DEVELOPMENT OF DOSIMETRIC TECHNIQUES FOR THE MEASUREMENT OF LOW ENERGY PHOTONS

by

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As members of the Viva Voce Committee, we certify that we have read the dissertation prepared by **Sunil Kumar Singh** entitled **"Development of dosimetric techniques for the measurement of low energy photons"** and recommend that it may be accepted as fulfilling the thesis requirement for the award of Degree of Doctor of Philosophy.

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I, hereby declare that the investigation presented in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree / diploma at this or any other Institution / University.

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List of Publications arising from the thesis

Journal

1. Development of a detector for the measurement of ambient dose equivalent, $H^*(10)$ at low and medium photon energies. Sunil K. Singh and M. S. Kulkarni. Applied Radiation and Isotopes 148C (June, 2019) pp. 213-217. DOI: 10.1016/j.apradiso.2019.03.042.
2. Wall thickness optimization of an ionization chamber for directional dose equivalent rate measurement at low and medium photon energies. Sunil K. Singh and M. S. Kulkarni, Radiation Protection Dosimetry (2018), pp. 1–6. DOI:10.1093/rpd/ncy171
3. Development of an ionization chamber for low and medium energy photon dosimetry, Sunil K. Singh and M. S. Kulkarni. Radiation Protection Dosimetry Volume 182, Issue 2, Pages 215–220. DOI:10.1093/rpd/ncy051
4. Development of an ionization chamber-based high sensitivity detector for the measurement of radiation dose from X-ray whole body scanners. Singh Sunil Kumar, Tripathi Sudesh M, Shaiju Liji, Sathian V, Kulkarni Mukund S: Radiat Prot Environ 2016;39:190-3. DOI: 10.4103/0972-0464.199979
5. Measurement of dose reduction factors for X-rays and its relevance in eye lens monitoring applications. Kumar Munish, Singh Sunil Kumar, Gaonkar Uma P, Sharma S D, Ratna P, Koul D K, Kulkarni M S, Datta D. Radiat Prot Environ 2017;40:142-8. DOI: 10.4103/rpe.RPE_27_17.
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7. Development of two element α-Al_2O_3:C based OSLD badge system using α-Al_2O_3:C for low energy photon dosimetry. Sunil K Singh, R B Rakesh, Munish Kumar, V Sathian and M S Kulkarni. (Under preparation)

Conferences

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2. Development of an Ionization Chamber based high sensitivity detector for the measurement of radiation dose from X-Ray Whole body Scanners. Sunil K. Singh, S. M. Tripathi, Liji Shaiju, V. Sathian, M. S. Kulkarni, p-184, 32nd IARP International conference on Radiological Safety in Work place, Nuclear facilities and Environment (IARPIC-2016), Feb 22-25, 2016, Anupuram Kalpakkam.
3. Study on various Personnel Dosimeters: Response in air and on phantom irradiations of energies from 33 to 662 keV. Amit Bhatnagar, Sunil K. Singh, Munish Kumar, J. K. Divkar, S Murali, Rajvir Singh and M S Kulkarni, p-236, 32nd IARP International conference on Radiological Safety in Work place, Nuclear facilities and Environment (IARPIC-2016), Feb 22-25, 2016, Anupuram Kalpakkam.
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Others

1. Measurement of low & medium energy ionizing radiation spectrum. Sunil Kumar Singh, Theme meeting on radiation metrology and national standards for ionizing radiation at AERB Auditorium, Anushaktinagar, Mumbai during July 9-10, 2015 page-29.
2. Studies on α-Al2O3:C based OSL badge for eye lens monitoring in India. Munish Kumar, M. S. Kulkarni, Ratna P., Amit Bhatnagar, Sunil Kumar Singh, Kamaldeep, C. Sunil, K. Biju, S. D. Sharma, S. M. Tripathi, N. Gaikwad, Sunil K. Yadav, A. A. Shanbhag, K. P. Muthe, D.A.R. Babu and D. N. Sharma, p-356, BARC newsletter founder's day special issue 2015.

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Dedicated to my family

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CONTENTS

SYNOPSIS

Use of low and medium energy photons in radiology, medical, industrial and R&D applications has increased many folds[1] in the recent past. This has led to an increased demand in monitoring of such areas for assessing the radiation dose; the radiation worker may receive while working in such areas. It also plays an important role from regulatory point of view. Various kind of active (Ionization chambers, Geiger Muller tubes, Diodes, MOSFETs, Quartz fiber dosimeters, Scintillators) and passive (TLDs, OSLDs, radio-chromic films) radiation detectors are used for radiation monitoring applications. Nearly all these radiation detectors show a low to very high energy dependent response[2] for photon energies below 200 keV.

The protection quantities (effective dose and equivalent dose) are used as "limiting quantities" to specify exposure limits to ensure that the occurrence of stochastic health effects is kept below acceptable levels and that tissue reaction are avoided. In external radiation dosimetry, the protection quantities are not directly measureable and cannot be used for radiation protection purpose. Therefore operational quantities are defined by ICRU[3] which are used to correlate the dosimeter responses. The operational quantities provide a conservative estimate of the protection quantities related to exposure. For area monitoring, the operational quantity, ambient dose equivalent [$H^*(10)$] is used for monitoring of whole body dose due to strongly penetrating radiation[4] while directional dose equivalent [$H'(d)$] is used for estimation of dose to skin and eye lens. Similarly for monitoring of dose to individual, the operational quantity personal dose equivalent, $H_p(10)$, is used.

Majority of the radiation monitors still record dose in old units: for example, exposure in Roentgen, ‘R’ or Sievert, ‘Sv’ (where 1 Sv = 100 R), which cannot be directly correlated to any protection or operational quantity at lower energies. Therefore, a need is felt for designing special radiation detector having better sensitivity and characterizing it for measuring or monitoring operational quantities at these lower energies. Therefore, the current study aims to develop an ionization chamber having energy independent response over a wide range of energies so that it can be used for the dosimetry of low and medium energy photon radiation (above 15 keV). The study also involves establishing a passive dosimeter for monitoring the operational quantity, personal dose equivalent [$H_p(10)$].

A dosimetric grade X-ray machine is used to generate various ISO 4037-1 (1996) specified narrow series (N-15, N-40, N-60, N-80, N-100, N-120, N-150, N-200 and N-250), fluorescence (F-Mo, F-Cd, and F-Sn) and other customized reference X-ray beam qualities with average energy ranging from 12 – 210 keV. The output of X-ray machine, in the form of these characterised beam qualities, are then standardized in terms of air kerma (K_{air}) / rate, using a free air ionization chamber (FAIC)(5) in conjunction with a reference class electrometer. The FAIC is a parallel plate ionization chamber and is termed as an absolute standard for the measurement of air kerma. The above beam qualities are collimated and standardized in the laboratory at a height of 100 cm above the ground level and at a distance of 200 cm from the centre of the focal spot of X-ray machine. The X-ray beams were collimated using a lead collimator which provides a field size of 40 cm x 30 cm at distance of 200 cm. A laser-based alignment system was used to align the centre of the aperture of the FAIC with the focal spot of the X-ray machine. The measured air kerma rate ($\dot{K}_T$) for ISO 4037-1(6) specified beam qualities are then converted to dose equivalent rate (personal dose equivalent for whole body dose in personal monitoring, ambient dose equivalent for whole body dose in area monitoring and directional dose equivalent for skin and eye lens dose in area monitoring) using air kerma to dose equivalent conversion coefficient [$h_K(d;H)$]. This measured air kerma rate of all the beam qualities and evaluated dose equivalent rate of ISO 4037-1 beam qualities serves as standard photon source/beam output during the measurements.

Ionization chamber is the simplest of all the gas-filled radiation detectors[7] and is widely used for the detection and measurement of X-rays, gamma rays and beta particles. It is less affected by incident photon energy as compared to other detectors. Studies using spherical and cylindrical wall ionization chambers show that the chamber sensitivity at lower energies strongly depends on the thickness and the curvature of the wall. It is also observed that a thin and plane walled ionization chamber is best suited[8] for the air kerma based radiation monitoring for low and medium energy X-ray fields. Therefore, ionization chamber was selected and studies were carried out to optimize its wall thickness so that a uniform energy response can be achieved in the measurement of ambient and directional dose equivalent rates. This thesis presents the development and characterization of a thin and plane wall ionization chamber, having 900 cc volume, to study its energy response with air kerma (K_{air}) rate and dose equivalent rate at low and medium photon energies using various build up caps. Five PMMA build up caps of thickness 1 mm, 2 mm, 3 mm, 4 mm and 10 mm were used to study the effect of wall thickness at various low and medium energy photon fields and arrive at an optimized wall thickness where a uniform or flat energy response could be achieved. For the monitoring of dose to whole body i.e. measurement of ambient dose equivalent rate, the experimentally evaluated optimized wall thickness is 10 mm PMMA. Similarly, the experimentally evaluated optimum wall thickness for monitoring of dose to skin and eye lens is found to be ~ 6 μm (minimum wall thickness available in this laboratory) and 4 mm PMMA respectively. The plane wall ionization chamber having wall thickness of 10 mm shows a prominent angular response at lower energies. Therefore, a cylindrical ionization chamber having 10 mm PMMA wall thickness was developed and characterized at the same ISO 4037-1 X-ray beam qualities for the monitoring of ambient dose equivalent rate.

The use of X-ray based whole body human scanners (WBHS) are being explored by various homeland security agencies to detect plastic explosives, drugs or illegal transport of dangerous items concealed under cloth or body cavities. While using these WBHS's, the person being screened posses a radiation risk and thus may needs monitoring. ANSI/HPS N43.17[9] recommended a dose limit of 0.25 μSv (~ 25 μR) per scan from general purpose X-ray based WBHS. In order to check the compliance of such a low dose limit, a very high sensitivity, large volume ionization chamber (volume: 135 liters) was developed and characterized for its dose linearity, collection efficiency and energy response using various customized X-ray beam qualities. This ionization chamber was used to measure dose per scan from WBHSs.

Studies were carried out for developing a two-element passive optically stimulated luminescence (OSL) dosimeter badge for monitoring of whole-body dose due to low and medium energy photons beams. The four element plastic OSLD card consisting of a highly sensitive four thin α-Al_2O_3:C[10] OSL dosimeter discs, was used to study the energy response of α-Al_2O_3:C OSL discs under various cupper filter thicknesses. A dose computation algorithm is developed to estimate dose from highly penetration ionizing radiation up to ~ 200 keV (photons).

In summary, the thesis presents the experimental work and analysis on development of ionization chamber based active dosimeter and optically stimulated luminescence based passive dosimeter for the monitoring of operation quantities ambient dose equivalent, directional dose equivalent and personal dose equivalent for low photon energies, below 200 keV. The thesis is organized in six chapters as given below:

Chapter 1: General Introduction to External Radiation Dosimetry.

This chapter describes the basic concepts related to external radiation dosimetry for low energy photons. It covers interaction of photons with matter, various types of radiation sources and radiation detectors. The chapter also discusses the energy dependent angular emission of photo electrons or Compton recoil electrons and its impact on dosimetry of low energy photons. The chapter briefly discusses the working principle of ionization chamber and related parameters influencing low energy photon dosimetry. This chapter also covers the principle of a TL/OSL dosimeter (passive dosimeter) and their dosimetric parameters. Energy response of various radiation monitors available in the laboratory is presented and the need of energy independent radiation monitors highlighting their importance in low energy photon dosimetry has been brought out. The chapter also covers extensive literature survey in this area.

Chapter 2: Standardization of radiation (X-ray) fields.

This chapter briefly describes the generation of various direct (unfiltered) and filtered X-ray beam qualities (Bremsstrahlung and characteristics) using dosimetric grade X-ray machine, as per recommendations of ISO 4037-1. These filtered and direct X-ray beams are further characterized by experimentally measuring their first half value layer (HVL) and second HVL (air kerma based). The validity of ISO 4037-1 beam qualities were also established by experimentally measuring the spectral resolution of all beam qualities. The dosimetric measurements are carried out using free air ionization chamber which is energy independent and absolute air kerma measurement standard for X-rays. This chapter also describes the experimental measurement setups, secondary standards ionization chamber and role of other equipments used during standardization of X-ray beams. The output of the X-ray beams are standardized in the form of air kerma and is further converted to ambient dose equivalent, directional dose equivalent and personal dose equivalent by using appropriate air kerma to dose equivalent conversion coefficient. The chapter also covers the numbers of X-ray beam qualities along with their average energies available in the laboratory for their use in energy response characterization of various detectors.

Chapter 3: Development of a large volume ionization chamber for dosimetric evaluation of Whole-body human scanners.

This chapter describes the need to develop a highly sensitive, large volume ionization chamber for the dosimetric evaluation of whole-body human scanners (WBHS). It also describes the dose limit recommendations of ANSI/HPS N43.17-2009 and its requirements in measurement of dose from whole body X-ray scanners. To fulfil the need of measurement and ANSI requirement, a thin wall large volume (135 litre) ionization chamber was designed and developed. The ionization chamber was calibrated against a secondary standard 600 cc Saint-Gobain make ionization chamber which is in turn calibrated against free air ionization chamber. For the calibration of 135 litre ionization chamber, various customized direct reference X-ray beams (unfiltered) were standardized and used. The calibrated 135 litre ionization chamber, along with 600 cc Saint-Gobain make ionization chamber was used to characterize and measure dose per scan from X-ray based whole body human scanner. Measured data was analysed as per ICRP-74, ISO 4037 and ANSI/HPS N43.17-2009 guidelines. Measured dose per scan for a transmission type WBHS in its low dose mode was found to be acceptable (< 0.25 μSv) as per ANSI/HPS N43.17-2009 recommendations.

Chapter 4: Development of Ionization chambers for low energy photon dosimetry

This chapter describes the design and development of ionization chambers for the monitoring of operational quantities. It includes the development of 900 cc ionization chamber for different wall thickness of PMMA, using build up caps, and its wall thickness optimization. Studies were carried out at various photon energies for the estimation of an optimized wall thickness for the measurement of radiological quantities air kerma, ambient dose equivalent and directional dose equivalent. The chapter also discusses the limitations in the use of an optimized plane walled ionization chamber for area monitoring and survey instruments. Angular response of this plane wall ionization chamber is measured at low energy photon beams, which indicated a poor angular response. Therefore, a 225 cc PMMA cylindrical ionization chamber was developed and characterized as a secondary standard for the direct measurement of ambient dose equivalent rate. The angular response of this ionization chamber was evaluated at the photon energy 12 keV (lowest ISO narrow series beam quality available). The 225 cc ionization chamber is found to comply with the requirement of ISO 4037-4 concerning the energy dependent response of a secondary standard dosimeter used for protection level radiation dosimetry.

Chapter 5: Low energy photon dosimetry based on α-Al_2O_3:C passive OSL dosimeter.

This chapter describes the studies on the development of two element OSLD badge using indigenously developed, highly sensitive, α-Al_2O_3:C optically stimulated luminescence (OSL) phosphor. α-Al_2O_3:C is considered as the reference OSL phosphor world over. Thin α-Al_2O_3:C dosimeters sandwiched between two plastic sheets (7 mm diameter, 0.14 mm thick) were prepared for this study. The studies were carried out for the monitoring of whole-body dose and personal dose equivalent, using ISO 4037-1 specified low and medium energy photon beam qualities available in the laboratory. Thin α-Al_2O_3:C OSL discs mounted on the four element OSLD card was used to study the energy response under various copper filter thicknesses. The experimental results on the energy response under various copper filter thicknesses was used to develop algorithms for evaluation of whole body dose and personal dose equivalent ($H_p(10)$) and the results are presented.

Chapter 6: Summary and conclusion

This chapter gives a summary of the work performed during the course of work and the main conclusions drawn from it. A brief on the scope of the future work is also brought out.

Main highlights of the work are:

- Developed a large volume (135 litre) high sensitive ionization chamber to measure dose from X-ray based whole body human scanners.

- Wall thickness optimization studies carried out using a developed thin plane wall ionization chamber (900 cc) along with various thickness build up caps.
- A cylindrical ionization chamber (225 cc) was developed as a secondary standard for monitoring of ambient dose equivalent.
- Studies for the development of α-Al_2O_3:C based passive dosimeter was carried out.

The above developments constitute definite progress towards providing solution for developing instruments for monitoring of operational quantities. It is no longer necessary to measure air kerma or exposure using the non-operational quantity-based radiation monitors and makes judgment-based assumptions in assessing the dose (in terms of protection quantities) at lower energies. Using the optimized wall ionization chamber-based radiation monitors; direct monitoring of ambient dose equivalent can be performed. The sensitivity of ionization chamber varies linearly with the mass of the air/gas enclosed in ionization chamber thus large sensitivity ionization chambers can also be fabricated by either increasing the volume of ionization chamber or by pressurizing the ionization chamber.

The thesis makes a serious attempt to improve the quality and accuracy of dose equivalent estimation using the developed detector. The thesis presents experimental results to address one of the outstanding issues in the area of external dosimetry for low energy photons (the energy response of detector). The output of this work will lead to production of reliable, accurate and quality radiation monitors.

The methodology used here for establishment of secondary standard detector for ambient dose equivalent rate may find applications in other areas such as establishment of secondary standard for directional dose equivalent measurement (i.e. for the dosimetry of skin and eye lens doses).

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LIST OF ABBREVIATIONS

ANSI	American Standards Institute
BNC	Bayonet Neill Concelman
CPE	Charge particle equilibrium
CW-OSL	Continuous wave optically stimulated luminescence
DDE	Directional dose equivalent
DRD	Direct reading dosimeter
FAIC	Free air ionization chamber
FWHM	Full width at half maximum
HVL	Half-value layer
IAEA	International Atomic Energy Agency
IC	Ionization Chamber
IC	Interventional cardiology
IC	Ionization chamber
ICRP	International Commission on Radiological Protection
ICRU	International Commission on Radiation Units and Measurements
IEC	International Electro-technical Commission
IR	Interventional radiology
ISO	International Standards Organization
KERMA	Kinetic energy released per unit mass
LED	Light emitting diode
LET	Linear energy transfer
LM-OSL	Linearly modulated optically stimulated luminescence
MeV	Million Electron Volts
NCRP	National Council on Radiation Protection and Measurements

OSL	Optically Stimulated Luminescence
OSLD	Optically-Stimulated Luminescence dosimeter
PMMA	Polymethyl methacrylate
PMMA	Polymethyl methacrylate
POSL	Pulsed optically stimulated luminescence
RPL	Radio-photoluminescence
TL	Thermally stimulated luminescence
TLD	Thermo-luminescent dosimeter
TRS	Technical Reports Series
WBD	Whole body dose
WBHS	Whole body human scanner