The use of Ge-doped optical fibres in external beam radiotherapy dosimetry

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THE USE OF GE-DOPED OPTICAL FIBRES IN EXTERNAL BEAM RADIOTHERAPY DOSIMETRY

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Abstract

The need for better characteristics of a radiation dosimeter arises from the requirement to verify the advanced techniques now employed in radiotherapy such as Intensity Modulated Radiation Therapy (IMRT), Intensity Guided Radiation Therapy (IGRT) and Cyberknife. To-date, one of the most promising dosimeter is thermoluminescent (TL) Ge-doped silica dioxide (SiO$_2$) optical fibre. It has been established that it provides excellent spatial resolution, flexibility, modest cost, a non-hygroscopic nature, and excellent radiation response characteristics. In this study, the TL yield of 9 µm Ge-doped optical fibres (Ge-9 µm) has been investigated, establishing their key dosimetric characteristics: for verification of dose distributions in IMRT prostate dosimetry; for measuring out-of-field photon. These results show that the fibres offer consistent linearity between TL yield and dose for doses from 0.05 Gy up to 10 Gy for photon and electron beam energies, with reproducibility of better than 5%. For all investigated megavoltage photon and electron beam energies, the fibres also offer angular-, dose rate-, and temperature-independence, while a small energy-dependent response was found, of between 6 to 11%. However, at kilovoltage potentials there is significant energy dependence. When held at room temperature results show fading of 11% 133 days post-irradiation. In addition, Ge-doped optical fibre was observed to verify doses to within 3% of the IMRT radiotherapy treatment planning system predicted doses and LiF TLDs (TLD-100 and TLD-700) for the 6 MV and 15 MV energy photon beams used. The fibres have demonstrated potential for use in measuring IMRT out-of-field photon dose when using 6 MV photons, however when conducting 15MV irradiations, the fibres’ response needs to be corrected to account for the activation neutron dose. Ge-doped fibres also represent a viable system for use in mailed audit radiotherapy programmes; in particular measuring beam output under reference conditions as demonstrated in a postal dosimetry audit at selected Malaysian radiotherapy centres. The audit methodology has been developed with an expanded uncertainty of 4.22 % at 95% confidence interval for the energy photon beams used.
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<td>Al</td>
<td>Aluminium</td>
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<td>APMP</td>
<td>Asia Pacific Metrology Programme</td>
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<td>LET</td>
<td>Linear Energy Transfer</td>
</tr>
<tr>
<td>MARPA</td>
<td>Medical Physics Association, and Malaysian Radiation Protection Association</td>
</tr>
<tr>
<td>MNA</td>
<td>Malaysian Nuclear Agency</td>
</tr>
<tr>
<td>MOSTI</td>
<td>Ministry of Science, Technology, and Innovation</td>
</tr>
<tr>
<td>MOSFETs</td>
<td>Metal Oxide Semiconductor Field Effect Transistors</td>
</tr>
<tr>
<td>MPPs</td>
<td>Multipurpose Phantom</td>
</tr>
<tr>
<td>NCRRI</td>
<td>National Cancer Research Institute</td>
</tr>
<tr>
<td>Nd</td>
<td>Neodymium</td>
</tr>
<tr>
<td>NTCP</td>
<td>Normal Tissue Complications Probability</td>
</tr>
<tr>
<td>OAR</td>
<td>Organ at Risk</td>
</tr>
<tr>
<td>PARSORT</td>
<td>Parotid-Sparing Intensity Modulated versus Conventional Radiotherapy in Head and Neck Cancer</td>
</tr>
<tr>
<td>PIXE</td>
<td>Proton-Induced X-ray Emission</td>
</tr>
<tr>
<td>PSDL</td>
<td>Primary Standard Dosimetry Laboratory</td>
</tr>
<tr>
<td>PTV</td>
<td>Planning Target Volume</td>
</tr>
<tr>
<td>RER</td>
<td>Relative Energy Response</td>
</tr>
<tr>
<td>RPC</td>
<td>Radiology Physics Centre</td>
</tr>
<tr>
<td>RPC</td>
<td>Radiological Physics Centre</td>
</tr>
<tr>
<td>SBRT</td>
<td>Stereotactic Body Radiotherapy</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscopy</td>
</tr>
<tr>
<td>Sm</td>
<td>Samarium</td>
</tr>
<tr>
<td>SSDL</td>
<td>Secondary Standard Dosimetry Laboratory</td>
</tr>
<tr>
<td>Yb</td>
<td>Ytterbium</td>
</tr>
</tbody>
</table>
Chemotherapy, radiotherapy and surgery are the three main established treatment techniques for treating cancer. These three treatment options are used alone or in combination, depending on the decision made by oncologists. Normally, surgery is performed either prior to radiotherapy or chemotherapy or as a stand alone treatment. Chemotherapy is the treatment using anticancer drugs to eradicate cancer cells (Brighton and Wood, 2005), whereas in radiotherapy the use of ionizing radiation is employed, either as x rays or radioactive isotopes (Kane, 2003). The aim of radiotherapy is to tailor a tumouricidal dose envelope to a target volume and to deliver as low a radiation dose as possible to all other normal tissues (Webb, 2001).

One of the most advanced forms of 3-Dimensional conformal radiotherapy (3D-CRT) techniques is Intensity Modulated Radiation Therapy (IMRT). IMRT is a technique widely used in the treatment of patients with prostate cancer, the most commonly occurring male cancer in the United States and Western Europe, head and neck, nasopharyngeal carcinoma and breast cancer (Warmkessel, 2006). It utilizes sub-beams or multileaf collimators (MLC) in varying the radiation beam intensity to precisely irradiate a targeted tumour. The technique promises improved radiotherapy over that provided by conventional techniques (Schaly et al, 2004), including enabling the tumour to be treated with a uniform high dose, capability for shaping the dose distribution to match the shape of the tumour (Mayles et al, 2007), reduction in morbidity in decreasing the radiation received by the normal tissues (Williams, 2003), potentially improving patient outcomes (Bhide and Nutting, 2010; Boyer et al, 1997) and also in enabling dose pointing.
However, despite the increased dosimetric benefits of IMRT, there are a number of technical difficulties which require further investigation and improvement, especially in validating patient doses using conventional dosimetry systems. There are a few case studies that suggest that limitations in conventional dosimeter systems may reduce the effectiveness of the IMRT technique in minimising the patient’s normal tissue complications (Webb, 2001).

For instance, measurements of the photon dose component distant from the treatment field, determined by TLD-100, have been observed to be highly inaccurate for 18 MV photons (Sneed et al, 1995, Kry et al, 2007a). The issue arises for high photon energy (>10 MV) IMRT due to production of neutrons in the accelerator head. This is of concern as this may lead to secondary cancer induction (Hall et al, 2006).

Evaluation of the accuracy of the dose calculated using treatment planning systems (TPS) is needed prior to the patient undergoing radiation therapy treatment. This arises due to limitations in the accuracy of the raw data entered into the TPS that describe the characteristics of the input radiation beams and of the calculation algorithm used in obtaining doses at any point (Angelo et al, 1999). These evaluations are more crucial in advanced delivery techniques such as Intensity Modulated Radiation Therapy (IMRT), because this technique requires more multifaceted dose calculations and geometric accuracy, especially in the regions of high dose gradient. Thus, sophisticated, established and high cost equipment is needed in order to support quality assurance (QA) systems for IMRT facilities to implement this technique in clinical use (Cheung, 2006). Therefore, a number of research groups are investigating and developing various materials to be used as IMRT dosimeters with reasonable cost. One promising material is doping phosphors such as lithium fluoride with impurities of magnesium and titanium. However, this material has several drawbacks such as its hygroscopic nature, its response is energy and dose dependent, it is expensive and has poor spatial resolution of a few mm.

The need for accuracy in radiotherapy is well established and a lot of effort has been put into quality assurance (QA) to ensure high and continued quality in radiation treatment for all patients, so as to optimise clinical outcomes. Recommended levels in
consistency and accuracy in delivery of absorbed dose to a target volume in radiotherapy dosimetry are to at least ±5% (ICRU 24, 1976). Other reviews recommend more strict limits of dose delivery of +/-3.5% (Mijnheer, 1987) and +/-3% (Brahme, 1984). Therefore, audit and dosimetry intercomparisons have been introduced as audit tool to detect errors that might occur due to inexact implementation or misinterpretation of recommendations, equipment problems or mistakes. These may range from lithium fluoride thermo luminescence dosimeter (TLD) audits, as organised by the IAEA, or on-site visits using ionisation chambers and appropriate phantoms. The complexity of parameters audited generally involves three sequential steps that cover basic reference dosimetry through to in vivo dosimetry or advanced radiotherapy techniques. These steps comprise of i) examination of beam output under reference conditions using high energy photon beams, ii) examination of dose delivered along the beam central axis for photon and electron beams under reference and non-reference conditions and iii) examination of dose under reference, non-reference condition off-axis for open and wedged symmetric and asymmetric fields for photon beams (Izewska et al, 2007). To-date the phosphor based thermoluminescence dosimetry (TLD) has been the favoured postal dose audit tool of several agencies such as the International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO) in their IAEA/WHO TLD postal dose audit programme (Izewska et al, 2000), the European Society for Therapeutic Radiology and Oncology-European Quality Assurance Network (ESTRO) for the ESTRO/EQUAL quality assurance network (Ferreira et al, 2000) and the Radiological Physics Centre (RPC) for mailed TLD systems in North America (Kirby, 1992).

The aim of this present study is to investigate the alternative use of an amorphous material (silica dioxide doped with Germanium) as a potential medical dosimeter. In this dissertation it is established that the Ge-doped optical fibres have advantages compared to other dopent materials for dosimetry given its wide useful dose range, small physical size, it avoids the use of high voltage or cables and has the capability to provide excellent TLD characteristics. To the best knowledge of the author, Ge-doped optical fibre has not yet been widely employed in clinical oncology such as in advanced radiotherapy technique verification and audit dosimetry study. There exists
little in the published literature that actually establishes the dosimetric characteristics of Ge-doped optical fibres. The studies described in this dissertation have focused particularly on establishing the use of Ge-doped optical fibres as a tool to verify absorbed dose in IMRT treatment planning and the potential of its use as a mailed audit dosimeter in intercomparison audit exercises.

1.1 Motivation and goals

This dissertation is constructed on the basis of four published peer reviewed papers (Mohd Noor, N et al, 2010, Mohd Noor, N et al, 2011a, Mohd Noor, N et al, 2011b, Bradley et al, 2011) and a fifth in preparation, with discussions focusing on the use of the new amorphous material Ge-doped optical fibre as a potential dosimeter in radiation fields. Understanding the TL dosimetric characteristics of such material allows a discussion of its application in radiation dosimetry and in dosimetric audit.

In order to understand the work that follows, chapter 2 focuses on radiation dosimetry and introduces the phenomenon of thermoluminescence studies on Ge-doped SiO2 optical fibres and presents a detailed review of published works in this field. The advanced form of radiotherapy delivery technique, Intensity Modulated Radiotherapy (IMRT), is also discussed. The effects of dosimetry intercomparisons in ensuring consistent radiation dose delivery to the patient, and the current development of dosimetry audits in other countries has also been reviewed.

In chapter 3, a detailed review is provided of the research carried out for this dissertation of Ge-doped optical fibres in a variety of applications. An investigation of Ge-doped optical as a TL dosimeter in radiotherapy, the screening process and investigation of key dosimetric characteristics of such fibres including glow curve reproducibility, linearity, fading, energy-, dose rate-, angular-, temperature-dependence is discussed.

In chapter 4, the potential of Ge-doped optical fibres as an out-of-field dosimeter for high energy IMRT, where the possibility of photo-neutron production is present, is investigated. Use has been made of an anthropomorphic phantom (RANDO) for photon irradiation measurements delivered over the range of nominal energies 6–
15MV as typically used in IMRT treatment of prostate cancer. The Ge-doped fibre TL system is compared with the more commonly used lithium fluoride material, TLD-100, the latter being corrected at 15MV for their response to thermal neutrons. The implications for secondary cancer induction are considered.

In chapter 5, the potential of Ge-doped optical fibres to evaluate IMRT prostate verification plans is investigated. The verification plans using the Varian Eclipse treatment planning system for two prostate cancer patients were created using an Alderson Rando Anthropomorphic Phantom CT data-set. Measurements were performed using the Rando phantom at nominal energies of 6 MV and 15 MV. Ge-doped optical fibre TL yields were compared with dose determined through the use of the treatment planning system and also with the well-established TL lithium fluoride (LiF) dosimetry system (Harshaw TLD-100 and TLD-700).

In chapter 6, work is presented aimed at establishing the potential of a mailed commercial Ge-doped optical fibre TLD system in measuring absorbed dose under reference conditions. A dosimetric intercomparison of selected Malaysian radiotherapy centres is then presented based upon the use of Ge-doped optical fibres. The methodology of measuring absorbed dose under reference conditions using such fibres has been developed based on the IAEA/WHO TLD audit programme. Prior to the audit, a preliminary pilot audit irradiation was also carried out using three different linear accelerators located in one UK radiotherapy centre. Subsequent to these irradiations the mailed audit of the eight selected Malaysian radiotherapy centers was carried out.

A summary of the main findings of this thesis and recommendations for future work is outlined in Chapter 7.
The present chapter is intended to give a more detailed preface to the Ge-doped SiO$_2$ optical fibres structure, the defect and added impurities and the theoretical background of thermoluminescence in fibres. In addition, a brief introduction to the concept of IMRT is also covered, with special emphasis on its role in improving local tumour control together with the associated radiotherapy treatment planning. Explanations of the IMRT techniques are beyond the scope of this thesis, the focus instead being more towards understanding the parameters that potentially affect the accuracy of Treatment Planning Systems (TPS) to verify the techniques, in particular, when involved with the use of higher energies. Today there is also considerable interest in dosimetric intercomparison procedures for ensuring consistent radiation dose delivery to the patient. In order to understand the roles of dosimetry intercomparison in radiotherapy, this area has been reviewed, highlighting the different available techniques that are used in the procedures and analysing the advantages and disadvantages of each technique. In addition, current developments in dosimetry intercomparison internationally are also reviewed.

2.1 Radiation dosimetry

In radiotherapy treatment it is crucial that we may verify the dose distribution due to the possible normal tissue complications of the dose delivered. It is impractical to measure dose distribution directly in patients treated with radiation. Therefore, there is a need for dosimetry systems which offer features that may accurately verify the delivered dose to the patient. These features include tissue equivalence, high spatial resolution, accurate and precise dose measurement, linear response with dose over a
wide range, a well-characterised dose-rate-, energy- and angular response, stability, time and cost savings, 3D measurement and high sensitivity (Oldham et al, 2003; Izewska and Rajan, 2005) (Figure 2.1). However, no dosimetry systems fulfil all such requirements and usually optimum requirement capabilities will depend on the particular dosimetric purpose (Mobit and Kron, 2007). Therefore, a good knowledge of the advantages and disadvantages of the multitude of available systems allow a suitable choice of the detector to be used.

2.1.1 Theory of thermoluminescence

The theory of thermoluminescence dosimetry is based on the capability of imperfections in crystals to absorb and store the energy of ionizing density, which upon subsequent heating is re-emitted in the form of electromagnetic radiation, mainly in the visible wavelength (Marinello et al, 1992; 2007). The total light output is then detected and correlated to the absorbed dose received by the TL materials. To explain the mechanism for TL it is conventional to refer to the band theory of
multiatomic crystalline structures (Figure 2.2) (McKinlay 1981; McKeever, 1988). This theory describes the various bands of energy that exist within a material’s atomic lattice. A forbidden gap lies between the conduction band and the valence band. Normally, charges cannot occupy the forbidden zone (Khan, 2010). However, the presence of impurities to the atomic lattice, can lead to a change in the band structure of the material to make it possible for charges to exist within the forbidden gap.

Upon TL materials being irradiated, free electrons and holes are produced. The electrons are free to move within the solid in the conduction band for a short time. There are three possible fates for such electrons; (i) to be trapped at metastable energy states (defects), (ii) to de-excite back into the valence band and recombine with holes either radiatively (fluorescence) or non-radiatively and (iii) to be captured at de-excitation positions (luminescent centres) already activated by holes as a result of the irradiation, and then to deactivate the centre with the emission of light (Marinello et al., 1992; 2007).

By heating the material (thermal de-excitation), the electrons trapped at the defects acquire adequate energy to be released from the trap into the conduction band again. As previous there are three possible outcomes for electrons; (i) being retrapped at defects, (ii) de-excite into the valence band and recombine radiatively or non-radiatively with holes, (iii) recombine radiatively at a hole-activated luminescent center (Marinello et al., 1992; 2007). The light output in the third process is known as thermoluminescence. A photomultiplier tube is used to capture the light and convert the integrated light output into an electronic signal. By plotting the intensity of total light output against time or temperature, a thermoluminescence spectra or glow curve is obtained (Mobit and Kron, 2007). Subsequent to readout, the TL material either returns to its original state or requires a further annealing process in order to restore it (Marinello et al., 1992; 2007).
Unlike crystalline solids, there is no complete model of TL for amorphous solids. Thus, the present description will make use of that for conventional crystalline structure model (Yusoff et al., 2005), noting that the de-trapping process is adequately described by such a model (Hashim et al., 2009a); once the doped fibres have been irradiated, the free electrons generated are trapped in lattice defects or impurity traps that are much less localised than in crystalline media. This accounts for the broader glow curves. Heating the TL material causes the lattice atoms to vibrate, releasing the trapped electron and holes in the process (Mobit and Kron et al., 2007). The germanium doped media examined in this study is observed to form deep electron traps, thus suppressing the potential thermal fading of a signal in such TL systems (Yaakob et al., 2011b). As with other TL media, the emission of the light is proportional to the absorbed dose (Ong et al., 2009). According to ICRU 1980 (ICRU, 1980), the definition of absorbed dose, D, is the mean energy, d\(\bar{E}\), imparted by ionizing radiation to a material of mass, \(dm\), or simply the ratio of \(\frac{d\bar{E}}{dm}\). The SI unit for absorbed dose is the gray (Gy) and is defined as (1 Gy = 1 J/kg).
2.2 Current thermoluminescence dosimetry techniques

Thermoluminescence dosimetry (McKeever, 1988; Mc Kinlay, 1981) has been used in radiation medicine over the past seventy years (Daniels, 1953). However as is well-established, the luminescence phenomenon actually lead to the discovery of x-rays in 1895 by Roentgen (Podgorsak, 2005). It is now renowned as a versatile tool for dosimetry of ionising radiation, including for gamma-, beta- and x-ray irradiations (Pradhan, 1981). This is due to the wide variety of TL materials and their different physical forms such as crystal ribbons, micro-rods, powder, cards, bulbs, solid pellets, and teflon-based chips (Mobit and Kron, 2007) that make it useful in a multitude of applications, as in for instance radiotherapy, radiation protection, quality assurance and in vivo dosimetry (Marinello et al, 1992). The main advantages of TL dosimeter features are their small physical size (up to a few mm), angular independence of dose reading, tissue-equivalence in some cases ($Z_{eff}$ of 8.31 for lithium fluoride) and free standing dosimeter; hence no electronic cables or auxiliary equipment are needed during dose measurements (Kron, 1995). This makes them well suited for use in in vivo dosimetry, for point dose measurements in tissue-equivalent phantoms and in mailed intercomparison audits (Mobit and Kron, 2007). Furthermore, being an integrative dose recorder, the TLD is also capable of measuring dose accumulated from conformal and dynamic radiotherapy such as stereotactic radiosurgery (Kron, 1999).

There is a vast amount of published literature describing applications of well established TL-material in medicine, such as LiF:Mg,Ti, LiF:Mg,Cu,P and CaSO4:Dy. However, in the majority of radiotherapy centres the use of TLD in routine clinical application is limited because these kinds of phosphor materials have several notable pitfalls, including being hygroscopic, having relatively poor spatial resolution (approximately up to a few mm) and are expensive.

In recent years a number of research groups have investigated and developed various materials to be used as medical radiation dosimeters. One of the most promising materials is thermoluminescent (TL) silica dioxide ($SiO_2$) optical fibre. Unlike phosphor TLD, silica optical fibres have an excellent spatial resolution, with a physical diameter of just a few tens of microns (Hashim et al, 2009a). Other factors
that favour the use of optical fibres for radiation dosimetry are their water and corrosion resistance (Abdullah et al., 2001). This is due to the presence of an outer plastic polymer (Abd Latip, 2009). In addition, the fibres demonstrate reproducibility and reusability without any detriment to the dose-response (Espinosa et al., 2006). They have a low residual signal (Hashim et al., 2009a) and modest cost (Abdullah et al., 2001).

2.2.1 Optical Fibre structures

Optical fibres are generally made from doped silica glass and are typically intended to be used to transmit digital information over long distance through light transport. These are generally long and thin strands about the diameter of a human hair. Hundreds or thousands of these optical fibres are arranged in bundles called optical cables (Zanger and Zanger, 1991). There are three components that constitute the fibre optic for their application. These are the coating or jacket, the cladding and the core as shown in Figure 2.3.

![Schematic of optical fibres](CSE Cables Ltd, 2011)

These three components are arranged in concentric circles beginning at the centre of the cable interior. In the centre or first layer of optical fibres is the core, made of variously doped silica where the light signals are transmitted. Currently, there are a range of commercially available diameter ranges of the core, from 4 micrometers up to in excess of 62.5 micrometers (Figure 2.4). This second layer of optical fibre has been designed as an internal reflective boundary, ensuring near total internal reflection, and also in order to shield the core from any interference from outside. The reflective index of this layer is less than the core to provide for total internal reflection (Figure 2.5) and avoiding loss of light signal (Zanger and Zanger, 1991). Generally, the cladding and the core cannot be separated from each other as they are
manufactured together as a single silica glass piece with different compositions of dopant or impurities. The outermost part of the optical fibres is known as the plastic sheath or buffer or coating or jacket. It is a UV-cured urethane acrylate composite material applied to the outside of fibres during the process of manufacturing (Mynbaev and Scheiner, 2000). It protects the cladding from moisture and physical damage. In the applications described in this dissertation, this layer is stripped off to avoid burning in the read-out and annealing process (Ong et al, 2009). Currently there are two types of optical fibre, namely multi-mode fibres and single-mode fibres. Both of them have different application and characteristics. Table 2.1 describes the differences between them. The optical fibres used in this study are single and multi-mode commercial optical fibre manufactured by INOCORP (Canada), with core diameters of 9 μm and 50 μm respectively.
Table 2.1 Summary of the differences between the two types of optical fibre used in this dissertation.

<table>
<thead>
<tr>
<th></th>
<th>Single-mode fibres (SMF)</th>
<th>Multi-mode fibres (MMF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the core</td>
<td>9 µm</td>
<td>62.5 and 50 µm</td>
</tr>
<tr>
<td>Diameter of the cladding</td>
<td>125 µm</td>
<td>125 µm</td>
</tr>
<tr>
<td>Diagram and structure of optical fibres</td>
<td><img src="image" alt="Diagram of optical fibres" /></td>
<td><img src="image" alt="Diagram of optical fibres" /></td>
</tr>
</tbody>
</table>

![Figure 2.4 Single and multi-modes fibres with different core diameters (CSE Cables Ltd, 2011).](image)

<table>
<thead>
<tr>
<th>Numerical apertures (NA)</th>
<th>i) NA depends on the dimension of the core. Thus the NA for single-mode is small.</th>
<th>i) NA is larger since the core of the multi-mode is large compared to single-mode.</th>
</tr>
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<tbody>
<tr>
<td>- dimensionless number that characterizes</td>
<td></td>
<td>ii) Require less precision to splice and work.</td>
</tr>
<tr>
<td>the range of angles over which the system</td>
<td></td>
<td></td>
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<tr>
<td>can accept or emit light.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other features</td>
<td>i) Low cost ~USD 10 per metre for Ge-doped fibres with 9 µm (INOCOP, Canada).</td>
<td>i) Higher cost~ USD 35 per metre for Ge-doped fibres with 50 µm (INOCOP, Canada).</td>
</tr>
<tr>
<td></td>
<td>ii) Operates for nearly all visible light wavelengths.</td>
<td>iii) Ability to allow numerous modes of light to be transmitted simultaneously.</td>
</tr>
<tr>
<td></td>
<td>iii) Allows for long distance transmission.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>ii) Limited distance of transmission.</td>
</tr>
</tbody>
</table>
2.2.2 Structure of silicon dioxide

Almost 90% of all solids, either artificially prepared or naturally occurring, are in the crystalline form, meaning that the constituent atoms and molecules are regular repeating pattern (Figure 2.5). Established TL materials such as LiF:Mg,Ti, LiF:Mg,Cu,P and CaSO₄:D are examples of the crystalline materials. If the solids are not crystalline, they are known as amorphous (Wemple, 1973). Examples of amorphous solids are the cladding and cores of optical fibres used in the present study, mainly prepared from silicon SiO₂ (Shalek et al, 2005). Generally, SiO₂ is known as silica and occurs in crystalline and amorphous forms (Napierska et al, 2010). Quartz and glass are examples of SiO₂ in the crystalline and amorphous form respectively. Unlike crystalline solids, amorphous solids are devoid of long-range periodic order (Figure 2.6). However, this does not mean that amorphous solids are structurally completely random. It is because the distance between atoms must be bigger than the size of the hard spheres. Moreover, in many cases there are several forms of short-range order. For example, the tetragonal order of crystalline SiO₂ is still apparent in amorphous SiO₂ as illustrated in Figure 2.7.
Figure 2.6: a) Crystalline SiO$_2$ (Quartz) shows periodical order of atoms arrangement; b) Amorphous SiO$_2$ (Glass) shows unorganized order of atoms (Adapted from Yaakob et al, 2011b).

Figure 2.7 Tetragonal crystalline silica dioxide (quartz) and amorphous silica dioxide (glass). Arrow indicates the short-range order of silica, where the tetragonal order of crystalline SiO$_2$ is still apparent in amorphous SiO$_2$ (NDT Education Resource Center).

2.2.3 Defects and impurities

Although crystalline solids show a periodic crystal structure, the arrangement of atoms or molecules in most crystalline material is never perfect, due to the regular patterns being interspersed by crystallographic defects (Ehrhart, 1991). Defects or imperfections occur in the TL materials, either crystalline or amorphous solids, due to the adding of impurities (dopants) in the lattice structures during the growth process of the materials (Mobit and Kron, 2007). Impurities are defined as a substance inside a confined amount of solid, gas or liquid which has different chemical compositions to the compound or material (Siegel, 1982). Impurities are introduced in the solids for
a particular purpose. For example in fibre applications, doping amorphous SiO₂ with selected impurities such as germanium dioxide (GeO₂) will increase the refractive index of the core of fibres to enable guidance of light. Fortuitously for this study, the germanium has replaced the silicon in their structure, acting as the defect centre (Hashim, 2009a) (Figure 2.8). The presence of defects within the silicon dioxide is thus central to the phenomena of TL production. It also increases the TL sensitivity of fibres to various types of radiation (Yusoff et al, 2005). Pure silica dioxide (without added any dopants in the core of fibres for instance) has been found to have the least sensitivity to radiation and is not known to exhibit TL properties (Huston et al, 2001; Mobit and Kron, 2007). It has also been established that the sensitivity of Ge-doped fibres to megavoltage photon beam irradiations is superior to that produced by other types of commercially produced silica fibres doped with elements such as aluminium (Al), neodymium (Nd), erbium (Er), and samarium (Sm) (Hashim et al, 2009a; Safitri et al, 2008), providing in particular a wide range of dose sensitivity.

![Ge-doped silica dioxide](image)

Figure 2.8 The simplified structures of Ge-doped silica dioxide (Adapted from Yaakob et al, 2011b)

TL output might be expected to increase with impurities (dopants) concentration (Mobit and Kron, 2007). This is in concordance with Khanlary and Townsend (1993) who found the radiative decay paths of the absorbed energy is greatest in those fibres that contain the most imperfections, whether they are in the form of dopants or defects that are induced by thermal and/or radiation. However, beyond an optimized concentration, the TL sensitivity of the Ge-doped fibres decreases as demonstrated in Figure 2.9. This is due to the reduced distance between the traps as the number of traps and recombination centres increases. This raises the probability for the light emitted from one recombination process to be absorbed by an electron which is then
subsequently trapped elsewhere, a phenomenon called self-absorption (Yussoff et al, 2005).

Figure 2.9 The TL response to an X-ray dose of 10 Gy for variously doped silica samples at different dopant concentrations. The TL sensitivity of Ge-doped fibres was found to decrease at a doping concentration of approximately 0.20% mol. Note that the samples in this study were prepared using the Sol-gel technique. Reprinted from Yussoff et al, (2005) with permission from Elsevier.

2.3 Development of germanium doped optical fibre

The basic dosimetric characteristics of Ge-doped optical fibres with 9µm core diameter (Ge-9µm) including linearity with dose, fading and energy dependence have been investigated in detail by Abdulla et al (2001), Hashim et al (2009a, 2009b, 2010), Ramli et al (2009), Abdul Rahman et al (2011b), Issa et al (2011a), Asni et al (2009) and Yaakob et al (2009, 2011a, 2011b, 2011c). Conversely Ge-doped optical fibres with 50µm core diameter (Ge-50µm) has only previously been characterised by Ong et al (2009). Most of these studies involved a variety of radiation sources, including photons, neutrons, electrons, alphas and protons. All of these investigations have observed that the TL performance of an irradiated optical fibre is influenced by the type of fibre including the type of dopant material (impurity), diameter of the fibre core (in which the dopant materials have been distributed) and the radiation parameters. More recently has been the use of Ge-doped silica optical fibres in various situations such as in interface radiation dosimetry (Abdul Rahman et al, 2011a), synchrotron microbeam radiation therapy dosimetry (Abdul Rahman et al, 2010) and brachtherapy dosimetry (Issa et al, 2011b). In this dissertation, the
dosimetric characteristics of Ge-9 µm have been established for measuring out-of-field photon dose in IMRT techniques; for verification of dose distributions in IMRT prostate dosimetry; and for measuring beam output in mailed dosimetry audits. In the following a review is presented of previous studies of Ge-doped silica fibres.

Abdulla et al (2001) was among the first to carry out a TL study on commercially available Ge-doped silica based optical fibres (Ge-9µm) using a gamma emitting source (60Co). The fibre was prepared in the form of 1 cm length rods of mass of approximately 0.3 mg each. The fibres were irradiated to radiation doses 1 to 120 Gy. The results showed that Ge-doped fibres have good reproducibility of TL readout through five repeat cycles and a linear dose response across the studied dose range with a correlation coefficient, $r^2=0.95$. The TL signal from Ge doped fibre has a fast fading characteristic of about 2% within 6 hours and a slow fading component of 7% within a one month storage time. The lower detectable limit of radiation dose for this type of optical fibre was suggested to be 0.02 Gy.

Studies on the same type of fibre (Ge-9µm) were extended by Hashim et al (2009a, 2009b, 2010) and Ramli et al (2009) in order to characterize the fibres response to low-energy X-rays (49.8 kVp), megavoltage photons (6 MV), $^{90}$Sr / $^{90}$Y β-rays (respective maximum energies of 545 keV and 2288 keV), accelerated electrons (6 MeV up to 12 MeV), accelerated protons (2.5 MeV), α-particles (5.954 MeV) and fast neutrons (10 keV to 10 MeV). A Varian Clinac 2100C accelerator producing 6 MV photons and electron energies in the range 6-, 9- and 12 MeV was used in order to observe the response of the Ge-doped fibres subjected to the photon and electron irradiations. The fibres were sandwiched between solid water™ phantom material and were delivered a dose in the range of 1 to 4 Gy. The irradiation set-up parameters included a source to surface distance of 100 cm, a dose rate of 400 cGy min$^{-1}$ and field size of 10 x 10 cm$^2$. In examining the minimum detectable dose and shape of the glow curve for such fibres, the same irradiation set-up parameters were used for photon and electron irradiations. The response of Ge-doped measurements showed a linear dose–response over the investigated dose range from 1 to 4 Gy for 6 MV photons and 6 to 12 MeV electrons. The inferred minimum detectable dose for 6 MV photons was argued to be 30 µGy for Ge-doped fibres. The peak of the Ge-doped fibre glow curve was between 210ºC to 240ºC; the broad glow curve being
characteristic of amorphous media. Afterwards, to investigate the TL response of Ge-doped fibres subjected to fast neutron, the fibres were exposed in close contact with an $^{241}$AmBe source of activity 10.6 GBq for exposure times of 1-, 2-, 3-, 5- and 7-days in a neutron tank filled with water. Comparisons were made against the Monte Carlo N-particle code (MCNP) version 5(V5), used in order to simulate the neutron irradiation experiment. It was observed that for the Ge-doped fibres used in the experiment, a linear dose response was obtained when subjected to fast neutrons from such an $^{241}$Am Be source, exposed for durations of up to seven days. The MNCP5 simulation also exhibits a similar pattern, although varying in sensitivity. Proton irradiations were carried-out using a 2.0 MV Tandetron$^{\text{TM}}$ accelerator located at Surrey University ion beam centre, providing 2.5 MeV energy protons. Some twenty fibres were irradiated with a beam current of 40 pA, for exposure times of between a few seconds up to 7 minutes. Results show an initial linear relationship with dose but with subsequent approach to saturation at longer exposure times. This is because the trapping levels are now all occupied. A $^{90}$Sr / $^{90}$Y turntable beta irradiator was also used in investigating beta dose response, providing a dose rate of approximately $1.79 \times 10^{-4}$ Gy min$^{-1}$. The purpose was in part to compare the TL response to sealed source beta emitters against accelerated electrons using a linear accelerator, in particular to see the capability of the fibres to measure low doses. The fibres were exposed for 17 hours and a dose of approximately 0.18 Gy was given. The results, taking into account inter fibre variability of the Ge-doped fibre measurements, show agreement to better than 10% with measurements obtained from accelerated electrons. Subsequently, in regard to the TL response of Ge-doped SiO$_2$ subjected to alpha particles, a sealed source of $^{241}$Am with activity 173.3 kBq and a dose-rate of 51.1 $\mu$Gy hr$^{-1}$ at an irradiation distance of 10 cm was used. The Bragg peak for alpha particles of energy 5.486 MeV for Ge-doped fibres was localised around a range in air of 4.5 cm from the point of emission at an air pressure of 750 ± 10 mmHg. Finally, investigation was made by these workers, examining dopant concentration along the fibres, use being made of either proton-induced x-ray emission (PIXE) or thorough estimation of the effective atomic number, $Z_{\text{eff}}$ using scanning electron microscope (SEM) and energy dispersive x-ray spectroscopy (EDXRS) analysis. Here it is to be noted that the dopant concentration of the SiO$_2$ fibre is important in seeking the optimal TL yield. The main problem with commercial SiO$_2$ fibres is the non-
uniformity in distribution of added dopants and impurity concentration in the core of the fibres, causing variation in TL yield to an extent that may limit the application of such fibres. The variability occurs as a result of the production method for the optical fibres, the dopants in the core tending to unevenly diffuse. As a result large numbers of fibres were cut to the same length (~0.6 cm) and were irradiated with the same dose, the resultant TL response depending on the dopant concentration and type of dopant. The dopant concentration for Ge-doped fibres (9µm) in this study was observed to be in the range of 0.53 to 0.71mol% with an effective atomic number of between 11.9 to 13.4.

Abdul Rahman et al (2011a) found that the Ge-doped fibres have a weak dependence on dose-rate in the range of 2.4 to 2.9% for photons and 3.4 to 3.9% for electrons, i.e. within 4% measurement uncertainty. For both of photon and electron energies, a consistent trend towards lower response was observed in the TL yield at high dose rates when compared with the response at lower dose rates. This resulted from fibres being irradiated between dose rates of 100 to 600 cGy min⁻¹ using photon beams in the range of accelerating potential 6 to 15 MV and dose rates between 100 and 1000 cGy min⁻¹ using electron beams in the energy range of 9 to 20 MeV. They subsequently also observed that the Ge-doped fibres showed potential for use in synchrotron microbeam radiation therapy (Abdul Rahman et al, 2010), the fibres demonstrating a linear response over the dose range from 1 Gy to 2 kGy fulfilling the needs of synchrotron microbeam radiotherapy dosimetry, with entrance doses usually of less than 2 kGy. More recently, Abdul Rahman et al (2011b) have demonstrated the possibly of using the Ge-doped fibres for interface radiation dosimetry, in particular to measure photoelectron dose enhancement. This study involved irradiation using a photon beam of relatively low energy (90 kVp) to deliver a dose of 30 kGy at a dose-rate of 222 cGy/min. Two phantoms designed to emulate a synovial membrane treatment setup were fabricated, one as a polyurethane cube and the other as a Perspex cube, each containing a reservoir of iodine in the centre. These phantoms allow a measurement of photoelectron dose enhancement in terms of elevated percentage depth dose (PDD) resulting from surface contact between the optical fibres and an iodine contrast medium. Comparison was made with measurements of dose distant from the iodine reservoir using a stepped-design phantom. The fibres were inserted within the steps of the phantom, obtaining the dose deposited in soft tissue.
Verification of the experimental results was also carried out using Monte Carlo simulation. Results show the fibres to be capable of detecting dose enhancement due to increased photoelectron production, where the enhancement is about 60% above the photon dose component obtained in the absence of the iodinated contrast medium. Good agreement, to within ±5%, between experiment and simulation was obtained for both cases, also being in agreement with British Journal of Radiology values (BJR Supplement 25, 1996) for measurement of dose distant from the iodine reservoir.

Issa et al (2011a, 2011b) have examined the basic dosimetric characteristics for Ge-doped silica optical fibres irradiated in the kilovoltage energy range (90kVp and 300kVp), including linearity of dose response, reproducibility and fading effect. Central-axis percentage depth dose (PDD) values were also measured in this study. The Ge-doped fibres response was demonstrated to be linear with dose over the investigated range 0.1 to 6 Gy whilst the reproducibility of the fibres was found to be within ±2%. Minimal fading, was observed at less than 1.5% over a 12 hours period. PDD values obtained using optical fibres were found to agree with ionisation chamber measurements to within 2.1% and 1.1% at 90kVp and 300kVp respectively. Other experiments have also been carried-out to verify dose distribution for Low Dose Rate Brachytherapy (LDR) techniques, it being difficult using other techniques to obtain accurate dose measurement at high dose gradients, especially at distances close to the Brachtherapy sources (less than 2 cm). Prior investigations using Ge-doped fibres for actual Brachtherapy sources have determined the minimum detectable dose for the fibres from beta components and gamma/x-ray mediated dose. The fibres were exposed to $^{133}\text{Ba}$ and $^{60}\text{Co}$ sources and measurements were made using a Perspex phantom. In this study, use was also made of the EGSnrc/ DOSRZnrc Monte Carlo Code to simulate the $^{133}\text{Ba}$ and $^{60}\text{Co}$ irradiation experiments. Experimental and Monte Carlo simulation results were in agreement with each other to within 3% and 5% for $^{133}\text{Ba}$ and $^{60}\text{Co}$ respectively. Following the preliminary study, the actual LDR irradiations were performed along the axial and transverse direction, of the I-125 seed at angles 10° to 90° at distance from 1mm to 5cm using an OncoSeed I-125 (LDR) model 6711 seed. The measurements were carried-out using two separate designs of Perspex phantoms. Then, the results were verified with Monte Carlo simulation codes and Treatment Planning (VariSeed 8.0.2) values. Again, the experimental results compared well with the Monte Carlo simulation codes and Treatment Planning
values, to within 0.9% and 2.9% for the transverse axis and 3.7% and 3.8% for the central axis respectively.

Asni et al. (2009) performed a Monte Carlo N-Particle transport code version 5 (MCNP5) in order to investigate the energy response of Ge-doped optical fibres for various photon energies, ranging from 20 keV to 6 MV. The results obtained were compared with the energy response of TLD-100. The simulation results showed the same pattern of response from each TL medium, the optical fibres showing a greater response than TLD-100 to within 70% in the lower energy range and compared well with the TLD-100 in the higher energy ranges to within 0.5%.

Yaakob et al. (2009, 2011a, 2011b, 2011c) investigated the sensitivity, stability, reproducibility and fading of Germanium (Ge-9μm) and Aluminium (Al-9 μm) doped SiO$_2$ optical fibres for various electron (6-, 9- and 12 MeV) and photon energies (6- and 10 MV). The fibres were irradiated with low doses, ranging from 0.02 to 0.24 Gy for both photon and electron irradiations and high doses ranging from 0.2 to 4 Gy for electron irradiations only. The results have been compared with the TLD-100 response, the Al- and Ge-doped optical fibres having a linear dose–TL signal relationship for both high and low doses cases for photon and electron irradiations. In addition, in terms of sensitivity, the intensity of TL response of Ge-doped fibre is noticeably greater than the Al-doped fibres. From photon irradiation studies, systematic loss of TL signal was found in Ge-doped fibres, at approximately 22% compared to 40% in Al-doped fibres over a 14-day period of storage time for dose ranges from 1 to 4 Gy.

Ong et al. (2009), performed a study using a commercial germanium Ge-doped multimode-silica fibre with a 50 mm core diameter (Ge-50μm). Radiation sources offering a variety of photon energies were used. The researchers concluded that the fibre response was linear within the clinical relevant dose for all these energies, with reproducibility within 4 to 6%, energy- and dose- rate independence and fading of approximately 6% over a one month period. The central axis depth dose curves for 10 MV photons in a solid water phantom showed relatively good agreement with standard depth dose curves in water to within 4%. Finally 6% uncertainty of the sensitivity calibration system of the fibre was reported.
2.4 Intensity Modulated Radiation Therapy

2.4.1 Definition of IMRT

Intensity Modulated Radiation Therapy (IMRT) refers to ‘a radiation technique in which non-uniform intensity is delivered to the patient from different directions of the treatment beam to optimise the composite dose distribution’ (Figure 2.10) (Bortfeld, 2006). As mentioned in Chapter 1, IMRT is an extension of the 3D-CRT technique that is clinically shown to have superior dosimetric advantages compared to the conventional treatment at various cancer sites. Cheung (2006) has discussed three ways IMRT can be beneficial to the patient, (i) the probability of in-field recurrence is reduced by delivering the treatments with better dose conformity and coverage to the target (Figure 2.11) (ii) the degree of morbidity associated with treatment is minimized, hence reducing irradiation to normal tissue and (iii) the local control is improved by facilitating escalation of dose.

There are two main systems required in order to implement an IMRT technique in clinical practice, an IMRT treatment planning system and a delivery system. Usually, IMRT treatments are planned using inverse planning (Boyer et al, 2001), where the computer calculates non-uniform intensity maps for multiple beams directed from different position, subsequent to dose constraints to the target volume and organs at risk being specified mathematically (Ezzell et al, 2003). Analytical and iterative methods are two computerised approaches to achieve optimum intensity profiles and beam arrangements (Khan, 2010). The analytical method is involved with mathematical modelling in order to create a beam arrangement that would lead to the desired dose distribution. Whereas, the iterative method is the optimization process that devises the beams by iteratively adjusting to maximize the dose to the target volume and minimize the dose to critical organs (Khan, 2010). This second method is done using a dose volume histogram (DVH). In the work carried out for this dissertation, the Helios optimisation tool in the Eclipse planning system designed by Varian Medical Systems, Incorporated, which employs the use of an iterative algorithm, was employed.
Modern IMRT delivery techniques involve the use of multi-leaf collimators (MLCs). MLCs is a computer controlled device and consists of a number of absorbing tungsten leaves that can be positioned individually to create field openings with complex shapes (Figure 2.12) (Bortfeld, 2006; Ivanova, 2007). The leaves are conventionally moved from left to right (Williams, 2003). Generally, there are two methods to modulate the beam with the MLCs. There is the segmented technique (SMLC) in which the MLCs are moved a series of radiation exposures and the dynamic technique (dMLC) technique in which the MLCs are moved during the delivery of radiation (Williams, 2003). The second method, known as the sliding window technique is employed in the experiment work in this dissertation.

Figure 2.10 Illustration of the three dimensional (3D) views of the planning target volume (PTV), spinal cord, and parotid glands of the patient. IMRT dose distribution is generated using nine intensity modulated beams. The gray levels of the pixels distribution reflecting the intensity value. Reprinted from Boyer et al, (2001) with permission from Elsevier.

Figure 2.11 A dosimetry comparison between: a) Conventional 2D treatment; b) Conventional 3D conformal RT treatment; c) IMRT treatment. PTV is represented by the solid red line. The 100% and 70% of the prescription dose are shown by the green and red colour-washed areas. In IMRT treatment, a better dose conformity to the PTV has been achieved. Reprinted from Cheung, (2006) with permission from Biomedical Imaging and Intervention Journal.
Figure 2.12 Field openings with complex shapes are created by positioning individually the multi-leaf collimator (MLC). The intensity modulated fields being generated by dynamic moving leaves when the beam is ‘on’ (Varian Medical Systems, Inc).

2.4.2 Quality assurance and commissioning of IMRT

Despite all of its advantages, IMRT techniques require the establishment of quality assurance procedures. This is due to the possibility of a number of sources of uncertainty in the IMRT chain. There include; limitations in calculation algorithms in treatment planning system (TPS), tedious MLC calibration, verification of entire IMRT treatments, information on the patient and performance of the accelerator in low monitor unit (MU) settings, dose gradients and neutron dose contribution if higher energy photons are used. Therefore, IMRT QA has been reported as being high cost procedures, time consuming and laborious (Sadagopan et al, 2009, Budgell et al, 2005). However, to implement IMRT safely and effectively, the quality assurance that must be carried-out is critical. However treatment times will reduce through the use of IMRT, thus enabling the clinics to treat more patients with this technique. Moreover, the number and types of patients who could benefit from IMRT has also been reviewed and increased (Delaney et al, 2003; NRAG, 2007; Meyer et al, 2007).

A number of dosimetry studies on linear accelerator based IMRT treatments have been conducted in order in order to fulfill the need for high accuracy in geometric and dosimetric parameters. These studies vary in the range of dosimeters, phantoms and dose distribution analysis techniques employed (Low et al, 2011). Wagter (2004) discussed the requirements of the ideal dosimeter for IMRT in a conceptual pyramid form (Figure 2.13). He concluded that, at this point, there was no gold standard tool that can offer all the information required to quantitatively evaluate or compare dose
distributions. All these dosimeters have restrictions that need to be explicitly considered when conducting the evaluations. Relating to these findings, Low et al., (2011) provide recommendations for the proper operation of specific dosimeters as stated in the conceptual pyramid and also discuss their limitations.

![Conceptual pyramid](image)

Figure 2.13 a) Conceptual pyramid that associates with the various levels of dosimetric QA in IMRT; b) Methodology and tools suitable for each of the levels Reprinted from Wagter, (2004) with permission from Institute of Physics Publishing Ltd.

Generally, an ion chamber for point dose measurements with verification of the dose distribution in a two-dimensional (2D) plane using film are the favourite options chosen by radiation therapy staff and medical physicists for a patient-specific QA programme (Gagliardi et al, 2009). However, the use of portal dosimetry using electronic portal imaging devices (EPID) is increasing in demand and often performed through tissue-equivalent material prior to actual patient treatment (Van Elmpt et al, 2008). In vivo dosimetry, using metal oxide semiconductor field effect transistors (MOSFETs) (Varadhan et al, 2006), thermoluminescent dosimeters (TLDs) (Bedford et al, 2006) and semiconductor diodes (Higgins et al, 2003) placed on IMRT patients’ skin have also previously been studied. Further, intra-cavitary dosimetry using TLDs in a naso-oesophageal tube has also been investigated by Gagliardi et al, (2009) (Figure 2.14). In response to requirements for achieving the highest intercomparison levels and to support multi-institutional clinical trials, multi-purpose dosimetry phantoms such as “LEGO” (Jeong et al, 2011) (Figure 2.15a), “ELVIS” (Harisson et al, 2011) (Figure 2.15b) and “PMMA head and neck” (Han et al, 2008) (Figure 2.15c) has been designed and commissioned by various researchers and industrial groups.
In an inter-centre QA network for IMRT verification, a number of groups have developed their own guidelines and criteria for the acceptance of IMRT QA planning and delivery based on the facilities used (Fenoglietto et al., 2011). In the following a review of IMRT audit internationally is presented.

The European QUASIMODO group employed the use of a CarPet pelvis phantom, for dosimetric verification of IMRT of prostate cancer, this contained seven EDR2 radiographic films (Gilis et al., 2005) (Figure 2.16). A gamma tolerance criterion of 4
% (relative to the prescribed dose) and 3 mm (distance-to-agreement) was used.
Results show a maximum local deviation of 3.5% in the mean dose of the Planning
Target Volume (PTV) and 5% in the Organ at Risk (OAR) in the composite dose–area
histograms.

Figure 2.16 Transverse and sagittal view of the polystyrene slab (CarPet) phantom.
Indicated is the planning target volume (in black) surrounding an organ at risk.
Reprinted from Gilis et al., (2005) with permission from Elsevier.

In the United States, the Radiology Physics Centre (RPC) has employed a number of
pelvic/prostate and head and neck phantoms (Figure 2.17) to perform audit and
clinical trial credentialing for IMRT treatment. Credentialing was purposely
introduced by the RPC in order to enhance understanding of IMRT protocols, to
evaluate the ability, and educate staff to delivery accurate doses and to decrease the
deviation rate for figures submitted to clinical trials (Ibbott, 2008). The credentialing
for IMRT head and neck cases was first introduced in 2001. Results have shown that
of 250 institutions, 28% failed to deliver a dose distribution correctly even though the
generous passing criteria was 7% tolerance in dose and 4 mm distance to agreement
(DTA) (Table 2.2 ). In 2004, the credentialing for IMRT pelvic/prostate case was set
up. A total of 64 irradiations were performed. Of these, 86% successfully met the
irradiation criteria. A recent credentialing exercise reported by Ibbott and Followill,
(2010) showed that the passing rate for IMRT head-and-neck phantoms had increased
to 78% (Table 2.3). This may be because the technology has matured and increased
experience of staff using IMRT.
Figure 2.17 The RPC’s phantoms of Pelvic/Prostate (left hand figure) and the head and neck (right hand figure). Both of the phantoms are water-filled shells having inserts with anatomy of imageable target and organs at risk. The inserts contain LiF TLD dosimeters and radiochromic film. Reprinted from RPC website with permission from RPC.

Table 2.2 Result of IMRT credentialing by RPC (Adapted from Ibbott, 2008).

<table>
<thead>
<tr>
<th>Phantom</th>
<th>Prostate</th>
<th>Head and Neck</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiations</td>
<td>64</td>
<td>250</td>
</tr>
<tr>
<td>Pass</td>
<td>55</td>
<td>179</td>
</tr>
<tr>
<td>Fail</td>
<td>9</td>
<td>71</td>
</tr>
<tr>
<td>Year introduced</td>
<td>2004</td>
<td>2001</td>
</tr>
</tbody>
</table>

Table 2.3 Passing rates for five of the RPC’s anthropomorphic phantoms (Adapted from Ibbott and Followill, 2010).

<table>
<thead>
<tr>
<th>Site</th>
<th>Institutions</th>
<th>Irradiations</th>
<th>Pass rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>156</td>
<td>175</td>
<td>82%</td>
</tr>
<tr>
<td>Head and Neck</td>
<td>537</td>
<td>763</td>
<td>78%</td>
</tr>
</tbody>
</table>

In the United Kingdom, the Radiotherapy Trials Quality Assurance Group under the auspices of the National Cancer Research Institute (NCRI) offer a dosimetry QA service for centres entering national IMRT trials such as Parotid-sparing intensity modulated versus conventional radiotherapy in head and neck cancer (PARSPORT), Conventional or hypofractionated high dose intensity modulated radiotherapy for prostate cancer (CHHIP), COchlear sparing therapy and conventional radiation (COSTAR) and Intensity modulated and partial organ radiotherapy (IMPORT High) (Budgell et al, 2011). Recently a national dosimetric audit of IMRT has been carried-
out by Budgell et al, (2011) with the use of mailed film and alanine dosimeters. A total of 78 IMRT plans were submitted including 35 prostate plans, 32 head and neck plans (H&N), 4 breast plans, 5 prostate and pelvic node plans (PPN) and 2 others plans. All the plans were irradiated in a flat water-equivalent phantom at a depth of 5 cm by all the 57 participated radiotherapy centres in UK. For alanine measurements, four out of 78 plans checked showed a deviation more than ±5% from the dose envisaged by the treatment planning system. Apart from the three measurements outside more than 10% (-77.1%, -29.1% and 14.1%), the mean distribution was 0.999 with a standard deviation of 0.015. Whereas, for the film measurements more than 95% of the pixels passed a gamma criterion of 3%/3 mm for 176 investigated fields from simple IMRT plans (comprising prostate and breast plans). However, for multifaceted IMRT plans (especially head and neck), eight out of 245 fields attained less than 95% pixels passing a 4%/4 mm gamma criterion (Table 2.4). Based on the audit results, they conclude that the modelling and delivery of IMRT in the UK is accurate and has been performed safely. Currently a national rotational radiotherapy audit using the PTW 2D Array, PTW semiflex ionization chamber, alanine, and Gafchromic EBT2 film is underway (Hussein, personal communication).

<table>
<thead>
<tr>
<th></th>
<th>2%/2 mm</th>
<th>3%/3 mm</th>
<th>4%/4 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prostate</td>
<td>95.8%</td>
<td>99.2%</td>
<td>99.8%</td>
</tr>
<tr>
<td>H&amp;N</td>
<td>89.9%</td>
<td>95.9%</td>
<td>98.2%</td>
</tr>
<tr>
<td>Other</td>
<td>93.0%</td>
<td>98.0%</td>
<td>99.2%</td>
</tr>
<tr>
<td>All sites</td>
<td>92.9%</td>
<td>97.7%</td>
<td>99.2%</td>
</tr>
</tbody>
</table>

Table 2.4 Results for IMRT film measurements were analysed at 2%/2 mm, 3%/3 mm and 4%/4 mm of gamma criteria for each beam. Reprinted from Budgell et al, (2011) with permission from Elsevier.

A national IMRT dosimetry audit for 23 radiation oncology institutions in Switzerland was performed in 2008 with the ultimate goal to investigate the full IMRT planning and delivery chain (Schiefer et al, 2010). This study addressed concerns on the limitation of the dose calculation algorithm in IMRT techniques to accurately calculate a dose in an inhomogeneous area, especially in low-density regions. Therefore, a mail based audit involving ionization chamber and Lithium Fluoride (LiF) dosimeters were utilized. A total of 30 irradiated plans were performed.
using the CIRS thorax anthropomorphic phantom with inhomogeneities (Figure 2.18). Moreover, the absolute dosimetry of the applied beams was also investigated. As proposed by Knöös et al. (2006), the results have been grouped based on a type “a” or type “b” of dose calculation algorithms of Treatment Planning Systems (TPS). In the type “a” algorithms the effects of inhomogeneity are accounted for by applying corrections based on equivalent pathlength (EPL) and the changes in lateral transport of electrons are not modelled. The Eclipse modified Batho (ModBatho) algorithm and Eclipse equivalent tissue-air ratio algorithm (ETAR) are examples of type “a” algorithms. On contrast in the type “b” algorithms, the changes in lateral electron transport are modelled and examples in this group are Eclipse analytical anisotropic algorithm (AAA) and Pinnacle collapsed cone convolution superposition (CC) algorithm. For absolute dose measurements, the mean ratio between the dose derived from the single measured dose and calculated dose (TPS) was 1.007 ± 0.010 and 1.002 ± 0.01 for the ionization chamber and LiF dosimeter respectively. For IMRT planning verification, a type “b” dose algorithm gave a better agreement between the calculated dose and measured dose (for both LiF and ion chamber) compared to a type “a” dose algorithm in the lung tissue of the planning target volume (PTV). Whereas for regions outside the lungs, a small discrepancy was found for type “a” and “b” dose algorithms between measured dose (LiF dosimeter) and calculated dose values, relative to the prescribed dose \( \left( \frac{D_{\text{measured}} - D_{\text{stated}}}{D_{\text{prescribed}}} \right) \) which were 1.9 ± 0.4% and 1.4 ± 0.3% respectively. In conclusion, the results show the accuracy between the two algorithm types is similar in the absence of low-density mediums; whereas type “b” algorithm performs better in low-density mediums.
2.5 Current status and developments in radiotherapy audits and intercomparison

2.5.1 Dosimetry intercomparison

Dosimetry intercomparisons or dosimetric ‘audits’ are defined as a method of quality assurance (Ebert et al, 2009). It has been established as a useful tool to detect errors and estimate consistency in dosimetry status nationally and internationally (Nisbet et al, 1997; Thwaites et al, 1992; Ahmad et al, 2003; Izewska and Meghzifene, 2011). Many advantages of intercomparisons have been reported (Shafiq et al, 2009, Nisbet et al, 1998, Thwaites et al 2002a). The standard deviations and the incident of major discrepancies were observed to decrease in repeated intercomparisons. This was demonstrated by Nisbet et al (1997; 2003) in his electron calibration study where the standard deviation was decreased from 2.2% (in 1996) to 0.7% (in 2003). This is in concordance with findings by Atkocius et al (2001) of Lithuanian audits where the first audit conducted showed 33.3% of the 49 beams checked gave a deviation more than ± 5%, however after repeated intercomparison, all the audited beams demonstrated a deviation less than ± 3%. Other factors that favour the use of intercomparison for external audits are that the quality of clinical dosimetry and confidence of the hospital staff in dosimetry issues may be improved, in particular, when involved with radiotherapy centres from developing countries that have limited
resources, i.e. lacking professional training of medical physicists or inadequate dosimetry equipment (Swinnen et al., 2002; Rassiah et al., 2004). These can be achieved through the implementation of guidance and recommendations provided by the auditor at the end of the intercomparisons programme (Hourdakis et al., 2008). In addition, these outcomes have been extensively reported in IAEA/WHO TLD postal dose intercomparison services that have audited 1118 hospitals in developing countries in Europe, South-East Asia, Latin America, the Western Pacific and Africa (Izewska et al., 2002a).

2.5.2 Levels of intercomparisons audit systems

Various hierarchical structures of external audits for dosimetry have been developed by numerous national and international groups based on mailed TL dosimetry or on-site visits for examples the International Atomic Energy Agency (IAEA), the European Society for Therapeutic Radiology and Oncology-European Quality Assurance Network (ESTRO) and the Radiological Physics Centre (RPC) (Mobit and Kron, 2007; Izewska et al., 2002a). Four levels of intercomparison audit have been defined by the IAEA (Izewska et al., 2002a) and summarized in Table 2.5. Another structure with three levels has been described by Kron et al., (2002) from Australia based on their single dosimetry intercomparison exercises as shown in Table 2.6. A level III in their study would correspond to a level IV as discussed by Izewska et al. (2002a).

**Table 2.5 Intercomparison structure as defined by Izewska et al. (2002a).**

<table>
<thead>
<tr>
<th>Levels</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level I</strong></td>
<td>Postal audits for photon beams in reference condition. (e.g. IAEA/WHO and RPC postal TLD service)</td>
</tr>
<tr>
<td><strong>Level II</strong></td>
<td>Postal audits for photon and electron beams in reference and non-reference conditions on the beam axis.</td>
</tr>
<tr>
<td><strong>Level III</strong></td>
<td>The audits for photon beams in reference and non-reference conditions off-axis and dose at depth on the beam axis for electron beams.</td>
</tr>
<tr>
<td><strong>Level IV</strong></td>
<td>Audits for photon and electron beams in anthropomorphic phantoms.</td>
</tr>
</tbody>
</table>
Table 2.6 Intercomparison structure as defined by Kron et al (2002).

<table>
<thead>
<tr>
<th>Levels</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level I</td>
<td>Verify of absolute dose at one reference point.</td>
</tr>
<tr>
<td>Level II</td>
<td>Verify of absolute dose and relative dose distribution in a simple physical phantom.</td>
</tr>
<tr>
<td>Level III</td>
<td>Verify of absolute dose and dose distribution in an anthropomorphic phantom.</td>
</tr>
</tbody>
</table>

In the present study, based on the intercomparison level's structures as proposed (Izweska et al, 2002a), studies on the Level I and Level IV audits have been carried out and discussed in detail in chapters five and six respectively.

2.5.3 Intercomparison methodologies

There have been various intercomparison methodologies used ranging from postal TLD intercomparisons of reference beam calibration to site visits to investigate advanced radiotherapy techniques (Nisbet et al, 2008). Some intercomparisons have been run by a single centre (Thomas et al, 2002; Nisbet et al, 2008) whereas some of the groups have one or two central auditors visiting each centre in the group, or round robin approaches with different centres taking it in turns to audit each other. However, high levels of trust and good assistance between departments are needed (Thwaites et al, 2002a). Postal audit systems provide the most cost-effective method for carrying out intercomparison audit in terms of numbers of centres that can participate and large geographical areas that may be covered (Swinnen, 2005). Whereas on-site audit systems offer advantages of better accuracy and allow flexibility of approach both in terms of what can be tested and in terms of the associated procedural audit. Nevertheless, a number of challenges have been identified including high costs, time-consuming when involved with the complex audit (non-reference condition) (Budgell et al, 2011), and a limited geographical scale that could be covered (Sadagopan et al, 2009). To-date, many audits groups have designed more sophisticated phantoms for auditing more multifaceted and realistic treatment situations (Thwaites et al, 2002a). Some of them developed specific phantoms for audits group whereas others use the phantom for clinical trial audits (Thwaites et al, 2002b). Initially the intercomparison scope was limited to megavoltage photon dosimetry. Today the scope has been extended by several of the audit groups in order to fulfill the requirement of advanced radiotherapy techniques. Different treatment modalities have been investigated.
from kilovoltage photons, electrons, protons, brachytherapy to image registration algorithms (Nisbet et al, 2008).

2.5.4 National and international development of dosimetry audit
2.5.4.1 Development of dosimetry audit in the IAEA/WHO
2.5.4.1.1 IAEA/WHO postal dose audit program

The International Atomic Energy Agency (IAEA) (section of Dosimetry and Medical Radiation Physics, Nuclear Sciences and Applications Department) has been involved in radiation comparison for over 50 years. It initiated its first trial postal dose inter-hospital comparison program in 1965-1966 using Fricke- and LiF thermoluminescent dosimeters (TLDs). The World Health Organization (WHO) joined the program in 1968 and it has become known as the "Joint IAEA/WHO Dose Intercomparison Service for Radiotherapy" (Izewska et al, 2002a; Izewska and Meghzifene, 2011). The service has employed the use of LiF dosimeters with the aims of improving the accuracy and consistency of clinical dosimetry under reference conditions in radiotherapy hospitals worldwide (Izewska et al, 2003) (Level I) (Figure 2.19). The scientific and technical aspects of the service are lead by the IAEA, whereas the WHO is responsible for local organization and the distribution of the TLDs to the participating centres (Izewska and Andreo, 2000). Once irradiated, the TLDs are evaluated at the IAEA dosimetry laboratory and the measured results are compared with stated values of the participant centres (Izewska et al, 2002a). Follow-up programmes have been taken for centres with deviation outside the acceptance limits of 5% (IAEA, 2002). The first stage of the service monitored the calibration of $^{60}$Co units; however in 1991, the scope of audit was extended by including megavoltage photon beams and electrons beams from linear accelerators (Izewska and Meghzifene, 2011). Today, IAEA/WHO monitors approximately 8500 beams in 1764 hospitals in 122 countries (Izewska and Meghzifene, 2011). Figure 2.20 shows the results of the IAEA/WHO TLD audits performed in 1666 hospitals in 121 countries during the period 1969 to 2009, involving approximately 7890 radiotherapy photon beams. 80% of the results show a percentage deviation within the acceptance limits (5%) (Izewska et al, 2010). There is an improvement in the number of hospitals who have achieved acceptance limits (from approximately 50% to >90%) compared to the results when the service was first incepted (Izewska et al, 2010).
Figure 2.19 TLD holders designed by IAEA are being used for postal dosimetry audits of high energy photon beams. A standard holder for on-axis measurements (left hand figure). Reprinted from Izewska et al, (2007) with permission from Elsevier. TLD holder designed by IAEA is being used for postal dosimetry audits of high energy electron beams (right hand figure). Reprinted from Izewska et al, (2010) with permission from IAEA.

Figure 2.20 Results of the IAEA/WHO TLD postal dose audits of radiotherapy hospitals for the delivery of absorbed dose to water under reference conditions during 1969 to 2009. Reprinted from Izewska et al, (2010) with permission from IAEA.

Since 1976, this service has been offered to Secondary Standards Dosimetry Laboratories (SSDLs) operating in several countries in order to monitor the consistency of dosimetry practice (Izewska and Meghzifene, 2011). It has been called the IAEA/WHO SSDL Network service. Nine laboratories participated in the early service and in the following years, the number increased to over 30. Currently, this network consists of 85 laboratories in 67 countries. Recent results discussed by Izewska et al, (2010) show that 97% of the results were within the acceptance limit 3.5% from 1997 to 2009 (Figure 2.21). Recently, the demand of advanced radiotherapy techniques such as IMRT and IGRT in treating cancer has developed rapidly. Therefore, the extension of current dosimetry audit to include measurements
in non-reference conditions is needed. Moreover, measurement in non-reference conditions was a major contribution to large deviations in several international audit studies such as ESTRO-EQUAL and RPC as mentioned earlier in section 2.4.2. Concerning this situation, Izewska et al, (2007) carried out an off-axis multi-national pilot study for photon beams; under on IAEA coordinated research project on the development of TLD-based quality audits for radiotherapy dosimetry. The previous TLD audit scope in reference conditions has been extended in this project. The modified IAEA TLD holder for non-reference irradiation was employed (Figure 2.22). A total of 146 non-reference condition measurements (consisting of different beam parameters) were carried-out and the results show deviation is within accepted limits with the mean distribution of 0.999 ± 0.012 (Figure 2.23).

Figure 2.21 Results of the SSDL IAEA/WHO TLD audits from 1997 to 2009. 29 deviations were found outside the acceptance limit of ±3.5% for 988 beam calibrations involving 71 laboratories including 304 high energy X ray beams (Δ) and 684 ⁶⁰Co (●) beams. Reprinted from Izewska et al, (2010) with permission from IAEA.

Figure 2.22 Modified holder for measurements in non-reference conditions, TLD positions are on-axis and off-axis. Reprinted from Izewska et al, (2007) with permission from Elsevier.
2.5.4.1.2 IAEA on-site visit

As mentioned in the previous section, once beam calibrations outside tolerance have been detected, detailed follow-up procedures are implemented. A second TLD check is offered to the particular centre to re-check the beam calibration. On-site visits using ionization chambers and appropriate phantoms will be carried-out by IAEA experts in radiotherapy physics when the discrepancies still cannot be solved by the centre or the national experts after the second TLD check (Izewska and Andreo, 2000). There are three levels of on-site review visits proposed by the IAEA (IAEA, 2007a). Level A and B are known as reactive or partial audit (reviews critical parts of the radiotherapy chain), whereas the Level C is called a comprehensive or proactive audits (assessing the entire process of radiotherapy chain (IAEA, 2007b). Further details regarding these levels are summarised in Figure 2.24.

![Figure 2.24 Levels of review visit (Adapted from IAEA, 2007a)](image-url)
The Quality Assurance Team for Radiation Oncology (QUATRO) has been developed by the IAEA in 2005 in order to establish the Level C review visits. The auditing team for QUATRO missions consists of three experts from IAEA members (a radiation oncologist, a medical physicist and a radiotherapy technologist) (Figure 2.25). The radiotherapy infrastructure; patient and equipment related procedures; radiation protection; staffing levels and professional training programmes for the local radiotherapy staff are included in the audit assessment (Izewska, 2010). Five years have passed since QUATRO was first introduced and approximately 50 audits on request from radiotherapy centres in Central and Eastern Europe, Asia, Africa, and Latin America have been conducted. Results of the audits show a few centres have been acknowledged for operating at a high level of competence, while others have received recommendations for improvement. However, through the comprehensive set of recommendations provided in these audits, the radiotherapy practice at participating centres has been improved (Izewska, 2010). Moreover, the gaps identified by auditors in technology, human resources and procedures are well documented by audited centres and have been used for further development of their centres.

Figure 2.25 The local staff at the Radiotherapy Department in Rijeka being taught the details of accurate dosimetry of a clinical radiation beam by a QUATRO medical physics expert (Adapted from IAEA website, 2011).

2.5.4.1.3 Treatment planning systems audit

In order to assist IAEA Member States in developing countries to achieve the accuracy of their treatment planning system (TPSs) at acceptance levels, IAEA, through its technical report series 430 (IAEA, 2004), has commissioned
comprehensive guidelines and protocols for 3D treatment planning systems. In addition to this report, five different multi-purpose phantoms commercially available have been employed for the IAEA Coordinated Research Project on Development of Procedures for Quality Assurance of Dosimetry Calculations in Radiotherapy (Figure 2.26) (IAEA, 2008a). These phantoms represent human anatomy structures and simulate the whole chain of external beam radiotherapy treatment planning activities (Gershkevitsh et al., 2008). The pilot studies have been conducted in Hungarian hospitals and the Baltic States (Gershkevitsh et al., 2010).

Figure 2.26 Five different multi-purpose phantoms commercially available for the IAEA comparison study: a) The EasyBody phantom (Euromechanics Medical GmbH); b) The Quasar phantom (Modus Medical Devices Inc.); c) Standard Imaging phantom 91235 (Standard Imaging Inc.); d) TomoTherapy cheese phantom (Gammex RMI); e) Thorax CIRS Phantom (Model 002LFC) (Computerized Imaging Reference Systems) (Adapted from IAEA, 2008a).

The CIRS Thorax phantom has been loaned by IAEA to the Hungarian Society of Medical Physics for the TPS audit. This phantom was tested on 10 treatment units at 9 different hospitals involving 11 TPS. Results show four out of eleven TPS audited were within the acceptance criteria, while the others had one or more measurements with larger deviations. Moreover, better agreement between calculations and measurements was found in low energy (6 MV) photon beams compared to high energy (15- and 18 MV) photon beams (Gershkevitsh et al., 2010). The range of observed dose deviations was presented and discussed. This enables the identification of ‘areas of need’ related to TPS such as data
input, CT calibration and beam calibration (Gershkevitsh et al., 2008), and leads to the improvement of services by the staff involved.

The five largest radiotherapy departments of the Baltic States region were audited for their TPS practice by following TRS 430. In total seven TPS have been evaluated. In the majority of clinical test cases, all TPS show good agreement between the calculated dose value and measured dose value with deviations less than 3%, with the exception of dose deviations up to 19.2% at points located in the lung equivalent material (Table 2.7). Apart from exceptions related to TPS algorithm limitations, the TPS audit in the Baltic States showed mostly acceptable results. Due to this audit, the awareness among the TPS user to be more responsible with their planning system and understand its limitations has been increased (Gershkevitsh et al., 2010).

Table 2.7 Results of TPSs audit in Baltic States (Adapted from Gershkevitsh et al., 2010).

<table>
<thead>
<tr>
<th>Test description</th>
<th>Measurement point #</th>
<th>Acceptance criteria %</th>
<th>Mean difference % [range]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard SSD 10×10cm² single field</td>
<td>3</td>
<td>2</td>
<td>0.0 [−1.4; 1.9]</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>4</td>
<td>−5.0 [−11.6; 0.8]</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3</td>
<td>−1.7 [−4.5; 4.6]</td>
</tr>
<tr>
<td>Extended SSD rectangular field (4×18cm²)</td>
<td>3</td>
<td>3</td>
<td>−0.5 [−5.2; 3.2]</td>
</tr>
<tr>
<td>Oblique incidence</td>
<td>1</td>
<td>3</td>
<td>−0.7 [−4.3; 4.4]</td>
</tr>
<tr>
<td>Field with blocked corners</td>
<td>3</td>
<td>3</td>
<td>−0.2 [−2.1; 2.2]</td>
</tr>
<tr>
<td>Four field 'box' technique</td>
<td>5</td>
<td>3</td>
<td>−0.4 [−2.5; 6.1]</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>4</td>
<td>1.6 [−6.6; 12.0]</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4</td>
<td>−2.8 [−11.9; 8.5]</td>
</tr>
<tr>
<td>Customised blocking, large low density \text{inhomogeneity}</td>
<td>2</td>
<td>3</td>
<td>0.3 [−1.4; 1.9]</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>4</td>
<td>6.7 [−8.9; 19.2]</td>
</tr>
<tr>
<td>L-shaped field with blocked central axis</td>
<td>3</td>
<td>3</td>
<td>0.4 [−3.3; 3.5]</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>5</td>
<td>2.0 [−2.6; 4.9]</td>
</tr>
<tr>
<td>3 field plan with asymmetrical wedged beams</td>
<td>5</td>
<td>3</td>
<td>0.4 [−2.0; 4.9]</td>
</tr>
<tr>
<td>3 field plan with non-coplanar beam arrangement</td>
<td>5</td>
<td>3</td>
<td>0.1 [−3.2; 5.2]</td>
</tr>
</tbody>
</table>

2.5.4.2 Development of dosimetry audit in the United Kingdom

Dosimetry intercomparisons have been carried-out extensively in all United Kingdom (UK) radiotherapy institutions over the last 30 years. These range from the intercomparison of megavoltage photons (Thwaites et al., 1992; Blake and Casebow,
2002), megavoltage electrons (Thwaites et al, 1992; Nisbet and Thwaites, 1997; Blake and Casebow, 2002), kilovoltage photons (Thwaites et al, 1992; Blake and Casebow, 2002) to brachtherapy source specification (Thwaites et al, 1992). Most of these intercomparisons have been initiated by the Institute of Physics and Engineering in Medicine (IPEM) involving cooperation with a national interdepartmental audit network. The network consists of eight groups which represent eight geographic regions of the UK. It has been set-up since the early 1990s as a consequence of the first UK comprehensive national dosimetry intercomparison which took four years to complete (Mckenzie et al, 2000; Thwaites et al, 1992).

Through this regional, set up the groups have performed their own audits by developing their own approach of audit methodologies and phantoms. However, they then can share or exchange their different approaches and experience with other groups. Thwaites et al (2002a) demonstrated that this network approach is cost effective, efficient and provides a flexible audit system for the UK. In addition to the network, a collaborative audit with the National Physical Laboratory (NPL) had also been carried out in order to establish the first level of a dosimetry chain (Thwaites et al, 1992). These extra audits have a twofold aim. The first is to raise any interregional differences that would be overlooked by the IPEM. The second is to investigate the dissemination of the UK code of practice of absorbed dose to the end of the calibration chain (Thomas et al, 2002). In 2000, the scope of these audits has been extended by including electron beams and low energy kilovoltage X ray.

The first national audit reported by Thwaites et al, (1992) employed the use of epoxy-resin phantom materials and ionization chambers as dose assessment tools. The phantom was designed by the IPSM Radiotherapy Topic Group (Figure 2.27) and had six removable rods, which could be replaced by an insert such as an ionization chamber. In total 64 radiotherapy institutions in the UK participated in the intercomparison. Results show the mean ratio of measured-to-stated dose of 1.003 was observed with a standard deviation (SD) of 1.5%. Three cases showed a deviation more than the 5% acceptance limit and were followed up, solving particular problems at these centres.
Subsequently, another national audit using electron beams was carried out by Nisbet and Thwaites, (1997). In total 52 radiotherapy centres participated. They also repeated the megavoltage photon calibration audit. An improvement was observed for the photon audit with the standard deviation (SD) reduced from 1.5% (Thwaites et al, 1992) to 1.0% (Table 2.8). 100% of the measurements were observed to be within the pre-set tolerance of 3% compared to 97% observed by Thwaites et al., (1992). The mean ratio of measured-to-stated dose for electron beams was 0.994 (SD 1.8%, 94% within 3%, 99% within 5%) (Thwaites et al, 2002a).

NPL has also carried out audit programmes for megavoltage photons, electron (3-22 MeV) and low and medium energy photons (10-300 kV) (Bass et al, 2008). Approximately 70 audits have been carried-out. The findings for megavoltage photons and electron audits were similar to that reported by Nisbet and Thwaites, (1997) and Thwaites et al, (1992). In addition to the results, the decrease in the standard deviation in both cases has also been observed (Table 2.9).

The Scottish+ group is one of the most active groups in the national interdepartmental audit UK network. This group has good collaborations with other audit organizations, nationally and internationally. The group is involved with basic dosimetry audit such as megavoltage photon beam calibration, electron beam calibration, kilovoltage, and brachytherapy calibration. The SD for all audited beams during 1992 to 2002 was within tolerances (Thwaites et al, 2002a) (Table 2.10). A Semi-anatomic epoxy resin based phantom has also been employed by the Scottish group for auditing breast-, lung-thorax- and head and neck treatment plans (Fig 2.28). Overall results showed 96% of measurements within a tolerance of 5% for breast plans, 100% tolerance for thorax plans,
and 97% to 100% tolerance for head and neck plans (90° wedge pair and oblique wedge pair) (Thwaites et al., 2002a).

**Table 2.8 Intercomparison of photon beam studies** (Adapted from Nisbet et al., 2008)

<table>
<thead>
<tr>
<th>Host</th>
<th>Ratio of measured-to-stated dose</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPL, 2008</td>
<td>1.003</td>
<td>0.7%</td>
</tr>
<tr>
<td>Nisbet and Thwaites, 1997</td>
<td>1.003</td>
<td>1.0%</td>
</tr>
<tr>
<td>Thwaites et al., 1992</td>
<td>1.003</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

**Table 2.9 Intercomparison of the electron beam studies** (Adapted from Nisbet et al., 2008)

<table>
<thead>
<tr>
<th>Host</th>
<th>Ratio of measured-to-stated dose</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPL, 2008</td>
<td>1.003</td>
<td>0.4%</td>
</tr>
<tr>
<td>Nisbet and Thwaites, 1997</td>
<td>0.994</td>
<td>1.8%</td>
</tr>
</tbody>
</table>

**Table 2.10 Audit results for calibration beam and single field parameters carried out by Scottish+ Group**

<table>
<thead>
<tr>
<th>Calibration beam</th>
<th>Ratio of measured-to-stated dose</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Megavoltage photon</td>
<td>1.001</td>
<td>1.1%</td>
</tr>
<tr>
<td>Electron calibration</td>
<td>0.997</td>
<td>1.8%</td>
</tr>
<tr>
<td>Kilovoltage calibration</td>
<td>1.001</td>
<td>1.6%</td>
</tr>
<tr>
<td>A range of geometric</td>
<td></td>
<td></td>
</tr>
<tr>
<td>parameters</td>
<td>1.000</td>
<td>1mm</td>
</tr>
<tr>
<td>Other single field dosimetric parameters</td>
<td>0.998</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
The National Trials QA centre based at Mount Vernon, The Royal Marsden, Clatterbridge and Velindre Hospitals have been established by the NCRI in order to support general QA requirements for clinical trials throughout the UK. They have seven levels of modules of QA clinical trial which can be participated in by all the UK’s radiotherapy centres as shown in Table 2.11. The results of the clinical trials for IMRT credentialing have been reviewed recently by Khoo et al., (2008); Clark et al., (2009) and Ciurlionis et al., (2011).

In vivo-, brachytherapy- and small field dosimetry have also been reviewed by some of the UK audit groups as part of possible compulsory requirements on quality assurance programmes in the future (Mcdonald and Mclellan, 2008; Drewell and Sankar, 2009; Edwards et al, 2009; Sander et al, 2010). The first attempt was reported by NPL, who designed the graphite calorimeter for the measurement of HDR brachytherapy and small field dose (Sander et al, 2010). Furthermore, NPL ready purchased a new optical scanner, IQSCAN, to set up an optical tomography system as a readout of 3D-dosimeters in order to verify 3D dose distributions. This has also been suggested in IAEA meetings (2002) to use gel dosimeters as one of the audit tools. Currently, NPL is still working to investigate suitable dosimeters to be used with the scanner (Pierce, 2008). Alanine is also being considered as a dosimeter in clinical practice. This is because of its characteristics; e.g. water equivalence, independent of energy and non-destructive read-out. NPL launched a mailed alanine reference dosimetry service in 1996 (Sharpe et al, 1996). This system has been used widely in intercomparison audit throughout the country.
Table 2.11 NCRI modules of QA (Adapted from NCRI Radiotherapy Clinical Trials Quality Assurance Web Site).

<table>
<thead>
<tr>
<th>Module</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 1</td>
<td>Anatomical site and trial specific questionnaire&lt;br&gt;Pre-trial plan submission according to trial protocol (QA team or centre example).&lt;br&gt;Ongoing advice to centres on protocol adherence.&lt;br&gt;No patient by patient QA</td>
</tr>
<tr>
<td>Module 2</td>
<td>Planning exercise prior to patient randomisation&lt;br&gt;Outlining exercise prior to patient randomisation&lt;br&gt;Ongoing advice to centres on protocol adherence and plan optimisation&lt;br&gt;No patient by patient QA</td>
</tr>
<tr>
<td>Module 3</td>
<td>Plan assessment for a selection of initial patients&lt;br&gt;Simulator image assessment for a selection of initial patients&lt;br&gt;Portal images assessment for a selection of initial patients&lt;br&gt;In-vivo dosimetry for a selection of initial patients</td>
</tr>
<tr>
<td>Module 4</td>
<td>Ongoing assessment of plans throughout the course of the trial&lt;br&gt;Ongoing assessment of portal images throughout the trial&lt;br&gt;In-vivo dosimetry on a selection of patients</td>
</tr>
<tr>
<td>Module 5</td>
<td>Individual site visit</td>
</tr>
<tr>
<td>Module 6</td>
<td>Pre-treatment assessment of patient volumes</td>
</tr>
<tr>
<td>Module 7</td>
<td>Pre-treatment assessment of plan</td>
</tr>
</tbody>
</table>
2.5.4.3 Development of dosimetry audit in the United States

The US NCI (National Cancer Institute) has provided funding for the Radiological Physics Centre (RPC) since 1968 in order to perform quality auditing of radiation therapy dose delivery at institutes that are participating in clinical trials. There are four types of monitoring methods that have been used by RPC in their QA programs. The methods are on-site dosimetry reviews visits, the remote LiF TLD audit of machine output calibration, credentialing for advanced technology clinical trials and review of patient treatment records (Ibbott, 2005; Ibbott and Followill, 2010). The RPC has employed the use of LiF TLD dosimetry and acrylic blocks (Figure 2.29) to perform remote audits of beam output of photon and electron beams in 1977 and 1982 respectively. The scope of audits was extended to include measurements of proton beams in 2007. In total, approximately 14000 beams have been monitored by the RPC every year. The established acceptance criteria is ±5%. The dose agreement has been improved after 30 years involvement with postal TLD audits (only 5% to 6% have failed to meet the acceptance criteria on the first measurement) (Ibbott and Followill, 2010). This is probably due to all these radiotherapy centres being consistently monitored by the RPC (Aguirre et al., 2002). The RPC has recently adopted Optically-Stimulated Luminescence (OSL) dosimetry as an alternative for remote dosimetry (Aguirre et al., 2009). The OSL system consists of a number of “nanoDot” dosimeters and MicroStar “InLight” readout devices manufactured by Landauer Corp. Their dosimetric characteristics have been established prior to the actual audits (Aguirre et al., 2009) (Figure 2.30). Their future work is to commission this system for auditing of proton beams and for use in the RPC’s phantoms.

More than 500 errors and 85 lapses in QA were observed at radiotherapy centres thorough RPC on-site dosimetry review. The majority of the errors were found in electron calibration, off-axis factors, wedge transmission, photon depth dose and implementation of new protocols e.g. TG-51 (Ibbott, 2005). Therefore, 70% of radiotherapy centres have received at least one recommendation for improvement from RPC auditors (Ibbott et al., 2008).
Figure 2.29 Three acrylic blocks are being used for RPC’s reference dosimetry. A) For electrons irradiation; B) For protons irradiation; C) For photons irradiation. (Ibbott and Followill, 2010).

Figure 2.30 NanoDot dosimeters are enclosed in a plastic packet that protects against contamination prior to shipping to the participant audit (left hand figure). A portable microStar reader is user friendly, convenient and provides accurate dose assessments (right hand figure) (Landauer Corp, 2011).

There are two components in credentialing techniques for monitoring advanced technology clinical trials. These are mailing of the RPC’s phantoms and the use of a treatment planning exercise, called a benchmark. Based on the findings reported by Ibbott et al, (2008) the treatment planning benchmarks can be used to detect software errors and reveal incorrect data entry. For instance the RPC’s brachytherapy benchmark test have identified errors in the implementation of the updated TG-43 protocol and corrections to the NIST 1999 standard for number of seed sources (Ibbott et al, 2008). Just 15 minor deviations out of 70 patients have been found by the Gynae Oncology Group 165, HDR cervix in credential centres compared to non-credentialed centres with 57 major deviations and 87 minor deviations out of 275 patients involved (Table 2.12). Follow-up programmes have taken benchmark cases that have failed to meet the acceptance criteria. The RPC auditors contact the
particular audited centre in order to explain the discrepancies and work together with them to resolve errors.

RPC’s anthropomorphic phantom irradiation results show the majority of radiotherapy centers failed to deliver a dose distribution within tolerance. With regard to head and neck measurements, more than 125 radiotherapy centres failed to meet acceptance criteria and had to perform a second irradiation check of the phantom. The acceptance criteria for all phantoms are 7% tolerance in dose and 4 mm distance to agreement (DTA), excluding the lung phantom where the criteria are 5% tolerance in dose and 5 mm distance to agreement (DTA) (Table 2.13).

Table 2.12 shows the deviation rate of several trials as a consequence of credentialing exercises (Adapted from Ibbott and Followill, 2010).

<table>
<thead>
<tr>
<th>Study</th>
<th>Major Deviations</th>
<th>Minor Deviations</th>
<th>Number of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTOG 95-17, HDR &amp; LDR Breast</td>
<td>0</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>RTOG 0019, LDR Prostate</td>
<td>0</td>
<td>6</td>
<td>117</td>
</tr>
<tr>
<td>GOG 165, HDR Cervix</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) Credentialed Centres</td>
<td>0</td>
<td>15</td>
<td>70</td>
</tr>
<tr>
<td>(ii) Non-credentialed Centres</td>
<td>57</td>
<td>87</td>
<td>275</td>
</tr>
</tbody>
</table>

Table 2.13 Results of credential techniques for RPC’s phantoms; delivered using 3D conformal radiation therapy (3D CFRT) irradiation (Adapted from Ibbott and Followill, 2010).

<table>
<thead>
<tr>
<th>Phantom</th>
<th>Radiotherapy centre</th>
<th>Irradiations</th>
<th>Fail rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liver</td>
<td>16</td>
<td>24</td>
<td>50%</td>
</tr>
<tr>
<td>Spine</td>
<td>18</td>
<td>16</td>
<td>25%</td>
</tr>
<tr>
<td>Lung</td>
<td>133</td>
<td>174</td>
<td>31%</td>
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<tr>
<td>Pelvis</td>
<td>156</td>
<td>175</td>
<td>18%</td>
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<tr>
<td>Head and Neck</td>
<td>537</td>
<td>763</td>
<td>22%</td>
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</table>
In five years of studies (2004-2008), three types of common error were identified during the RPC independent review of patient treatment records. These were transcription-, individual- and systematic errors. Results show the frequency of occurrence for these errors were 27%, 11% and 1% respectively. In addition to the results, 39% of the records reviewed had one or more of these types of errors (Ibbott and Followill, 2010). The reviewed results were conveyed to the radiotherapy centres promptly for further action to correct the errors. Once the errors were verified, the detailed of RPC’s calculation regarding the errors is conveyed, and the reasons of the discrepancy are investigated (Ibbott, 2005).

In conclusion, credential techniques are a good method to reduce the deviations in clinical trials. However, there are several notable pitfalls of this technique, including the resources needed, it is time consuming and the loss from the clinical trial pool of contributing radiotherapy centres of those that fail the credentialing test (Ibbott et al, 2008). To overcome the problems, RPC is resolved to make additional phantoms and try to ascertain criteria for prioritizing radiotherapy centres.
Ge-doped optical fibres offer excellent thermoluminescence properties, small physical size, an absence of high voltage or cables, a wide useful dose range, and modest cost. They are proposed herein as dosimeters in radiotherapy. This chapter investigates their dosimetric characteristics using a wide range of photon and electron beams energies. Initial work has concerned key dosimetric characteristics of such TL media, including reproducibility, linearity, fading, energy-, dose rate-, angular-, temperature dependence and effective atomic numbers of the fibres. Ge-doped fibres with 9 µm (Ge-9µm) and 50 µm (Ge-50µm) core diameters have been employed and a number of the dosimetric characteristics studied herein were compared against pure silica optical fibres and lithium fluoride thermoluminescent dosimeters (TLD-100 and TLD-700), considered to be TLD standards.

3.1 Materials
3.1.1 Ge-doped and pure silica optical fibres

The Ge-doped optical fibres used in the present investigations are single and multi mode commercial Ge-doped optical fibres manufactured by INOCORP (Canada), with core diameters of 9 µm and 50 µm respectively (Figure 3.1d). The cladding diameter for the two fibres was 116 ± 0.1 µm (Ge-9 µm) and 75 ± 0.1
µm (Ge-50 µm). Single mode commercial fibre of pure silica (SiO$_2$) with 125 µm cladding diameter, also produced by the same company, has also been employed in this study for purposes of comparison. In preparation of the optical fibres for irradiation, four essential steps were followed. Firstly, the outer polymer of the fibre was removed using a Miller fibre stripper (Miller, Cromwell, USA) (Figure 3.1e) to allow investigation of the TL yield of the fibre core. The outer polymer fibre was then cleaned using methyl alcohol (Figure 3.1c), removing any residual polymer layer. The fibre was then cut into 6 mm long pieces to form individual fibres, providing for convenience of handling and precision in metrology, using a Fujikura CT-30 cleaver (Fujikura, Tokyo, Japan) (Figure 3.1b). Each individual fibres was then weighed using a Sartorius balance (Sartorius, Goettingen Germany) (Figure 3.2) and average masses were found to be 0.200 ± 0.002 mg. In handling the fibre, use was made of vacuum tweezers, (Dymax 5, Surrey, UK) (Figure 3.1a), thus minimizing surface abrasion of the fibre and deposition of dust or finger oil that might alter emission characteristics during heating (Hashim et al, 2010). Finally, the fibres were annealed in a furnace (Carbolite,UK) or (Pickstone,UK) (Figure 3.3). This allows for the establishment of TL sensitivity through removal of residual deep traps and elimination of unstable low-temperature glow peaks, in addition to removing any background signal accumulated during transportation and storage (Hashim et al, 2009a; Espinosa et al, 2006). For this, the fibres were placed in an alumina ceramic boat or brass plate (Figure 3.4) covered with aluminium foil and annealed at 400°C for 1 hour. After that they were left in the furnace for 10 hours to cool to room temperature, those avoiding thermal stress on the fibres. Major metrological influences are environmental factors (temperature, humidity, as well as ultraviolet and visible light irradiation) and physical handling factors (sieving, dispensing and cleaning effects) (Hashim et al, 2009a). As part of the response to these influences, post annealed fibres were retained in a black box (Figure 3.5) to minimize exposure to light, both before and after irradiation (Mohd Noor, N. et al, 2010).
Figure 3.1 Apparatus for preparation of Ge-doped fibres: a) Vacuum tweezer; b) Cleaver; c) Methyl alcohol; d) Ge-doped optical fibres; e) Stripper.

Figure 3.2 Sartorius balance

Figure 3.3 Pickstone furnace
3.1.2 Screening process

Prior to use in any clinical applications, each batch should be screened to ensure the selection of individual dosimeters have approximately equal mass, length and sensitivity, discarding strands that do not satisfy the prescribed dimensions or that have sensitivity outside a defined range of the mean (Furetta, 2003). For a given radiation dose, a variation in TL yield of Ge-doped optical fibres is typical, due to variation in dopant concentration along the length of the optical fibres (Ramli et al, 2009). Therefore, every new batch of Ge-doped optical fibres should be selected through a screening process. A limit of ±5% of the group mean was applied, in accordance with the ICRU specifications (ICRU 24, 1976). In the present study, a large new collection of Ge-doped fibres were screened to establish individual performance, with use being made of an ionisation chamber placed at the same depth as the TL-detector in a perspex phantom. This was performed by irradiating the fibres to a dose of 3 Gy in a solid water phantom using 15 MV nominal photon energy, with 100 cm focus to surface distance (FSD), 10×10 cm² field size, delivered at a rate of 400 cGy/min to the depth of maximum dose using a Varian Linear Accelerator (LINAC) located at the Royal Surrey County Hospital (RSCH). After a period of 12 hours post irradiation, a Solaro TL reader (Vinten TLD, Reading, UK) was used to readout the TL yield, the fibres having been kept in a light-tight box to allow uniform control of thermal fading.
3.1.3 Lithium fluoride (TLD-100 and TLD-700)

To allow comparison of the Ge-doped optical fibres against a more established TL system, use has been made of lithium fluoride doped with magnesium and titanium (LiF:Mg,Ti) (TLD-100 and TLD-700) chips and disks. The chips were of dimension 3.2 × 3.2 × 0.89 mm while the disks were of 4.5 mm diameter × 0.89 mm thick, all were calibrated against a Farmer-type ionisation chamber (Figure 3.6). TLD-100 has a $^6\text{Li}$ content of 7.5% and a $^7\text{Li}$ content of 92.5%, whereas the more expensive TLD-700 has respective contents of 0.01 and 99.99%. The LiF dosimeters were first placed on a flat glass arrangement accommodating up to 100 chips and were annealed at 400°C for 1 hour, followed by 16 hours at 80°C using a furnace (Pickstone, UK) prior to irradiation. Finally they were left in an oven to cool down to room temperature.

![Figure 3.6 LiF dosimeter calibration Perspex phantom](image)

3.1.4 Solid water phantom

It is not practical to measure dose distribution directly in patients treated with radiation, therefore water tissue-equivalent phantoms have been introduced. An ideal phantom material will absorb and scatter photons in the same way as human tissue (Podgorsak, 2005). Ideally, for a given material to be a tissue or water equivalent, it must have the same effective atomic number the same number of electrons per gram and the same mass density as the particular tissue of interest (e.g. adipose tissue). Solid Water Phantoms (RMI4571 Gammex,) (Figure 3.7) of dimension 30 cm x 30 cm with various thicknesses
were used in this project. This material is also used as a dosimetric calibration phantom for photon and electron beams in the radiotherapy energy range (IPSM, 1990; IPEM, 2003).

Figure 3.7 A solid water phantom comprising several layers of individual thickness

3.2 Methods
3.2.1 Photon and electron beam arrangements
For the megavoltage photon beams investigated, high energy photon beams with accelerating potentials of 6-, 10- and 15 MV were employed; use being made of a Varian linear accelerator located at the Royal Surrey Country Hospital (RSCH). The fibres were positioned at the depth of dose maximum and 15 cm of backscatter phantom material was used below the optical fibres to ensure full scatter equilibrium (Figure 3.8). A focus to surface distance (FSD) of 100 cm and 10 x 10 cm² field size was selected for these measurements. The beam quality of megavoltage photon beams is specified to be the tissue phantom ratio $\text{TPR}_{20,10}$ (IPSM 1990; IAEA 2000). This is the ratio of absorbed doses at depths of 20 cm and 10 cm in water phantom for a constant source to detector distance. The important characteristics of this beam quality are that it is independent of electron contamination (IPSM 1990; IAEA 2000).

Figure 3.8 Set-up for photon beam
A Pantak DXT300 orthovoltage x-ray unit (Pantak Inc., Branford USA), also located at the Royal Surrey Country Hospital (RSCH), was used to generate kilovoltage x-ray beams, with accelerating potentials of 90- and 300 kVp. For 90 kVp irradiation, the focus to surface distance was 30 cm, use being made of a circular open-ended applicator (Figure 3.9). For 300 kVp irradiation, a focus-surface distance of 50 cm and a closed-ended applicator were used (Figure 3.10). For low energy photon beams the quality of the beam is expressed in terms of half-value layer (HVL) of the beam (IAEA, 2000; IPEMB, 1996). It is defined as the thickness of attenuating material required to reduce the measured air kerma in air to half of its original value. The HVL for the beams used of 90- and 300kVp were 2.5 mm Al and 2.8 mm Cu respectively (IPEMB, 1996).

![Figure 3.9 Set-up for 90 kVp photon beam](image1)

![Figure 3.10 Set-up for 300 kVp photon beam](image2)

For electrons beams, use was made of a Varian linear accelerator generating high energy electron beams of nominal 6-, 9- and 16 MeV. An applicator of 10 cm × 10 cm and a focus to surface distance of 100 cm were used (Figure 3.11). The beam quality for high energy electron beams is derived from measurement of the half-value depth in water, $R_{50}$ (IPEM, 2003; IAEA, 2000). It is the depth in which the dose in water is 50% of its maximum value.
3.2.2 Sr-90 beta particle source irradiator
A Sr-90 beta particle source irradiator, Stereo Mono Turntable (Lenco, Switzerland) located at the Radiation Lab, Department of Physics, University of Surrey, was used in order to determine the relative response of the optical fibres. The Sr-90 beta particle source is mounted above a rotating carousel which gives a uniform irradiation to the samples placed on the carousel. The automatic irradiator is based on a circular turntable with up to 30 positions for holding the TLD detectors, as shown in Figure 3.12. The radiation field is uniform along the radius of the irradiator. While no calibration certificate for the source is available, by using available information the present dose-rate was calculated to be 330mGy/h, see Appendix A for the detailed calculation.

3.2.3 Reproducibility
To study dose reproducibility, use was made of a nominal 6 MV energy photon beam. The dose rate was 200 cGy/min. A capsule containing 26 selected optical fibres was sandwiched in an epoxy resin water equivalent phantom, RMI4571 (Gammex-RMI,
Nottingham, UK) at the depth of dose maximum, with 15 cm of the phantom material below to ensure full scatter conditions. A focus to surface distance (FSD) of 100 cm and 10 x 10 cm$^2$ field size were selected, the optical fibres were irradiated to a dose of 2 Gy. The optical fibres were read out after a set delay of 24 hours. Five repeat irradiations were made to obtain the percentage reproducibility for the batch.

3.2.4 Linearity
To study linearity and energy dependence, use was made of megavoltage photon beams, kilovoltage photon beam and electron beams. To allow statistical analysis of the variation, thin-walled gelatine capsules were employed to contain the fibres (10 fibres in each capsule). A dose range of 5 cGy to 1000 cGy was studied, covering approximately the range of doses typically delivered in radiotherapy treatments, the former referring to 0.5 % of the central-axis dose, delivered at the periphery of a radiation field.

3.2.5 Dose rate dependence
To check the dependence of measured dose on dose-rate, 10 optical fibres were again placed in each capsule and irradiated by 6-, 10- and 15 MV photon beams, delivering doses of 1-, 2-, 3- and 4 Gy, for dose-rates ranging from 100 cGy/min up to 600 cGy/min.

3.2.6 Angular dependence
While it is conventionally understood that the SiO$_2$ fibres are amorphous, with little prospect of orientational dependency, the possibility of germano-silicate crystallites formed within the fibres cannot be ruled out. Such an occurrence could give rise to orientational dependency. With this possibility in mind and to rule out any real orientational dependency, Perspex phantoms were constructed for each of the three photon beam energies (6 MV, 10 MV and 15 MV), with different thickness in order to ensure charged particle equilibrium (Figure 3.13 and 3.14). The fibres were placed at the centre of the Perspex and irradiated at a dose rate of 600 cGy/min to a dose of 4 Gy, with the gantry of the linear accelerator rotated to various angles, ranging from 0° to 360° (Figure 3.15), to investigate the effect of irradiation angle on absorbed dose.
Figure 3.13 Sketch diagram of perspex phantom designed for, a) 6MV photon beam; b) 10MV photon beam; c) 15MV photon beam.
Figure 3.14 Perspex phantom design for a) 6MV photon beam; b) 10MV photon beam; c) 15MV photon beam.
3.2.7 Temperature dependence

For temperature dependence studies, 10 capsules were prepared, each containing optical fibres. These were put in a circulating water bath (NESLAB, Georgetown, Canada) (Figure 3.16). Water temperatures from 5 °C up to 50 °C were obtained at 5 °C increments. Each fibre capsule in turn was taken out of the water bath and irradiated immediately to deliver the planned dose in order to make sure the fibres were irradiated at close to the desired temperature settings. A dose rate of 600 cGy/min and nominal photon energy of 10 MV were used in this study.
3.2.8 Fading
Fading is the loss in TL yield as a result of a delay in readout time following irradiation (post-irradiation fading) or loss of signal sensitivity before irradiation (pre-irradiation fading). It is one of the important dosimetric characteristics of such TL material and has been studied extensively, both theoretically and experimentally for LiF:Mg,Ti (TLD-100, TLD-600, TLD-700) (Biran et al. 1996), CaSO4:Dy (TLD-900) (Wang et al., 1987), LiF:Mg,Cu,P (TLD-100H,TLD-600H, TLD-700H) (John et al., 2010; Luo, 2008) and CaF$_2$ (TLD-200, TLD-300, TLD-400) (Yazici et al., 2002) but not Ge-doped fibres. Fading results reported in the literature show considerable dissimilarity, in the range of (1%-10%) at 30 days, due to differences in experimental set-up as exemplified by storage-temperature and glow-curve peaks used to determine dose and annealing cycles (Rah et al., 2008). As is well established, fading can result from exposure to light (optical fading) and heat (thermal fading). Other causes of fading are much less well established, often referred to as anomalous fading. The present study focuses on post irradiation fading of two types of Ge-doped optical fibres (Ge-9µm and Ge-50µm). This work supports efforts to establish the fibres as mailed dosimeters for audit purposes (as discussed in detail in chapter 6), by examining delay in readout time subsequent to irradiation. Examination has also been made of changes in TL yield due to temperature change and dose levels, using fibres selected to provide a coefficient of variation (CV) of 3%. Results for fibres (9 µm and 50 µm core diameter) have been compared against those of lithium fluoride thermoluminescent dosimeters (TLD-100 and TLD-700).

3.2.8.1 Dose levels
A total of 1520 fibres (152 capsules with 10 fibres in each) and 350 chips of LiF dosimeters were irradiated to a series of dose levels: 0.5 Gy, 2 Gy and 10 Gy, delivered at a dose rate of 200 cGy/min using a 6MV photon beam. Five chips of each type of LiF dosimeter (Figure 3.17) and ten of each type of Ge-doped optical fibre dosimeter (Figure 3.18) were read out immediately after irradiation to obtain data at 0 hours. Further fibres and LiF dosimeters were kept in a black box at room temperature (21 ± 2)°C, these control fibres being used to account for background signal, also being stored together with the irradiated dosimeters. Samples of these were read out everyday up to 7 days and thereafter at periods of once per week up to
70 days post irradiation. Five control TLDs were readout at the same time as the others dosimeters.

Fading response was also obtained for dosimeters over a more protracted period of 133 days, irradiated to a dose of 2 Gy and maintained throughout at room temperature (21± 2)°C. Readouts were repeated on new sets of fibres, LiF and control dosimeters, at day 112 and finally at day 133.

![Figure 3.17](image1.jpg)

**Figure 3.17** LiF dosimeters were irradiated in a perspex phantom at the same depth as a Farmer-type ionisation chamber.

![Figure 3.18](image2.jpg)

**Figure 3.18** Ge-doped fibre dosimeters were sandwiched in the sheets of solid water phantom and bolus at depth of maximum dose of 1.5 cm.

3.2.8.2 Temperature change

A total of 440 fibre dosimeters (comprising 44 capsules with 10 fibres in each) and 220 chips of LiF dosimeters were used. As before, these were irradiated to a dose of 2 Gy under the same previous conditions. One capsule for each type of fibre dosimeter and five chips of each type of LiF dosimeter were read out immediately after irradiation, while the remaining capsules of fibre and LiF dosimeters were stored at a
temperature of -25 ± 2°C, at room temperature 21 ± 2°C, and at an elevated temperature of 35 ± 2°C. These account for a possible range of temperature experienced by the fibres during air transportations and in use in warm climates as may be experienced in a postal audit. A room freezer at the Faculty of Health and Medical Sciences, University of Surrey, (Figure 3.19) was used to achieve the low temperature while a microprocessor controlled hotplate (Whatman Hotplate 420, UK) (Figure 3.20) was used to keep other dosimeters at the elevated temperatures. The fibres and LiF dosimeters were read out everyday up to 7 days and thereafter at once per week for up to 31 days, also reading out the control dosimeters at those same times.

3.2.9 SEM and EDX analysis
Detection efficiency and tissue equivalence is dictated by the effective atomic number of a medium. In order to obtain effective atomic number of the Ge-doped fibres and pure silica fibres (SiO₂), Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) analysis was performed at the MicroStructural Studies Unit, University of Surrey. The elemental composition of the Ge doped optical fibre, of 50 μm and 9 μm core diameter and pure silica fibres was determined by SEM and EDX analysis, comparing against the information given by the manufacturer. The fibres used in this particular study were selected from those producing the greatest yields subsequent to irradiation by the Sr-90 source. This is important, ensuring that the existence of Ge in the fibres could be most easily detected during EDX analysis.

In the SEM/EDX analysis, the sample is first coated by gold using a sputtering procedure after being attached to the surface of the specimen stub (Figure 3.21a). A
MODEL RV3 sputtering machine (Edwards, Sussex, UK) was used for the gold coating procedure, as shown in Figure 3.21b and 3.21c, the gold being deposited in order to allow leakage of charge build-up, thereby minimizing electrostatic effects during the scanning process. The scanning process was performed over the surface, and along the cross-sectional area of the fibres. The X-ray spectrum was obtained by detecting the X-ray fluorescence emissions from the samples using the combination of the HITACHI S3200N (Hitachi, Tokyo, Japan) SEM with the ultra-thin window Energy Dispersive X-ray (EDX) detector (Figure 3.22). INCA Energy software (Oxford Instruments Nano Analysis, 2006) was used for both qualitative and quantitative elemental analysis.

Figure 3.21: (a) Preparation of the samples by attaching them to the surface area of specimen stub; (b) Sputtering machine used for gold coating procedure; this minimizes electrostatic effects during the scanning process by promoting leakage of charge build up; (c) The samples ready for scanning to be performed across the surface and cross-sectional area of the optical fibre core.
3.3 Readout and Glow curves

3.3.1 Readout

The basic principle of the TLD reader is shown in Figure 3.23 and detailed by Marinello, (1994); in simple terms, the reader system consists of a heating and light detection system.

The TL readers that are commercially available offer a range of heating systems, either through close contact of the heating arrangement with the TL material (using the heated support) or through non-contact procedures (using hot nitrogen gas). On the other hand, every one of the systems recognize the need for three stages of a heating phase, each at a different temperature; 1) preheating, 2) readout and 3) anneal stages. During the preheating stage, the TL materials are exposed to a temperature of, for instance, 160°C to release shallow traps (sweeping away the low temperature peaks, known as unstable peaks) (Solaro Manual, 1996). The readout stage is used to acquire the information for dosimetry, the so-called (stable) peaks and all TL signals are recorded during this stage. Nitrogen gas is employed throughout in order to reduce spurious TL phenomena (Mc Keever, 1985), diminishing for instance oxidation of the heating elements and thereby reducing the background signal (Solaro Manual, 1996).

The final stage of the heating phase is the annealing phase. Usually a high temperature will be involved at this stage in order to eliminate any residual (deep
lying) traps and re-establishing the original intrinsic background of the TL materials. In order to ensure TL materials have good reproducibility, the materials should then be cooled relatively rapidly using nitrogen gas.

The light detection system consists of a Photo-Multiplier tube (PMT) that detects the thermoluminescence light emission (infra-red filtered) and changes it into an electrical signal. This process arises after the emitted light is collected and guided into the PM Tube by a light guide, as shown in Figure 3.23. There are filters positioned in front of the PMT window in order to adapt the emission to the spectral response of the PM Tube and to the wavelength of the light emitted by the TL material to be readout (Marinello, 1994).

The electric signal is understood to be proportional to the light emission and will either be amplified and fed to an integrator or converted into pulses by two current-to-frequency converters (CTFC) and fed to a scaler (Marinello et al, 1992). The electric signal is converted to a train of pulses with a frequency proportional to the current. This signal, associated with the absorbed dose, is read-out and stored by an electrometer or otherwise protected on the hard disk of an associated computer. In order to acquire maximum information, most current readers will display glow curves during dose measurements.

Four types of TLD reader have been used throughout the present studies, due in part to technical problems but also providing familiarity with the range of TL readers that are produced. Thus, apart from the main Solaro reader, use was also made of Toledo, Harshaw 5500 and 4500 readers.

A MODEL 645 E ‘UNIVERSAL TOLEDO’ TLD reader (Vinten Instruments Ltd, Buckinghamshire, UK) (Figure 3.24) was used during the fading effect investigations. A nitrogen gas pressure of 0.5 bar was used during the readout. The following parameters were also used during the readout: preheating temperature of 160°C for 10 seconds; readout temperature of 300°C for 25 seconds with a heating phase rate of 25°C per second; annealing temperature of 300°C for 10 seconds to remove any residual signal in the fibres. The units of the measuring system used is counts (c). A
light source comprising $^{14}$C was used in order to monitor consistency of function of the machine.

![Figure 3.23 Principle of TLD readers. Adapted from (Barthe and Portal, 1990).](image)

LiF dosimeters were read out using a Harshaw 5500 Reader (Thermo Fisher Scientific Inc, Waltham, US) (Figure 3.25) located at the Regional Radiation Protection Service, Royal Surrey County Hospital. This reader was used to read the LiF response during investigations of out-of-field dose distribution and in-phantom IMRT prostate dosimetry verification (chapter 4 and 5 respectively). This automatic reader operates by using a linear hot gas heating system continuously provided by a nitrogen generator. This reader can accommodate up to 50 dosimeters per run on a CD type carousel (Harshaw 5500). The units of this measuring system are nano-coulomb (nC) charge accumulated. The following time-temperature profile (TTP) was used: preheat at 145°C for 10 seconds (s); read out temperature 300°C for 10 s and a heating rate phase of 17°Cs$^{-1}$, controlled by WinRems™ software.

A Solaro TLD reader (NE Technology Ltd, Reading, UK) in Figure 3.26 provided for the majority of Ge-doped optical fibre readouts, care being made to use a nitrogen gas atmosphere of 0.5 bar. Nitrogen gas was used to suppress spurious light signals from triboluminescence and also to reduce the oxidation of the heating element.
Triboluminescence is a potential issue in cutting of the fibres into 6 mm long pieces. During readout the following parameters were used: preheat temperature of 160°C for 10 seconds; readout temperature of 300°C for 25 seconds with a heating phase ramp rate of 25°C per second. An annealing temperature of 300°C was used for 10 seconds to remove any residual signal in the fibres. A light source comprising $^{14}$C was used in this reader in order to monitor consistency of function of the machine.

A Harshaw Manual Reader 4500 (Thermo Fisher Scientific Inc, Waltham, US) (Figure 3.27), also located at the Regional Radiation Protection Division, Royal Surrey County Hospital, was also used to read Ge-doped TL-yield 12-hours post-irradiation, providing account of any thermal fading. This system was used to read fibres during the out-of-field dose distribution, the investigation of in-phantom IMRT prostate dosimetry and the audit investigation studies (chapter 4, 5 and 6 respectively). This reader is a manual TLD with dual capability; hot gas and planchette modes. It has dual photomultiplier tubes connected to the electronics, thus enabling it to accommodate four element samples, further enabling reading of a sample in two channels at a time. It is PC controlled using the WinRems™ software. During the readout, the following parameters were used: preheat temperature 160 °C for 10 s; read out temperature 300 °C for 25 s and heating rate phase of 25 °Cs$^{-1}$. As before, the units of this measuring system are the nano-coulomb (nC) charge collection.

![Figure 3.24 Toledo reader](image1)

![Figure 3.25 Harshaw 5500 reader](image2)
3.3.2 Glow curves
Glow curves, obtained during readout, provide a plot of TL yield with variation in temperature, this being important in gaining a better understanding of the complex nature and properties of the TL medium. As such, each medium will produce characteristic glow curves, the detailed shape also reflecting the choice of temperature ramp-rate. In this study, crystalline (LiF dosimeters) and amorphous (Ge-doped dosimeters) materials have been employed. As illustrated in Figure 3.28, the Ge-doped dosimeters show a broad-peaked glow curve while LiF dosimeters (TLD-100 and TLD-700) show a narrow-peaked glow curve more indicative of a crystalline structure (Figure 3.29). Both of these sets of glow curves were obtained and plotted by using the TOLEDO TLD reader and also as a result of irradiation to a photon-mediated dose of 2 Gy, at a dose rate of 200 cGy/min using a 6MV photon beam. Figure 3.30, 3.31, and 3.32 show different shapes of glow curve for irradiated lithium fluoride and Ge-doped optical fibres obtained by use of the Harshaw 5500 TLD reader, Solaro and Harshaw 4500 readers respectively.
Figure 3.28 The characteristic glow curves of Ge-doped dosimeters obtained with the heating profile mentioned in section 3.3.1 and shown as the curve whose scale is depicted on the right-hand y-axis scale.

Figure 3.29 The characteristic glow curves of lithium fluoride dosimeters obtained with the heating profile outlined in section 3.3.1 and shown as the curve whose scale is depicted on the right-hand y-axis scale.
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Figure 3.30 The glow curves of lithium fluoride dosimeter obtained using the Harshaw 5500 TLD reader. The red line indicates the temperature change. The x-axis corresponds to a heating-time scale as shown in Figure 3.31 below.

Figure 3.31 The glow curves of Ge-doped optical fibres obtained using the Solaro TLD reader. The red line indicates the temperature change.

Figure 3.32 The glow curves of Ge-doped optical fibres obtained using the Hashaw 4500. The red line indicates the temperature change. The x-axis corresponds to a heating-time scale as shown in Figure 3.31 above.
3.4 Results and Discussion

3.4.1 Screening Process

In the screening process, 407 samples were irradiated to deliver a dose of 3 Gy using a linac operating at 15MV photons, at the dose rate of 400cGy/min. The TL yield per unit mass of the fibre was calculated and the summary results are shown in Figure 3.33. The mean of 407 optical fibres was 10.4E+06 corrected counts (Cc) and the standard deviation was 3.5E+06 prior to the ‘discard’ process. The uncertainty has been depicted as ± one standard error of the mean. All outlier dosimeters, in terms of TL yield response, were discarded from further use in order to achieve better than ±5% coefficient variation, as required for radiotherapy clinical applications (ICRU 24, 1976).

As a result, from the initial 407 samples, only 135 optical fibres remained, reflecting that these remaining fibres had relatively homogeneous dopant concentrations to within ±5%. This group of optical fibres which give a mean response of 12.4 E+06 corrected counts (Cc) and 4.9 E+05 standard deviation have been used to investigate the response of the fibres for different incident energies, dose rate, angulations of the beam, temperature dependence, and fading effects. In passing, it is to be noted with respect to Figure 3.33 that the inhomogeneity of dopant along the length of a fibre accounts for significant light loss in optical fibre communications. It is possible that a TL screening technique could be used in sampling fibres in optical-fibre Quality Control (QC).

Figure 3.33 Prior to sensitivity selection the standard deviation of fibres was found to be 3.5E+06. A total of 407 fibres were irradiated in the run that is represented by the present set of data.
3.4.2 Reproducibility

In this study, selected Ge-doped optical fibres within ±5% of the batch mean were employed, as detailed above. Figure 3.34 and 3.35 represent the situation indicating Ge-doped optical fibre reproducibility to be within ±5% coefficient of variation. No significant difference was found (ANOVA, p>0.05) between five repeated measurements. The results also proved that the screening process is able to control the issue of variation in dopant concentration along the length of the optical fibres, thus making the Ge-doped optical fibres suitable as an alternative detector for high treatment energies.

Figure 3.34 Reproducibility studies of Ge-doped fibres at 6 MV photon beam irradiation.

Figure 3.35 Mean of individual Ge-doped optical fibre response following five irradiation readout cycles. Note that every repeated exposure was obtained after performing full annealing and making use of the same irradiation parameters.
3.4.3 Linearity

Ideally, a good dosimeter reading should have linear response over a wide range of irradiation dose, lithium fluoride for example exhibits a small supralinearity effect for doses of more than 1 Gy (Olko, 2010). For the various beam energies studied, the fibre response for photon and electron irradiations was found to be linear for doses ranging from 5 cGy to 1000 cGy (Figures 3.36 to 3.38).

3.4.4 Energy dependence

It is further important in the use of the fibres that any energy dependence be characterised. Ong et al. (2009) have for instance investigated the response of 50 µm diameter core Ge-doped fibres irradiated to gamma rays of 397 keV and linac-generated megavoltage photon and electron beams, reporting no variation in energy response between 6 MV and 10 MV photons but finding a 12% higher response for 397 keV x-ray compared to the megavoltage irradiations. For electron beam irradiations at nominal energies of 5 MeV, 8 MeV, 12 MeV and 14 MeV, they found that responses increased by 15% with increase in energy. The authors state that this is probably due to the existence of low energy backscattered electrons whose response would be higher due to the high atomic number of the fibre (Ong et al, 2009).

In Figure 3.36, the Ge-doped optical fibres show an elevated response for the orthovoltage irradiations carried out herein compared to that obtained at megavoltage photon beam energies. At 90 kVp the response is greater by 82%, while at 300 kVp the response is greater by 40%. The increase in response at kV photon energies is expected, due to the associated inverse power dependency of detection efficiency upon incident energy.

At megavoltage energies smaller energy dependencies are observed, with a 6% and 8% decrease in response respectively at 10 MV and 15 MV compared to that obtained at 6 MV (Figure 3.37). This is almost certainly due to the mass energy absorption coefficient at 6 MV being higher than that for 10 MV and 15 MV photons, given by $1.75 \times 10^{-2}$ cm$^2$g$^{-1}$, $1.63 \times 10^{-2}$ cm$^2$g$^{-1}$ and $1.59 \times 10^{-2}$ cm$^2$g$^{-1}$ respectively (Asni et al, 2009).
For electrons, Figures 3.38, these show the energy dependence to increase by 6% and 11% at 9 MeV and 16 MeV respectively compared to that obtained at 6 MeV, in agreement with the earlier findings by members of this group (Hashim et al, 2009a), stopping power $\frac{dE}{dx}$ replacing the energy absorption coefficient $\mu_{en}$ applicable for photons.

The summary of energy response of the fibres to photon and electron beams are more clearly illustrated in terms of the TL yield for a given dose for a given incident energy, as shown in Figure 3.39 and Figure 3.40. The findings for 9µm Ge-doped fibres used in this study demonstrate that energy correction factors are required in order to calculate the absolute absorbed dose for lower energy photon beams and higher energy photon and electron beams.

![TL yield for kilovoltage photon energies](image_url)

Figure 3.36 Linearity of the TL response of the Ge-doped optical fibres for doses ranging from 5 cGy to 1000 cGy for kilovoltage photon energies.
Figure 3.37 Linearity of TL response of the Ge-doped optical fibres for doses ranging from 5 cGy to 1000 cGy for megavoltage photon energies.

Figure 3.38 Linearity of TL response of the Ge-doped optical fibres for doses ranging from 5 cGy to 1000 cGy for megavoltage electron energies.
CHAPTER 3: DOSIMETRIC CHARACTERISTICS

Summary of energy response for photon beams

Figure 3.39 Energy response for doses of 1 Gy to 4 Gy for megavoltage photon beams. The beam quality, T\textsubscript{PR}\textsubscript{20,10} values for 6, 10 and 15 MV were 0.66, 0.723 and 0.774 respectively.

Summary of energy response for electron beams

Figure 3.40 Energy response for doses of 1 Gy to 4 Gy for megavoltage electron beams. The beam quality, R\textsubscript{50} values for 6, 9 and 16 MeV were 2.50, 3.67 and 6.79 respectively.
3.4.5 Dose rate effect

Ideally a dosimeter should be independent of dose-rate. Ong et al., (2009) have investigated the TL response of Ge-doped fibres of 50 μm core diameter, finding them to be independent of dose rate. In the present study, Ge-doped fibres with 9 μm diameter core were also found to be independent of dose rate (Figure 3.41).

Figure 3.41 Dose rate effect for 6 MV, 10 MV and 15 MV photon beams

3.4.6 Angular Dependence

It is also important for the fibres’ response to be independent of the angle of the beam. This was found by Ong et al. (2009) for 50μm Ge-doped fibres diameter core. In the present study, Ge-doped fibres with 9 μm diameter core were found to have an angle independent response for 6 MV photons, as shown in Figure 3.42. The same form was also obtained at the other two megavoltage photon beam qualities (10 MV and 15 MV photon beams) as illustrated in Figure 3.43 and Figure 3.44. Here it should be clarified that microcrystalline structures could conceivably produce an orientational effect. While the absence of such observation may point to the fibres being manifestly amorphous with
little microcrystalline presence in evidence, in fact such effect may only be observed at low keV energies where Bragg’s law is operational. One possibility for the future study would be to examine angular dependence at energies provided at kV accelerating potentials where the photoelectric dependence might show an angular dependent response. However, for the radiotherapy applications investigated in this dissertation an angular independence may be assumed based upon these results.

Figure 3.42 TL response for Ge-doped fibres of 9 µm core diameter irradiated using 6 MV photon beams for various incident angles and normalised to the TL yield at 0°.

Figure 3.43 TL response for Ge-doped fibres of 9 µm core diameter irradiated using 10 MV photon beams for various incident angles and normalised to the TL yield at 0°.
Angular dependence and dosimetric response for 15MV photon irradiation

Figure 3.44 TL response for Ge-doped fibres of 9 µm core diameter irradiated using 15 MV photon beams for various incident angles and normalised to the TL yield at 0°.

3.4.7 Temperature effect

To a first approximation, with superficial traps excluded, the TL yield should also be independent of temperature. From the present experiment, Ge-doped fibres with 9 µm diameter core were indeed found to be independent of temperature over the range 5°C to 50°C (Figure 3.45). This is a significant finding, availing the TL fibre dosimetry system to applications in postal dosimetry audits (see later in chapter 6).

Figure 3.45 TL responses of fibres at various temperatures
3.4.8 Fading

In this study, all the dosimeters responses were normalized to the response at day two post-irradiation. Each data point indicates mean value together with error bars that represent percentage uncertainty for ten Ge-doped optical fibres and five LiF dosimeters.

3.4.8.1 Dose levels

Figures 3.46 a, b, c and d show post irradiation fading for Ge-doped optical fibre dosimeters (of 9 µm and 50 µm core diameter) and LiF TLD-100 and TLD-700 dosimeters respectively at dose levels of 0.5 Gy, 2 Gy and 10 Gy. All the TL results were compared with the TL output obtained at 70 days post irradiation. The dosimeters were all stored at room temperature. Within uncertainties, the level of fading for TLD-700 at doses of 0.5 Gy and 2 Gy, is 4% over a period of 70 days, this being the least loss in TL signal compared to the others TL dosimeter types where the loss in TL signal is in the range 7% to 12% for these doses. At a dose level of 10 Gy, the TL signal loss is 13% for lithium fluoride dosimeters and is a maximum of 16% for Ge-doped optical fibres.

Figure 3.47 shows post irradiation fading for all four forms of dosimeter for storage at room temperature (21± 2) °C, for storage times up to 133 days. The fading results were obtained by making comparison with the TL output at 133 days post irradiation. TLD-700 gave rise to the least loss in TL signal at ~ 4%, followed by TLD-100 at ~ 5%. A maximum signal loss of 5% has been observed for both forms of LiF dosimeters, being less than the 6% reported elsewhere (Biran et al, 1996). For Ge-50 µm and Ge-9 µm core diameters, the TL signal decreased with storage time by ~ 8% and 11% respectively.
Figure 3.46 Post-irradiation fading at different dose levels for: a) Ge-9 µm; b) Ge-50 µm core; c) TLD-100; d) TLD-700. The dosimeters were all stored at room temperature.
Figure 3.47 Post-irradiation fading of Ge-doped fibres and LiF dosimeters for storage times up to a maximum of 133 days.

3.4.8.2 Temperature change

Figures 3.48 a, b, c and d illustrate the normalised TL signal for Ge-9 µm and Ge-50 µm core diameter and LiF TLD-100 and TLD-700 respectively as a function of storage time, up to a maximum of 31 days, stored at low temperature (-25 ± 2°C), room temperature (21± 2°C), and an elevated temperature (35 ± 2°C). The TL results were compared with the TL output obtained at 31 days post irradiation. TL signal loss (fading) is observed to increase with temperature. At low temperature -25°C, TL signal loss is < 2% for Ge-50 and TLD-700 and is a maximum of < 4% for TLD-100 and Ge-9 µm core diameters. The TL signal for LiF dosimeters and for Ge-doped optical fibre dosimeters are reduced by 4% and < 6% respectively after a storage time of 31 days at room temperature. At elevated temperature, the TL signal was found to decrease by ~ 10% for both types of LiF dosimeter and by < 7% for Ge-doped optical fibre dosimeters. The findings for LiF dosimeters are similar to those reported elsewhere (Yazici et al, 2002; Burgkhardt, 1976) although not in accord with (Sprunck et al, 1996) who observed the fading of TLD-100 is negligible at room temperature and at 40°C.
3.4.9 Effective atomic number of Ge-doped and pure silica optical fibres (SEM and EDX analysis)

Scanning electron microscopy is a state of the art technique for the analysis and imaging of micro- and nanostructures. In this study, optical fibres without any dopant elements (Pure Silica) and doping with Ge were employed to determine surface information and composition details on the materials. Data sheets provided by the manufacturer showed the cladding diameters for both types of fibre of approximately 125µm, whereas core diameters for Ge-doped fibres were 9µm (Ge-9µm) and 50µm (Ge-50µm). Figures 3.49, 3.50 and 3.51 are SEM images of pure silica (SiO₂) and two types of Ge-doped optical fibre with different core diameters, in horizontal and cross-
sectional 100 μm concentration map views. In the horizontal section, both types of fibre were observed to have cladding diameter dimensions in the range 124μm to 125 μm; in cross section, pure silica (SiO₂) and Ge-9μm produced cladding diameters of 124 μm, whereas Ge-50μm was observed to have diameters of 121 μm. This was possibly due to deep stripping during removal of the outer polymer coating of the fibres as mentioned in section 3.1.1. In cross section, the core diameter for Ge-50μm was observed to be approximately 49.3μm.

![Figure 3.49 SEM images of pure silica optical fibres](image)

(a) Cross sectional view  (b) Horizontal view

Figure 3.49 SEM images of pure silica optical fibres

a) Cross section view of cladding diameter (left hand figure) b) core diameter of fibres (right hand figure)
Energy Dispersive X-ray (EDX) analysis is a valuable tool for qualitative and quantitative element analysis, for instance, in mapping elemental distribution and identifying the chemical composition of many materials. In line with expectation, the (EDX) spectrum in Figure 3.52a indicates the predominating presence of silicon (Si) and oxygen (O₂) peaks in the pure silica optical fibre specimen. The (EDX) spectra in figures 3.52b and 3.52c also reveal the existence of germanium (Ge) peaks in Ge-doped optical fibres in addition to the Si and oxygen peaks.

Ge-9µm show small concentrations in the range 0.09 to 0.13 mol % of germanium compared to the concentrations of germanium in the Ge-50 µm of 1.44 to 4.07 mol % as presented in Figure 3.53. To the best of this author’s knowledge, no publication on
the TL of fibres reports the concentrations in Ge-50 µm fibre. However, for the same Ge-9µm fibres, Hashim et al., (2009a) reported a value range of 0.15 to 0.19 mol % while another previous study, by Yusoff et al., (2005), reported a value of 0.25 mol %. Most of the germanium was observed to be distributed along the core of the optical fibres, whereas silica and oxygen are found throughout the optical fibres, as shown in Figure 3.54.

The effective atomic number, $Z_{\text{eff}}$, of any mixture can be defined in terms of a single index for a given composite material. In order to estimate $Z_{\text{eff}}$, the Mayneord equation (Khan, 2010) was used as given by:

$$Z_{\text{eff}} = (a_1 Z_1^m + a_2 Z_2^m + a_3 Z_3^m + \ldots + a_n Z_n^m)^{1/m} \quad (3.1)$$

where $a_1$, $a_2$, $a_3$, ...$a_n$ are the number of electron contributing from each element in the fibre to the total number of electrons in the mixture. The value of the index m adopted for photons for practical purposes is 2.94 (Khan, 2010). Thus,

$$Z_{\text{eff}} = (a_1 Z_1^{2.94} + a_2 Z_2^{2.94} + a_3 Z_3^{2.94} + \ldots + a_n Z_n^{2.94})^{1/2.94} \quad (3.2)$$

The value of $Z_{\text{eff}}$ for pure silica is found to be in the range 11.3 to 12.0. For Ge-9µm and Ge-50µm core diameter, $Z_{\text{eff}}$ are in the range of 11.6 to 12.1 and 13.2 to 13.7 respectively. Again, to the best of this author’s knowledge, there exist no publications reporting $Z_{\text{eff}}$ in Ge-50 µm fibres. Findings of $Z_{\text{eff}}$ obtained for Ge-9µm, reported by Hashim et al (2009a) and Yusoff et al, 2005 are presented in Table 3.1. These results indicate that a Ge-doped optical fibre is not tissue equivalent and as such the assessment of dose deposition in tissue would need to be corrected for this during the calibration process. This problem can be solved by including the non-tissue-equivalence effect in the calibration dose factor, all of the Ge-doped fibres readings being calibrated against a Farmer-type ionization chamber in a Perspex phantom. The calibration factor for the ion chamber converts the fibre readings directly into absorbed dose to water (Furetta, 2003).
Figure 3.52 EDX Spectrum of: a) Pure Silica; b) Ge-50µm; c) Ge-9µm
Figure 3.53 Quantitative EDX analysis of the elemental composition (% of weight) in:
- a) Pure Silica;
- b) Ge-50µm;
- c) Ge-9µm fibres.
Figure 3.54 EDX spot qualitative analysis shows the predominant elements in Ge-9µm (left hand figure) and Ge-50µm (right hand figure) fibres. Note that the brighter areas indicate higher concentrations of the element of interest. Note also that Lα₁ x-ray fluorescence analysis does not represent the full core diameter, due to self absorption in the glass.
Table 3.1 Summary of the effective atomic number for several of TL materials

<table>
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<tr>
<th>TL materials</th>
<th>Effective atomic number, $Z_{eff}$</th>
<th>Dopant concentrations ( % mol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanium (50µm core) (Present Study)</td>
<td>13.2 -13.7</td>
<td>1.44- 4.07</td>
</tr>
<tr>
<td>Germanium (9µm core) (Present Study)</td>
<td>11.6 -12.1</td>
<td>0.09-0.13</td>
</tr>
<tr>
<td>(Hashim et al, 2009a)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Yusoff et al, 2005)</td>
<td>11.7</td>
<td>0.25</td>
</tr>
<tr>
<td>Pure Silica (113µm core) (Present Study)</td>
<td>11.3 -12.0</td>
<td>-</td>
</tr>
<tr>
<td>LiF (Mg, Ti)</td>
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<td></td>
</tr>
<tr>
<td>LiF (Mg,Ti,Na)</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>Li$_2$B$_4$O$_7$:Cu</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>Soft Tissue</td>
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<td></td>
</tr>
<tr>
<td>Air</td>
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</tr>
<tr>
<td>CaSO4:Mn</td>
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<td></td>
</tr>
<tr>
<td>CaSO4:Dy</td>
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<td></td>
</tr>
<tr>
<td>CaF2:Mn</td>
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<td></td>
</tr>
<tr>
<td>CaF2:Dy</td>
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<td></td>
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<tr>
<td>Cortical Bone</td>
<td>14</td>
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</tr>
</tbody>
</table>

3.5. Conclusion

Dosimetric characterisation investigations show the Ge-doped optical fibres to have a good reproducibility, to within ±5% after five repeated measurements and linear response for all photon and electron beam energies for doses from 5 cGy up to 1000 cGy. The fibres were also found to be dose rate-, angular- and temperature-
independent. However, a small energy dependence in the fibre response was found in the range of 6% to 11% for all investigated megavoltage photon and electron beam energies. At kilovoltage potentials, there is significant energy dependence, as expected since here the photoelectric effect dominates the response. Concerning the effect of environmental temperature on the fibre, examination has been made of changes in TL yield due to temperature change and dose level, comparison being made with well-established lithium fluoride (TLD-100 and TLD-700). Fading in all of the TL dosimeters investigated is shown to be independent of dose and to decrease to a lesser extent with a reduced storage temperature. When held at room temperature, results showed TLD-700 produces the least fading, at only 4% while 9 µm diameter Ge-doped optical fibre dosimeters produced the greatest, at 11%.

In the present investigations of commercially available optical fibres, based on SEM and EDX analysis, the Ge-9 µm fibres were evaluated to have dopant concentrations in the range 0.09 to 0.13 mol % of germanium compared to the concentrations of germanium in the Ge-50 µm, 1.44 to 4.07 mol %. The value of $Z_{\text{eff}}$ for the pure silica was found to be in the range 11.3 to 12.0. For Ge-9µm and Ge-50µm core diameter, $Z_{\text{eff}}$ is found to be in the range 11.6 to 12.1 and 13.2 to 13.7 respectively (noting that the value of $Z_{\text{eff}}$ in soft tissue is 7.42 and 14 in cortical bone). Therefore, these results indicate that while Ge doped fibres (Ge-9µm and Ge-50µm) are not soft-tissue equivalent they are close to being bone equivalent medium.

As a final conclusion, the results of this study have shown that the fibres fulfil many desirable characteristics for a radiation dosimeter. However, careful selection via a screening process is needed in order to minimize the uncertainties involved.
In chapter 2, it is discussed that the development of IMRT techniques has increased rapidly in the 30 years since it was first invented (Brahme et al, 1982). This includes the suggestion on the use of high-energy photons in IMRT in order to achieve better target coverage and normal tissue sparing effect. However, despite the enhanced dosimetric profits of this, there are still concerns with regard to the use of IMRT using high photons (>10 MV), where the relative contribution of neutron dose to the overall dose increases. The present chapter’s aim is to investigate the potential of Ge-doped optical fibre thermoluminescent (TL) dosimetry in determining typical out-of-field doses for high energy IMRT. Furthermore, a comparison will be made with TLD-100 measurements, the latter being corrected at 15 MV for their response to thermal neutrons using the results of Kry et al, (2007a).

4.1 Typical out-of-field doses

In radiotherapy, out-of-field radiation is unwanted due to its potential to cause secondary malignancies (Stathakis et al, 2009; Followill et al, 2007; Howell et al, 2010; Kry et al, 2009) and non-somatic effects in pregnant women during radiotherapy treatment (Stovall et al, 1995). This issue raises more concern in IMRT and CT based image-guided radiation therapy. This is because these new techniques have been found to increase the out-of-field dose (Kry et al, 2009) as a result of primary leakage dose (Ramsey et al, 2006) and the contribution of neutron dose produced in the accelerator head (Schneider, 2006) for these techniques involved with high energy photon beams (>10 MV) (Followill et al, 2007). Previous out-of-field studies related to high energy IMRT have been carried out involving a number of linear accelerators
(Hall et al., 2003; Vanhavere et al., 2004; Howell et al., 2006; Kry et al., 2005a and 2005b). One of the examples is the study carried out by Kry et al., (2005a; 2005b) in an anthropomorphic phantom that indicated that out-of-field photon and neutron doses were diverse depending on the manufacture of the linear accelerator head. Howell et al., (2010) discovered that treatment planning systems (TPSs) miscalculated doses distant from the treatment field by an average of 40% for a clinical treatment delivered on a Varian Clinac 2100. This is due to the fact the systems are not purposely commissioned to calculate out-of-field dose (Das et al., 2008) and the accuracy of the systems was also found to decrease as the distance from the treatment field border increased (Kry et al., 2007b; Howell et al., 2010).

To measure the photon and electron doses delivered during radiation therapy, lithium fluoride thermoluminescent dosimeters such as TLD-100 and TLD-700 are used. TLD-100 has a $^6$Li content of 7.5% and a $^7$Li content of 92.5 % whereas the more expensive TLD 700, which is not routinely used in clinical settings, which has respective contents of 0.01% and 99.99 %. The TLD-100 was found to give a response not only to photons and electrons but also to neutrons as $^6$Li has a high thermal neutron cross section, whereas TLD-700 is unresponsive to neutrons due to the small percentage content of $^6$Li in the TLD-700 (Liu et al., 2001; Mendez et al., 2002). Therefore, in order to calculate the out-of-field photon dose alone from IMRT irradiation, especially in the higher energies (>10 MV), TLD-700 is suggested to be used. Kry et al., (2007a) found the TLD-100 response agrees with TLD-700 at 6 MV IMRT photon energy (Table 1a), however it overestimates the out-of-field doses when using 15 and 18 MV higher IMRT photon energies (Table 1b and Table 1c). This has also been observed by Sneed et al., (1995) where measurements of the photon dose component beyond the treatment field border calculated by TLD-100, have been found to be 91% tremendously inaccurate at 18 MV photon irradiations.

Although TLD-700 is an alternative dosimetry system to measure out-of-field dose in high energy IMRT, the cost and tedious preparation of this material still remain a problem. Thus, the aim of this study is to investigate the alternative use of Ge-doped optical fibre to measure the out-of-field doses for high energy IMRT as its advantages have been discussed in Chapter 3.
### Table 1a Out-of-field dose measurements in a Rando phantom at 6 MV. As expected the responses of TLD-100 and TLD-700 were in agreement, because there is no production of neutrons that occurs at the 6 MV energy (adapted from Kry et al, 2007a).

<table>
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<th>Distance from central axis (cm)</th>
<th>Dose (µGy/MU)</th>
<th>Difference</th>
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<td>Average</td>
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</table>

### Table 1b Out-of-field dose measurements in a Rando phantom at 15 MV. A systematic over-response has been found in TLD-100 dose measurement; approximately 12µGy/MU compared with the TLD-700 response. This is due to the contribution of neutron dose from the 15 MV therapy beam (adapted from Kry et al, 2007a).

<table>
<thead>
<tr>
<th>Distance from central axis (cm)</th>
<th>Dose (µGy/MU)</th>
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</table>
4.2 Methods

4.2.1 Ge-doped Optical fibres and TLD-100

In this study use has been made of single mode commercial Ge-doped silica glass optical fibres (INOCORP, Canada) with a core diameter of 9 μm and a cladding diameter of 116 ± 0.1 μm. A total of 500 selected fibres (50 capsules with 10 fibres in each) were eventually employed for the investigations of out-of-field dose as a result of the screening process. A detailed description of the screening process is discussed in chapter 3. Dose calibration was performed by irradiating the selected Ge-doped optical fibres with 6 MV and 15 MV photon beams (using a Varian Linear accelerator and 100 cm FSD, 10 × 10 cm² field size) at 400 cGy/min dose-rate. The fibres were irradiated with doses ranging from 0.2 cGy up to 100 cGy. To allow comparison of the Ge-doped optical fibres against a better established TL system, use has been made of TLD-100 chips. The response of these to neutrons resulting from 15 MV x-ray irradiation was corrected using the results of Kry et al. (2007a) who compared TLD-100 with TLD-700.

4.2.2 Alderson RANDO anthropomorphic phantom and measurements

For this project, use was made of a female RANDO phantom (The Phantom Laboratory, Salem, NY) version ARTF 1025, with height 1.55 m, weight 50 kg and transverse sections (of which there are 31 in all) 2.5 cm thick, each section containing a matrix of 5 mm diameter holes, depth 2.5 cm, spaced at 1.5 cm×1.5 cm to accommodate tissue-equivalent and lung tissue-equivalent

<table>
<thead>
<tr>
<th>Distance from central axis (cm)</th>
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<th>TLD-100 (µGy/MU)</th>
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<th>(%)</th>
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<td>35</td>
<td>3.6</td>
<td>33.0</td>
<td>29.3</td>
<td>807</td>
</tr>
<tr>
<td>40</td>
<td>2.7</td>
<td>27.7</td>
<td>25.0</td>
<td>936</td>
</tr>
<tr>
<td>52.5</td>
<td>2.3</td>
<td>27.0</td>
<td>24.7</td>
<td>1064</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>26.6</td>
<td>487</td>
</tr>
</tbody>
</table>

Table 1c Out-of-field dose measurements in a Rando phantom at 18 MV. A systematic over-response has been found in TLD-100 dose measurement; approximately 27µGy/MU compared with the TLD-700 response. This is due to the contribution of neutron dose from the 18 MV therapy beam (adapted from Kry et al, 2007a).
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plugs (Figure 4.1). The plugs can be replaced by TLD-100 and Ge-doped optical fibre holders (Figure 4.2a). Measurements were made as a function of distance along the z-axis of the phantom, away from the Planning Target Volume (PTV), the latter being understood to be located about the central axis of the beam.

![Figure 4.1 A female RANDO phantom (The Phantom Laboratory, Salem, NY)](image)

4.2.3 Treatment planning and irradiation

Individual IMRT verification plans were produced for the RANDO phantom, based on data from two patients with pathologically diagnosed prostate cancers of different prostate volume. IMRT five-field verification plans were produced for each set of patient data and each plan was used for both the 6 MV and 15 MV photon irradiations. Figure 4.2b and 4.2c show an example of such plans (Plan 1 and Plan 2) for patient 1 and patient 2 respectively.

![Figure 4.2a Ten optical fibres were contained in each black plastic rod holder, subsequently inserted into specific holes to replace the tissue-equivalent plugs.](image)

A total of eight phantom measurements were performed, four using the Ge-doped fibres, to accommodate the two cases for the two energies, and an equivalent four for the LiF dosimeters.
Figure 4.2b Transverse, coronal and sagittal view of IMRT prostate verification plan 1 for the RANDO phantom (consisting of 5 radiation fields). The first row represents the plan of 6 MV photon beam irradiation whilst, the plan of 15 MV is represented by the second row.
Figure 4.2c Transverse, coronal and sagittal view of IMRT prostate verification plan 2 for the RANDO phantom (consisting of 5 radiation fields). The first row represents the plan of 6 MV photon beam irradiation whilst, the plan of 15 MV is represented by the second row.
4.2.4 Typical in-field and out-of-field dose measurements

Typical in-field and out-of-field dose measurements (the latter meaning dose measurements made outside of the PTV) were carried out using approximately 130 TLD-100 and 50 capsules of Ge-doped optical fibres distributed along the length of the RANDO phantom at two specific (x,y) co-ordinates, the location of the x-position changing with the lateral extent of the RANDO phantom. All irradiations were performed using the same Varian Linear Accelerator as discussed above, doses being delivered either with 6MV or 15MV for the IMRT verification plans. As inferred above, the phantom was positioned on the patient couch of the Varian Linear accelerator (Figure 4.2d and Figure 4.2e) and irradiations were made using an focus to axis distance (FAD) of 89 cm.

Figure 4.2d Set-up of the phantom on the Varian Linear Accelerator.

Figure 4.2e Screen shots taken for the desktop layout of 4D Integrated Treatment Console (4DITC) in the radiotherapy department in the Royal Surrey County Hospital (RSCH) after positioning the phantom. Shown on the boxes 1,2,3,4 are the upper view and saggital view of the phantom.
4.3 Results and discussion

4.3.1 Ge-doped dose calibration curve

A linear relationship between TL-yields and dose (cGy) for both 6 MV (Figure 4.3) and 15 MV energies was observed (Figure 4.4). For nominal photon energies of 6 MV the correlation coefficient, $r^2$ is 0.9988 and for 15MV the correlation coefficient, $r^2$ is 0.9979.

![Figure 4.3 Calibration curve for Ge-doped optical fibres form 6 MV photon beam irradiations.](image)

![Figure 4.4 Calibration curve for Ge-doped optical fibres for 15 MV photon beam irradiations.](image)
### 4.3.2 In-field and out-of-field doses

For 6 MV irradiations, Figures 4.5 and 4.6 show the average absorbed doses measured by the optical fibres to be in agreement with TLD-100 values, the error bars representing the standard error of the mean reading of the several dosimeters in that position. For both the in-field and out-of-field evaluations no difference is observed between the Ge-doped fibre and TLD-100 measurements; statistical analysis showing differences between the average dose measured using TLD-100 and optical fibres to be insignificant \( p = 0.532 \) and \( 0.206 \) for the individual IMRT verification plans 1 and 2 respectively.

![Graph](image)

Figure 4.5 Average doses obtained for 6 MV irradiations, measured using TLD-100 and Ge-doped optical fibres for Plan 1 for a PTV of 104.1 cm\(^3\). The TLD-100 and Ge-doped optical fibres response at doses (from 40 mGy to 2300 mGy) measured up to 10cm from the PTV are shown within the inset figure in figure 4.5. The inset figure has the same units as the main figure.
Figure 4.6 Average doses obtained for 6 MV irradiations, measured using TLD-100 and Ge-doped optical fibres for Plan 2 for a PTV of 79.7 cm$^3$. The TLD-100 and Ge-doped optical fibre response at doses (from 30 mGy to 1990 mGy) measured up to 10cm from the PTV are shown as inset in the figure 4.6. The inset figure has the same units as the main figure.

For 15 MV irradiations, as expected, a significant difference is to be noted between TLD-100 (both corrected and uncorrected for neutron dose; see below) and optical fibre measurements for both sets of plans for out-of-field measurements, a situation that is not observed for in-field measurements (Figure 4.7 and 4.8). The findings for TLD-100 are similar to these reported by Kry et al., (2007a). The p-value for the out-of-field measurements was found to be significant at < 0.05.

Here it is to be noted that TLD-100 contains 7.5% $^6$Li, the thermal neutron absorption cross-section of which is large, ~ a few thousand barn (Ermolaev, 1997; Nuclear Data Evaluation Lab, 2008), influencing the average dose measurements to a considerable extent. The estimates of discrepancies as observed by Kry et al., (2007a) have been
used to offset the present TLD-100 results for the effects of neutron dose, as shown in the two figures. A systematic TLD-100 over-response of approximately 11 mGy and 13 mGy for plan 1 and plan 2 respectively was found as compared with the TLD-100 results (corrected for thermal neutron dose). For optical fibre measurements, a systematic over response for both plan 1 and plan 2 was observed of approximately 8 mGy. Conversely, the thermal neutron absorption cross-section of the major constituents of the optical fibre, germanium and silica, are both relatively small at \( \sim 10 \text{ barn} \) and \( \sim 1 \text{ barn} \) respectively (Nuclear Data Evaluation Lab, 2008 as also discussed in Hashim, 2009a). The Ge-doped fibre results have not been corrected for neutron dose.

![Figure 4.7 Average doses obtained for 15 MV irradiations, the graph showing TLD-100 (uncorrected) and TLD-100 (corrected for thermal neutron dose), compared to Ge-doped optical fibre for Plan 1. The TLD-100 and Ge-doped optical fibre response at doses from 20 mGy to 2000 mGy are shown as inset in the figure 4.7 measured up to 10cm from the PTV. The inset figure has the same units as the main figure. The in-field doses being apparent that here the contribution from the neutron dose component to the overall dose is relatively unimportant.](image)

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Figure 4.8 Average doses obtained for 15 MV irradiations, the graph showing TLD-100 (uncorrected) and TLD-100 (corrected for thermal neutron dose), compared to Ge-doped optical fibre for Plan 2. The TLD-100 and Ge-doped optical fibre response at high doses from 30 mGy to 1211 mGy are shown as inset in the figure 4.8 measured up to 10cm from the PTV. The inset figure has the same units as the main figure. Again, with the in-field measured doses it is apparent that here the contribution from the neutron dose component to the overall dose is relatively unimportant.

4.4 Conclusion

Ge-doped optical fibres show considerable promise as high spatial resolution dosimeters, being capable of determining typical in and out-of-field doses for 6 MV energy photon beams. The in-dose measurements at 6 MV and 15 MV show an insignificant contribution to the overall doses from the thermal neutron component, as expected. In contrast, for out-of-field measurements a highly significant contribution of thermal neutrons to the overall doses is seen in Ge-doped optical fibres at 15 MV, whereas at 6 MV no influence of thermal neutrons to the overall doses is observed. As a result of the finite but relatively small Ge neutron absorption cross-section for photon energies above the photo-neutron production threshold (~ 10 MV), it is clear that the optical fibres systematically over respond by approximately 8 mGy from the
TLD-100 (corrected for thermal neutron dose) value because of this photo-neutron component. Nevertheless, the Ge-doped optical fibre could be used in IMRT radiotherapy if suitable corrections were to be made for neutron dose when conducting 15MV irradiations.
5

USE OF GE-DOPED FIBRES FOR IN-PHANTOM IMRT PROSTATE DOSIMETRY

Intensity-modulated radiation therapy (IMRT) represents a new paradigm that involves multimodality imaging, tumor control probabilities (TCP) (ACR-ASTRO, 2011), three-dimensional (3-D) dose calculation and optimization (Low et al, 1998), internal organ motion and setup uncertainties (NCI, 2006), normal tissue complication probabilities (NTCP) (Niemierko, 1991) and dynamic beam delivery of inhomogeneous beam intensities (Ezzell et al, 2003). Generally, IMRT techniques involve the combination of many processes as shown in Figure 5.1 (Meyer et al, 2007; Ezzell et al, 2003).

For cancer treatment the IMRT treatment planning system (TPS) has become a key element in the radiotherapy process. As a hardware and software system, each TPS may include errors of different kinds such as during the software upgrade process, intentional or unintentional changes in data or software files and inaccuracies in algorithms and
models (Jacky et al, 1990). For these reasons QA procedures have to be implemented at the commissioning stage and during ongoing clinical routine running of a TPS. One of the essential parts of QA of the whole treatment planning process is dosimetric verification of an IMRT plan prior to the actual patient treatment (Smith and Dieterich, 2011). This is because the TPS accuracy and precision are an issue of the highest importance in order to maintain the quality of an IMRT program and is prudent with the assurance of patient safety (Hashim, 2006).

As a result, quality assurance (QA) recommendations and guidelines have been suggested by several international agencies such as ACR-ASTRO Practice Guideline for IMRT (ACR-ASTRO, 2011), NCI Guideline for the use of IMRT (NCI, 2006), AAPM Guidance document on IMRT (Ezzell et al, 2003) and SSRMP “Physical and Dosimetric Checks in Teletherapy (Born et al, 1992) in order to facilitate medical physicists implementing quality assurance procedures of TPS for IMRT. However, to support IMRT QA in clinical practice, complex equipment and significant physicist effort is needed. Consequently, a lot of research has been carried out by manufacturers of medical devices for developing new systems to be employed as user-friendly IMRT dosimeters with reasonable cost.

Commonly, to verify the IMRT plan, the use of an anthropomorphic phantom is often recommended (Ezzell et al, 2003), as the phantom’s design mimics human anatomy and consists of various interchangeable tissue equivalent and heterogeneous medium inserts for ion chamber and thermoluminescent dosimeter measurements (Al-Jarrah et al, 2010).

In the present study, the focus is on the application of commercial TL Ge-doped silica fibres for verifying in-phantom three-dimensional IMRT dose distributions for high energy photon beams. It has been established that the sensitivity of Ge-doped fibres to megavoltage photon beam irradiations is superior to that of other silica fibres doped with elements such as Al, Nd, Yb, Er and Sm (Hashim et al, 2009a; Safitri et al, 2008). In this study, examining complex IMRT distributions, the dose delivered by 6 MV and 15 MV photons is measured by Ge-doped fibres and compared with lithium fluoride thermoluminescent dosimeter (LiF TLD) measurements. IMRT verification plans using
the Varian Eclipse treatment planning system for two prostate cancer patients were created using Alderson Rando Anthropomorphic Phantom CT data-sets. In total, 12 Rando phantom measurements were performed using 6 MV and 15 MV photon beam irradiations.

5.1 Lithium fluoride and Ge-doped optical fibre thermoluminescence measurements

5.1.1 Preparation of Ge-doped Optical fibres

A total of 400 selected 6 mm-long pieces of single-mode commercial Ge-doped optical fibre of 9µm diameter manufactured by (INOCORP, Quebec, Canada) were used in this study. These fibres, having a similar sensitivity, were prepared in groups of ten in black plastic capsules and used to provide a response within ±3.5% coefficient of variation (CV) after a screening process. A detailed description of the screening process is provided in chapter 3.

The selected Ge-doped optical fibre capsules were subsequently used to ascertain dose calibration factors so that they could serve as relative dosimeters. Dose calibration factor evaluation was performed by sandwiching the capsules in an epoxy resin water equivalent phantom, RMI4571 (Gammex-RMI, Nottingham, UK) at the depth of dose maximum, with 15 cm of the phantom material below to ensure full scatter conditions using a Varian Linear accelerator with a 100-cm FSD, 10×10 cm² field size, with doses delivered at a dose rate of 400 cGy/min. For 6 MV and 15 MV nominal energy photon beams, doses ranging from 10 cGy up to 300 cGy were delivered.

For Ge-doped optical fibre, the Harshaw Manual Reader 4500 series was used to read TL-yield 12-hours post-irradiation. During the readout, the following time-temperature profile (TTP) parameters were used: preheat temperature 160 °C for 10 seconds (s); read out temperature 300 °C for 25 s and heating rate cycle of 25 °Cs⁻¹.

5.1.2 Preparation of lithium fluoride (TLD-100 and TLD-700) dosimeters

Comparison of Ge-doped optical fibre results were made using Harshaw TLD-100 disks and TLD-700 chips. Both types of LiF TLD were calibrated against a Farmer-type ionisation chamber in a Perspex phantom for both 6 and 15 MV photons. As for the
fibres, dose response was obtained over the dose range 10 cGy – 300 cGy. After irradiation, LiF TLDs were read out using a Harshaw 5500 Reader with the following time-temperature profile: preheat at 145°C for 10 seconds (s); read out temperature 300°C for 10 s and a heating rate cycle of 17°Cs⁻¹.

5.2 Treatment Planning and IMRT irradiation conditions

Using a Varian Eclipse treatment planning system (TPS) and Alderson Rando Anthropomorphic Phantom CT data-sets, two prostate IMRT plans (‘Patient 1’ and ‘Patient 2’) were created for five 6 MV and five 15 MV beams.

A total of 35 uniformly distributed locations were identified in the female rando phantom over the regions covered by the planned dose distribution in order to carry out the Ge-doped optical fibre, TLD-100 and TLD-700 dose measurements (Figure 5.2). These positions were chosen to cover high and low dose regions within the IMRT dose distribution at slice of interest (slices 27 to 29) as shown in Figure 5.3. Figures 5.4a, 5.4b, 5.5a and 5.5b show a detail of such plans for 6MV and 15MV irradiations for Patient 1 and Patient 2 respectively. The plans were then delivered to the LiF TLD and Ge-doped optical fibre loaded Rando phantom using a Varian Clinac 2100C. In total, 12 phantom measurements were performed, four using the Ge-doped fibres, to accommodate the two cases for the two energies, and an equivalent eight for the LiF dosimeters (TLD-700 and TLD-100).

In order to compare the mean dose values calculated by the TPS with the Ge-doped fibres, the 35 identified locations for Ge-doped optical fibres were simulated by contouring them as 1.5 cm and 0.45 cm diameter cylinders on the Rando phantom CT slices. Subsequently, a dose-volume histogram (DVH) was calculated and used to determine the mean dose. Conversely, to get the TPS mean dose values for LiF TLDs, the point dose tool was used rather than contouring. This is because the length of the LiF TLDs is just 0.89 mm thick compared to the optical fibre holder length of 1.5cm. The point dose tool was used to give an estimation of mean dose value for each of the 35 LiF TLDs locations. An average of four dose points for each location was taken to simulate the doses that would be measured by the LiF TLDs.
Figure 5.2 3D Distribution of positions of Ge-doped optical fibres and LiF TLDs (highlighted) from 3D view of the Rando phantom prostate CT image.

Figure 5.3 Ge-doped optical fibres and LiF TLDs were loaded in Slice 27 through slice 29.
Figure 5.4a The prostate IMRT plan of Patient 1 for 6 MV photon beam irradiation. The numbers represent the positions of Ge-doped optical fibres and LiF TLDs in a Rando phantom CT-slice.
Figure 5.4b The prostate IMRT plan of Patient 2 for 6 MV photon beam irradiation. The numbers represent the positions of Ge-doped optical fibres and LiF TLDs in a Rando phantom CT-slice.
Figure 5.5a The prostate IMRT plan of Patient 1 for 15MV photon beam irradiation. The numbers represent the positions of Ge-doped optical fibres and LiF TLDs in a Rando phantom CT-slice.
Figure 5.5b The prostate IMRT plan of Patient 2 for 15MV photon beam irradiation. The numbers represent the positions of Ge-doped optical fibres and LiF TLDs in a Rando phantom CT-slice.
5.3 Results and discussion

5.3.1 Dose response curve for Ge-doped optical fibres

Figure 5.6 identifies there to be a linear relationship between TL yield and dose (cGy) for nominal photon energies of 6 MV (with correlation coefficient, \( r^2 = 0.9966 \)) and 15MV (with correlation coefficient, \( r^2 = 0.9947 \)). Note the lower sensitivity to 15 MV irradiations, in line with the expected lower detection efficiency.

![Graph showing dose response curve for Ge-doped optical fibres](image)

Figure 5.6 Ge-doped optical fibre calibration curve for 6MV and 15 MV photon irradiations

5.3.2 Comparison graphs

Plots of TPS calculated dose values (cGy) versus TL measured dose values (cGy) are provided in Figures 5.7a, 5.7b, 5.8a, 5.8b, representing results for the two cases (Patient 1 and ‘Patient 2’) for the two nominal photon energies used. For 6 MV irradiations, Figure 5.7a and Figure 5.7b show that all types of dosimeter investigated provide good agreement with the calculated dose values, the average discrepancy being 1.4% (TLD-700), 1.8% (TLD-100) and 2.2% (Ge-doped optical fibres). It can also be seen that for the Ge-doped optical fibres, doses in the high dose region agree well with the best fit
dotted line between calculated dose values and measured dose value when compared to TLD-700 and TLD-100. Conversely for the low dose region better agreement is found for LiF TLD values. However, all dosimeter discrepancies have been shown to be insignificant (p >0.05), i.e. within measurement uncertainty.

Good agreement between calculated dose value and measured dose value has also been found for 15 MV irradiation, noting there to be insignificant contribution of thermal neutron dose to the in-field total dose for high energy photon beam irradiation (Kry et al, 2007)(Figure 5.8a and 5.8b). Conversely for out of field doses, as investigated with the same dosimeters as used herein in chapter 4, the TLD-100 and Ge-doped fibres were shown to be sensitive to the out of field thermal neutron component for an incident 15 MV nominal beam energy. The average discrepancy has been found to be 2.0%, 2.1%, and 2.5% for Ge-doped optical fibres, TLD-700 and TLD-100 respectively when compared with the calculated dose value.

Figure 5.7a Comparison between dose values as calculated by the TPS (Patient 1) and dose values obtained by TLD measurements for 6 MV photon beam irradiation. The dotted straight line shown in the graph represents the ideal situation where the calculated dose values have perfect positive correlation with measured dose values.
Figure 5.7b Comparison between dose values as calculated by the TPS (Patient 2) and dose values obtained by TLD measurements for 6 MV photon beam irradiation. The dotted straight line shown in the graph represents the ideal situation where the calculated dose values have perfect positive correlation with measured dose values.

Figure 5.8a Comparison between dose values as calculated by the TPS (Patient 1) and dose values obtained by TLD measurements for 15 MV photon beam irradiation. The dotted straight line shown in the graph represents the ideal situation where the calculated dose values have perfect positive correlation with measured dose values.
Figure 5.8b Comparison between dose values as calculated by the TPS (Patient 2) and dose values obtained by TLD measurements for 15 MV photon beam irradiation. The dotted straight line shown in the graph represents the ideal situation where the calculated dose values have perfect positive correlation with measured dose values.

5.4 Conclusion

Most sophisticated and advanced IMRT techniques for radiotherapy demand high levels of accuracy and precision that exceed the requirements of conventional radiotherapy treatment planning and delivery techniques. In comparison to standard conformal radiotherapy, there is a greater jeopardy of errors. Thus, it is important to verify the entire process of the IMRT treatment plan before a patient's dose delivery, due to the fact that ultimate errors can cause a severe complication. Present findings on this study demonstrate the use of Ge-doped optical fibre TL dosimetry offers excellent potential in verifying high and low dose regions for in-phantom IMRT treatment planning system (TPS) to within 3% of the Eclipse predicted doses and measured LiF TLDs determined dose for the particular high energy photon beams used.
Quality audits and intercomparisons are highly important in ensuring control of processes in any system of endeavour. Present interest in this study is in control of dosimetry in teletherapy, there being a need to assess the extent to which there is consistent radiation dose delivery to the patient. In this chapter, we review significant factors that impact upon radiotherapy dosimetry, focusing upon the example situation of radiotherapy delivery in Malaysia, examining existing literature in support of such efforts. A number of recommendations are made to provide for increased quality assurance and control. In chapter 3, the dosimetric characterisation of a TLD system based on the use of commercially available Ge-doped optical fibres was discussed. This is taken further in section 6.6, where the evaluation of its potential as a mailed dosimeter in measuring beam output under reference conditions at selected Malaysian radiotherapy centres is examined.
6.1 Dosimetry audit and intercomparison

The medical use of radiation and the supporting dosimetry are well understood processes, controlled in accordance with established international practices and tolerances. Protocols supporting these continue to evolve in line with the notion of continuing quality improvement. Present interest concerns therapeutic applications and in particular, the accuracy and precision of delivery of the elevated doses that support curative and palliative scenarios, towards promoting quality of life of the sufferer. Discrepancies from prescribed doses have potential subtle, severe or even lethal consequences, depending on the magnitude of discrepancies. In regard to manifest discrepancies, one draws attention to a number of well-publicised radiotherapy incidents, catalogued and analysed by the International Atomic Energy Agency (IAEA, 2000). Not least among the considerable efforts that have been devoted in national and international contexts towards minimising errors and uncertainties in dose delivery is the dosimetric audit and intercomparison exercise. As part of the quality assurance (QA) process, to ensure continuing improvement in the quality in radiation treatment (Nisbet et al, 1998; Thwaites et al, 1992), the dosimetric audit has an important role in ensuring optimised clinical outcomes. In this respect, in order to achieve consistency and accuracy in delivery of absorbed dose to a target volume in radiotherapy, the ICRU (International Commission on Radiation Units and Measurements) issued Report 24, calling for dose delivery to be within at least ± 5% of the prescribed dose (ICRU, 1976). Others reviews have recommended stricter limits on dose delivery, as for instance, ± 3.5% (Mijnheer, 1987) and ± 3% (Brahme, 1984). Here, the dosimetry audit and intercomparison exercises have been introduced as part of the effort towards conforming to such recommendations, seeking to detect errors, inexact implementation, or misinterpretation of recommendations, equipment issues or mistakes (Nisbet et al, 1997). Chapter 2 has provided a comprehensive review of such audit and intercomparison. In this chapter the particular circumstances of Malaysia are considered.

6.2 Legislative framework in Malaysia

Malaysia is one of the Southeast Asian countries with a population of approximately 28 million (Figure 6.1). Its main economic activities are fuelled by its natural resources,
but are expanding more in the industrial sector. It has nuclear and radiation technology being used mainly in industrial, medical research and education; however it does not have nuclear power. It has a small nuclear reactor (1 MV) used in research and isotope production. Currently, the Malaysian government is planning to build nuclear power plants in order to support the growing needs of energy in congested areas. Therefore, a representative from IAEA has been invited to discuss future steps.

![Map of Malaysia](image)

Figure 6.1 Map showing the country of Malaysia, comprising Peninsular Malaysia (otherwise referred to as West Malaysia) and Malaysian Borneo (otherwise referred to as East Malaysia).

The Atomic Energy Licensing Act 1984 (Act 304) is the primary instrument in controlling the use of ionising radiation in industrial and medical sectors in Malaysia. The Act is supported by its subsidiary regulations which provide safety standards for radiation practices, guidelines for licensing and enforcement activities and transport requirements for radioactive materials and waste. Some of these regulations are currently under review, with new regulations yet to be approved. The Act replaced the previous Radioactive Substances Act 1968, in April 1984, due to the rapid growth of atomic energy activities in Malaysia. The Act has a clause for the formation of the Atomic Energy Licensing Board (AELB) to operate as the highest authority in order to enforce the requirements act and its subsidiary regulations (Mohd Ali, 2004). It also has a clause identifying the Director General of Health Malaysia as the authority enforcing requirements of the Act and its subsidiary regulations for medical activities.
In addition to the Act and its regulations, the legal framework is also supported by other legally binding circulars, standards, and guidelines together with non-legally binding local rules and instruction manuals (Figure 6.2).

In order to ensure that the existing Act and regulations continue to be appropriate for current technology without neglect of the social and economic factors in Malaysia, the AELB with the help of the International Atomic Energy Agency (IAEA) has initiated a process of revision. Progress of the revision exercise process has been slow for a number of reasons, the current status of the revision and the recommendations of the IAEA have been discussed by Mohd Ali, (2004). In parallel, with the help of several international bodies, the Ministry of Health Malaysia is developing more specific and comprehensive regulations concerning control of the use of ionising radiation in the medical sector.

Figure 6.2: Organisational arrangements for control of sources of ionising radiations in Malaysia
6.3 Development of dosimetry audits in Malaysia

The Atomic Energy Licensing Board (AELB) and the Ministry of Health Malaysia (MOH), the principal authorities for ensuring radiation safety within the country, have played an important role in dosimetry audit development in Malaysia. Together with other agencies such as the Malaysian Nuclear Agency (MNA) (http://www.nuclearmalaysia.gov.my), the Malaysian Association of Medical Physics (MAMP) (http://www.mamp.org.com), the Association of Private Hospitals (APHM) (http://www.hospitals-malaysia.org), and the Malaysian Radiation Protection Association (MARPA) (http://www.marpa.org.my), national research, and development (R&D) efforts are now well established. As a member state, Malaysia also receives assistance from the IAEA in the form of expert visits and financial support (Daud, 1996).

The Malaysian Secondary Standard Dosimetry Laboratory (SSDL), established within the MNA is recognized by the Malaysian accreditation body as a national calibration laboratory for radiation protection and radiotherapy purposes. This laboratory is, for instance, responsible for providing personal dosimeters to all users in Malaysia, having now done so for in excess of 18 years (Mohd Ali, 2004); it also ensures that all instruments used in radiation at therapy, protection and environmental levels are calibrated. For present interest this includes radiation survey meters and therapy dosimeters (ion chambers), calibrated following the relevant IAEA Codes of Practices, as provided for by the IAEA as a Primary Standard Dosimetry Laboratory (PSDL) (Kadni, 2005).

In medical radiation practices, currently, in Malaysia there are 32 linear accelerators (Samat et al, 2009a), 7 cobalt-60 teletherapy machines, 15 brachytherapy units, 11 simulators and 4 computerised tomography units, operating in 21 radiotherapy and oncology centres (Samat et al, 2009a; Lim, 2006). In order to ensure these facilities produce consistent and accurate absorbed dose delivery, audits and intercomparison exercises are being carried out, predominantly by the MNA SSDL, with cooperation from the Ministry of Health Malaysia.
6.4 Participations of audit and intercomparison programmes

Most prominent among the audit and intercomparison programmes have been those for megavoltage photon beams, being a programme organized by the IAEA/WHO (Samat et al, 2009a) in collaboration with the MNA. Thirty seven such exercises have been carried out over the period 1985-2008. Other programmes in which the MNA have similar involvement are: kilovoltage photon beams (Ng et al, 1998) (carried out from 1993-1995), electron beams (Mohd Ali, 1995); dose equivalent $H_P (10)$ in mixed n-$\gamma$ fields (Mohd Ali, 2004). and deep dose ($H_P (10)$) and skin dose ($H_P (0.07)$) assessments. Other than IAEA involved evaluations, there has also been an intercomparison study by Rassiah et al, (2004) organized as a collaboration between the University of Malaya Medical Centre (UMMC) and the University of Wisconsin, Radiation Calibration Laboratory (UWRCL). Figure 6.3 provides a summary of published results of ion chamber and TLD intercomparison studies of $^{60}$Co beam (cobalt units) and high-energy photon beams (linear accelerators) carried out in a number of countries, the numbers highlighted in yellow pointing to results from Malaysia. In general, three types of dosimeters have been used in these intercomparisons: ionisation chambers (Samat et al, 2000), Lithium fluoride thermo luminescence dosimeters (TLD’s) (Samat et al, 2009a) and alanine (Mohd Ali, 2004). To-date, $^{60}$Co, 6MV, 10MV, 15MV, and 18MV energies have been checked by the MNA for beam calibrations (Samat et al, 2009a).

The results for TLDs and ion chambers comparisons (given as percentage deviations between stated doses and IAEA mean dose), show that the discrepancies are well within the IAEA limit of $\pm 3.5\%$ (Figure 6.4). Conversely, results of the TLD studies carried out by Rassiah et al, (2004) showed there to be a few centres yielding deviations of greater than $\pm 5\%$ (Figures 6.5 and 6.6), being traced to errors in irradiation set-up such as incorrect field size or SSD and sometimes to lack of physics support at $^{60}$Co beam facilities.
Figure 6.3 Summary of intercomparison studies for a number of countries, based on measurements by ion chambers and TLDs; the numbers highlighted by larger font are results from Malaysia. Each data point includes a box representing ± 1 SD about the mean value (where information is available). The whiskers represent the minimum/maximum ratio of measured dose to the expected dose, up to ±15%. The values above each box represent the number of beams for which measurements were made.
Figure 6.4: The range of discrepancies reported for TLD and chamber comparisons (for $^{60}$Co beam and four high energy photons beams). Reprinted from Samat et al, (2009a) with permission from Oxford University Press.

Figure 6.5 and 6.6: Differences in TLD response between Malaysian Linac (6 MV beam) and $^{60}$Co beam sites with UWRCL using 6 MV and $^{60}$Co beam. Reprinted from Rassiah et al, (2004) with permission from Springer.

In 2000, MNA also used alanine dosimeters for an IAEA intercomparison, to check on its gamma calibration facilities and the deviations were found to be within the acceptable limit set by IAEA i.e. ± 5% (Mohd Ali, 2004).
6.5. Benefits of Malaysian national dosimetry audits and problems reported

Currently, there are no known published reports concerning radiotherapy incidents in developing countries in Asia or Africa (WHO, 2008). In addition, the paucity of data regarding quality control of delivery of dose in such regions leads to no real understanding of the extent to which quality is maintained. The only published studies have concerned evaluation of dosimetry practices in a number of developing countries, focusing on measurements carried out by Izweska et al (2003; 2006). In regard to Malaysia, the intercomparison programme has increased confidence in the accuracy and consistency of dose delivery in radiation therapy (Rassiah et al, 2004; Samat et al, 2009b). Furthermore, an external audit of oncology practices enables identification of ‘areas of need’ in terms of gaps in knowledge and skills of the staff involved (Shafiq et al, 2009).

Thus said, there remains a number of unsolved problem in seeking to implement a comprehensive audit intercomparison programme in Malaysia, including a lack of experienced medical physicists (Rassiah et al, 2004) and high workloads for the radiation oncology staff (Ng et al, 1998; Shakespeare et al, 2006). Considering the comprehensive review of the audit programme discussed in chapter 2 and the availability of the equipment audit in Malaysia, a number of recommendations are here offered in addressing the problems stated above. These are:

(i) While Samat et al, (2009a) noted results from a Malaysian postal audit at radiotherapy level 1 (postal audits for photon beams in reference condition, see chapter 2), it would seem necessary to extend future auditing activities to level 2 (postal audits for photon and electron beams in reference and non-reference conditions on the beam axis) as proposed by the IAEA (Lim, 2006, Izweska et al, 2007);

(ii) Device checks should be made towards the end of the dosimetry chain (Thwaites et al, 2002a) (where the doses within a standard phantom for a planned treatment are measured, covering checks of basic dosimetry, patient data acquisition, treatment planning and delivery);

(iii) Strengthening of radiotherapy infrastructures to improve the audit outcomes to make this comparable with that of developed countries and to enhance the training of medical
radiation physics staff and suitable dosimetry facilities (Shafiq et al., 2009; Martenka et al., 2008);

(v) Good networking between the Malaysia government, private sectors, and non-government organisations are needed in order to lead to improvement of treatment facilities and to be able to have knowledge transfer between the centres similar to the UK’s audit networking systems (Thwaites et al., 2002a);

(vi) In vivo dosimetry should be promoted (Thwaites et al., 2002b);

(vii) Independent dosimetry checks in co-operation with peers should be encouraged (IAEA, 2002);

(viii) An audit systems like the UK’s should be followed which include the use of intercomparisons themselves, implementation of Quality Systems and regular Quality audit via Regional Dosimetry audit networks (Nisbet et al., 2008);

(ix) To achieve high accuracy of delivered dose to radiotherapy patients, quality assurance programmes addressing radiotherapy facilities, dosimetry and processes should be supported, strengthened, and promoted;

(x) Clinical audit should be included in the dosimetry checklist in order to fulfil assured clinical practice (Martenka et al., 2008);

(xi) In order to increase dosimetry audit expertise and the number of medical physicists well trained in complex radiotherapy techniques, special clinical training courses such as IMRT/IGRT and Dosimetry Audits should be frequently organized by the national authority. In these courses, experts in radiotherapy dosimetry from IAEA, EQUAL and RPC could be invited;

(xii) Resolution of the issue of a lack of medical physics staff is an issue perhaps to be initiated by The Public Service Department of Malaysia and Ministry of Health working with universities to promote the profession of medical physics. This may include provision of scholarships and opportunity to have industrial training (hands-on) in government and private hospitals, and with the Malaysia Nuclear Agency.
6.6 Mailed Ge-Doped Optical Fibre Thermoluminescence Dosimetry Audit of Radiotherapy Dose Delivery

The aim of the present investigation, using high energy photon beams, is to undertake a pilot study aimed at establishing the potential of a mailed commercial Ge-doped optical fibre TL-system in measuring beam output under reference conditions. The silica-glass optical fibre used is single-mode INOCORP (Canada) Ge-doped optical fibre, core diameter 9 μm and cladding diameter 116 ± 0.1 μm. The preliminary Ge-doped optical fibre irradiations were performed using the Varian linear accelerator located at Royal Surrey Country Hospital (RSCH). A set of three photon beams of 6-, 10- and 15 MV were employed. Note that the standard daily output of the linear accelerator at RSCH was performed by using 30 x 30 cm solid water phantom at the reference depth (for 6MV and 10 MV, this is 2 cm, whereas for 15 MV, it is 3 cm). The SSD was set to 100 cm and the field size to 10 x 10 cm². The output is normalized to be 1cGy/MU at 100 cm SSD at the depth of maximum dose (d_{max}) and 10 x 10 cm² field size.

Prior to the audit, a large collection of Ge-doped fibres were screened to establish individual performance using an ionisation chamber placed at the same depth as the TL-detector in a perspex phantom. Only fibres providing a response within ±5% of the batch mean and reproducibility of better than 5% were used in this audit.

6.6.1 Individual sensitivity factor and the calibration coefficient factor for Ge-doped optical fibres.

The individual sensitivity factor, S_i, and the calibration coefficient factor for Ge-doped optical fibres, N, need to be determined prior to the audit exercise. S_i is defined as an individual correction factor or relative intrinsic sensitivity factor concerning the i^{th} dosimeter. This takes account of reading variations due to the individual sensitivity of each fibre, sources of variation include dopant inhomogeneity, environmental factors such as storage temperature and thermal history of the samples. Consequently, it is periodically necessary to evaluate the S_i factor for a given batch; small variations in the sensitivity factors, can result in a relatively large uncertainty in the absorbed dose (Furetta, 2003).
To obtain the $S_i$, the uniformity of the delivered beam to the centre of the Perspex phantom first needed to be observed using EDR films. The EDR films were placed at the entrance face, centre and exit face of the Perspex phantom and irradiated to a dose of 2 Gy at reference depth of 2.3 cm, 25 x 25 cm$^2$ field sizes, dose rate of 200 cGy/min with source to surface distance (SSD) of 100 cm using a 6 MV photon energy. Afterwards, the film was processed using a Kodak processor and analysed using the OmniPro software (IBA Dosimetry GmbH, Germany). The result of the films (Appendix B) showed the delivered beam was approximately uniform (~ ± 3 %) at the centre of the Perspex phantom, thus no corrections needed to be applied for beam uniformity.

To obtain the $S_i$, irradiations were made in a Perspex phantom set-up, consisting of 120 selected optical fibres and a lateral hole at depth of 2.3 cm to place the ion chamber in. Use was made of a 6 MV photon beam and a dose of 2 Gy at the reference depth of 2.3 cm, with source to surface distance (SSD) of 100 cm, delivered at dose rate 200 cGy/min and field size of 25 x 25 cm$^2$ using a Varian Linear Accelerator (LINAC) located at the Royal Surrey County Hospital (RSCH). In order to deliver a known dose to the fibres, a revised calculation of monitor units is needed since use has been made of a large field size (25 x 25 cm$^2$) and shallow reference depth (2.3 cm). This is being different from the output specification point at the d$_{max}$ and 10 x 10 cm$^2$ field size as shown in Figure 6.7. Five repeated irradiations were performed for this purpose. Ge-doped optical fibres having the same $S_i$, were retained in groups of fifteen to be loaded into black plastic capsules and were used to determine the calibration coefficient factor, $N$ characterised as a function of TPR$_{20,10}$.

Figure 6.7 Perspex phantom set-up consisting of 120 optical fibres (left hand figure) and a lateral hole at depth 2.3 cm to place the ion chamber (right hand figure).
As a relative dosimeter, the Ge-doped optical fibres need to be calibrated against absolute dosimetry systems such as a calibrated ion chamber before they are used (IAEA, 2000). In this study the Ge-doped fibres were calibrated against a Farmer ionization chamber (NE Technology Limited, Berkshire RG7 5PR, England). The Farmer ionization chamber used in this study was a NE 2571 graphite walled ionization chamber, cross-calibrated against a NE 2611 NPL secondary standard ionization chamber. The latter has been calibrated with the NPL reference standard ionization chambers of type NE 2561 or 2611. These reference standard ionization chambers have been calibrated in terms of absorbed dose to water traceable to the UK primary standard of absorbed dose for photon beams at the National Physical Laboratory, England (NPL) (Pearce et al, 2010). Graphite calorimeters are the primary standards for absorbed dose at NPL, which have been used to calibrate at least three reference standards in graphite, these reference standards being ionization chambers of type NE 2561 or NE 2611 (Pearce et al, 2010). The conversion factors determined by Burns (1994) and confirmed by Nutbrown et al (2002) have been employed in order to convert the absorbed dose to graphite into absorbed dose to water.

The calibration coefficient factor, $N$, is used to convert the TL signal deposited in a fibre into the absorbed dose to water. The calibration coefficient factor $N$, for Ge-doped fibres was determined by irradiating fibres to a dose of 2 Gy using 6 MV photon energy delivered at a rate of 200 cGy/min under reference conditions in a Qados water phantom using the Ge-doped optical fibre holder. The fibres were positioned at 10 cm depth (the depth of measurements in reference condition, recommended by IAEA, 2000), at the distance of 100 cm from the source within the irradiation field of 10x10 cm$^2$. The absorbed dose to water was determined using a Farmer ionisation chamber placed at the same depth as the Ge-doped optical fibres, being connected to a Thermo Electron NE 2620 electrometer. The absorbed dose from the Farmer ionisation chambers reading was determined according to the IPSM 1990 Code of Practice (Figure 6.8).

Tissue Phantom Ratio (TPR$_{20,10}$) is a measure of the beam quality describing the approximately exponential decrease of a photon depth dose curve beyond the depth of maximum dose $Z_{\text{max}}$ (IAEA, 2000; IPSM 1990). In order to obtain the tissue phantom ratio at the depth of 20 cm and 10 cm using optical fibres, the optical fibres were sandwiched in a solid water phantom using bolus and the sheets of solid water phantom.
at 20 cm and 10 cm depth and irradiated consecutively. The optical fibres were irradiated with normal 6 MV, 10 MV, and 15 MV photon beams energies respectively, with 10 x 10 cm$^2$ field size, 100 cm focus to axis distance (FAD), 2 Gy, and 200 cGy/ min. A total of 15 cm of backscatter was used below the optical fibres location to ensure phantom scatter equilibrium. Two repeated irradiations at each energy were undertaken.

The fibres were also characterised for linearity with dose, fading, dose-rate effects, temperature and angular dependence to ensure the tightest possible control of influencing factors, use being made of megavoltage energy photon beams of nominal 6 MV, 10 MV and 15 MV as discussed in detail in Chapter 3. Finally, a total of 60 capsules were prepared for a preliminary audit exercise at the Royal Surrey Country Hospital.

![Figure 6.8 Ion chamber (left hand figure) and Ge-doped fibres holder (right hand figure) placed in QADOS water tank.](image)

6.6.2 Preliminary audit exercise at the Royal Surrey County Hospital

Prior to mailing of the optical fibres to participating radiotherapy centres in Malaysia, the audit methodology was developed and checked in a preliminary pilot audit exercise. This exercise has been carried out at the Department of Medical Physics, Royal Surrey County Hospital in order to select the fibre capsules with suitable dosimetric characteristics. A total of 60 capsules of selected Ge-optical fibres were irradiated to an absorbed dose to water of 2 Gy using a purpose-built holder, based on the IAEA TLD holder design (Figures 6.9a and 6.9b) and a Qados water tank. The following conditions were used: 6 MV energy, 10 cm depth, 10 cm x 10 cm$^2$ field size, and 100 cm-nominal source-to-surface distance (SSD)
(Figure 6.10). The absorbed dose to water obtained from optical fibre measurements have been compared against measurements obtained using an ionisation chamber placed at the same depth as the Ge-doped optical fibres.

Figure 6.9 a) Ge-doped optical fibres holder and constituent support parts; b) Schematic of assemble holder with the Ge-doped fibres capsule for Ge-doped irradiation.

Figure 6.10 Ion chamber and Ge-doped fibres have been placed in QADOS water.
Dose to water from ion chamber measurement has been determined according to the IPSM 1990 Code of Practice, whereas the dose to water determined from fibre measurements have been determined using an equation based on that used in the IAEA TLD audit systems developed by Izweska et al (2007). No corrections were applied for dose rate, angular and temperature effect, the fibres being found to be dose rate-, angular- and temperature-independent. For energy dependence, no correction factor was applied because the energy used in the audit exercise is the same as the energy used in order to calibrate the Ge-doped optical fibres. Fading corrections were found to be unnecessary since there was no delay in reading out the Ge-optical fibres following irradiation. The TL yield of fibres was also found to be linear in the dose range used in this audit exercise, and hence no correction was required for non-linearity.

6.6.3 Malaysian mailed radiotherapy centres and Ge-doped optical fibres dosimetry audit

In this study, an audit was carried out for eight Malaysian radiotherapy centres located at seven locations throughout the country, covering the west, east, north, and south of Peninsular Malaysia and one location in Malaysian Borneo, as shown in Figure 6.11.

Figure 6.11 The location of the eight Radiotherapy centre participating in the audit exercise. Seven centres are in Peninsular Malaysia and one centre is in Malaysian Borneo.

Capsules selected as a result of the preliminary audit exercise were mailed to these centres for irradiation to an absorbed dose to water of 2 Gy at 10 cm depth under reference conditions. To ensure a standardized irradiation procedure, four Ge-doped optical fibre capsules, a Ge-doped optical fibre holder, a radiotherapy centre specific details sheet, a technical instruction sheet and a
dose data report sheet were sent to each radiotherapy centre (Appendix C). First three of the Ge-doped fibre capsules need to be irradiated while the fourth capsule is the control capsule, which must not be irradiated as it is used to record environmental influences during transportation and storage. Using the returned fibres and completed data, TL readings were taken from the irradiated and control dosimeters. Finally, the results were analysed according to practices noted by the IAEA (IAEA,2000) and from this, a report of the variation from the standard 2 Gy dose was constructed, in terms of fibre TL yield and data quoted by participant centres.

6.7 Absorbed dose, calibration coefficient and correction factors for Ge-doped optical fibres

6.7.1 Calculation of absorbed dose from irradiated Ge-doped optical fibres

The absorbed dose from use of Ge-doped optical fibres was determined by comparing the response of the fibres with the readings given by the ion chamber. In order to calculate absorbed dose from Ge-doped optical fibre measurement, $D_{fibres}$, the following equation based on the IAEA TLD audit system developed by Izweska et al (2008) was employed:

$$D_{fibres} = \bar{R}NK_{Si}K_{hol}K_{fad}K_{lin}K_{engy}K_{dose-rate}K_{tem}K_{ang}$$  (6.1)

where $\bar{R}$ and $N$ are the average fibre response and the average calibration coefficient of the fibres in three irradiated capsules respectively. The factors correct for individual characteristics ($K_{Si}$), the Ge-doped optical fibre holder ($K_{hol}$), fading ($K_{fad}$), linearity ($K_{lin}$), energy dependence ($K_{engy}$), dose-rate dependence ($K_{dose-rate}$), temperature dependence ($K_{tem}$), and angular dependence ($K_{ang}$).

6.7.2 Average reading of Ge-doped optical fibres

This investigation involved a total of three capsules for each beam check, as mentioned previously. Each capsule contains 15 fibres from which the average readings are obtained. In order to calculate the average reading, $\bar{R}$, of these three capsules, $n$, the following equation was employed.

$$\bar{R} = \left(\frac{1}{n}\sum_{i=1}^{n}R_i - B\right)$$  (6.2)
where \( R_i \) is the fibres response of the \( i^{th} \) capsule irradiated to an absorbed dose to water of 2 Gy. \( B \) is the average background reading. Fibres response is given in units of nC.

### 6.7.3 Calibration coefficient of Ge-doped optical fibres

The average calibration coefficient, \( N \), obtained from the \( n \) reference Ge-doped optical fibre capsules were determined in accord with the equation:

\[
N = \frac{1}{n} \sum_{i=1}^{n} \frac{D_i}{(R_i - B)}
\]  

(6.3)

where \( D_i \) and \( R_i \) are the dose given to the \( i^{th} \) capsule and the mean reading of the 15 optical fibres in the \( i^{th} \) capsule respectively, and \( B \) is the average background reading. The calibration coefficient is given in Gy/nC.

For calibration irradiations, the absorbed dose given to the optical fibres, \( \bar{D}_i \), is compared against measurements obtained using an ionisation chamber placed in the solid water phantom at the same depth as the optical fibres, following the IPSM 1990 Code of Practice, as follows:

\[
\bar{D}_i = \bar{C} N_{D,W} K_{T,P} K_{ion}
\]  

(6.4)

where \( \bar{C} \) is the mean of the ion chamber readings, \( N_{D,W} \) is the calibration factor of the ionization chamber (obtained from the National Physics Laboratory calibration certificate), \( K_{T,P} \) is a correction for the influence of temperature and pressure and \( K_{ion} \) is a correction for ion recombination (Pearce et al., 2010).

### 6.7.4 Individual correction factor

The value of individual Ge-doped optical correction factor, \( S_i \), was determined applying the relation of Furetta (2003):

\[
S_i = \sum_{i=1}^{n} \frac{\bar{R}_{ref}}{R_i - R_{ref}}
\]  

(6.5)
where \( \bar{R}_{ref} \) is the average of the reference irradiated dosimeters, \( R_i \) is the reading of the \( i \)th fibre capsule annealed and irradiated at a well defined dose \( D \), and \( R_{oi} \) is the background reading of the same dosimeter after annealing but without being irradiated.

6.7.5 Holder correction factor

The Ge-doped optical fibre holder is of the same design as the IAEA TLD holder, having the same attenuation characterisation. For the IAEA holder attenuation correction factors have previously been evaluated experimentally and analytically by Izewska et al (1996, 2007). Afterwards, Hultqvist et al., (2010) simulated the holder at reference conditions using the Monte Carlo code PENELLOPE in order to determine the correction factors. Results of the simulation were found to be in agreement with the experimental results obtained by Izewska and co-workers. As a result, the simulated results have been used to plot a linear fit in order to obtain a holder correction factor for beam qualities applied in this study.

6.7.6 Energy correction factor

The energy correction factor, \( K_{energy} \), is the ratio of the fibres response per unit dose \( (R/D) \), computed at a prescribed dose as close as possible to 2 Gy at the photon beam quality of \( TPR_{20,10(6\,MV)} \) to the fibres response per unit dose computed at a prescribed dose of 2 Gy at the photon beam quality of \( TPR_{20,10} \) at the given photon energy.

\[
K_{energy} = \frac{(R/D)_{TPR_{20,10(6\,MV)}}}{(R/D)_{TPR_{20,10}}} \quad (6.6)
\]

6.7.7 Fading correction factor

The fading function, \( f_{fad} \), is defined as the ratio of the fibres response, \( f_i \), read on day \( x \), to the response, \( f_0 \), of the fibres response read on day \( x_0 \).

\[
f_{fad} = \frac{f_i}{f_0} = \frac{f_0 [ (y_0 - d) e^{-ks} + d ]}{f_0} = (y_0 - d) e^{-ks} + d
\]

(6.7)
where \( y_0, d \) and \( k \) are coefficients obtained from the fit in Figure 6.16. The fading correction factor, \( K_{fad} \), is the ratio of the fading function of the Reference Dosimeter, \( RD \), to the fading function for the Participant Dosimeter, \( PD \).

\[
K_{fad} = \frac{f_{fad}(x_{RD})}{f_{fad}(x_{PD})} = \frac{(y_0 - d)e^{-kx_{RD}} + d}{(y_0 - d)e^{-kx_{PD}} + d}
\] (6.8)

6.7.8 Linearity, Temperature-, Angular, and Dose-rate Dependence Factors

No corrections were applied for dose rate, angular and temperature dependences, the fibres being found to be dose rate-, angular- and temperature-independent. In addition, the fibres response was also found to be linear over the dose range used in this audit exercise, thus the dose linearity correction factor was also deemed to be negligible.

6.8 Uncertainties of Ge-doped fibres

Uncertainty is a measure of the goodness of a result. An analysis of uncertainties involved in the Ge-optical fibres dose determination has been performed as suggested in IAEA (2000). It is noted that the uncertainty appraisal in IAEA (2000) also follows the guidance provided by the ISO document (1992) entitled ‘Guide to the Expression of Uncertainty in Measurement’ (GUM). The first corrected edition of this document was published in 1995 and a second corrected edition entitled ‘Evaluation of measurement data-Guide to the expression of uncertainty in measurement GUM 1995 with minor corrections (JCGM 100:2008)’ published in 2008. These were prepared by the Joint Committee for Guides in Metrology Working Group 1 (JCGM-WG1) in order to accompany the GUM.

According to JCGM 100:2008, in most cases a measured \( Y \) is determined from \( N \) other quantities \( X_1, X_2, \ldots, X_N \) through a functional relationship \( f \), such that:

\[
Y = f(X_1, X_2, \ldots, X_N)
\] (6.9)

Thus, estimation of the measured \( Y \), represented by \( y \), is achieved from equation 6.9 using input estimates \( x_1, x_2, \ldots, x_N \) for the values of the \( N \) quantities \( X_1, X_2, \ldots, X_N \) and given by

\[
y = f(x_1, x_2, \ldots, x_N)
\] (6.10)
There are two types of uncertainty of measurement used in the present work; Type A (denoted as $u_a$) and Type B (denoted as $u_b$). Type A standard uncertainties are evaluated based on statistical analysis of a series of independent observation such as calculating the standard deviation of the mean, performing least squares fits to calculate the parameters of the fitted lines and running analysis of variance (ANOVA). Examples of the Type A standard uncertainties involved in this study are mean fibre reading, fading-, holder-, energy correction factors and individual sensitivity of fibres.

Type B uncertainties are not based on a statistical data analysis and also cannot be estimated by repeat measurements (IAEA, 2000). They may instead include use of data information in calibration reports or previous measurement data, manufacturer’s specification sheets and use of the experimenter’s general knowledge of the properties of instruments and materials. An example of a type B uncertainty given by IAEA (2000) is rectangular or uniform probability distribution, given by the standard uncertainty, $u_b$:

$$u_b = \frac{a}{\sqrt{3}}$$

(6.11)

where $a$ is the estimated maximum limits $-a$ and $+a$. In this study, examples of uncertainty that can be categorized as type B are temperature- and ion recombination correction factors, chamber and Ge-doped optical fibre positioning.

The sensitivity coefficient or partial derivative, $c_i = \frac{\partial f}{\partial x_i}$, determines how the output estimate, $y$, varies with alteration in the values of the input estimate $x_i$ (JCGM 100, 2008).

The following equation has been derived if the variation is due to the standard uncertainty of the estimate $x_i$.

$$u_i(y) = |c_i|u(x_i)$$

(6.12)

The combined uncertainty, $u_c(y)$, of dose calculation from Ge-doped optical fibre measurements is formed of the uncertainty of dose determination through the use of an ion chamber and the system itself. This type of uncertainty uses statistical rules for combining variances. In this study, the combined uncertainty has been expressed as a sum of terms,
each of which represents the estimated variance associated with the output estimate, \( y \), generated by the estimated variance associated with each input, estimated as \( x_i \). The following equation shows the combined uncertainty formula if the input quantities are uncorrelated.

\[
{u_c}^2(y) = \sum_i [c_i u(x_i)]^2 
\]  
(6.13)

To calculate the expanded uncertainty, \( U_p \), having a level of confidence, \( p \), the combined uncertainty, \( u_c(y) \), is multiplied by a coverage factor, \( k_p \) as shown in the equation below:

\[
U_p = k_p u_c(y) 
\]  
(6.14)

The result of a measurement is commonly written as \( Y = y \pm U_p \) which has an approximate level of confidence, \( p \). The value of \( K_p = 1 \), \( K_p = 2 \) and \( K_p = 3 \) correspond to confidence limits of approximately 68%, 95% and 99% respectively.

6.8.1 Uncertainty of an average reading of Ge-doped optical fibres

The uncertainty in the average reading of Ge-doped optical fibres is given by:

\[
u(R) = \frac{\sum \sigma_i}{\sqrt{n I}}
\]  
(6.15)

where \( \sigma_i \) is the standard deviation of the fibres response of the \( i \)th capsule, \( I \) is the number of capsules used in the investigation and \( n \) is the number of fibres per capsule.

6.8.2 Uncertainty of the calibration coefficient of Ge-doped optical fibres

There are three major relative uncertainties that contribute in measuring the calibration coefficient factor of Ge-doped fibres, comprising of the relative uncertainty in the readings of Ge-doped fibres within a capsule \( u(R_i) \), uncertainties in the absorbed dose to water given by the ionization chamber \( u(D_i) \) and uncertainties in the positioning of the Ge-doped fibres \( u(pR_i) \). Uncertainty due to the background reading, \( B \) is disregarded as its magnitude is smaller than the mean reading of a capsule (Hultqvist, 2006). Thus, in order
to calculate the uncertainty of a calibration coefficient of Ge-doped optical fibres, the combined relative uncertainty, $u_c$ is used, (Hultqvist, 2006) and is given by:

$$u_c(N) = \sqrt{\frac{u(D_i)^2 + u(R_i)^2}{n}} = \sqrt{\frac{\left(\frac{u(D_i)^2 + u(R_i)^2}{n}\right) + u(pR_i)^2}{n}}$$

(6.16)

where $n$ is the number of reference Ge-doped optical fibre capsules.

The relative uncertainty in $u(D_i)$ is influenced by uncertainty in pressure, temperature and ion recombination. To calculate the uncertainty in pressure and temperature, three contributing sources of uncertainty are suggested by the IAEA (2008b) which are calibration, resolution, and repeatability (uncertainty in mean readings). Repeatability is a Type A uncertainty, therefore the standard error of the mean of pressure and temperature readings is used in order to obtain the uncertainty. The calibration and resolution of pressure and temperature are considered as Type B uncertainties. So, assuming a rectangular distribution, the equation in 6.11 will be used to calculate the uncertainty. The sensitivity coefficient for temperature and pressure are determined using the equation recommended by the IAEA (2008b). The uncertainty due to the ion recombination is estimated in the same way as given in the NPL report IR 24 of Pearce et al (2010).

According to the IAEA (2008b), the contribution to uncertainty in the beam output due to Type B factors comprise of uncertainties in positioning of the NE 2611 secondary standard ionization chamber and the NE 2571 Farmer ionization chamber under calibration as well as the uncertainty in the Qados water phantom positioning during calibration of the NE 2611 secondary standard and the NE 2571 Farmer ionization chamber. To determine the uncertainty due to positioning of the NE 2571 Farmer ionization chamber, equation 6.12 has been employed whereas a rectangular distribution is assumed in order to obtain the uncertainty due to Qados water phantom positioning.

A similar situation appears in the next step of the irradiation process of the Ge-doped optical fibres, due to the uncertainties in the positioning of the Ge-doped fibres at the 10 cm reference depth and the uncertainty arising from the water phantom positioning. Consequently, the same procedure is used in determining the uncertainties.
6.8.3 Uncertainty in an individual correction factor

The uncertainty of an individual correction factor \( u_c \) is obtained using the combined relative uncertainty provided by the following equation:

\[
\begin{align*}
  u_c \left( K_{S_i} \right) = \sqrt{u \left( \frac{R_{\text{net}}}{R_{\text{ref}}} \right)^2 + u \left( R_i \right)^2} \tag{6.17}
\end{align*}
\]

where \( u \left( \frac{R_{\text{net}}}{R_{\text{ref}}} \right) \) is the relative uncertainty of the reference irradiated dosimeters and \( u \left( R_i \right) \) is the relative uncertainty in the mean reading of a capsule. Again the uncertainty due to the background reading is disregarded as its magnitude is considered to be smaller than the mean reading for a capsule.

6.8.4 Uncertainty in the holder correction factor

Uncertainty in the holder correction factor has been calculated using a least squares method. The measured holder correction values have been determined from Monte Carlo simulation by Hultqvist et al, (2010), plotted against \( TPR_{20,10} \), making a linear fit. Subsequently, the standard error of the calculated data is determined by using:

\[
\begin{align*}
  u(K_{\text{hol}}) = \sqrt{\frac{1}{N-2} \sum_{i=1}^{N} \left( y_i^{\text{(measured)}} - y_i^{\text{calculated}} \right)^2} \tag{6.18}
\end{align*}
\]

where \( y_i^{\text{(measured)}} \) is the holder correction value (measured values), \( y_i^{\text{calculated}} = mx + b \) is the estimation of the \( y \)-value from the best-fit line obtained in Figure 6.14, \( N \) is the number of the detector used in the fit.

6.8.5 Uncertainty in the fading correction factor

The uncertainty in the fading correction factor is determined by error propagation according to the formulation:

\[
\begin{align*}
  u(K_{\text{fad}}) = \sqrt{\left( \frac{\partial K_{\text{fad}}}{\partial y_0} \right)^2 u(y_0)^2 + \left( \frac{\partial K_{\text{fad}}}{\partial d} \right)^2 u(d)^2 + \left( \frac{\partial K_{\text{fad}}}{\partial k} \right)^2 u(k)^2} \tag{6.19}
\end{align*}
\]
where \( \mu(y_0), \mu(d) \) and \( \mu(k) \) are the uncertainties in the coefficients \( y_0, d \) and \( k \) obtained from nonlinear regression. The values for \( \mu(y_0), \mu(d), \) and \( \mu(k) \) were 0.0119, 0.0168 and 0.01837 respectively. Including the partial derivatives the variance becomes:

\[
\begin{align*}
\sigma(K_{fad})^2 &= \left( \frac{\partial}{\partial y_0} \right)^2 u(y_0)^2 + \left( \frac{\partial}{\partial d} \right)^2 u(d)^2 + \\
&\quad + \left( \frac{\partial}{\partial k} \right)^2 u(k)^2
\end{align*}
\]

(6.20)

where \( x_{RD} \) and \( x_{PD} \) are the time delays between the irradiation and read-out of the reference- and participant dosimeter respectively.

6.8.6 Uncertainty in the energy correction factor

Uncertainty in the energy correction factor is calculated from least squares fit, in the same manner as the uncertainty in the holder correction factor:

\[
\sigma(K_{Engy}) = \sqrt{\frac{1}{N-2} \sum_{i=1}^{N} (y_{i_{\text{measured}}} - y_{i_{\text{calculated}}})^2}
\]

(6.21)

where \( y_{i_{\text{measured}}} \) is the measured energy correction factor, \( y_{i_{\text{calculated}}} = mx + b \) is the estimation of the \( y \)-value from the best-fit line achieved in Figure 6.15 and \( N \) is the number of the detector used in the fit.

6.8.7 The combined uncertainty of the absorbed dose, calibration coefficient and correction factors of Ge-doped optical fibres

All the individual parameters used for calculating the absorbed dose from an optical fibre measurement in equation 6.1 are assumed to be independent of each other. Therefore, in order to calculate the combined relative uncertainty, \( u_c \) the square root of the sum of square uncertainties of each individual parameter is employed (Izweska et al, 2008):

\[
u_c(D_{fibres}) = \sqrt{u(R)^2 + u(N)^2 + u(K_{Tri})^2 + u(K_{fibres})^2 + u(K_{fad})^2 + u(K_{Engy})^2}
\]

(6.22)
6.8.8 Uncertainty of deviation in the ratio \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \)

Generally all the audit results are reported as the ratio of the obtained dose as calibrated at reference centres, \( D_{\text{fibres}} \), to the dose quoted by the participating centres, \( D_{\text{participant}} \). To calculate the uncertainty in this ratio, the following equation was applied:

\[
\begin{align*}
    u\left( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \right) = & \sqrt{\frac{u_c(D_{\text{fibres}})^2 + u(D_{\text{participant}})^2}{I}} \\
    \text{(6.23)}
\end{align*}
\]

where \( u_c(D_{\text{fibres}}) \) is the uncertainty in the dose obtained from the fibre measurement, \( u(D_{\text{participant}}) \) is the uncertainty in the dose quoted by the participating centres according to the IAEA Code of Practice TRS 398 (IAEA, 2000). The number of fibres used to determine the ratio is represented by \( I \).

6.8.9 Reporting the audit results

According to (ISO, 1992) the percentage relative deviation between the obtained and quoted dose is defined as:

\[
    \Delta D = 100\% \frac{D_{\text{participant}} - D_{\text{fibres}}}{D_{\text{fibres}}} 
\]

(6.24)

In this study, an acceptance limit of ±5\% (0.95 ≤ \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) ≥1.05) has been set for this deviation, as previously used by the ESTRO quality assurance network (EQUAL) and the IAEA TLD postal programme. Deviation of more than ±5\% and less than ±10\% (0.90 ≤ \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) ≥0.95) or (1.05 ≤ \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) ≥1.10) are considered minor and deviations exceeding ±10\% (\( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) ≤ 0.90 or \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) ≥1.10) are regarded as major (IAEA, 2000).

Full details of the audit results are mailed to participating centres if the deviation is within the acceptance limit. However, if there is a deviation outside tolerance, the participating centre is informed that there has been a deviation but are not informed of its magnitude or deviation and will be asked to repeat the measurement again as soon as possible. In the case
of a major deviation following the repeat measurement, the SSDL Malaysia is informed and a detailed on-site audit visit carried out by SSDL Malaysia may then be required.

6.9 Results and discussion

6.9.1 Preliminary audit exercise

For the preliminary pilot audit in the UK, corrections for dose rate, angular and temperature effects and energy dependence in the absorbed dose to water calculation were unity. The correction for fading was also close to unity since there was no delay between irradiation and the readout time for the Ge-optical fibres. In addition, the fibres response was also found to be linear with dose in the dose range used in this pilot audit, 2 Gy and therefore the dose linearity is also taken to be unity.

6.9.1.1 Uncertainty in average reading of Ge-doped optical fibre capsules

From an original 60 Ge-doped capsules, with a mean distribution of 0.97 and standard deviation of 4.6% (Figure 6.12a), a total of 38 capsules were observed to provide good agreement with the stated dose, giving a mean distribution of 0.99 with standard deviation of 2.7% (Figure 6.12b). Further to Figure 6.12b, using equation 6.15 the standard error of the mean for a single Ge-doped optical fibre capsule does not exceed 0.5%, which also supports the homogeneity of Ge-doped capsules based on 95% confidence level of sensitivity. Capsules with values outside of the range of acceptable readings were discarded and a new batch set of Ge-doped capsules were obtained with optimum uniformity in TL response and these were used as mailed dosimeters in the current dose intercomparison exercise of selected Malaysian radiotherapy centres. The selection process for Ge-doped capsules has to be made with attention to detail in order to minimise the uncertainty involved in calculating the absorbed dose to water measurements.
Figure 6.12a Histogram of the relative TL responses ($D_{\text{stat}}/D_{i}^{th}$ capsule) of 60 Ge-doped optical fibres capsules. Note that $D_{\text{stat}}$ is the dose actually stated by RSCH relative to $D_{i}^{th}$ capsule, the dose obtained by the $i^{th}$ capsule. Distribution of the mean is 0.970 with 0.046 standard deviation.

Figure 6.12b Histogram of the relative TL responses ($D_{\text{stat}}/D_{i}^{th}$ capsule) of 38 Ge-doped optical fibres capsules. Note that as before $D_{\text{stat}}$ is the dose actually stated by RSCH relative to $D_{i}^{th}$ capsule, the dose obtained by the $i^{th}$ capsule. Distribution of the mean is 0.990 with 0.02 standard deviation.
6.9.2 Uncertainty in calibration coefficient factor of Ge-doped fibres

As stated previously in section 6.8.2, the combined uncertainty of dose obtained from Ge-doped optical fibre measurement is due to the uncertainty of dose determination through the use of an ion chamber and the fibre system itself. Both uncertainties comprise of relative uncertainty in the readings of Ge-doped fibres, uncertainties in the absorbed dose to water given by the ionization chamber and then due to positional uncertainties by the fibres.

The uncertainty arose from a relative uncertainty in reading of a Ge-doped fibre capsule of 0.43%, and is explained in detail in 6.9.1.1. According to the equation 6.4, the absorbed dose to water given by the Farmer ionization chamber, was calculated using the IPSM 1990 Code of Practice. According to the ion-chamber certificate provided by the NPL, the expanded uncertainty for the ionization chamber calibration coefficient $N_{d,w}$ was 1.5%. To provide a 95% level of confidence, the $N_{d,w}$ has been multiplied by a coverage factor of $k = 2$. Thus, the Type A uncertainty in the calibration coefficient $N_{d,w}$ for the ionization chamber was estimated to be 0.75%.

The Type A uncertainty for the mean ion chamber reading $\overline{C}$, and correction for the temperature $K_T$, and pressure $K_P$, were determined using equation 6.15 and found equal to 0.10%, 0.08% and 0.08% respectively. The type B uncertainty for $K_T$, $K_P$, ion chamber and water phantom positioning was evaluated according to the IAEA-TECDOC-1585 (IAEA, 2008b), the uncertainty being estimated as the standard deviation of the rectangular distribution expressed in equation 6.11.

In order to estimate the uncertainty in the measured temperature, a maximum error of 0.5°C was estimated between the readings of the digital thermometer and the reference digital thermometer during calibration. The maximum resolution of the digital thermometer used was approximated as 0.1°C with a sensitivity coefficient of 0.0845. Thus, assuming a rectangular distribution, the combined Type B uncertainty in measured temperature was found to be 0.03%.

To calculate the uncertainty in measured pressure, a maximum error of 0.1mmHg was estimated between the readings of the barometer and the reference barometer used in calibration. Thus by assuming a rectangular distribution, this gave an 0.06% uncertainty.
The resolution of the digital barometer was 0.01 mmHg. Again by assuming a rectangular distribution, this gives an uncertainty of 0.006% and is thus considered to be a negligible contribution to uncertainty. The sensitivity coefficient for pressure is 1.0000; therefore, the uncertainty of Type B in measured pressure is 0.06%.

Uncertainty in ion recombination was estimated as 0.1%, the same as estimated from the NPL report IR 24 (Pearce et al., 2010). Assuming a rectangular distribution, this uncertainty is 0.06%.

The maximum uncertainty in displacement of the ion chamber and Ge-doped optical fibres from their position at 100mm depth has been estimated as 0.1mm. Thus, the sensitivity coefficient was found from the normalized depth dose curves to be 0.40% mm\(^{-1}\). Assuming a rectangular distribution, the Type B uncertainty in the ion chamber and Ge-doped optical fibres position was found to be 0.02%.

In positioning the Qados water phantom, the rectangular distribution has again been assumed, leading to a relative uncertainty in positioning of the phantom of 0.003%, assuming a maximum error in the displacement of 0.05 mm relative to the source to surface distance (SSD) of 1000mm.

The combination of the three major relative uncertainties contributing to the estimation of the calibration coefficient factor of Ge-doped fibres is presented in Table 6.1. As mentioned in section 6.6.3, three capsules are used to obtain the mean of TL readings. Therefore, the combined uncertainty in the Ge-doped calibration coefficient of 0.51 is used.
Table 6.1 Summary of combined individual uncertainties in the calibration coefficient factor of Ge-doped fibres

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Combined A,B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Dose to water given by ionization chamber (D)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration coefficient, <em>N&lt;sub&gt;d,w&lt;/sub&gt;</em></td>
<td>0.75</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Mean ion chamber reading, <em>C</em></td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td><em>K&lt;sub&gt;T&lt;/sub&gt;</em> (correction for temperature effect)</td>
<td>0.08</td>
<td>0.03</td>
<td>0.09</td>
</tr>
<tr>
<td><em>K&lt;sub&gt;P&lt;/sub&gt;</em> (correction for pressure effect)</td>
<td>0.08</td>
<td>0.06</td>
<td>0.1</td>
</tr>
<tr>
<td><em>K&lt;sub&gt;i&lt;/sub&gt;</em> (correction for ion recombination)</td>
<td>0.06</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>Ion chamber positioning</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Qados water phantom positioning</td>
<td>0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.77</td>
<td>0.09</td>
<td><strong>0.78</strong></td>
</tr>
<tr>
<td><em>Ge-doped-position (pR)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge-doped fibres positioning</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Qados water phantom positioning</td>
<td>0.003</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.02</td>
<td>0.02</td>
<td><strong>0.02</strong></td>
</tr>
<tr>
<td><em>Ge-doped-reading (R)</em></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reading reproducibility, <em>R</em></td>
<td>0.43</td>
<td></td>
<td><strong>0.43</strong></td>
</tr>
<tr>
<td>Uncertainty in capsule</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>One capsule</em></td>
<td>0.88</td>
<td>0.09</td>
<td>0.88</td>
</tr>
<tr>
<td><em>Two capsules</em></td>
<td>0.62</td>
<td>0.07</td>
<td>0.63</td>
</tr>
<tr>
<td><em>Three capsules</em></td>
<td><strong>0.51</strong></td>
<td><strong>0.05</strong></td>
<td><strong>0.51</strong></td>
</tr>
</tbody>
</table>
6.9.3 Uncertainty in an individual correction factor

Uncertainty in the individual correction factors was determined by plotting the histogram of relative standard deviation of the individual correction factors as shown in Figure 6.13. The relative standard deviation of the histogram is 2%. The maximum and minimum value is 2.8% and 1.4% respectively. Uncertainty in this correction factor is a major contribution to the combined uncertainty in the determined dose from fibres.

![Frequency distribution of the relative standard deviation of individual correction factors of 38 capsules.](image)

6.9.4 Uncertainty in a holder correction factor

As mentioned in section 6.7.5, the graph in Figure 6.14 is a linear fit, allowing calculation of the holder correction factor for each beam quality used in this study. The standard error of the calculated data, using equation 6.18, is 0.1%. 

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6.9.5 Uncertainty in energy-dependence correction factor

The uncertainty in the energy correction factor was calculated from the linear fit shown in Figure 6.15, using equation 6.21. The uncertainty estimate was 0.01%, a relatively small contribution to the combined uncertainty in the determined dose from fibres.

6.9.6 Uncertainty in the fading correction factor

Using equation 6.20, the uncertainty in fading values was fitted to a single exponential decay as illustrated in Figure 6.16. To calculate the uncertainty equation 6.20 was utilized. The estimated uncertainty in this fading correction factor is 0.03%.
Figure 6.15 Linear fit to energy correction factor for Ge-doped fibres. Each data point corresponds to the average of results from two capsules. The response of each photon beam was normalized to the response for 6MV photon energy. The beam quality, TPR\textsubscript{20,10} values for 6, 10 and 15 MV were 0.66, 0.723 and 0.774 respectively.

Figure 6.16 Exponential Decay: Single exponential decay fit to 14 measured fading values. Each data point corresponds to the average reading of 30 optical fibres from two capsules. The values for y\textsubscript{o}, d and k were 0.9967, 0.8726 and 0.0378 respectively.

6.9.7 Combined and expanded uncertainty in determined dose of fibres

Table 6.2 gives the summary of combined uncertainties associated with the absorbed dose determination in water for 6 MV and 10 MV photon beam energy as a result of the use of the Ge-doped fibre system. Based on equation 6.22, the combined uncertainty in the
determined dose of Ge-doped optical fibres was 2.11% for the high energy photon beams used. Thus, the expanded uncertainty is 4.22% after multiplication by a coverage factor $k = 2$ (IAEA, 2008b). This uncertainty provides a level of confidence of approximately 95%. The uncertainty of each individual parameter described in Table 6.2 is two standard deviations (2 SD).

**Table 6.2 Summary of combined individual uncertainties in determined dose of Ge-doped optical fibre system.**

<table>
<thead>
<tr>
<th>Uncertainties</th>
<th>Type A (%)</th>
<th>Type B (%)</th>
<th>Comb. A,B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical fibres reproducibility, $R$</td>
<td>0.43</td>
<td></td>
<td>0.43</td>
</tr>
<tr>
<td>Calibration coefficient, $N$</td>
<td>0.51</td>
<td>0.05</td>
<td>0.51</td>
</tr>
<tr>
<td>Individual correction, $K_{S_i}$</td>
<td>2.00</td>
<td></td>
<td>2.00</td>
</tr>
<tr>
<td>Holder correction, $K_{hol}$</td>
<td>0.10</td>
<td></td>
<td>0.10</td>
</tr>
<tr>
<td>Fading correction, $K_{fad}$</td>
<td>0.03</td>
<td></td>
<td>0.03</td>
</tr>
<tr>
<td>Energy correction, $K_{engy}$</td>
<td>0.01</td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.11</strong></td>
<td><strong>0.05</strong></td>
<td><strong>2.11</strong></td>
</tr>
</tbody>
</table>

6.9.8 Uncertainty in the ratio of $\left( \frac{D_{fibres}}{D_{participant}} \right)$

Uncertainty in the ratio of $\left( \frac{D_{fibres}}{D_{participant}} \right)$ has been calculated in accord with equation 6.23.

All ion chambers used in Malaysia are calibrated at the Malaysian SSDL; the Malaysian SSDL factors are traceable to the IAEA and sequentially traceable to the Bureau International des Poids et Mesures (BIPM). The uncertainty attributed to the SSDL is 1.2% at a 95% confidence (two standard deviation) determined by the IAEA, (2000).
Using $u(D_{\text{participant}})$ as 1.20% and $u_t(D_{\text{fibres}})$ as 2.11, $u\left(\frac{D_{\text{fibres}}}{D_{\text{participant}}}\right)$ provides an uncertainty of 1.40%.

### 6.9.9 Malaysian postal dose audit results

A mailed audit of eight selected Malaysian radiotherapy centres was carried out with a total of eight beam calibrations being checked. Three of the participating centres were from general hospitals, while the other five were private medical centres. The most commonly used dosimetry protocol in Malaysia to determine absorbed dose to water is the IAEA TRS 398. Table 6.3 shows in part the ionization chamber and electrometer systems used in water phantom for calibration. Note that the Wellhofer FC65G ionization chamber (IBA, Schwarzbruck, Germany) connected to a UNIDOSE electrometer (PTW, Freiburg, Germany) is commonly used in Malaysia. All of the ionization chambers listed herein are calibrated at the Malaysian Secondary Standard laboratory once per year. Seven out of the eight participating radiotherapy centres in this audit study have already participated in LiF TLD postal dose audit programmes organized by various international agencies such as the IAEA, ESTRO and the Forum for Nuclear Cooperation in Asia (FNCA) Radiation Oncology project. Of those participating in previous audits, as in Table 6.3, all were found to produce values in the range less than ±3%, noting the acceptance limit to be ±5%.

The present postal dose audit, based on the use of Ge-doped optical fibres, is the first of its kind to be carried out not only in Malaysia but worldwide. The results of the audit are shown in Figure 6.17. Each data point corresponds to the average from three capsules of Ge-doped fibres. The histogram corresponds to ratios of the obtained dose as calculated at the RSCH ($D_{\text{fibres}}$) relative to the dose quoted by the Malaysian radiotherapy centres ($D_{\text{participant}}$). The mean ratio of measured to quoted dose was 0.99 with a standard deviation of 3%. The ratio of the results varies between a minimum dose of 0.92 and a maximum of 1.03. One out of eight beams checked was shown to produce a deviation of more than ±5% but less than ±10%. The particular centre has never previously participated in any audit programme involving mailed TLDs. Hence, investigation showed that as a result of misinterpretation of the instructions on how to carry out the irradiation,
the Ge-doped fibres were subjected to an incorrect dose. The particular centre was informed about the issue and asked to perform a second measurement.

Figure 6.18 shows the distribution of results following the repeat measurement. The mean distribution is now 1.00 with a standard deviation of 1.3%. The maximum and minimum result of the ratio is 1.03 and 0.99 respectively, all now being within the acceptance limit (±5%). Izewska and Andreo, (2000) stated that “only 65% of the hospitals that received TLD for the first time produced results within the acceptance limit (±5%), while 81% of the institutions participating regularly in the audits have produced results within the (±5%)limits”. Of importance is that such efforts, viz regular (periodic) participation in external audits, can help to maintain accurate dosimetry, especially so in developing countries where such support is invaluable (Rassiah et al, 2004).

---

Figure 6.17 Histogram of the relative TL responses \(D_{\text{fibres}}/D_{\text{participant}}\) of the eight participating Malaysian radiotherapy centres. Note that \(D_{\text{fibres}}\) is the dose obtained at the RSCH relative to the dose quoted by the Malaysian radiotherapy centres, \(D_{\text{participant}}\). The distribution of the mean is 0.99 with 0.03 standard deviation.
Figure 6.18 Histogram of the relative TL responses ($D_{\text{fibres}}/D_{\text{participant}}$) of the eight radiotherapy centres following one repeat irradiation. Note that $D_{\text{fibres}}$ is the dose obtained at the RSCH relative to the dose quoted by the Malaysian radiotherapy centres, $D_{\text{participant}}$. The distribution of the mean is 1.00 with 0.01 standard deviation.

6.10 Conclusion

In conclusion, following review of the development of dosimetry audits and the conduct of one such exercise in Malaysia, it is apparent that regular periodic radiotherapy audits and intercomparison programmes should be strongly supported and implemented worldwide. The programmes to-date demonstrates these to be a good indicator of errors and of consistency between centres. 9 µm diameter core Ge-doped fibres represent a viable system for use in mailed audit radiotherapy programmes. Analysis of contributing uncertainties in this audit programme have included optical fibres reproducibility, calibration coefficient of fibres, individual correction factors, holder correction, fading correction, and energy correction. The combined uncertainty in the determined Ge-doped dose was 2.11% for the high energy photon beams used; the expanded uncertainty is 4.22%. This analysis is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%.
A total of eight beams have been checked in eight radiotherapy Malaysian radiotherapy centres. One out of the eight beams checked produced an unacceptable deviation; this was found to be due to unfamiliarity with the irradiation procedures. Prior to a repeat measurement, the mean ratio of measured to quoted dose was found to be 0.99 with standard deviation of 3%. Subsequent to the repeat measurement, the mean distribution was 1.00, and the standard deviation was 1.3%. Uncertainty in the ratio \( \frac{D_{\text{fibres}}}{D_{\text{participant}}} \) calculated using equation 6.23 was found to be 1.4%.
### Table 6.3: Types of facility in the participant radiotherapy centres in Malaysia, together with supporting data provided by those centres.

<table>
<thead>
<tr>
<th>Radiotherapy centres</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model of accelerator</td>
<td>Siemens Primus</td>
<td>Elekta Synergy</td>
<td>Siemens Primus, Siemens MXE2</td>
<td>Elekta Synergy</td>
<td>Elekta Precise</td>
<td>Siemens Primus</td>
<td>Varian Clinac</td>
<td>SL 20 Philips</td>
</tr>
<tr>
<td>Nominal X-ray beam energy (MV)</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>10</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>TPR20,10</td>
<td>0.68172</td>
<td>0.675</td>
<td>0.73</td>
<td></td>
<td></td>
<td></td>
<td>0.6729</td>
<td></td>
</tr>
<tr>
<td>D20,10</td>
<td>0.5862</td>
<td></td>
<td></td>
<td></td>
<td>0.590</td>
<td>0.633</td>
<td></td>
<td>0.581</td>
</tr>
<tr>
<td>Ionization Chamber</td>
<td>Wellhofer FC65G</td>
<td>Extradin A12 Farmer</td>
<td>PTW 30013</td>
<td>NE 2571 Farmer</td>
<td>Wellhofer FC65G</td>
<td>Wellhofer FC65G</td>
<td>Wellhofer FC65G</td>
<td>Not provided</td>
</tr>
<tr>
<td>Electrometer</td>
<td>PTW UNIDOSE</td>
<td>Supermax Standard Imaging</td>
<td>PTW UNIDOSE</td>
<td>Wellhofer dose 1</td>
<td>PTW UNIDOSE</td>
<td>Wellhofer dose 1</td>
<td>Wellhofer dose 1</td>
<td>Not provided</td>
</tr>
<tr>
<td>Calibration phantom</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>Previous Audit</td>
<td>IAEA, 2007 - 2.1% (6 MV)</td>
<td>IAEA, 2006- Machine 1- 1%(6MV)</td>
<td>IAEA, 2008- Machine 2- 0.7% (6 MV)</td>
<td>Never participated</td>
<td>FNCA Radiation Oncology, 2010 - 1% (10MV)</td>
<td>IAEA, 2002- 1.2% (6 MV)</td>
<td>IAEA, 2003- 1.5% (10 MV)</td>
<td>Not provided</td>
</tr>
</tbody>
</table>
7

FINAL DISCUSSIONS AND FUTURE WORK

7.1 Final Discussions

The interest in thermo luminescence (TL) dosimetry has increased substantially in recent years. The Ge-doped optical fibre is a viable TL system for use in radiotherapy dosimetry, due to its excellent radiation response characteristics. In Chapter 3 it was found that 9 µm core diameter Ge-doped fibres (Ge-9µm) fulfill many desirable characteristics for a radiation dosimeter. The fibre was found to show only small energy dependence (6 to 11 %) at megavoltage higher photon and electron energies but gave significant energy response for kilovoltage photons beams. The fibres showed linear response at all photon and electron beam energies for doses from 5cGy to 1000 cGy. The fibres were also found to be angular-independent as well as dose-rate independent for megavoltage photon beams. Concerning the effect of temperature on the fibre, the result shows that the fibre response was independent of temperature. This chapter also provides information about stability of the fibres in term of fading. Comparison was made of changes in the TL yield of Ge-doped fibres (Ge-9µm and Ge-50µm) and Lithium fluoride (LiF) dosimeters (TLD-100 and TLD-700) for varying temperature and dose. Results show an accountable systematic fading of Ge-doped fibres dosimeters, making them suitable for trans-national dose audit programmes. For both Ge-doped optical fibres and LiF dosimeters the rate of post-irradiation fade is independent of dose but systematically dependent upon storage temperature. The maximum signal loss of 5% and 11 % have been observed for both forms of LiF dosimeters and (Ge-9µm) optical fibres dosimeters respectively, following 133 days of storage at room temperature, while for the more sensitive (by a factor of 12) 50 µm
core diameter fibres, under the same conditions, the fading was significantly less, at ~8%.

Prostate cancer is a leading cause of cancer-related death in man (Warmkessel, 2006). The use of intensity modulated radiotherapy (IMRT) techniques provides a means for radiation dose delivery to achieve the desired dose distributions to optimise the treatment of the disease. However, in order to fully benefit from such treatment, knowledge on the accuracy of Treatment Planning Systems (TPS) to validate the IMRT delivered absorbed dose received by the patient is required. In Chapter 2, we have introduced the IMRT techniques with the focus on the advantages and limitations of these techniques. In Chapter 4 the neutron dose contribution to the absorbed dose assessment, when the use of higher energies to deliver IMRT was considered. The results have demonstrated that (Ge-9µm) optical fibre dosimeters offer potential for use in IMRT radiotherapy verification when using 6 MV photons. The need to correct their response to neutrons when conducting 15MV irradiations was also demonstrated. Similarly, in Chapter 5, for the 6 MV and 15 MV nominal photon energies used, the Ge-doped optical fibre is shown to verify target doses to within 3% of the TPS predicted doses and LiF TLDs.

In Chapter 6, radiotherapy dosimetry audit activities in Malaysia have been reviewed. The findings conclude that audit activities in Malaysia should be developed further and supported in order to ensure consistency between centres. The first level of intercomparison audit as described in Chapter 2 was checked, use being made of 9 µm core diameter Ge-doped silica fibres (Ge-9µm). This is in line with the recommendation by Izewska et al (2007) to utilize this step before initiating subsequent audit levels. Eight selected Malaysian radiotherapy centres were involved in this audit. Furthermore, we have utilised the IAEA postal audit methodology represented in the literature as the basis of a model to develop an audit methodology for Ge-doped optical fibres. A preliminary audit to check this methodology was carried-out prior to the actual audit. A refinement to the novel absorbed dose to water equation proposed by Izewska et al (2008) has also been presented, introducing the correction for individual Ge-doped fibres factor, $S_i$. This is introduced to overcome the non-uniformity distribution of dopant concentration in the fibres. This chapter also provides details of the uncertainty-analysis covering this audit programme. This refers to the work
(Hultquist, 2006; Izewska et al, 2007; Pearce et al, 2010). For high energy photon beams, the combined uncertainty in the Ge-doped system was 2.11%. The audit carried out to-date indicates that one out of eight centres has shown a minor deviation. Unfamiliarity of the physicist of the particular centre with the irradiation procedures was found to be a possible cause of the deviation. The mean ratio of measured to quoted dose was found to be 0.99 with standard deviation 3%, prior to repeated measurement. Following repeated measurement of the audit, the mean distribution was found to be 1.00 with standard deviation 1.3%. Using equation 6.23, uncertainty in the ratio of dose measured by fibres to the dose stated by the participants is found to be 1.4%.

The work carried out to-date has resulted in a number of national and international conference presentations, abstracts and proceeding papers. The list of these various publications is included in Appendix D.

7.2 Future Work

This thesis raises some important questions, which require further experimental investigation. First in this respect is that there is a significant contribution of thermal neutron to out-of-field dose measured by Ge-doped optical fibres; when IMRT techniques involving higher photon energies (>10 MV) are employed. This raises the question of quantifying the magnitude of this effect for different treatment sites. This could be achieved through Monte Carlo calculations or measurements using an appropriate neutron detector (Hussein et al, 2011).

In intra-cavitary dosimetry, the use of treatment planning systems (TPS) to assess the delivered dose is limited due to the presence of air cavities inside the patient (Gagliardi et al, 2009). Considering all of the benefits of Ge-doped optical fibres highlighted in Chapter 2, in particular the non-hygroscopic nature of these glassy media, fibre dosimeters offer tremendous potential for their use in intra-cavitary dosimetry for IMRT. In addition, due to its small physical size (a few tens of microns), providing high spatial resolution make it suitable to use in cyberknife dosimetry. Cyberknife technique and small field dosimetry in general, require accurate measurements of
output factors at distances less than 5mm e.g. for trigeminal neuralgia which employs the use of a 5mm collimator (Rah et al, 2008).

Results in Chapter 3 and Chapter 6 show that Ge-doped fibres could be used as a mailed photon dosimetry method. It is suitable for audit programs since it adheres to all the conditions that apply in an audit programs. Therefore, the aim of any future series of experiments should be extend to next higher levels of intercomparison audit, in particular for auditing electrons beams. This has also been suggested by Nisbet et al, (2008), where audit groups should tighten tolerances for standard audits and continually develop to include more complex levels when it is observed that the tolerances for reference levels are met.

In term of sensitivity, the 50 µm core diameter Ge-doped silica fibres (Ge-50 µm) has been observed to be more sensitive compared to 9 µm core diameter Ge-doped silica fibres (Ge-9 µm) by a factor of 12 as described in chapter 3. This dosimetric characteristic is important and may lead to application in environmental dosimetry and in diagnostic radiology. However, the minimum detectable dose with Ge-50 µm core diameter fibres and its response subject to charged particles (electron, alpha, beta, and proton) and an uncharged particle (neutron and photon) is still unknown. Therefore, future studies should include more detailed evaluation of this including the fading effect for longer periods of time post-irradiation. This would provide additional confidence to the use of this type of fibre (Ge-50 µm) as postal dosimeters in international dose surveys that focus on the accuracy of dose delivery in radiotherapy centres across the globe (noting that delays of one to two months in return of the dosimeters to the authority reading out the fibres can be anticipated).


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