DEVELOPMENT OF FABRICATED GERMANIUM-DOPED OPTICAL FIBRES FOR BREAST CANCER ELECTRON BEAM DOSIMETRY

By

ZABARIAH BINTI ZAKARIA

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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Chairman : Associate Professor Noramaliza binti Mohd Noor, PhD
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In radiotherapy, electron beams are applied for superficial tumour treatment of less than 5 cm deep. Comparison between dose distribution in the patient and the distribution calculated by the treatment planning system (TPS) is essential to develop a novel radiation therapy. The response from the detector can be correlated to the dose received by the patients using the relationship between the doses at different places. An accurate absorbed dose measurement is easily performed with a well-functional detector. A new dosimeter, namely, Fabricated Germanium Doped Optical Fibres (FGDOFs) is developed by MCVD technique for electron beam dosimetry. Three objectives are addressed in this work: basic dosimetric characteristics, advanced dosimetric characteristics, and the clinical application of FGDOFs in breast cancer electron beam dosimetry. Clinically, investigations on breast dosimetry are conducted using the developed FGDOFs. Two types of FGDOFs, cylindrical fibre (CF) and flat fibre (FF) are doped with 2.3 and 6 mol% germanium. Electron beam energies from 6 MeV to 12 MeV, doses from 1 Gy to 5 Gy, dose rates from 100 to 600 cGy/min, focus to surface distance of 100 cm, and various field sizes are employed to analyse the FGDOFs dosimetric capabilities.

Comparisons are made with commercial fibres, Lithium Fluoride (LiF) chips, GafchromicTM EBT3 films (EBT3 films), and ionisation chamber (IC). In terms of reproducibility, both CF and FF had a coefficient of variation of less than 5%. FGDOFs demonstrated a linear thermoluminescence (TL) response across the examined doses and energies. In terms of sensitivity, FF had a higher sensitivity by a factor of two compared to CF. The minimum detectable dose calculated has shown that FGDOFs is good at low-dose detection. Insignificant differences ($p > 0.05$) are found for FGDOFs with a percentage difference within ± 5% in terms of field size and dose-rate dependence. Conversely, FGDOFs showed energy

dependency with a $p \leq 0.05$ (95% confidence level). 23FF showed the lowest signal fading loss between 4.1 % and 5.9 % for a storage period of 13 days.

Percentage depth dose of FGDOFs exposed to 9 MeV electron in a *solid water*^{TM} phantom is within 5% and agreeable to IC with no notable variations found in the build-up and fall-off regions. Higher signals produced by FF can be explained by their kinetic parameters such as maximum temperature (T_{max}), activation energy (E_a), and peak integral (PI) based on the glow curve deconvolution. For FGDOFs, T_{max} exhibits a consistent pattern from peak 1 to peak 5. FGDOFs also presented no discrepancies over the electron energies regarding the output factor. The combined uncertainties for 23CF, 23FF, 6CF, 6FF and LiF chips and EBT3 films were less than 3.5% with a coverage factor of k=1.

For clinical applications in electron beam breast dosimetry, mean absorbed dose of FGDOFs showed an insignificant difference at $p > 0.05$ for skin dose, small and large tumour volume measurement when compared to the calculated dose obtained from the TPS. In conclusion, the developed FGDOFs, particularly FF, is found to be suitable for electron beam dosimetry.

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

PEMBANGUNAN GENTIAN OPTIK DOP GERMANIUM YANG DIFABRIKASI UNTUK DOSIMETRI KANSER PAYUDARA SINAR ELEKTRON

Oleh

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Dalam radioterapi, sinar elektron telah digunakan untuk merawat tumor di permukaan pada kedalaman yang kurang daripada 5 cm. Perbandingan antara taburan dos dalam pesakit dan kiraan melalui sistem rawatan terancang (TPS) adalah penting dalam membangunkan terapi sinaran baru. Gerak balas daripada pengesan boleh menghubungkan dos yang diterima oleh pesakit dengan dos pada tempat yang berlainan. Pengukuran dos terserap yang tepat dapat ditentukan dengan mudah melalui pengesan yang dapat berfungsi dengan baik. Sebuah dosimeter yang baharu, iaitu gentian optik dop germanium yang difabrikasi (FGDOFs) telah dibangunkan melalui teknik MCVD untuk dosimetri sinar elektron. Tiga objektif telah dinyatakan dalam kajian ini: ciri dosimetrik asas, ciri dosimetrik lanjutan, dan aplikasi klinikal FGDOFs dalam dosimetri kanser payudara sinar elektron. Secara klinikal, pemeriksaan terhadap dosimetri payudara telah dijalankan dengan menggunakan FGDOFs yang telah dibangunkan. Dua jenis FGDOFs yang digunakan iaitu gentian silinder (CF) dan gentian leper (FF) yang telah didop dengan 2.3 mol% dan 6 mol% germanium. Sinar elektron yang mempunyai tenaga dari 6 MeV sehingga 12 MeV, dos dari 1 Gy sehingga 5 Gy, kadar dos dari 100 sehingga 600 cGy/min, jarak 100 cm dari fokus ke permukaan, dan pelbagai saiz medan telah digunakan untuk menganalisis kebolehan dosimetrik FGDOFs.

Perbandingan dibuat dengan gentian komersial, cip Litium Florida (LiF), filem GafchromicTM EBT3 (filem EBT3) dan kebuk pengionan (IC). Dari segi kebolehasilan, kedua-dua CF dan FF menunjukkan pekali variasi yang kurang daripada 5%. FGDOFs menunjukkan tindak balas thermopendarcahaya (TL) yang linear merentasi julat dos dan tenaga yang diuji. Dari segi sensitiviti, FF adalah lebih sensitif berbanding CF dengan faktor kuasa dua. Dos minimum yang boleh dikesan menunjukkan bahawa FGDOFs mampu mengesan sinaran dos-rendah. Perbezaan yang tidak nyata ($p > 0.05$) ditunjukkan oleh FGDOFs

dengan peratusan perbezaan ± 5% dari segi saiz medan dan kebergantungan kadar dos. Sebaliknya, FGDOFs menunjukkan kebergantungan tenaga dengan $p \leq 0.05$ (tahap keyakinan 95%). 23FF menunjukkan kemerosotan isyarat paling rendah antara 4.1 % dan 5.9 % bagi tempoh simpanan selama 13 hari.

Peratus kedalaman dos oleh FGDOFs apabila didedahkan kepada 9 MeV sinar elektron dalam fantom *solid water*^{TM} berada dalam lingkungan 5% dan boleh diterima seperti IC tanpa kelainan variasi yang ketara pada kawasan terbina dan terjatuh. Isyarat tinggi yang dihasilkan oleh FF boleh ditentukan melalui sifat parameter kinetik seperti suhu maksimum (T_{max}), tenaga pengaktifan (E_a), dan kamiran puncak (PI) berdasarkan lengkungan bara dekonvoluted. Bagi FGDOFs, T_{max} mempamerkan corak yang konsisten dari puncak 1 sehingga puncak 5. FGDOFs juga menunjukkan tiada ketidaksamaan bagi tenaga-tenaga elektron melalui faktor luaran. Gabungan ketidakpastian bagi 23CF, 23FF, 6CF, 6FF, cip LiF dan filem EBT3 adalah kurang daripada 3.5% dengan faktor liputan k=1.

Dalam aplikasi-aplikasi klinikal untuk dosimetri payudara sinar elektron, purata dos terserap bagi FGDOFs menunjukkan perbezaan tidak nyata pada $p > 0.05$ untuk dos pada kulit, ukuran isipadu tumor kecil dan besar apabila dibandingkan dengan dos kiraan yang diterima daripada TPS. Secara kesimpulan, FGDOFs yang dibangunkan, terutamanya FF, adalah bersesuaian untuk penggunaan dosimetri sinar elektron.

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Ea	Activation energy
ANOVA	Analysis of variance
AAPM	American Association of Physicist in Medicine
BIPM	International Bureau of Weights and Measures
$Al_2O_3:C$	Carbon-doped aluminium oxide
cGy	CentiGray
cm	Centimetre
R^2	Coefficient of determination
CaF_2	Calcium Fluoride
$CaF_2:Mn$	Calcium Fluoride doped with Manganese
$CaSO_4:Dy$	Calcium Sulphate doped with Dysprosium
CB	Conduction band
CV	Coefficient of Variation
CGCD	Computerized glow curve deconvolution
Cu	Copper
CF	Cylindrical fibre
CoP	Code of Practice
CRN	Continuous random network
EDX	Energy-Dispersive X-ray
E_f	Equilibrium Fermi level
E_g	Energy difference between these bands
Z_{eff}	Effective Atomic number
FOM	Figure of merit
FF	Flat fibre
FGDOFs	Fabricated Germanium Doped Optical Fibres

FSD	Focus to surface distance
FRGS	Fundamental Research Grant Scheme
Ge	Germanium
$GeCl_4$	Germanium tetrachloride
g	Gram
Gy	Gray
HTP	High temperature peak
OH	Hydroxyl
IAEA	International Atomic Energy Agency
IARC	International Agency for Research on Cancer
ICRU	International Commission on Radiation Units and Measurements
IGRT	Image guided radiation therapy
IKN	Institut Kanser Negara
IMRT	Intensity Modulated Radiation Therapy
IPS	Insentif Putra Siswazah
IPSM	Institute of Physical Sciences in Medicine
IPEM	Institute of Physics and Engineering in Medicine
IORT	Intraoperative Radiation Therapy
kGy	KiloGray
LET	Linear energy transfer
LINAC	Linear accelerator
LiF	Lithium Fluoride
$Li_2B_4O_7$	Lithium Borate
LTP	Low temperature peak
MDD	Minimum Detectable Dose
Mg	Magnesium

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
Z_{max}	Maximum dose
T_{max}	Maximum peak temperature
MV	Megavolt
µm	Micrometer
mg	Miligram
mm	Milimetre
MoH	Ministry of Health
mol%	Percentage molar
min	Minute
MCVD	Modified chemical vapour deposition
MU	Monitor units
MMU	Multimedia University
nC	NanoCoulomb
NCI	National Cancer Institute
NHS	National Health Service
NIST	National Institute of Standards and Technology
NPL	National Physics Laboratory
NSPCCP	National Strategic Plan for Cancer Control Program
ODC	Oxygen-deficient centres
OF	Output factor
OSL	Optically-stimulated luminescence
OSLD	Optically-stimulated luminescence dosimeter
O_2	Oxygen
P	Phosphorus
PDD	Percentage depth dose
PI	Peak integral

PMT	Photomultiplier tube
PMMA	Polymethylmethacrylate
POL	Peroxy linkages
QA	Quality assurances
R	Recombination centre
R_{50}	Half-value depth in water
RT	RT
SEM	Scanning electron microscope
SEM-EDX	Scanning Electron Microscope with Energy-Dispersive X-ray
SSDL	Secondary Standard Dosimetry Laboratory
Si	Silica
SiO_2	Silica dioxide
$SiCl_4$	Silica tetrachloride
SSD	Source to surface distance
SD	Standard deviation
Th	Thulium
Ti	Titanium
TL	Thermoluminescence
TLD	Thermoluminescence dosimeter
TPS	Treatment planning system
WHO	World Health Organization
VB	Valence band
Z	Atomic number

CHAPTER 1

INTRODUCTION

1.1 Research Background

In recent years, several new materials have emerged as the basis for new dosimeters. Over the years, several studies have investigated optical fibres as a new TLD in clinical dosimetry. The structure of optical fibres is based on silicon dioxide (SiO_2) and offers the advantage over LiF chips of being impermeable to water, which increases their potential application in RT. The study of optical fibre dosimeters is first investigated by Abdulla et al., (2001) for photon irradiation. Yet, the recent studies proposed the application of undoped and doped optical fibres as dosimeters in dosimetry (Alyahyawi et al., 2017). The common problem with undoped optical fibres is the intrinsic defects of SiO_2, which causes limited thermoluminescence (Entezam et al., 2016).

Many studies consider fabricated and commercial Germanium doped (Ge-doped) optical fibres dosimeters to demonstrate positive values as dosimeters (Begum et al., 2015; Benabdesselam et al., 2013b; Bradley et al., 2012; Fadzil et al., 2014; Hassan et al., 2017; Noor et al., 2012b). The Ge-doped optical fibres exhibit linear responses up to 10 Gy when exposed to X-rays (Begum et al., 2015). To demonstrate high potential as dosimeters, the properties of TLD in dosimetry applications include glow curve, dose-response, sensitivity with highly linear dose-responses and excellent reproducibility over the entire dose range (Nawi et al., 2015).

Over the past five years, the properties of fabricated Ge-doped optical fibres (FGDOFs) for photon, proton and gamma beam dosimetry have been extensively investigated by several researchers. In particular, the characteristics of FGDOFs for photon beams have been used in numerous applications, such as a dose audit for postal RT (Fadzil et al., 2014), measurement of patient dose in X-ray diagnostic procedures (Ramli et al., 2015) and dosimetry in small fields (Lam et al., 2019). Similarly, the characteristics of FGDOFs are also being investigated in the measurement of proton beams (Hassan et al., 2017) as well as gamma irradiation for food irradiation dosimetry (Noor et al., 2015) and the thermoluminescence (TL) response of Ge-doped flat fibres (Nawi et al., 2015). The current interest concerns the incredible advances that have been made in RT technology in recent years and the associated advances required in dosimetric capabilities to support and extend the application limits of dosimeters.

According to the World Health Organization (WHO), there will be 48,638 new cases of cancer statistically registered in Malaysia in 2020. (https://gco.iarc.fr/today/data/factsheets/, 16 December 2022). Breast cancer is the biggest contributor to this statistic with 8418 new cases. As the numbers could increase every year, the government and society need to take actions.

However, effective cancer prevention strategies, early detection interventions and cancer treatments can help reduce these numbers. In addition, the need for new technology is becoming more urgent.

The primary application of electron beam in dosimetry includes skin cancer (Andreozzi et al., 2016; Diamantopoulos et al., 2014; Ding, 2021), chest wall irradiation for breast cancer (Kunheri et al., 2021; Wang et al., 2017), administration of boost treatments (Kindts et al., 2019; Salem et al., 2015) and intraoperative radiation therapy (IORT) (Liuzzi et al., 2015; López-Tarjuelo et al., 2014; Martínez-García et al., 2015; Sedlmayer et al., 2017). Most clinical applications can be successfully conducted using X-ray. However, the electron beam offers the distinct advantage of a lower doses to the deeper tissues and a higher surface doses.

In the application of electron beam dosimetry, the radiation dosimeter is used to measure the dose into the patient either directly or indirectly. There are two types of radiation dosimeters: passive and active. Examples of dosimeters used in dosimetry are diamond (Bassanese et al., 2023), films (Molina-romero et al., 2018), plastic scintillators (Katsunori et al., 2020) and gel (Mariotti et al., 2022). According to the Standard Code of Practice (CoP) for clinical measurement from International Atomic Energy Agency Technical Report Series 457 (IAEA TRS-457), the most commonly used luminescent dosimeters are passive type phosphor-based thermoluminescent dosimeters (TLD) (IAEA, 2011). Examples of TLD are lithium fluoride (LiF) doped with impurities such as magnesium and titanium (LiF:Mg,Ti), and LiF doped with magnesium, copper and phosphorus (LiF:Mg,Cu,P), as these materials are equivalent in human tissue. Other TLDs such as calcium sulphate doped with dysprosium ($CaSO_4$:Dy), aluminium oxide doped with carbon (Al_2O_3:C) and also calcium fluoride doped with manganese (CaF_2:Mn) are used because of their high sensitivity. However, these TLD materials have some drawbacks, including gyroscopic effects and relatively poor spatial resolution of up to a few millimetres (McKeever and Moscovitch, 2003).

High-energy electron beams are first introduced for radiotherapy (RT) in the 1930s using a Van de Graaff generator (Hong, 2014). In the 1970s, the high-energy linear accelerator (LINAC), which has a multi-energy electron capacity, is increasingly used in electron beam therapy. Modern high-energy LINAC, which typically delivers electron beam energies in the range of 4 MeV to 22 MeV, has been widely used in RT treatment. The selection of megavoltage electrons for treatment compared to other types of radiation (photons, protons, and neutrons) is due to their advantageous properties of having a finite range and more scattering at the surface (Sonja et al., 2016). Therefore, electron beam offers a unique option for the treatment of superficial tumours with less than 5 cm deep (Jong et al., 2018). The electron beam is often used in conjunction with an X-ray beam, either as a boost or as a mixed treatment to achieve a specific isodose distribution (Khan, 2016). Electron beam therapy is easier to shield than photon therapy because the dose is superficial and the dose to adjacent organs at risk is virtually minimised (Kry et al., 2017).

1.2 Problem Statement

The ionisation chamber (IC) is the most reliable dosimeter for the calibration of electron beams in RT. However, positioning the ionisation chamber in the irradiation field of the electron beams can be a major challenge, especially when measuring small fields (Amin et al., 2011). As far as RT applications are concerned, the ionisation chamber is relatively large and does not meet the requirements for detailed measurement of dose distribution in tissue. As mentioned in the IAEA, the properties of the ionisation chamber that affect the correction factor of the dosimeters are pressure, temperature, electrometer calibration, polarity effect, and ion recombination, which should be taken into account in the calibration to calculate the absorbed dose. For some accelerators that have high electron energies, the intrinsic homogeneity may be poor at larger fields. This can be improved by using a smaller field size where the resulting electrons are scattered by the collimator or applicator, as reported by the IAEA-398 (IAEA, 2000).

Various papers in the literature have shown that dosimeters with metal oxide semiconductor field effect transistor (MOSFET) exposed to therapeutic electron beams are commonly used in RT (Agostinelli et al., 2012; Manigandan et al., 2009; Petoukhova et al., 2017; Soriani et al., 2007). However, the difficult handling of the MOSFET dosimeter by the surgical team could be a limitation of this detector, as it needs to be encased in sterile components and attached to the bed, avoiding twisting of the wires (López-Tarjuelo et al., 2014).

Previous studies have generally investigated the good characteristics of TLD in electron beam dosimetry (Almeida et al., 2018). TLD are often used to determine patient dose in radiation diagnostics and external beam RT (Liuzzi et al., 2015). Instead, the drawbacks of LiF of TLD characteristics are also be highlighted in studies. LiF has a high residual signal, loss of sensitivity at high temperatures and very limited use in RT centres as it has several notable drawbacks such as being hygroscopic, having relatively poor spatial resolution and being expensive (Fernández et al., 2016). Bravim et al. (2014) also showed that LiF has a problem where dosimeter responses depend on the average electron energy impinging on the surface of the phantom and the dosimeter. Massillon et al. (2006) observed that LiF behaves supra-linearly at a dose greater than 10 Gy for gamma irradiation.

As mentioned earlier, optical fibres have been investigated as potential new TLD due to their advantages over LiF TLD. For example, a study by Noor et al. (2014) showed that commercially available Ge-doped optical fibres offer good reproducibility while being independent of dose rate, beam angle and temperature. However, the non-uniform Ge distribution over the entire length has limited the use of optical fibres in clinical applications. Therefore, these dosimeters are ideally suited for use in telecommunications. Indeed, studies with FGDOFs have shown that their radiation sensitivity is superior to other alternative dopants such as erbium, ytterbium, aluminium, samarium and neodymium (Entezam et al., 2016). The outcomes of this study highlight the promising dosimetric properties of FGDOFs, which exhibit low residual signal, modest cost, and demonstrate reproducibility without loss of dose-response and linearity within the energy range of electron beam therapy. The approach is entirely novel. To the best of the author's knowledge, no other published reports show the use of FGDOFs for electron beam dosimetry.

1.3 The Main Objectives of the Study

1.3.1 General Objective

Establishment of versatile, novel dosimetric characteristics of FGDOFs for use in breast dosimetry with electron beam irradiation.

1.3.2 Specific Objectives of the Study

This study is designed to achieve the following specific objectives:-

1. To determine the basic dosimetric characteristics of FGDOFs irradiated with an electron beam in terms of reproducibility, dose linearity, minimum detectable dose (MDD), energy dependence at a depth of dose maximum (Z_{max}), field size dependence, dose rate dependence and fading effect.
2. To determine the advanced dosimetric characteristics of FGDOFs consisting of the percentage depth dose (PDD) curve between FGDOFs and conventional method using ionisation chamber (IC) or Gafchromic™ EBT3 film (EBT3 film), glow curve analysis of FGDOFs, and output factor (OF).
3. To establish the mean absorbed dose of FGDOFs to electron beams in breast dosimetry compared to treatment planning system (TPS) calculations, Gafchromic™ EBT3 films and LiF chips.

1.4 Significance of the Study

The main findings of this study will reiterate the benefits of health technology offering FGDOFs as a potential alternative to TLD in RT. The dosimetric characterisation of FGDOFs for electron beams in breast dosimetry may provide a new insight for clinical application. A complementary analysis of the different Germanium concentrations will lead to the best choice of FGDOFs for electron beam dosimetry by investigating the basic and advanced dosimetric characteristics. In addition to the potential for use in electron beam dosimetry, the investigations of the dosimetric characteristics of the FGDOFs will expand its application in breast dosimetry.

1.5 Limitation of the Study

This clinical application focuses only on the 10 MeV electron beam generated by the Elekta Synergy linear accelerator, as this energy is used to treat breast cancer at the Institut Kanser Negara, Putrajaya.

1.6 Research Phases

Figure 1.1 shows the following three phases of this study. In Phase 1, the fibres are first fabricated with a Germanium dopant of 2.3 mol% and 6 mol% in different shapes (cylindrical and flat). The process involves preforming and drawing the fibres. The FGDOFs used in this study are referred to as flat fibre (hereafter referred to as FF) and cylindrical fibre (hereafter referred to as CF). The FF used is doped with 2.3 mol% and 6.0 mol% Germanium with outer dimensions of 603 µm × 379 µm and 627 µm × 171 µm, respectively. On the other hand, the CF used is doped with 2.3 mol% and 6.0 mol% Germanium with outer diameters of 475 µm and 613 µm, respectively.

Phase 2 focuses on basic and advanced dosimetric characterisation tests. Basic dosimetric characteristics include reproducibility, dose linearity, MDD, energy dependence, field size dependence, dose-rate dependence and fading signal effect. Comparisons are made with commercial fibres. At the same time, advanced characterisation tests of the FGDOFs with respect to the PDD, glow curve and OF are performed.

Finally, in Phase 3, mean absorbed dose of FGDOFs is compared with calculations of the treatment planning system (TPS), EBT3 films and LiF chips in electron beam breast dosimetry. The uncertainty analysis of the absorbed dose measurement is also performed in the third phase.

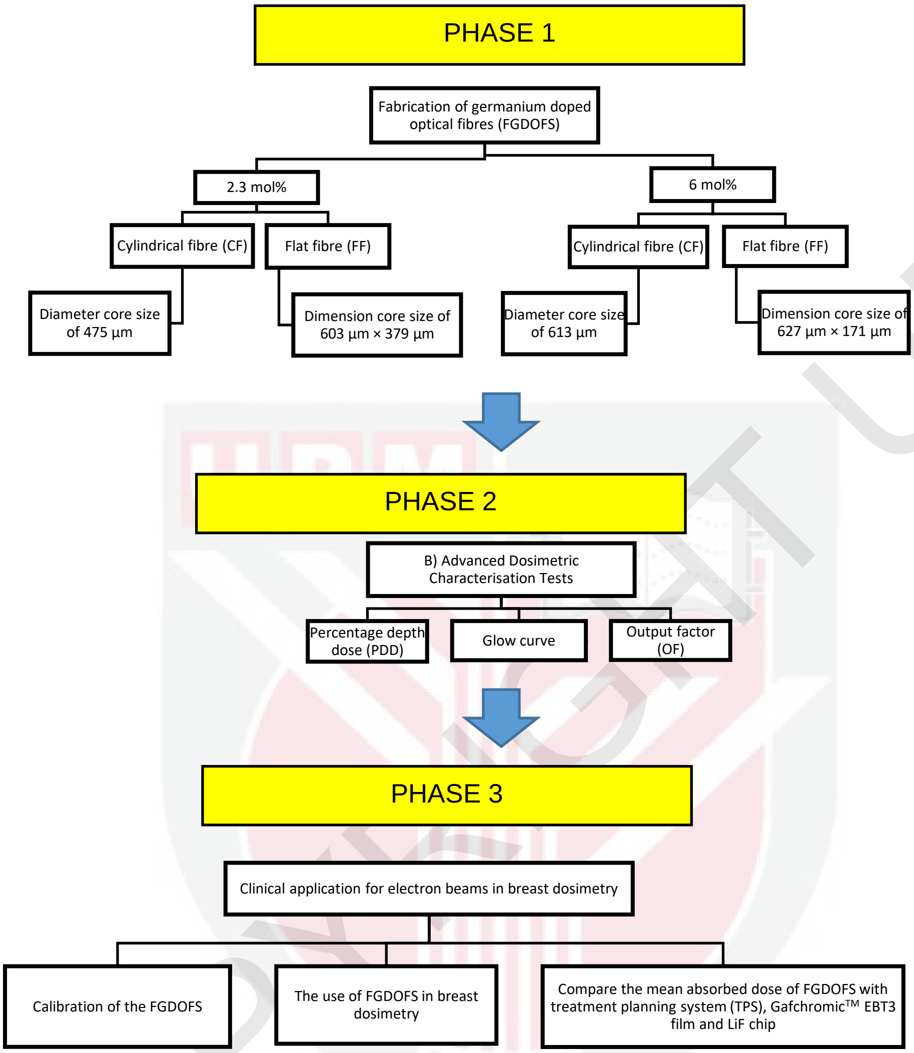

Figure 1.1 : Phases of research

1.7 Structure of Thesis

Chapter 1 describes briefly an introduction of the subject matter, outlining the problem statement, research objectives of the present works, significance and limitation of the study and details of the thesis structure.

Followed by Chapter 2 is a review of the works of literature on the topic of interest, including the theory and mechanism of the thermoluminescence phenomena and structure of silica optical fibre with details of its defect and impurities. The review continues to a specific part in the development of Germanium Doped optical fibres for Radiation Dosimetry Systems for commercial as well as FGDOFs while going into more detail about the ideal dosimetric characteristics of FGDOFs in aspects of accuracy, precision, reproducibility, dose linearity, dose-rate and energy dependence along with fading effect, directional dependence, spatial resolution and physical size. Lastly, the review goes into the electron beam therapy.

Chapter 3 elaborates on the details of the sample preparation method before moving on to Scanning Electron Microscope with Energy-Dispersive X-ray (SEM-EDX) analysis. The following methodologies involve basic and advanced dosimetric characterisation tests for FGDOFs, absorbed dose calibration and calculation of FGDOFs, EBT3 films and LiF chips using customised calibration phantom. The detailed methodology on clinical application of FGDOFs in Electron Beam Dosimetry for breast dosimetry is presented as the next step by using Female Rando® Woman (RAN 100) involving computed tomography (CT) scanning simulation, treatment planning, preparation and irradiation of FGDOFs, LiF chips and EBT3 films. The comparisons of mean absorbed dose between FGDOFs with TPS calculations, LiF chips and EBT3 film measurements are made in this chapter.

All results and discussions of each experimental works in Chapter 3 have been described in Chapter 4. The chapter elaborated on the findings of screening and grouping of FGDOFs, SEM-EDX analysis with effective atomic number, basic and advanced dosimetric characterisation test for FGDOFs, absorbed dose calibration and measurement in FGDOFs, EBT3 films and LiF chips as well as clinical application of FGDOFs in breast dosimetry.

Chapter 5 is the final chapter summarizing the outcome of the thesis while suggesting a future study plan for the FGDOFs in electron beam dosimetry.

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