UNIVERSITI PUTRA MALAYSIA

DOSIMETRIC CHARACTERISTICS OF FABRICATED GE-DOPED SILICA OPTICAL FIBRES FOR SMALL FIELD RADIATION DOSIMETRY IN RADIOTHERAPY

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By

LAM SIOK EE

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Faculty : Medicine and Health Sciences

Advances in radiation treatments have resulted in the increased use of small treatment fields with millimeter scale and high dose in treating small tumours. The determination of absorbed dose may not be as accurate as previously achieved for the standard radiotherapy applications using broad treatment fields due to the presence of charged particle disequilibrium, occlusion of the primary radiation source and volume averaging effect of dosimeter. This study is pertaining to the potential of the locally fabricated 6 mol% Germanium-doped (Ge-doped) silica fibres to be utilised in the small-field dosimetry. Three fibre types, cylindrical fibres (CF) (483 µm) and flat fibres (FF) (273 x 67 μm^2) fabricated from the 6 mol% Ge-doped preform and commercial Ge-doped 50 µm-core fibres (COMM), were used. The time-temperature profiles (TTP) for the fibre readouts and the effect of TTP on the kinetic parameters of the glow curves as well as the dosimetric characteristics of fabricated Ge-doped silica fibres were investigated prior to the output factors study of a dedicated linear accelerator. A constant TTP (preheat 80 °C and heating rate 30 $°Cs^{-1}$) was employed in all fibre readouts due to the centrally distributed glow curves enabling complete capture of the thermoluminescent (TL) glow curve, the stability of this situation across three fibre types and the near proportionality of peak integral and peak temperature of the deconvoluted glow peaks. Two Perspex phantoms were custom-made for the studies of angular dependency and output factors of the fibres. The FF offer superior performance compared to that of the CF in terms of dose repeatability (2% to 6%), angular independence (± 3%) and dose-rate independence. For doses up to 80 Gy delivered using 6 MV photon beams, the FF exhibit a highly linear dose response ($R^2 \geq 99\%$). While both CF and FF were pulled from the same preform, the CF have been found to contain greater Ge concentration (2.58 ± 0.18 wt%) as compared to that of the FF (1.45 ± 0.15 wt%) due to the difference in Energy Dispersive X-ray Spectroscopy line scanned on these two different shaped fibres. The dose sensitivity of FF with the least dose variability in 3 x 3 cm^2 and 10 x 10 cm^2 fields is adequate for the current intended use in high-dose advanced radiotherapy. The notable signal fading of the fabricated fibres (25% for FF; 34% for CF) over the period of 31 days post-irradiation with a dose of 5 Gy would need to be carefully accounted for in small-field application. The Independent T-Test shows there to be no significant difference between the normalised TL responses measured for each fibre type (p values $>$ 0.05) in 3 x 3 cm^2 and 10 x 10 cm^2 fields. The output factors measured using FF (0.69 to 0.99) in the circular fields (6 to 15 mm) are much higher than those of CF, radiochromic EBT3 and ionization chamber CC01, with the exception of 4 mm field where output of FF is comparable to that of EBT3 (output of EBT3 is 1.15x the output of FF). This study provides a promising support for the viability of fabricated fibres, particularly FF as an optical-fibre based dosimeter for use in small-field dosimetry.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

CIRI-CIRI DOSIMETRIK GENTIAN OPTIK SILIKA GE-DOP FABRIKASI UNTUK DOSIMETRI SINARAN MEDAN KECIL DALAM RADIOTERAPI

Oleh

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Mei 2019

Pengerusi : Noramaliza binti Mohd Noor, PhD
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Kemajuan dalam rawatan radiasi telah menyebabkan peningkatan dalam penggunaan medan rawatan kecil berskala milimeter dan dos yang tinggi untuk merawat tumor yang kecil. Penentuan dos mungkin tidak tepat seperti yang telah dicapai untuk aplikasi radioterapi standard yang menggunakan medan besar disebabkan oleh kehadiran ketidakstabilan zarah, penghalangan sumber radiasi utama dan kesan isipadu purata dosimeter. Kajian ini berkaitan dengan potensi gentian optik silika 6 mol% Germanium-dop (Ge-dop) fabrikasi yang digunakan dalam dosimetri sinaran medan kecil. Tiga jenis gentian iaitu gentian silinder (CF) (483 μm) dan gentian rata (FF) (273 x 67 μm^2) yang diperbuat daripada 6 mol% Ge-dop prefom dan Ge-dop gentian komersial 50 μm-teras (COMM) telah digunakan. Profil suhu masa (TTP) untuk bacaan gentian dan kesan TTP terhadap parameter kinetik lengkung cahaya gentian dan juga ciri-ciri dosimetrik daripada gentian Ge-dop fabrikasi telah diselidik terlebih dahulu sebelum pengukuran terhadap faktor pengeluaran daripada pemecut linear khusus. TTP pemalar (pra pemanasan 80 °C dan kadar pemanasan 30 $°Cs^{-1}$) digunakan dalam pembacaan semua gentian kerana penangkapan lengkung cahaya termoluminesin (TL) yang hampir lengkap, kestabilan keadaan ini untuk ketiga-tiga jenis gentian serta perkadaran hampir integral puncak dan suhu puncak daripada puncak cahaya dekonvoluted. Dua fantom Perspex telah dibuat untuk kajian pergantungan sudut dan pengukuran faktor pengeluaran. FF menunjukkan prestasi yang unggul berbanding dengan CF dari segi pengulangan dos (2% hingga 6%), kebebasan sudut (± 3%) dan kebebasan kadar dos. Untuk dos sehingga 80 Gy yang disampaikan dengan menggunakan penyinaran 6 MV foton, FF menunjukkan tindak balas yang sangat linear ($R^2 \geq 99\%$). Walaupun CF dan FF diperbuat daripada prefom yang sama, CF didapati mengandungi kepekatan Ge yang lebih tinggi (2.58 ± 0.18 wt%) berbanding dengan FF (1.45 ± 0.15 wt%) kerana perbezaan dalam Spektroskopi Sinar-X Penyebaran Tenaga pengimbasan baris pada kedua-dua gentian dengan bentuk yang berlainan. Namun,

untuk kegunaan dalam aplikasi yang menggunakan dos yang tinggi, FF mempunyai sensitiviti dos yang mencukupi dan FF juga menunjukkan variasi dos yang paling kurang dalam medan radiasi 3 x 3 cm^2 dan 10 x 10 cm^2. Pengurangan isyarat dengan ketara daripada gentian fabrikasi selama tempoh 31 hari pasca penyinaran dengan menggunakan dos 5 Gy (25% untuk FF; 34% untuk CF) perlu diambil kira dalam aplikasi medan kecil. Ujian T bebas menunjukkan tidak terdapat perbezaan yang ketara antara tindak balas TL yang diukur untuk setiap gentian (nilai $p > 0.05$) dalam medan radiasi 3 x 3 cm^2 dan 10 x 10 cm^2. Faktor pengeluaran yang diperoleh daripada FF (0.69 hingga 0.99) dalam medan bulat (6 hingga 15 mm) jauh lebih tinggi berbanding dengan CF, EBT3 radiokromik dan ruang pengionan CC01, dengan pengecualian medan 4 mm di mana faktor pengeluaran FF adalah setanding dengan EBT3 (pengeluaran EBT3 adalah 1.15 kali pengeluaran FF). Kajian ini memberikan dorongan yang memberangsangkan untuk gentian fabrikasi, terutamanya FF diguna pakai sebagai dosimeter berasaskan gentian optik untuk dosimetri medan kecil.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
AVM	Arteriovenous Malformation
BSE	Backscattered Electrons
CF	Cylindrical Fibres
COF	Capillary Optical Fibres
COMM	Commercial Fibres
CoP	Code of Practice
CPE	Charged Particle Equilibrium
CV	Coefficient of Variation
CVD	Chemical Vapour Deposition
DEF	Dose Enhancement Factor
E_a	Activation Energy
EDX	Energy Dispersive X-ray Spectroscopy
FAD	Focus-to-Axis Distance
FF	Flat Fibres
FFF	Flattening Filter Free
FOM	Figures of Merit
FSD	Focus-to-Skin Distance
FWHM	Full Width at Half Maximum
IAEA	International Atomic Energy Agency
IMRT	Intensity Modulated Radiation Therapy
IPSM	Institute of Physical Sciences in Medicine
LINAC	Linear Accelerator
MC	Monte Carlo
MCVD	Modified Chemical Vapour Deposition
MDD	Minimum Detectable Dose
MMF	Multi-Mode Fibre
MU	Monitor Unit
MV	Megavoltage
OD	Optical Density
OF	Output Factors
PA	Pituitary Adenomas
PCF	Photonic Crystal Fibres
PI	Peak Integral
PMMA	Polymethyl Methacrylate
PMT	Photomultiplier Tube
PSD	Plastic Scintillation Detectors
PTV	Planning Target Volume
QE	Quasi-Equilibrium
ROI	Region of Interest
RPS	Relatively Pure Silica
SBRT	Stereotactic Body Radiotherapy
SEM	Scanning Electron Microscope
SFD	Stereotactic Field Diode
SMF	Single-Mode Fibre
SRS	Stereotactic Radiosurgery
SRT	Stereotactic Radiotherapy

SSDL	Secondary Standard Dosimetry Laboratory
SWP	Solid Water^{TM} Phantom
TGN	Trigeminal Neuralgia
TIFF	Tagged Image File Format
TL	Thermoluminescent / Thermoluminescence
TLD	Thermoluminescent Dosimeter
T_{max}	Maximum Temperature
TPS	Treatment Planning System
TTP	Time-Temperature Profile
VMAT	Volumetric Modulated Arc Therapy

CHAPTER 1

INTRODUCTION

1.1 Background

Conventional radiation therapy is defined as having a treatment field ranging from 4 x 4 cm^2 to 40 x 40 cm^2 while conventional dosimetry is referred to as the determination of absorbed dose to water using ionization chamber calibrated based on International Atomic Energy Agency (IAEA) TRS-398 or American Association of Physicists in Medicine (AAPM) TG-51 dosimetry protocols for the radiation beams used in radiotherapy. However, special or advanced radiation therapy techniques that make use of small fields ($\leq$ 3 x 3 cm^2) such as stereotactic radiosurgery (SRS), intensity modulated radiotherapy (IMRT) or volumetric modulated arc therapy (VMAT), Tomotherapy and Gamma Knife or CyberKnife do not comply with the aforementioned conventional reference dosimetry protocols.

For calibration using the standard dosimetry methodology, the commercial detector is well enclosed by a uniform radiation field where the source of radiation of the linear accelerator (LINAC) can be fully viewed by the detector. However, the beam output from the LINAC is expected to be lower due to the presence of lateral charged particle disequilibrium when the calibration or dose measurement is carried out using small fields where the detector is not well encompassed in a uniform radiation field (i.e. partially viewed source) (Alfonso et al., 2008; Das et al., 2008a). Charged particle disequilibrium is described as the charge carriers (electrons) that deliver the energy (dose) to the treatment field, leaving the field without being replaced by the charge carriers entering from the adjacent area.

Unlike the standard photon dosimetry, small field dosimetry reveals a number of additional problems arise which subsequently lead to the definition of small-field conditions. Broadly, two types of small-field conditions exist: beam- and detector-related (Seuntjens, 2015). The first case concerns the lateral charged particle disequilibrium and the occlusion of the primary photon source as seen from the point of measurement (detector's point of view), the latter giving rise to overlapping penumbra. In the second case, particular concerns are detector-related field perturbations relative to small field size as well as possible volume averaging effects that increase with increasing detector volume (Das et al., 2008a; Laub and Wong, 2003; Seuntjens, 2015).

Owing to the loss of charged particle equilibrium (CPE), undesirable deviations from the intended treatments are created, resulting in reduced doses in small fields. It is of paramount importance that a dedicated LINAC equipped with SRS system delivers a single large radiation dose of 80 Gy to treat a small target with 4 mm or 5 mm circular cones, as in the treatment of trigeminal neuralgia (Jang et al., 2011; Wang et al., 2010). SRS is an advanced non-invasive radiotherapy technique that employs photon beams which deliver high radiation dose to treat small lesions and functional disorders of the brain using collimated photon beams (Tyler et al., 2013). In comparison to conventional radiotherapy (treatment fields of $\geq 4 \times 4$ cm^2), the stereotactic radiation treatments require greater dosimetric accuracy and precision such as ensuring a tight margin on the planning target volume and reducing a sharp dose outside the marginated target. This is because the treatment target is often located close to critical organs and subjected to high dose treatment. The surrounding normal tissue may be at risk of being exposed to the radiation dose if the requirements mentioned earlier are not met.

Various point- or planar detectors have been investigated in small-field situations. Owing to their excellent spatial resolution and near tissue equivalence, radiochromic films are recommended for dose measurements in high dose gradient small photon fields (Huet et al., 2012; Tyler et al., 2013). However, for these a number of precautions are needed due to the uncertainty arising from film polarization (Butson et al., 2009), non-uniformity of the scanner response, variation of pixel values in the region of interest for optical density measurements, film handling techniques and finally a requirement for a somewhat tedious post-processing process (Huet et al., 2012). Although silicon diodes offer the advantages of real-time readout and good spatial resolution, they nevertheless exhibit angular response (Araki et al., 2003) and dose-rate dependence (Saini and Zhu, 2004). Diamond detectors, offer near tissue equivalence and small sensitive volume, providing accurate measurements of small field profiles, this being dependent upon the diamond detector type used (Laub and Crilly, 2014; Laub and Wong 2003). Thus said, corrections are required for dose-rate dependence, with pre-irradiation of the detector also needing to be carried out in order to stabilise diamond response (Betzel et al., 2012; Laub and Wong, 2003; Pappas et al., 2008).

Numerous investigations on thermoluminescence (TL) response of germanium (Ge) doped silica telecommunication fibres to ionizing radiations have been performed to understand the dosimetric characteristics of these commercial Ge-doped silica optical fibres. The basic dosimetric characteristics of commercial Ge-doped silica optical fibres with 9 μm-core diameter have been studied thoroughly by various research groups such as Hashim et al. (2009, 2010), Ramli et al. (2009), Issa et al. (2011, 2012, 2013) and Yaakob et al. (2011a, 2011b, 2011c). The advantages and potential applications of the doped silica optical fibres have also been well described by Bradley et al. (2012). In recent years, several research groups have embarked on the development of TL silica-based materials by producing optical fibres with enhanced sensitivity using the modified chemical vapour deposition (MCVD) method (Abdul Sani et al., 2014; Alawiah et al., 2015b; Begum et al., 2014; Bradley et al., 2014, 2015; Ibrahim et al., 2014; Mahdiraji et al., 2015a; Mohd Noor et al., 2015, 2016; Nawi et al., 2015).

Although many research groups have investigated the optical fibres in various applications such as radiotherapy with high energy photon and electron beams, brachytherapy, gamma radiation and ultraviolet dosimetry system, there are still a lack of studies on optical fibres in small fields, and the usability of optical fibres in measuring the output factors in small-field radiation therapy has yet to be studied. Besides, the readout parameters used to obtain the reading from the optical fibres have not been adequately studied by other researchers. Therefore, this study focuses on the feasibility of the in-house fabricated Ge-doped silica optical fibres in small fields (down to few mm) by first evaluating the optimum parameters used to readout the fabricated fibres and the dosimetric characteristics of the fabricated fibres prior to the study of the output factors in small fields.

1.2 Problem Statement

The findings from the studies on the commercial Ge-doped silica optical fibres show highly desirable dosimetric characteristics: increased sensitivity, minimal fading and highly linear dose-response correlation (Abdul Rahman et al., 2012; Mohd Noor et al., 2012; Ong et al., 2009; Yaakob et al., 2011a). However, the dopant concentration of the commercial Ge-doped silica telecommunication fibres is inhomogeneous along the length of an optical fibre, resulting in a non-uniformity of the sensitivity and larger range of the TL responses (Bradley et al., 2012).

The positive findings from the commercial Ge-doped telecommunication fibres served as the foundation in producing the non-commercially available Ge-doped silica optical fibres with favourable dosimetric characteristics that suit the needs in various applications (Bradley et al., 2012). The optical fibres can be tailored made by altering the TL sensitivity using the MCVD method that introduces dopants at chosen concentrations (Bradley et al., 2012). Therefore, the evaluation of the performance of fabricated fibres is essential to give new insights into developing a well-characterised silica optical fibre in the future (Bradley et al., 2014). Moreover, the establishment and assessment of the basic dosimetric characteristics of the fabricated fibres are pivotal prior to making an accurate measurement of absorbed dose and the dosimetric verification of simulated small therapeutic fields.

The Ge-doped silica optical fibres have demonstrated a great potential to be developed as a TL dosimeter that can be used in various applications such as radiotherapy, diagnostic radiology, ultraviolet dosimetry system and food irradiation industry. However, different time-temperature profile (TTP) parameters of the TL reader have been employed by many researchers in various TL studies. Although the same model of TL dosimeter (TLD) reader (Thermo Scientific™ Harshaw TLD™ 3500, USA) was used to study the TL response of the silica optical fibres, it was noticed that different TTP parameters were being used, as shown in Table 1.1. Based on the literature review, none of these studies has adequately addressed the effects of the reader's TTP parameters, specifically with regard to preheat temperature and heating rate on the kinetic parameters of the TL glow curve of the Ge-doped silica optical fibres.

Table 1.1: TTP Parameters of a Thermo Scientific™ Harshaw TLD™ 3500 Reader Utilised by Several Research Groups.

Authors	TTP Parameters		Types of Silica Optical Fibres				
	Preheat (°C)	HR (°Cs^{-1})	COMM	Fabricated Fibres			
				Pure	FF	CF	PCF
Alawiah et al. (2015b)	50	25		✓			
Alawiah et al. (2017)	60	3			✓		
Begum et al. (2014)	80	10				✓	
Mahdiraji et al. (2015a)	50	25				✓	✓
Mahdiraji et al. (2015b)	50	25	✓				
Mahdiraji et al. (2015c)	50	25			✓	✓	
Mohd Noor et al. (2015)	180	35	✓		✓		
Nawi et al. (2015)	40	10			✓		
Ong et al. (2009)	80	10	✓				
Zahaimi et al. (2014)	160	25	✓			✓	□

Heating rate and Ge-doped commercial-, flat-, cylindrical-, and photonic crystal fibres are denoted by HR and COMM, FF, CF and PCF.

Furthermore, a greater percent of disagreement among different commercial detectors was reported when the output factors were measured in the small fields. Jang et al. (2011) found a discrepancy of ≥ 10% for the output factors when measured with Gafchromic EBT film, p-type silicon diode detector and 0.015 cc ionization chamber in radiation fields of < 20 mm. The percentage disagreement was greater between the measured output factors and the standard output factors when the detectors were used to measure the output factors in the smallest field size of 5 mm, i.e. 11% difference for 0.015 cc and around 3.5% difference for diode and Gafchromic EBT film (Jang et al., 2011). In addition, Masanga et al. (2016) found a deviation of 13% in the measured output factors in 6 MV and 10 MV flattening filter free photon beams among the detectors (IBA CC01, PTW 60019 microDiamond, PTW 31018 microLion, Sun Nuclear Edge detector and Extradin A16 ion chamber) in the smallest fields of 6 mm x 6 mm, and no specific detectors were suitable to be utilised in the measuring output factors in field size of less than 1.6 x 1.6 cm^2. Although commercial Ge-doped multimode optical fibres (CorActive, Canada) has been used to study the small-field radiotherapy in the preliminary study conducted by Alalawi et al. (2014b), dosimetric parameters only included the percentage depth dose and the beam profiles measurements. To the best of my knowledge, none of the previous studies was conducted to measure the output factors using the Ge-doped silica optical fibres. Therefore, it is worth investigating the suitability of the Ge-doped silica optical fibres in measuring the relative dosimetry of the output factors.

1.3 Significance of the study

Although numerous investigations have been carried out on the commercial and tailor-made Ge-doped silica optical fibres, the findings from this study will add new knowledge regarding the parameters used to readout the optical fibres, dosimetric characterisation of the in-house tailor-made Ge-doped silica optical fibres and the applicability of the fabricated Ge-doped silica fibres in output factor measurements in small fields.

This study presents a possible relationship between the reader's TTP parameters and the kinetic parameters of TL glow curves for the commercial and tailor-made Ge-doped silica optical fibres. Besides, an analysis of the effect of heating rate on the shape of TL glow curves was carried out to serve as a guide in choosing the specific TTP parameters to readout all the Ge-doped fibres.

The high spatial resolution of the Ge-doped silica optical fibres (3 mm in length) was used in this study to cater to the small field dosimetry. The data obtained for the dosimetric characteristics of the in-house fabricated Ge-doped optical fibres are vital for future studies to optimise the performance of the fabricated fibres in radiation detection, specifically in advanced radiation therapy such as stereotactic radiosurgery that uses high precision radiation and single high dose to treat tumour in small fields (as small as 4 mm to 5 mm).

To the extent of my knowledge, none of the studies employed the use of Ge-doped silica optical fibres to measure the output factors in radiotherapy that uses small fields ($\leq$ 3 x 3 cm^2). Data obtained from the output factor measurements would provide a better understanding of the feasibility of dose measurement using Ge-doped optical fibres, particularly the small-field output factors in comparison to other types of detectors.

1.4 Research Questions

1. What are the effects of heating rate and preheat temperature on the TL intensity of the fabricated Ge-doped silica optical fibres?
2. What are the effects of heating rate on the shape of the TL glow curve?
3. What are the dosimetric characteristics of the 6 mol% Ge-doped fabricated fibres?
4. Do 6 mol% Ge-doped fabricated fibres exhibit better dosimetric characteristics compared to the commercial Ge-doped 50 μm-core silica optical fibre?
5. What are the elemental compositions of the 6 mol% Ge-doped fabricated fibres?
6. How well do 6 mol% Ge-doped fabricated fibres perform in output factor measurements in small fields as compared to the commercial Ge-doped 50 μm-core fibre, radiochromic EBT3 film and ionization chamber CC01?

1.5 Research Objectives

1.5.1 General Objective

To study the potential of in-house fabricated Germanium-doped silica optical fibres to be utilised in small field dosimetry.

1.5.2 Specific Objectives

1. To determine the elemental composition of the Ge-doped silica optical fibres using scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX).

2. To determine the TTP of the TL reader for the readout of Ge-doped silica optical fibres, and the possible relationship between TTP and kinetic parameters of TL glow curves of Ge-doped silica optical fibres.

3. To determine dosimetric characteristics (linearity, dose sensitivity, repeatability, fading, dose-rate effect, angular dependence and minimum detectable dose) of the fabricated 6 mol% Ge-doped silica optical fibres and compare with those of commercial Ge-doped 50 μm-core optical fibres.

4. To measure the output factors using the fabricated 6 mol% Ge-doped silica optical fibres in six circular fields and compare with those of commercial Ge-doped 50 μm-core optical fibres, small ionization chamber CC01, and radiochromic EBT3 film.

1.6 Limitation of the Study

This study only focuses on the 6 MV photon beam because this energy generated by Novalis Tx^{TM} dedicated LINAC, has been used to perform irradiations for stereotactic treatment to treat tumour. The 6 MV of Novalis Tx^{TM} dedicated LINAC for radiosurgery, is termed as 6 MV SRS mode which allows the use of high dose rate (1000 cGy/min) for cancer treatment. Moreover, only limited commercial detectors are available at the National Cancer Institute, Putrajaya, Malaysia (established in 2014) that could be used to compare with the performance of the fabricated Ge-doped silica optical fibres in the output factor study.

1.7 Research Framework

Figure 1.1 illustrates the framework of this study. First, the preform was produced with Ge dopant concentration of 6 mol% and thereafter being pulled into two types of silica optical fibres: cylindrical fibre (483 µm ± 7 µm) and flat fibre (273 µm x 67 µm) ± 5 µm. This study focuses on the parameters used for fibre readouts, dosimetric characteristics of the tailor-made Ge-doped silica optical fibres and the determination of the output factors in small fields.

Knowledge regarding the readout parameters is important in obtaining the optimum TL responses from the optical fibres especially when the fabricated fibres are subjected to higher doses. The dosimetric characteristics of the fabricated Ge-doped optical fibres are essential as they describe the performance of the fabricated fibres being used in this study, unlike those commercial telecommunication Ge-doped fibres that are employed by various research groups for different applications.

In order to investigate the feasibility of the fabricated Ge-doped silica optical fibres in the output factor measurements, other commercial detectors such as radiochromic EBT3 films and IBA CC01 air-filled ionization chamber as well as the commercial Ge-doped 50 µm-core fibres were used.

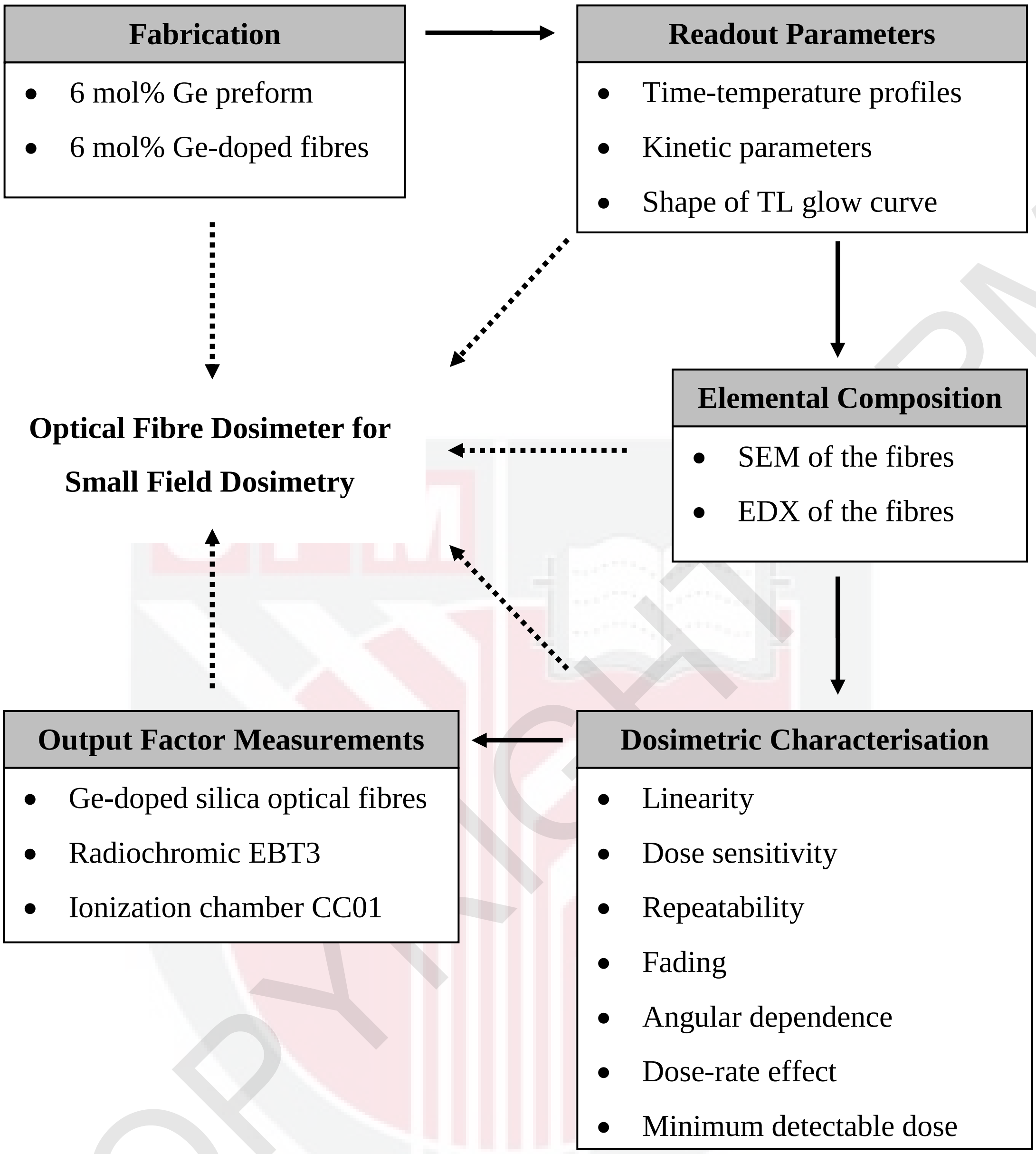

Figure 1.1: Research Framework. Bold Arrows Indicate the Flow of the Research Study; Dotted Arrows Indicate the Focuses of the Present Study.

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BIODATA OF STUDENT

Lam Siok Ee was born on 14th April 1986 in Segamat, Johor. She received her primary and secondary education in SJKC Sino English and SMK Puteri as well as the pre-university education in St. Paul's Institution, Seremban, Negeri Sembilan. She was awarded Bachelor of Health Science (Medical Radiation) and Master of Science (Medical Physics) from Universiti Sains Malaysia in 2010 and 2011, respectively. She continued to pursue her doctoral studies in Applied Physics at Universiti Putra Malaysia (UPM) in 2013 with the research project focusing on the feasibility of the Ge-doped silica optical fibres in the small-field dosimetry in radiotherapy. She was awarded a scholarship by the Ministry of Higher Education Malaysia to further her PhD studies. During the course of her studies, she contributed in research proposal writing and thereafter managed to secure a grant amounting to around RM 12000 from Universiti Putra Malaysia in 2014 and a science fund of around RM 180000 from Ministry of Science, Technology and Innovation Malaysia (MOSTI) in 2015 with the help from her supervisor and supervisory committee. She presented part of her research findings orally in 13th International Symposium on Radiation Physics held in Beijing in 2015 with subsequent publication of the findings in Radiation Physics and Chemistry journal. She also published her remaining research findings in Results in Physics journal. Additionally, she and her supervisor successfully obtained a patent certificate for the invention of a cylindrical Perspex dosimetry phantom. Besides attending the local conferences, she also participated in various seminars organised by the School of Graduate Studies, UPM such as the seminars entitled Professional Skills and Academic Career Preparatory, just to name a few.

LIST OF PUBLICATIONS

Published

Lam, S.E., Alawiah, A., Bradley, D.A., & Mohd Noor, N. (2017). Effects of time-temperature profiles on glow curves of germanium-doped optical fibre. *Radiation Physics and Chemistry*, *137*, 56-61. (2017 Impact Factor: 1.435)

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