DETERMINATION OF OPTICALLY STIMULATED LUMINESCENCE DOSIMETRIC CHARACTERISTICS AND SUITABILITY FOR ENTRANCE SURFACE DOSE ASSESSEMENT IN DIAGNOSTIC X-RAY EXAMINATIONS

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DEDICATION

This thesis is dedicated to my parents

Late Alhaji Musa Danladi and Hajiya Maryam Muhammad Lukman.

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ABSTRACT

The availability of Optically Stimulated Luminescence (OSL) dosimeter system developed by Landauer Inc. (Glenwood IL) has greatly improved radiation dosimetry application in the medical field. Recent studies with OSL dosimeters (nanoDots) gave much emphases to patient radiation exposure in radiotherapy but ignoring the potential risks from radiographic examinations. This study focused on the measurement of entrance surface dose (ESD) resulting from radiographic examination. Monitoring procedures have been developed by the International Atomic Energy Agency (IAEA) to estimate ESD, while considering exposure parameters and patient's characteristics. However, dosimetric properties of the OSL system must be characterized to ascertain its suitability for ESD measurements in medical radiography due to energy dependence and over-response factors of the Al_2O_3 material. This thesis consists of three phases: 1) evaluating stability of the new OSL dosimetry system, 2) characterizing the nanoDots in radiographic energy range from 40 kV to 150 kV with typical doses ranging from 0 to 20 mGy, and 3) assessing suitability of the nanoDots for ESD measurement in routine X-ray examinations. The dosimetric characteristics of the nanoDots in the above energy range are presented in this study, including repeatability, reproducibility, signal depletion, element correction factor, linearity, angular and energy dependence, and dose measurement accuracy. Experimental results showed repeatability of below 5% and reproducibility of less than 2%. OSL signals after sequential readouts were reduced by approximately 0.5% per readout and having good linearity for doses between 5 – 20 mGy. The nanoDots OSL dosimeter showed significant angular and energy dependence in this energy range, and corresponding energy correction factors were determined in the range of 0.76 – 1.12. ESDs were determined in common diagnostic X-ray examinations using three different methods including direct (measured on phantom/patient) and indirect (without phantom) measurements with nanoDots OSL dosimeters, and CALDose_X 5.0 software calculations. Results from direct and indirect ESD measurements showed good agreement within relative uncertainties of 5.9% and 12%, respectively, in accordance with the International Electrotechnical Commission (IEC) 61674 specifications. However, the measured results were below ESDs calculated with CALDose_X 5.0 software. Measured eye and gonad doses were found to be significant compared to ESDs during anterior-posterior (AP) abdomen and AP skull examinations, respectively. The results obtained in this research work indicate the suitability of utilizing nanoDots OSL dosimeter for entrance surface dose assessment during diagnostic X-ray examinations.

ABSTRAK

Ketersediaan dosimeter OSL (Optically Stimulated Luminescence) yang dibangunkan oleh Landauer Inc. (Glenwood IL) telah menambah baik aplikasi dosimetri sinaran dalam bidang perubatan. Kajian terbaharu dengan dosimeter OSL (nanoDots) memberi lebih penekanan kepada dedahan sinaran terhadap pesakit dalam radioterapi tetapi mengabaikan potensi risiko daripada pemeriksaan radiografi. Kajian ini memberi tumpuan kepada pengukuran dos permukaan masuk (ESD) yang terhasil daripada pemeriksaan radiografi. Prosedur pemantauan telah dibangunkan oleh Agensi Tenaga Atom Antarabangsa (IAEA) untuk menganggarkan ESD, sambil mempertimbangkan parameter dedahan dan ciri-ciri pesakit. Walau bagaimanapun, sifat dosimetri sistem OSL mesti dicirikan untuk menentukan kesesuaiannya bagi pengukuran ESD dalam radiografi perubatan disebabkan oleh faktor kebersandaran tenaga dan lampau-sambutan oleh bahan Al_2O_3. Tesis ini merangkumi tiga fasa: 1) menilai kestabilan sistem OSL yang baharu, 2) pencirian nanoDots dalam julat tenaga radiografi daripada 40 kV sehingga 150 kV dengan dos tipikal daripada 0 sehingga 20 mGy, dan 3) menilai kesesuaian nanoDots bagi pengukuran ESD dalam pemeriksaan sinar-X rutin. Ciri-ciri dosimetri nanoDots dalam julat tenaga di atas dibentangkan dalam kajian ini, termasuk keterulangan, kebolehulangan semula, penyusutan isyarat, faktor pembetulan unsur, kelinearan, kebersandaran sudut dan tenaga, dan kejituan pengukuran dos. Dapatan eksperimen menunjukkan keterulangan adalah di bawah 5% dan kebolehulangan semula adalah kurang daripada 2%. Isyarat OSL selepas bacaan berjujukan berkurang kira-kira 0.5% setiap kali bacaan dan mempunyai kelinearan baik untuk dos di antara 5 − 20 mGy. Dosimeter OSL nanoDots menunjukkan kebersandaran sudut dan tenaga yang ketara dalam julat tenaga ini, dan faktor pembetulan tenaga yang sepadan ditentukan dalam julat 0.76 - 1.12. ESD ditentukan dalam pemeriksaan diagnosis sinar-X menggunakan tiga kaedah yang berbeza termasuk pengukuran langsung (diukur pada fantom/pesakit) pengukuran tidak langsung (tanpa fantom) dengan dosimeter OSL nanoDots, dan pengiraan menggunakan perisian CALDose_X 5.0. Keputusan dari pengukuran ESD secara langsung dan tidak langsung menunjukkan persetujuan yang baik dalam ketidakpastian relatif masing-masing sebanyak 5.9% dan 12%, selaras dangan spesifikasi Suruhanjaya Elektroteknikal Antarabangsa (IEC) 61674. Bagaimanapun, dapatan terukur adalah di bawah ESD yang dikira menggunakan perisian CALDose_X 5.0. Dos terukur di mata dan gonad didapati lebih ketara berbanding dengan ESD yang diukur semasa pemeriksaan abdomen anterior-posterior (AP) dan tengkorak AP. Keputusan yang diperolehi dalam kajian ini menunjukkan kesesuaian menggunakan dosimeter OSL nanoDots untuk penilaian dos permukaan masuk semasa pemeriksaan diagnostik sinar- X.

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LIST OF ABBREVIATIONS

AAPM	-	American Association of Physicists in Medicine
Al_2O_3:C	-	Aluminium Oxide doped with Carbon
AP	-	Anterior Posterior
BMI	-	Body-Mass Index
BSF	-	Backscatter Factor
BSS	-	Basic Safety Standard
CBCT	-	Cone-Beam Computed Tomography
CF	-	Conversion Factor/Calibration Factor
CT	-	Computed Tomography
CW-OSL	-	Continuous Wave – Optically Stimulated Luminescence
CV	-	Coefficient of Variation
DRK	-	Dark Current
DRL	-	Diagnostic Reference Level
EC	-	European Commission
ECF	-	Energy Correction Factor/Element Correction Factor
ESAK	-	Entrance Surface Air Kerma
ESD	-	Entrance Surface Dose
EU	-	European Union
FDD	-	Focus to Detector Distance
FSD	-	Focus to Surface Distance
FTD	-	Focus to Table top Distance
GE	-	General Electric
HVL	-	Half Value Layer
IAEA	-	International Atomic Energy Agency
ICRP	-	International Commission on Radiation Protection
ICRU	-	International Commission on Radiation Units
IEC	-	International Electrotechnical Commission
IKN	-	Institute Kanser Negara
INAK	-	Incident Air Kerma
KV XVI	-	Kilo Voltage X-ray Volume Imager

LAT - Lateral
LED - Light Emitting Diode
LM-OSL - Linear Modulated – Optically Stimulated Luminescence
LNT - Linear No Threshold
MNA - Malaysian Nuclear Agency
MOSFET - Metal Oxide Semiconductor Field Effect Transistor
OSL - Optically Stimulated Luminescence
OSLD - OSL Dosimeter
PA - Posterior Anterior
PET - Positron Emission Tomography
PMT - Photo-Multiplier Tube
POSL - Pulsed-Optically Stimulated Luminescence
PSDL - Primary Standard Dosimetry Laboratory
PTB - Physikalisch-Technische Bundesanstalt
QA - Quality Assurance
QC - Quality Control
SD - Standard Deviation
SF - Sensitivity Factor
SSD - Source to Sample Distance
SSDL - Secondary Standard Dosimetry Laboratory
TL - Thermo-Luminescence
TLD - TL Dosimeter
UNSCEAR - United Nation Scientific Committee on Effects of Atomic Radiations

LIST OF SYMBOLS

I - Final Intensity
I_0 - Initial Intensity
Z_{eff} - Effective Atomic Number
Z - Atomic Number
μ - Absorption Coefficient
$h\nu$ - Photon Energy
E - Energy
E_e - Electron Energy
E_b - Electron Binding Energy
τ - Photoelectric Cross-section
N - Number of Atoms per unit Volume
θ - Angle
mc^2 - Rest-mass Energy
k - Boltzmann’s Constant
T - Temperature
n - Trapped Charge Concentration
p - Rate of Stimulation
Φ - Photon Flux
σ - Photo-ionisation Cross-section
λ - Wavelength
$f(D)$ - Dose Response Function
D - Absorbed Dose
$S(n)$ - OSL signal on n readings
$\bar{\varepsilon}$ - Energy Imparted
$R_{in,\ out}$ - Radiant energy
Q - Charge
H_T - Dose Equivalent
w_R - Weighing Factor
K_i - Incident Air Kerma
$K(d)$ - Air Kerma at the Measurement Point

d_{FTD} - Distance between Tube Focus to Patient Support

d_m - Distance from table top to reference point

t_p - Patient’s organ thickness

K_e - Entrance Air Kerma

$Y(d)$ - Tube Output

P_{It} - Current-Exposure time product

ρ - Density

μ_{en} - Mass-Energy Absorption Coefficient

R_{uL} - Upper Limit of measured to delivered dose ratio

R_{LL} - Lower Limit of measured to delivered dose ratio

H_0 - Lowest Dose

H_1 - Conventional True Dose

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

The use of optically stimulated luminescence (OSL) technique for a variety of radiation dosimetry applications in recent years is increasing due to the dramatic growth in the use of ionizing radiation for clinical purpose. Since the inception of OSL technique for dosimetry applications in the 80s, a good number of studies have been carried out to comprehend the luminescence properties of different materials (Huntley, Godfrey-Smith and Thewalt, 1985). The most essential factors that define a successful measurement in radiation dosimetry are traceability, consistency and accuracy, particularly in radiology and radiotherapy where the outcome is highly dependent on the radiation dose delivered to the patient (IAEA, 2009). The need for radiological techniques such as general radiography and computed tomography (CT) for diagnostic purposes has increased significantly in the last few decades which resulted to high demand of radiation monitoring mechanisms to assess the risk-to-benefit relationship associated with the use of these modalities and to keep the dose levels of patients and personnel as low as reasonably achievable (ALARA) in order to avoid the risk of cancer induction associated with diagnostic radiations.

Estimation of doses in diagnostic radiology is usually done by entrenching a dosimeter in the patient’s/personnel’s body or tissue-equivalent phantom. Both thermoluminescence dosimeter (TLD) and OSLD are known to be utilized for radiation dosimetry including personal monitoring, in-vivo dosimetry and estimation of dose index in computed tomography (CT) from the dose profiles (Endo *et al.*, 2012). The application of optically stimulated luminescence (OSL) technique is not limited to personal and medical dosimetry, but has recently been used for the assessment of environmental dose using naturally occurring minerals in luminescence dating and retrospective dosimetry which serve as leap forward in the development of OSL readers (Yukihara and McKeever, 2008).

The use of X-rays in diagnostic radiology has contributed immensely to the identification and treatment of countless number of diseases and helps to improve the health of people, but at the same time, radiation doses from diagnostic radiology have the largest contributions to the combined dose from all artificial sources of radiation which is attributed to the large number of X-ray examinations performed annually (IAEA, 2007). According to the recent analysis by United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), an estimated 3.6 billion diagnostic X-ray examinations are undertaken annually worldwide (UNSCEAR, 2011). This shows that there is high increase of patient exposure to ionizing radiation in order to provide a proper diagnosis at the same time using high exposure to produce images of good quality. Therefore, dosimetric technique is required in diagnostic X-ray imaging systems in order to determine the dosimetric parameters for establishing diagnostic reference levels (DRL) and assessing the average dose to the tissues and organs at risk.

Any exposure to ionising radiation is presumed to give rise to a risk of detrimental effects, such that one has to recognize that there is certain degree of risk involved and must limit the radiation dose to a level at which the assumed risk is considered to be acceptable or permissible in view of the benefits derived from such procedures (ICRP, 1977). Part of the European Union recommendation for efficient radiation protection was to reduce unproductive and needless radiation exposure by optimization of protection measures and use of dose limits (European Commission, 1999). This is because despite the net benefit in these procedures supersede the risk, the potential for radiation-induced injuries to patient remain possible.

Assessment of dose and determination of dosimetric parameters would not be possible without evaluating the associated dosimetry equipment performance as part of the requirement and quality assurance process (IAEA, 2007). It is therefore necessary and essential to test the performance of new dosimetry equipment for quality control and assurance. Entrance surface dose (ESD) is an important parameter in assessing the dose delivered to patient in a single radiographic exposure. The European Union (EU) has identified this physical quantity as one to be monitored as a diagnostic reference level (DRL) which permits optimization of patient dose. Patient doses in diagnostic X-ray examinations can be best estimated in terms of the entrance surface dose (ESD) per radiograph or dose area product (DAP) for the complete examination (European Commission, 1996). However, TLD is the most widely used dosimeter for ESD measurement in clinical dosimetry but the prevailing potentials of OSLD to be used for nearly real time dosimetry has given OSL a good level of superiority in some aspects (McKeever and Moscovitch, 2003). Monte Carlo simulations of the energy deposition from X-ray exposure can also be achieved, provided the irradiation conditions related to the X-ray procedure and anatomy of the patient under study are well defined (Meghzifene *et al.*, 2010). By means of dosimeter or ionization chamber, ESD can also be measured directly with the use of suitable phantoms (Ng and Yeong, 2014).

The availability of commercial OSL dosimeters has also contributed to the successful applications of OSL technique for clinical and personal use. The InLight and nanoDots OSL dosimeters made of up Al_2O_3:C produced by Landauer had extensively been used for dosimetry applications in recent years (Yukihara and McKeever, 2008). But the use of this dosimetry system is not rapidly migrating into diagnostic radiology especially radiography, with majority of the recent studies giving emphasis to image quality and overlooking the possible risk of radiation exposure to patients.

1.2 Problem Statements

In a properly managed diagnostic X-ray examinations, the radiation doses which typically range from 1 – 20 mGy are far much lower than those capable of producing noticeable serious radiation injury (IAEA, 2007). Yet, there may be no such lower dose limit for the instigation of some deleterious effects (stochastic effects). Such small doses may give rise to malignant neoplasia and radiation-induced mutation, which in turn may form the basis of hereditary effects. Thus, the possible risk from small doses due to exposure to ionizing radiation is perhaps owing to these types of biological changes and any increment of doses to individuals from X-ray carries certain amount of risk, even though the risk may be extremely small. According Linear No Threshold (LNT) hypothesis, any dose, whatever small, can produce a detriment and the risk excess of developing a radiation-induced disease increases with the dose to the individual linearly (Ferdeghini, 2014). However, the appropriate action that should be taken to prevent unnecessary exposure in radiography is to regularly monitor the radiation dose used for each procedure using a suitable technique by trained staff (IAEA, 2007).

This has attracted a lot of research interest to the use of OSL dosimeters as potential alternative to the well-known TLDs. TLDs are highly sensitive devices and have been used extensively on patients as well as on phantoms. But the destructive readout feature of the TLD limits the reanalysis of the absorbed dose. (McKeever and Moscovitch, 2003; Meigooni *et al.*, 1995; Olko, 2010). Measurement using ionization chambers can also be made with high degree of accuracy than other dosimeters, but require sophisticated electrometer circuit and storage facility, and are not always used on patients due to their bulkiness and connecting cables that inconvenience the patient mobility with potential interfering shadow on the radiograph (Merchant, 1933; Massoud E, 2014; Ponmalar *et al.*, 2017). Despite good reproducibility and real-time readout of the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) based dosimeter, the presence of finite lifetime and temperature dependence limit their application (Ponmalar *et al.*, 2017; Rahman *et al.*, 2016; Rivera-Montalvo, 2016).

Owing to their excellent dosimetric attributes, the aluminium oxide based (Al_2O_3:C) OSL dosimeter developed by Landauer Inc, have been used extensively in clinical radiotherapy (Mrčela *et al.*, 2011; Andersen, Aznar and Boetter-Jensen, 2003; Dunn *et al.*, 2013; Jursinic, 2007; Jursinic, 2010; Ponmalar *et al.*, 2017; Viamonte *et al.*, 2008), and diagnostic radiology procedures including computed tomography (CT) (Al-Senan and Hatab, 2011; Ding and Malcolm, 2013; Scarboro *et al.*, 2015; Tawfik *et al.*, 2013; Yukihara *et al.*, 2009; Yusuf *et al.*, 2014), fluoroscopy (Akselrod, Botter-Jensen and McKeever, 2006; Gasparian *et al.*, 2010; Perks, Yahnke and Million, 2008), and mammography (Al-Senan and Hatab, 2011; Alothmany *et al.*, 2016; Perks, Yahnke and Million, 2008). In spite of the interesting features of the Al_2O_3:C OSLDs in radiation dosimetry, which include high sensitivity, good precision for low dose measurements, possible re-analysis, high speed readout and elimination of thermal annealing steps (McKeever and Moscovitch, 2003; Olko, 2010), all-inclusive literature review revealed that the use of Al_2O_3:C OSLDs in general X-ray is not well-established. This is attributed to the fact the material over-respond to low energy X-rays about 3 – 4 times at an effective energy of ~40 – 50 keV compared to higher energy photons from ^{60}Co or ^{137}Cs due to its high effective atomic number (11.28), resulting to certain level of energy dependence (Yukihara *et al.*, 2009).

The principal goal of this research is to characterize the nanoDot OSLDs in radiography energy range (40 – 150 kV), with the aim of providing solutions involving over-response and energy dependence associated to the Al_2O_3 material in low energy X-ray, and to assess the suitability of the nanoDot OSLDs for entrance surface dose (ESD) assessment in diagnostic X-ray examinations. The major significance and relevance of this research is to offer an alternative for ESD determination using OSL through provision of new data for common X-ray examinations and relevant dosimetric characteristics. The problem statement of the study is shown schematically in Figure 1.1.

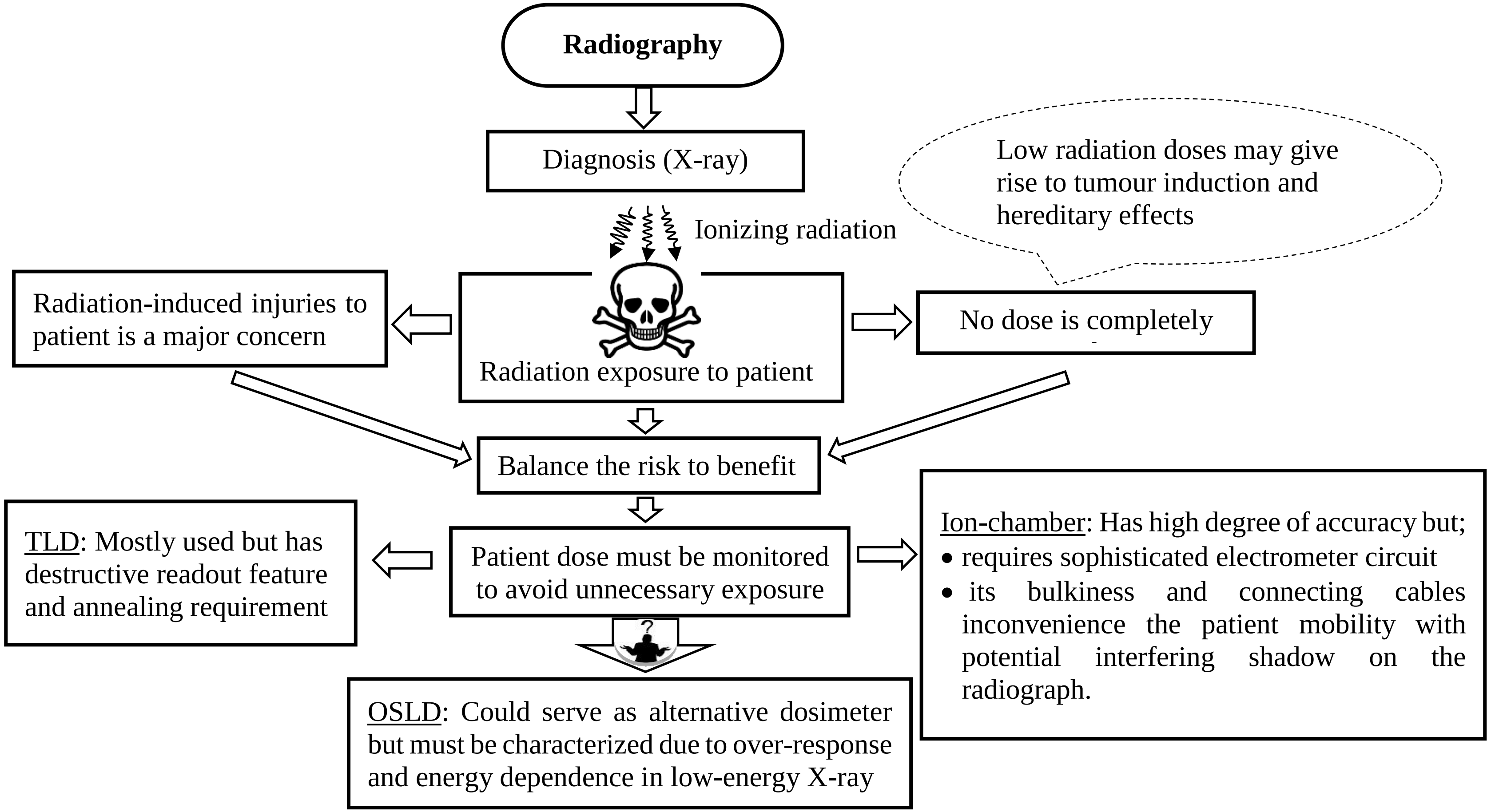

Figure 1.1 Schematic diagram of the research problem statement.

1.3 Aim and Objectives of the Research

This study is aimed to characterize the new OSL dosimetry system in UTM supplied by Landauer Inc and evaluate its suitability for clinical dosimetry in general X-ray. The objectives of this research are as follows;

(a) To calibrate and evaluate the stability of the new Landauer InLight MicroStar OSL dosimetry system.

(b) To investigate the dosimetric characteristics of the nanoDots OSLD including repeatability, reproducibility, dose linearity, signal depletion, element correction factor, angular dependence, and energy dependence in radiography energy range from 40 kV – 150 kV with typical doses ranging from 0 – 20 mGy.

(c) To assess the suitability of the nanoDots OSLD for direct and indirect ESD measurements in Chest, Abdomen, Skull, and Thoracic spine radiography, with associated eye, thyroid and gonad doses using adult anthropomorphic phantom and compare with CALDose_X 5.0 software calculations.

1.4 Scope of the Research

The current study involves the evaluation of the InLight microStar reader performance, characterization of the OSL dosimeters and their applications for ESD measurement in common X-ray examinations. The scope of this study is itemized as follows;

The baseline of the OSL reader performance was established by assessing the reader stability based on background signal fluctuations. Afterwards, the microStar reader was calibrated using OSL dosimeters irradiated to 80 kV X-ray beam and dose levels of 0 – 30 mGy for low dose calibration and 0 – 1000 mGy for high dose calibration.

The nanoDot OSLDs dosimetric characteristics were evaluated in radiation qualities for radiography (RQR) by assessing the repeatability, reproducibility, signal depletion, dose-response linearity, individual dosimeter element correction factors, energy dependence, angular dependence and dose measurements accuracy in the energy range from 40 – 150 kV using typical doses in radiography ranging from 0 -20 mGy.

Entrance surface doses (ESDs) were measured using the so-called *Indirect measurement* and *Direct measurement* methods based on the IAEA procedures described in Technical Report Series No. 457. Direct measurements were performed using anthropomorphic whole-body phantom, while indirect measurements were performed in the absence of backscatter material. The common X-ray examinations that were considered are: AP abdomen, LAT abdomen, AP chest, PA chest, AP thoracic spine and AP skull.

Mathematical software known as CALDose_X 5.0 was utilized to calculate ESDs in the X-ray examinations mentioned earlier, using the same exposure parameters as employed in the measurement methods. The measured ESDs were then validated by comparison with CALDose_X software calculations, published works and established international diagnostic reference levels (DRLs).

Doses to the critical organs such as eye, thyroid and gonad were also measured using direct method during the AP abdomen, AP chest and AP skull examinations.

1.5 Thesis Outline

This thesis is designed to give a broad overview of the use of optically stimulated luminescence dosimetry for entrance surface dose measurements in radiography. The steps taken for achieving this goal was exclusively experimental, which involved understanding the basic technique required for ESD estimation in common X-ray examinations.

The thesis is however sectioned into chapters, with Chapter 2 effectively describing the general principles of dosimetry in radiography and OSL technique, as well as their previous and current status. Chapter 3 momentarily outline the materials involved in carrying out this research and briefly describe the methods used. Chapter 4 is made up of results and discussion in the order of the outlined objectives; i.e., evaluation of the microStar performance and stability, characterization of the OSL dosimetry system, and measurement and evaluation of entrance surface dose in diagnostic X-ray examinations. Chapter 5 will consist of conclusions based on the results obtained and offer some recommendations that might improve future studies involving the use of Landauer OSL dosimetry system in radiographic dose and energy range.

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