECC range for calibration dosimeters (to generate the Reader Calibration Factor, RCF). The RCF was generated as follows:

$$RCF = \langle Q_c \rangle \div D \quad \text{.....(2)}$$

Where,

$\langle Q_c \rangle$ is the average corrected charge integral and

D is the absorbed dose (1.00 Gy) delivered to the TLDs[10].

The Reader used is shown in Figure 7.

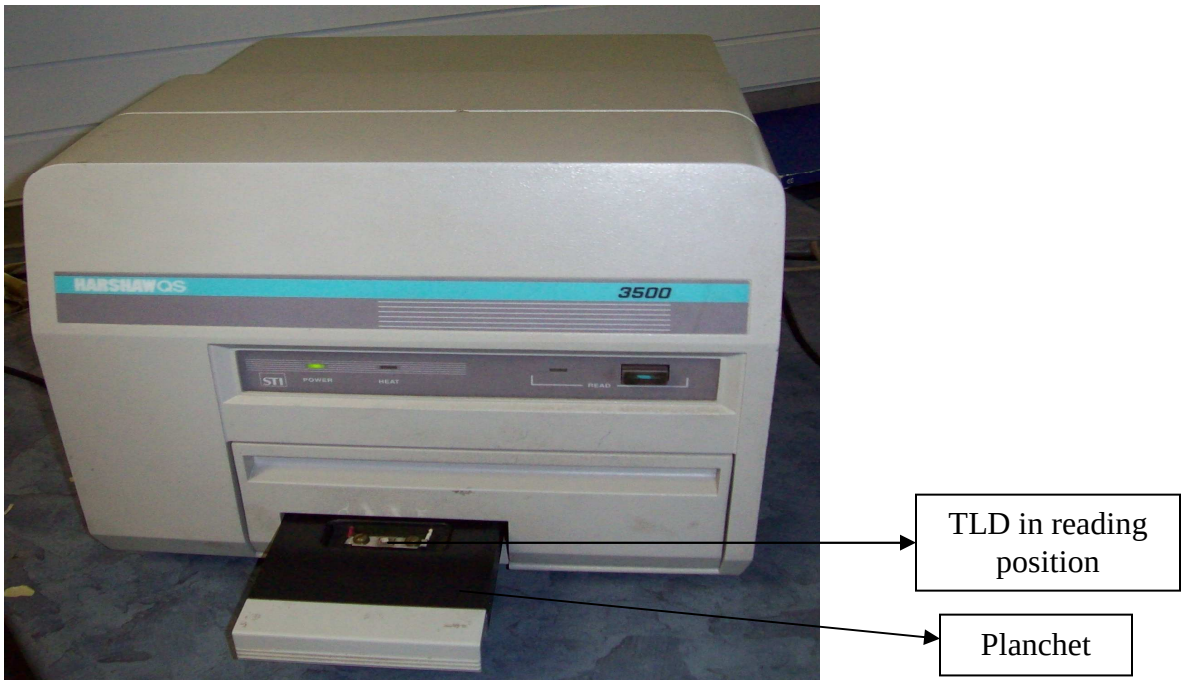

Figure 7: The reader type LTM that was used to read the TLDs

The Oven and the Reader were connected to a dedicated personal computer that used Theldo and WinRems software for initiating the annealing and reading programs respectively.

2.1.4 Radiation facilities

A calibrated orthovoltage machine manufactured by Gulmay, Germany was used to deliver 1.00 Gy to the TLDs. A calibrated Toshiba LX40 radiotherapy simulator, Japan was used to deliver a known diagnostic dose of 1.00 cGy to the TLDs. The TLDs were placed on the surface of a 30 x 30 x 17.6 cm^3 Polymethylmethacrylate (PMMA) phantom during both irradiations. A radiographic film was used to check the dose uniformity of the absorbed dose delivered.

2.2 Data collection procedures

2.2.1 Absorbed dose delivery verification procedure at orthovoltage

The absorbed dose delivered by the orthovoltage machine was determined using the in-phantom method described in the American Association of Physicists in Medicine Task Group 61[19]. The chamber was placed at a depth of 2 cm. A 10 x 10 cm² applicator was used to define the field size at 50 cm SSD. Different filters with varying thicknesses were used to harden the beams. The machine monitor unit (time) was calculated to deliver a dose of 1.00 Gy at the surface. A photograph of the experimental set-up is shown in Figure 8.

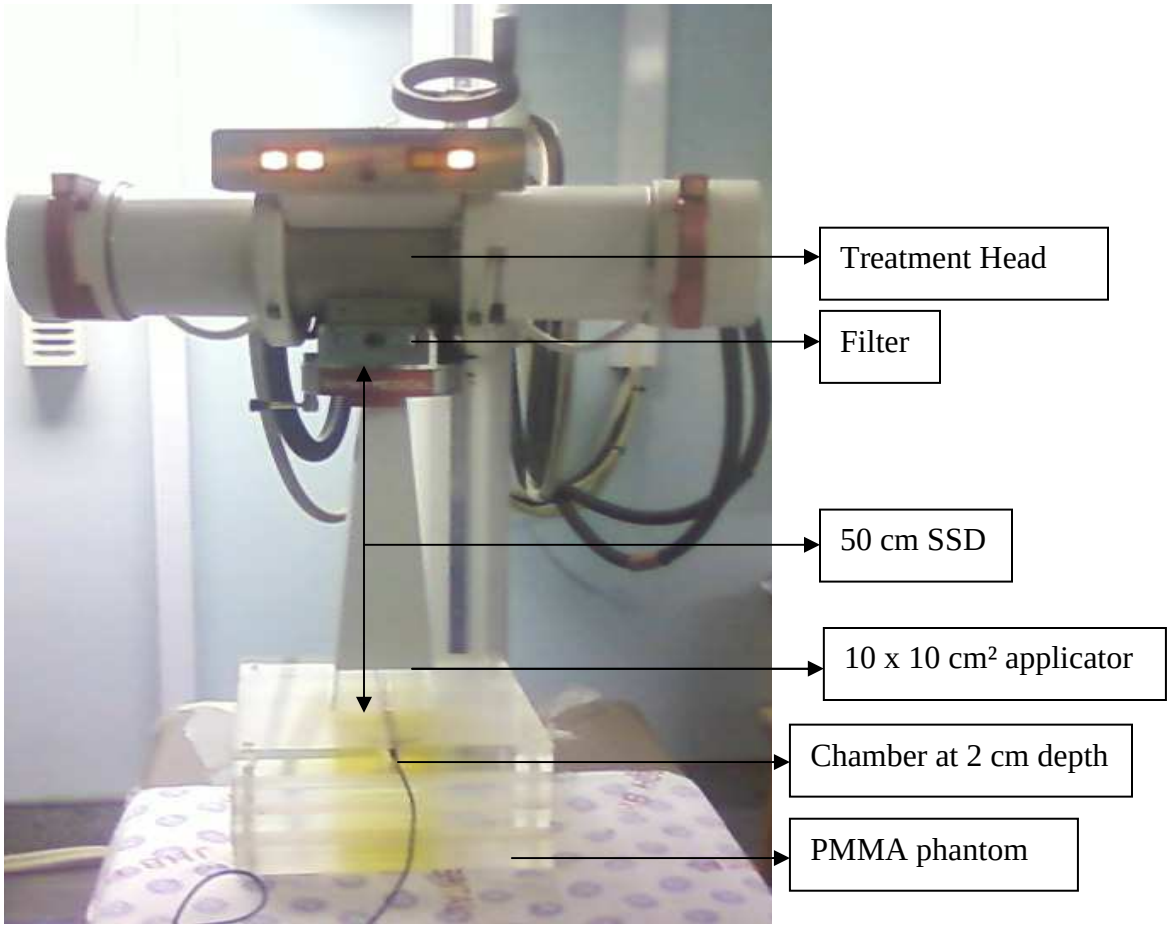

Figure 8: Experimental set-up for absorbed dose delivery verification at orthovoltage.

The absorbed dose to the phantom at the depth of 2 cm was calculated using the formula;

$$D_{W,Z=2cm} = MN_K P_{Q,chamb} P_{sheath} \left[\left(\frac{\overline{U_{en}}}{\rho} \right)^{w}_{air} \right]_{water} \quad \text{.....(3)}$$

Where,

M is the electrometer reading (charge) corrected for temperature and pressure.

N_k is air-kerma calibration factor, for a specified X ray beam quality.

$P_{Q,chamb}$ is the overall chamber correction factor that accounts for the change due to the change in beam quality between calibration and measurement and to the perturbation of the photon fluence at the point of measurement by the chamber, and the chamber stem, which is dimensionless.

P_{sheath} is the correction for photon absorption and scattering in the waterproofing sleeve.

$\left[\left(\frac{\overline{U_{en}}}{\rho} \right)^{w}_{air} \right]_{water}$ is the mean mass-energy absorption coefficient ratio for water to air averaged over the photon spectrum at the reference point in water in the absence of the chamber.

The absorbed dose at the depth of 2 cm was then converted to absorbed dose at the surface of the phantom by using the percentage depth dose (PDD). This was done for the 95 kV_p (3.00 mm Al HVL), 180 kV_p (1.00 mm Cu HVL), and 300 kV_p (3.00 mm Cu HVL) therapy beams.

2.2.2 Confirmation of reference absorbed dose at the simulator

The reference absorbed dose to be delivered to the TLDs in the diagnostic beam was determined using the in-phantom formalism described in IAEA Technical Report Series 457 for calculating the entrance surface air kerma rate[13]. The fluoroscopic mode of the radiotherapy simulator was used. The TLDs were exposed to an 80 kV_P beam of 2.97 mm Al HVL. The simulator was set to a fluoroscopic time of 30 s and tube loading of 40

mAs. A field size of 25 x 25 cm² at 100 cm focus to table top was used. A reference dose of 1.00 cGy was delivered to the ionization chamber at the surface of the PMMA phantom as shown in Figure 9.

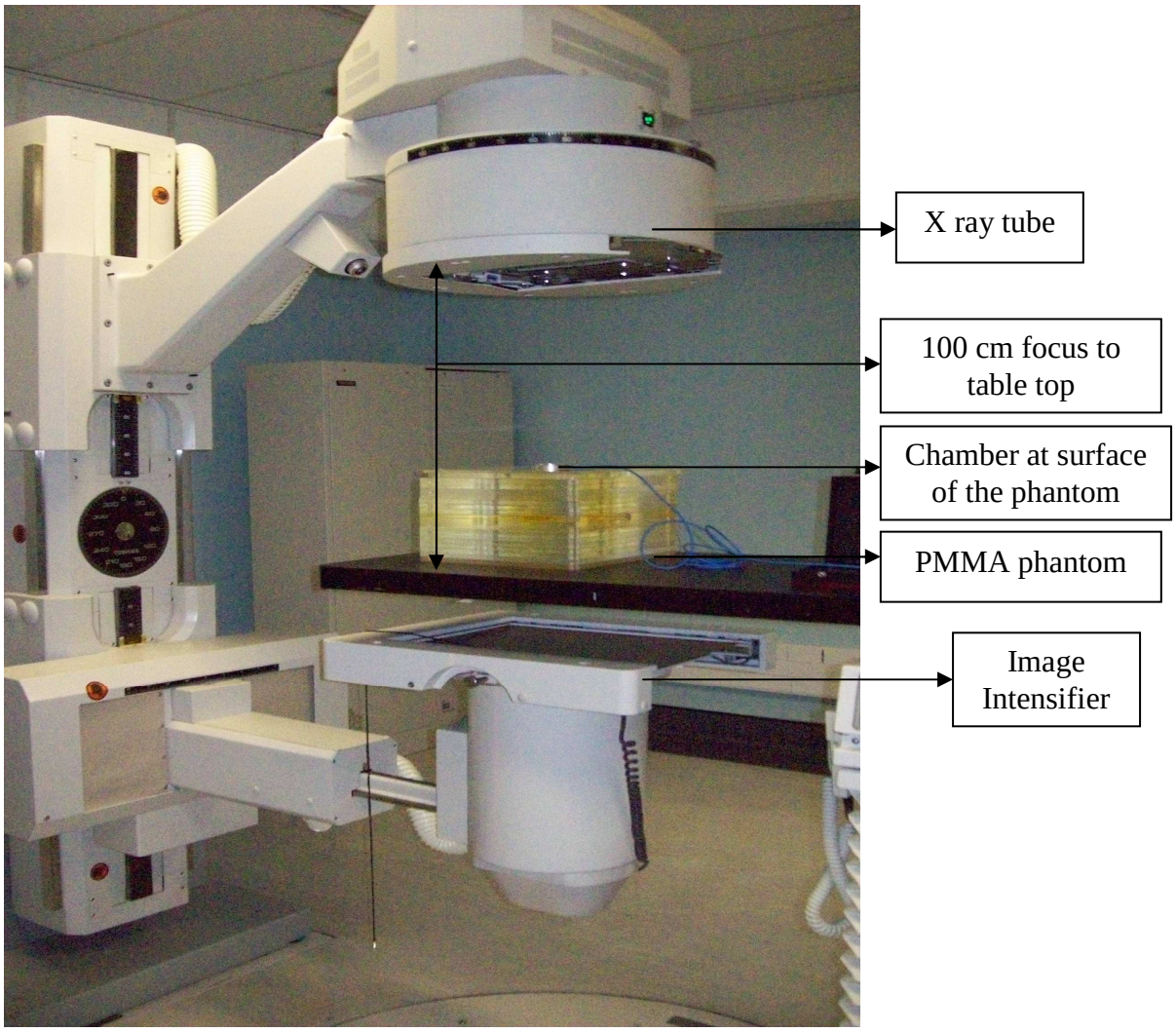

Figure 9: Experimental set-up for reference absorbed dose in simulator

The entrance surface air kerma rate was calculated using the formula;

$\acute{K}_e = (M\ N_{k,\,Q.}\ K_Q\ B_w) / (B_{PMMA})$……..….(4)

Where;

M is the electrometer reading (charge), with the centre of the sensitive air cavity placed at the surface, corrected for temperature and pressure.

$N_{k,\,Q.}$ is the chamber calibration coefficient

K_Q is the factor which corrects for difference in the response of the dosimeter at the calibration quality, Q**.**, and at quality, Q of the clinical X ray beam.
B_w is the back scatter factor in terms of air kerma for water
B_{PMMA} is the back scatter factor in terms of air kerma for PMMA.
The entrance surface air kerma rate was obtained in cGy (The term entrance surface air kerma rate was used to represent the absorbed dose in accordance with the protocol)[13].

2.2.3 TLD calibration procedures at orthovoltage

After irradiation, the TLD responses were read and stored in a database for calibration. EECs for the calibration dosimeters were generated from the database. Only TLDs that were within the ± 10 % accepted range for calibration dosimeters were selected for the calibration of the reader. The RCF was generated from the data base by applying the EECs of calibration dosimeters generated above. The RCF was then stored for future use.

The field dosimeter ECCs were generated by applying the RCF and setting the ECC range to the ± 20 % accepted range for field dosimeters. All TLDs that were within the accepted range were kept for calibration while others (marked as bad dosimeters) were removed from the batch. The absorbed dose measured was obtained by applying the RCF and the individual ECCs of the TLDs. The absorbed dose obtained was then stored for analysis. After the calibration process had been completed, the TLDs were irradiated again to an arbitrary absorbed dose of 2.00 Gy and read.

2.2.4 TLD calibration procedures at the simulator

The data collection procedures were repeated with the same set of TLDs for an absorbed dose of 1.00 cGy from the simulator. After the calibration process had been completed, the TLDs were irradiated to an arbitrary absorbed dose of 2.00 cGy and read.

3.0 RESULTS AND DISCUSSION

3.1 Absorbed dose delivery verification results at orthovoltage

The absorbed dose at the surface derived from the ionization chamber measurement at the 3 kilovoltage therapy beams, was 1.00 ± 0.01 Gy.

3.2 TLD calibration results at orthovoltage

At the start of the experiment, a calibration was performed in the 95 kV_p therapy beam to generate an RCF file. 20 TLDs were irradiated to known absorbed doses in the 180 kV_p and 300 kV_p therapy beams. Only 40 % of the TLDs were within ± 10 % of the delivered absorbed dose in the 180 kV_p beam and only 25 % in the 300 kV_p beam. Separate RCF file were therefore generated for each beam quality.

95 kV_p

7 of the TLDs had a raw response that were out of range (i.e. more than ± 10 %) and were therefore not used as calibration dosimeters. The RCF value was calculated to be 0.39 nC / Gy. 3 of the TLDs had ECCs that were out of the accepted range (i.e. ± 20 %) and were discarded. The remaining TLDs were all within ± 10 % of the 1.00 Gy delivered, except TLD D3 as shown in Table 4. For the 2.00 Gy irradiation, all TLDs were within ± 10 %.

Table 4: The results of TLDs exposed to an absorbed dose of 1.00 and 2.00 Gy in the 95 kV_p therapy beam.

Dosimeter ID	Absorbed dose (Gy) (1 Gy irradiation)	Absorbed dose (Gy) (2 Gy irradiation)
C3	0.93	1.95
C4	0.96	1.97
C6	0.92	1.90
C7	0.91	1.92
D3	0.89	1.92
D4	0.91	1.93
D5	0.94	1.96
D6	0.95	1.96
D7	0.95	1.97
E3	0.93	1.91
E4	0.91	1.93
E6	0.94	1.96
E7	0.94	1.95
F4	0.93	1.92
F5	0.95	1.96
F6	0.95	1.97
F7	0.92	1.91
Mean ± SD	0.93 ± 0.02	1.94 ± 0.02

180 kV_p

9 of the TLDs had a raw response that were out of range (i.e. more than ± 10 %) and were therefore not used as calibration dosimeters. The RCF value was calculated to be 0.30 nC / Gy. 3 of the TLDs had ECCs that were out of the accepted range (i.e. ± 20 %) and were discarded. The remaining TLDs were all within ± 10 % of the 1.00 Gy delivered as shown in Table 5. For the 2.00 Gy irradiation, all TLDs were within ± 10 %.

Table 5: The results of TLDs exposed to an absorbed dose of 1.00 and 2.00 Gy in the 180 kV_p therapy beam.

Dosimeter ID	Absorbed dose (Gy) (1 Gy irradiation)	Absorbed dose (Gy) (2 Gy irradiation)
C3	1.05	2.01
C4	1.07	2.09
C6	1.03	2.05
C7	1.00	2.01
D3	1.06	2.08
D4	1.04	2.06
D5	1.06	2.07
D6	1.03	2.05
D7	1.05	2.03
E3	1.05	2.08
E4	1.05	2.06
E6	1.05	2.06
E7	1.08	2.05
F4	1.08	2.06
F5	1.09	2.08
F6	1.04	2.02
F7	1.04	2.04
Mean ± SD	1.05 ± 0.04	2.05 ± 0.03

300 kV_p

9 of the TLDs had a raw response that were out of range (i.e. more than ± 10 %) and were therefore not used as calibration dosimeters. The RCF value was calculated to be 0.24 nC / Gy. 3 of the TLDs had ECCs that were out of the accepted range (i.e. ± 20 %) and were discarded. The remaining TLDs were all within ± 10 % of the 1.00 Gy delivered as shown in Table 6. For the 2.00 Gy irradiation, all TLDs were within ± 10 %.

Table 6: The results of TLDs exposed to an absorbed dose of 1.00 and 2.00 Gy in the 300 kV_p therapy beam.

Dosimeter ID	Absorbed dose (Gy) (1 Gy irradiation)	Absorbed dose (Gy) (2 Gy irradiation)
C3	0.99	2.01
C4	0.97	1.98
C6	0.98	1.96
C7	1.01	1.95
D3	0.98	1.97
D4	0.97	1.99
D5	0.97	1.95
D6	0.98	1.95
D7	0.99	1.96
E3	0.96	1.97
P4	0.97	1.98
E6	0.98	1.94
F4	0.97	1.93
F5	0.98	1.94
F6	0.95	1.97
F7	0.95	1.98
Mean ± SD	0.98 ± 0.02	1.96 ± 0.02

3.3 Confirmation of reference absorbed dose result at simulator

The absorbed dose measured by the ionization chamber at the kilovoltage diagnostic beam was 1.00 ± 0.01 cGy.

3.4 TLD calibration results at the simulator

8 of the TLDs had a raw response that were out of range (i.e. more than ± 10 %) and were therefore not used as calibration dosimeters. The RCF value was calculated to be 0.01 nC

/ Gy. 5 of the TLDs had ECCs that were out of the accepted range (i.e. ± 20 %) and were discarded. 12 of the TLDs were within ± 10 % of the 1.00 cGy delivered as shown in Table 7. For the 2.00 cGy irradiation, all TLDs were within ± 10 %.

Table 7: The results of TLDs exposed to an absorbed dose of 1.00 and 2.00 cGy in the 80 kV_p diagnostic beam.

Dosimeter ID	Absorbed dose (cGy) (1 cGy irradiation)	Absorbed dose (cGy) (2 cGy irradiation)
C4	1.03	2.01
C6	0.89	2.09
C7	1.03	2.06
D3	1.06	2.04
D4	1.08	2.04
D5	0.99	2.01
D6	1.03	2.05
D7	1.15	2.09
E3	1.08	2.03
E4	0.83	2.10
E6	1.05	2.07
F4	0.96	2.05
F5	1.00	2.02
F6	0.99	1.95
F7	0.99	2.02
Mean ± SD	1.01 ± 0.08	2.04 ± 0.04

Overall, the results of the absorbed dose obtained when a separate RCF was generated for each beam quality showed that about 85 % of the TLDs produced results that were within ± 10 %. In the fluoroscopic diagnostic beam, 3 (20 %) of the TLDs deviated more than ± 10 %. This deviation could be due to experimental uncertainties. There was no significant deviation from linearity in the response when the TLDs were exposed to 2.00 Gy from the therapy beams and 2.00 cGy from the diagnostic beam.

In this study, separate calibrations of the TLDs in each beam quality have been employed to overcome energy dependence of the TLDs. The generation of a separate calibration factor (RCF) for each beam quality improved the overall result compared to a single calibration factor. No correction factors derived from published models[26] were applied in this work. The TLDs were also given a known absorbed dose in the 300 kV_p therapy beam and then read using the RCF of the 180 kV_p therapy beam. 60 % of the TLDs were within the ± 10 % of the absorbed dose delivered. This shows that the use of a single calibration factor used across medium energy beams could be investigated further.

In general, the results confirm that the TLDs are energy dependent. This result agrees with that of Krasa et al.[22] who showed that GR200A TLDs were energy dependent. The ratio of stopping powers or mass energy absorption coefficients of TLD to water is often used to describe variation of TLD response with varying photon energy[25]. However, there are other factors that affect the variation of TLD response with energy such as the thickness of the TL material, texture (i.e. roughness or smoothness of the TLD surface) of the TL material and doping (i.e. mixture of different materials), which may make it difficult to accurately predict the variation of TLD response with energy theoretically. In some cases, the use of monoenergetic photon beams along with mathematical models have been employed to predict the energy dependence of TLD response [23,24]. Correction factors for different beam qualities have also been generated to compensate for this effect[26]. According to Kron et al.[23], variation in TLD response could be due to the assumption that the response at low energies reduces exponentially whereas at medium energies, it varies according to the energy dependence from the photoelectric effect.

4.0 CONCLUSION

1. The same set of GR-200A TLDs could be used across both kilovoltage therapy and diagnostic fluoroscopy environments for in-vivo dosimetry purposes if an accuracy of ± 10 % is considered acceptable, however a separate calibration needs to be done at each beam quality.

2. A further study into other fluoroscopic diagnostic beam qualities should be considered.

3. A further study into the radiographic mode of the simulator and/or other diagnostic modalities should be considered also.

4. Individual dosimeters from a batch should be carefully identified and sorted during the calibration process prior to use in the clinic for in-vivo dosimetry.

5. An extended study into absorbed dose linearity behaviour should be considered as there is not enough data in this report to confirm this relationship.

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