

**DEVELOPMENT OF DOSIMETRIC TECHNIQUES FOR THE
MEASUREMENT OF LOW ENERGY PHOTONS**

by

SUNIL KUMAR SINGH

(PHYS01201504014)

BHABHA ATOMIC RESEARCH CENTRE, Mumbai

*A thesis submitted to the
Board of Studies in Physical Sciences
in partial fulfillment of requirements*

for the Degree of
DOCTOR OF PHILOSOPHY

of

HOMI BHABHA NATIONAL INSTITUTE

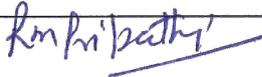
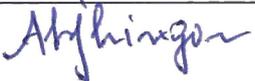
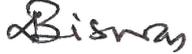


December, 2018

Homi Bhabha National Institute

Recommendations of the Viva Voce Committee

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.

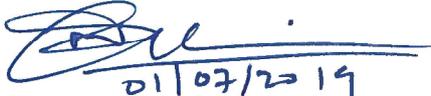
Chairman: Dr. R. M. Tripathi		Date 1/7/2019
Guide / Convener: Dr. M. S. Kulkarni		Date 01/07/2019
External Examiner: Dr. Akhil Jhingan		Date 1.7.19
Member 1: Dr. D. C. Biswas		Date 1.7.19
Member 2: Dr. S. D. Sharma		Date 1/7/2019
Member 3: Dr. S. K. Jha		Date: 1-7-2019
Technology Advisor: Dr. G. Haridas		Date: 1/7/2019

Final approval and acceptance of this thesis is contingent upon the candidate's submission of the final copies of the thesis to HBNI.

I hereby certify that I have read this thesis prepared under my direction and recommend that it may be accepted as fulfilling the thesis requirement.

Date: 01/07/2019

Place: BARC, Mumbai



Dr. M. S. Kulkarni

(Guide)

Statement by Author

This dissertation has been submitted in partial fulfillment of requirements for an advanced degree at Homi Bhabha National Institute (HBNI) and is deposited in the Library to be made available to borrowers under rules of the HBNI.

Brief quotations from this dissertation are allowable without special permission, provided that accurate acknowledgement of source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the Competent Authority of HBNI when in his or her judgment the proposed use of the material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author.



Sunil Kumar Singh

DECLARATION

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.



Sunil Kumar Singh

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.
6. Development of an algorithm to estimate eye lens dose in terms of operational quantity $H_p(3)$ using head TLD badge. B Madhumita, C. Sneha, V. Dipali, S.M. Pradhan, A.K. Bakshi, D. Datta, S.M. Tripathi and S. K. Singh, Radiation Protection Dosimetry, Volume 178, Issue 4, 1 March 2018, Pages 364–373, DOI: 10.1093/rpd/ncx123.

7. Development of two element α -Al₂O₃:C based OSLD badge system using α -Al₂O₃:C for low energy photon dosimetry. Sunil K Singh, R B Rakesh, Munish Kumar, V Sathian and M S Kulkarni. (Under preparation)

Conferences

1. Ambient Dose Equivalent Rate Based Detector for Low / Medium Energy Photon Dosimetry. Sunil K. Singh, V. Sathian and M. S. Kulkarni, 33rd IARP International conference on Developments towards improvement of Radiological Surveillance at Nuclear Facilities and Environment (IARPIC-2018), P-102, Jan 16-20, 2018, DAE Convention Centre, Mumbai.
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.
4. Low and medium energy standard X-Ray calibration facility in BARC. Sunil K. Singh, S.M. Tripathi, Liji Shaiju, V. Sathian and D.A.R. Babu, 31st IARP national Conference on "Advances in Radiation Measurement Systems and Techniques" at BARC, Mumbai during 19 - 21 March 2014, page 38.

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.



Sunil Kumar Singh

Dedicated to my family

Acknowledgements

I express my deep and profound gratitude to my guide Dr. M. S. Kulkarni, Head, Radiation Standards Section, RSSD, BARC and technical advisor Dr. Haridas G., HPU in-charge, RRCAT, for their valuable guidance and encouragement throughout the course of this work. Despite their busy schedule, they stood by my side patiently, supervised my academic progress, reviewed my work and gave their valuable suggestions from time to time.

I am extremely grateful to Dr. Pradeepkumar K. S., Associate Director, HS&E Group, and Head, Radiation Safety & Systems Division, Bhabha Atomic Research Centre, Mumbai for his constant encouragement during the course of this research work.

I am indebted to my wife (Smt. Priyanka Singh) who always instilled faith in me, extended her moral support and motivated me during the entire course of this work.

I express my humble and heartfelt gratitude to Shri Ashok Kumar Mahant, Ex-Head, Radiation Standards Section, RSSD to help me understand low energy photon dosimetry in the beginning of my carrier in RSSD, BARC. He also taught me how to deal with the measurements of ultra low level currents generated in ionization chambers and the complexities involved.

I gratefully acknowledge the cooperation and support extended by Dr. Munish Kumar for the OSL measurements.

Special thanks are due to Dr D. B. Kulkarni and Shri R. B. Rakesh for the valuable technical discussions. I also acknowledge the cooperation, help and support extended by RSSD workshop while fabrication of the ionization chambers and related accessories.

I would also like to thank Smt. Shobha Ghodke, RSSD, Shri V. Sathian, RSSD and Shri D. B. Paranjape (RACD) for their help during the spectrometric measurement of X-ray beam qualities.

I thank the Doctoral Committee members Dr. R. M. Tripathi, Dr. D. Biswas, Dr. D. D. Rao, Dr. G. Haridas, Dr S. D. Sharma and Dr S. K. Jha for their valuable suggestions and comments during presentations and reviews.

Last but not the least I wish to extend my sincere thanks and gratitude to all my friends, colleagues in Radiation Standards Section, RSSD and all those who directly or indirectly helped me during the course of the PhD work.



Sunil Kumar Singh

CONTENTS

SYNOPSIS.....	xviii
LIST OF FIGURES.....	xxviii
LIST OF TABLES.....	xxxii
LIST OF ABBREVIATIONS	xxxv
CHAPTER 1: General Introduction to External Radiation Dosimetry	1
1.1 Classification of radiation	1
1.2 Classification of ionizing photon radiation.....	1
1.3 Interactions of photon with matter.....	2
1.3.1 Photoelectric effect.....	3
1.3.2 Compton scattering.....	5
1.3.3 Pair production.....	6
1.4 Fundamental radiation dosimetry quantities.....	7
1.4.1 Particle number.....	8
1.4.2 Radiant energy.....	8
1.4.3 Fluence.....	8
1.4.3.1 Energy fluence.....	8
1.4.3.2 Photon fluence rate.....	9
1.4.4 Interaction Coefficients	9
1.4.5 KERMA.....	10
1.4.6 Exposure	11
1.4.7 Exposure rate.....	12
1.4.8 Air kerma, K_{air} , to exposure conversion.....	12
1.5 Basic concept of radiation protection and related quantities.....	12
1.5.1 Protection quantity.....	13

1.5.1.1	Absorbed dose to tissue.....	13
1.5.1.2	Equivalent dose to tissue.....	14
1.5.1.3	Effective dose.....	14
1.5.2	Operational quantity.....	14
1.5.2.1	Operational quantities for area monitoring	15
1.5.2.1.1	The ICRU sphere phantom.....	15
1.5.2.1.2	Expanded radiation field.....	16
1.5.2.1.3	Expanded and aligned radiation field.....	16
1.5.2.1.4	Ambient dose equivalent.....	16
1.5.2.1.5	Directional dose equivalent.....	17
1.5.2.2	Operational quantities for individual monitoring.....	17
1.5.2.2.1	Personal dose equivalent.....	17
1.6	X-Rays.....	18
1.6.1	Characteristic radiation.....	18
1.6.2	Bremsstrahlung X-Rays.....	19
1.6.3	Directional distribution of fluorescence vs. bremsstrahlung.....	20
1.6.4	X-ray filtration.....	20
1.6.5	Beam quality.....	22
1.6.5.1	HVL measurement.....	23
1.7	X-ray dosimetry.....	24
1.7.1	Ionization chamber.....	25
1.7.1.1	Cavity ionization chamber.....	25
1.7.1.2	Free air ionization chamber (FAIC)	26
1.7.1.3	Corrections in ionization chambers for influential quantities.....	31
1.7.1.3.1	Correction of air density and humidity.....	31

1.7.1.3.2	Correction for ion recombination (saturation correction)	32
1.7.1.3.3	Correction for polarity effect.....	33
1.7.1.3.4	Correction for photon attenuation.....	33
1.7.2	Basic physical quantity in external dosimetry.....	33
1.7.3	Passive detectors.....	34
1.7.3.1	Thermally stimulated luminescence.....	34
1.7.3.2	Optically Stimulated Luminescence (OSL)	36
1.7.3.2.1	Continuous wave optically stimulated luminescence.....	37
1.7.3.2.2	Linearly modulated optically stimulated luminescence.....	37
1.7.3.2.3	Pulsed optically stimulated luminescence.....	38
1.7.3.3	Comparison of OSL and TL Techniques.....	39
1.7.3.4	OSL phosphor (Al ₂ O ₃ :C)	40
1.8	Study of energy dependent response of radiation monitors	40
1.9	Work carried out by earlier researchers (literature survey)	41
1.10	Summary.....	43
CHAPTER 2: Standardization of radiation (X-ray) fields.....		44
2.1	Introduction.....	44
2.2	Standard X-ray beam qualities.....	45
2.2.1	Free Air Ionization Chamber.....	46
2.2.2	Electrometer.....	48
2.2.3	Thermometer.....	48
2.2.4	Barometer.....	49
2.2.5	ISO 4037-1 (1996) standard.....	49
2.2.5.1	Conditions for producing reference radiation (ISO 4037-1).....	51
2.2.6	Metal filters.....	52

2.2.7	K-fluorescence X-ray generating setup.....	52
2.2.8	Laser based alignment system.....	53
2.2.9	Secondary standards.....	53
	2.2.9.1 Secondary standard for fluorescence X-ray beams	54
	2.2.9.2 Secondary standard for customized X-ray beams.	55
2.3	X-ray beam quality measurement.....	56
	2.3.1 Additional filtration.....	57
	2.3.2 HVL measurement.....	58
	2.3.3 Spectrum measurement.....	59
2.4	X-ray beam output measurement.....	66
2.5	Uncertainty evaluation.....	67
2.6	Output of ISO 4037-1 beams in form of operational quantities.....	69
CHAPTER 3: Development of a large volume ionization chamber for dosimetric		
	evaluation of whole body human scanners.....	72
3.1	Introduction.....	72
3.2	ANSI/HPS N43.17-2009.....	73
3.3	Transmission type whole body human scanner.....	74
3.4	Detector requirements.....	74
3.5	Design of ionization chamber.....	75
3.6	Need of a secondary standard.....	77
3.7	Calibration of 600 cc ionization chamber.....	78
3.8	Beam uniformity measurement at 500 cm.....	79
3.9	Sensitivity measurement of 135 litre ionization chamber.....	81
3.10	Dose rate linearity response of ionization chamber.....	82

3.11	Dosimetric evaluation of transmission type X-ray whole body human scanner.....	83
3.12	Radiological characterization of WBHS.....	85
3.12.1	HVL measurement.....	86
3.12.2	Measurement of exposure at various heights.....	87
3.12.3	Measurement of average exposure using 135 litre ionization chamber.....	88
3.13	Evaluation of effective dose per scan.....	90
3.13.1	Evaluation of effective dose per scan (ICRP 74)	90
3.13.2	Evaluation of reference effective dose per scan (ANSI/HPS N43.17-2009).....	92
3.13.3	Evaluation of ambient dose equivalent per scan (ISO 4037)	93
3.14	Summary of analysed results.....	95
3.15	Conclusion.....	96
CHAPTER 4: Development of Ionization chambers for low energy photon dosimetry...97		
4.1	Introduction.....	97
4.2	Development of a detector for wall thickness optimization studies.....	101
4.2.1	Ionization chamber for studying wall thickness optimization (design).....	101
4.2.2	Measurement technique.....	102
4.2.3	Charge collection efficiency and linearity of developed ionization chamber.....	103
4.2.4	Rate Linearity of developed ionization chamber.....	105
4.2.5	Air kerma based energy response of developed 900 cc ionization chamber.....	105
4.2.6	Evaluation of optimized wall thickness for monitoring of operational quantity, ambient dose equivalent 'ADE', $H^*(10)$	107

4.2.7	Optimized wall thickness evaluation for monitoring of operational quantity, directional dose equivalent ‘DDE’, H'(3)	109
4.2.8	Optimized wall thickness evaluation for monitoring of operational quantity, directional dose equivalent ‘DDE’ (skin dose), H'(0.07)	111
4.2.9	Secondary standard dosimeter requirement conformity.....	112
4.2.9.1	Conformity for ambient dose equivalent based monitoring	113
4.2.9.2	Conformity for directional dose equivalent (eye lens dose) based monitoring.....	114
4.2.9.3	Conformity for directional dose equivalent (skin dose) based monitoring.....	114
4.2.10	Limitations of the developed ionization chamber.....	114
4.3	Development of a standard ionization chamber for monitoring of ambient dose equivalent.....	114
4.3.1	Design of 225 cc ionization chamber.....	115
4.3.2	Verification of wall thickness uniformity.....	117
4.3.3	Energy response of chamber.....	118
4.3.4	Conformity of secondary standard dosimeter requirement.....	118
4.3.5	Conclusion.....	120
CHAPTER 5: Low energy photon dosimetry based on α -Al ₂ O ₃ :C passive OSL dosimeter.....		121
5.1	Introduction.....	121
5.2	Selection of dosimetric material and design.....	123
5.3	Irradiation system.....	123
5.4	Optimization of filter thickness.....	124
5.5	OSL Reader system.....	126

5.6	Method for estimation of true dose rate.....	127
5.7	Dosimetric analysis (whole body dose based response)	128
5.8	Analysis on personal dose equivalent based response.....	130
5.9	Conclusions.....	132
CHAPTER 6: Summary and conclusion.....		134
6.1	Summary of work.....	134
6.1.1	Standardization of reference radiation beams for energy response testing of radiation monitors.	134
6.1.2	Evaluation of dose per scan from a transmission type X-ray based whole body human scanner.....	135
6.1.3	Development of a detector for dosimetric measurement of operational quantities.....	136
6.1.4	Studies on development of a passive dosimeter for personal dosimetry.	137
6.2	Conclusions: Highlights of the work.....	138
6.3	Scope of the work for future studies.....	139
REFERENCES		140

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 measurable 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}_r) 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 $\sim 6 \mu\text{m}$ (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 poses a radiation risk and thus may need monitoring. ANSI/HPS N43.17⁽⁹⁾ recommended a dose limit of 0.25 μSv ($\sim 25 \mu\text{R}$) 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 $\alpha\text{-Al}_2\text{O}_3\text{:C}^{(10)}$ OSL dosimeter discs, was used to study the energy response of $\alpha\text{-Al}_2\text{O}_3\text{:C}$ OSL discs under various copper filter thicknesses. A dose computation algorithm is developed to estimate dose from highly penetration ionizing radiation up to $\sim 200 \text{ keV}$ (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 ($< 0.25 \mu\text{Sv}$) 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 -Al₂O₃:C passive OSL dosimeter.

This chapter describes the studies on the development of two element OSLD badge using indigenously developed, highly sensitive, α -Al₂O₃:C optically stimulated luminescence (OSL) phosphor. α -Al₂O₃:C is considered as the reference OSL phosphor world over. Thin α -Al₂O₃: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 -Al₂O₃: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 -Al₂O₃: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).

References:

1. John Le Herona, Renato Padovanib, Ian Smithc, Renate Czarwinskia, “Radiation protection of medical staff”, European Journal of Radiology, Volume 76, Issue 1, October 2010, Pages 20-23.
2. "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.
3. ICRU Report 51 (1993): Quantities and Units in Radiation Protection Dosimetry.
4. Podgorsak E B, “Radiation Oncology Physics: A handbook for Teachers and Students”, Vienna: IAEA 2005.
5. Burns D T and Buermann L, “Free-air ionization chambers”, Metrologia 46 S9-S23 (2009).
6. ISO Standard 4037-1, (1996), X and gamma reference radiation for calibrating dosimeters and doserate meters and for determining their response as a function of photon energy – Radiation characteristics and production methods, First Edition, Case Postale 56, CH -1211, Geneva 20, Switzerland.
7. Knoll G F, Radiation Detection and Measurement, 3rd edition, John Wiley & Sons, 2000.
8. Mahant A K, Singh S K, Vinatha S P, "Development of ion chambers for the measurement of low energy synchrotron radiation", Nuclear Instruments and Methods in Physics Research A 601 (2009) 354–357.
9. ANSI/HPS N43.17 (2009), Radiation Safety for Personnel Security Screening Systems Using X-ray or Gamma Radiation.

10. B. Hu, Y. Wang and W. Zealey, "Performance of Al₂O₃:C optically stimulated luminescence dosimeters for clinical radiation therapy applications", *Australasian Physical & Engineering Sciences in Medicine* Volume 32 Number 4, 2009.

LIST OF FIGURES

Figure 1.1: Schematic diagram of the photoelectric interaction.....	4
Figure 1.2: Angular distribution of photoelectrons.....	4
Figure 1.3: Schematic diagram of the Compton scattering.....	6
Figure 1.4: Angular distribution of Compton scattered photons.....	6
Figure 1.5: Relative importance of photoelectric, Compton scattering and pair-production..	7
Figure 1.6: Representation of expanded radiation field.....	16
Figure 1.7: Phantoms used for calibration of personal dosimeters: (a) Water slab phantom, (b) Water pillar phantom and (c) Rod phantom.....	18
Figure 1.8: X-ray spectrum from 100 keV electrons on a thick W target.....	19
Figure 1.9: Comparison of the directional distributions of K X-rays (solid curves) and bremsstrahlung (dashed curve) for 50 and 500 keV electrons incident on a thin silver target.....	21
Figure 1.10: Evaluation of HVL_1 and HVL_2 for beam quality N-120	24
Figure 1.11: Block diagram of a typical cavity (cylindrical) ionization chamber	26
Figure 1.12: Block diagram of typical electrometer connections to ionization chamber	26
Figure 1.13: Schematic plan view of a parallel-plate free-air ionization chamber	27
Figure 1.14: The free air ionization chamber geometry discussed in the proof	28
Figure 1.15: A valence / conduction band model of the TL mechanism with (a) Exposure phase and (b) Reading phase	35
Figure 1.16: CW-OSL profile with a constant stimulation power	38
Figure 1.17: LM-OSL profile with stimulation power increased linearly with time	38
Figure 1.18: POSL profile with constant power pulsed stimulation	39

Figure 2.1: Photograph of X-ray machine available in the laboratory.....	44
Figure 2.2: Block diagram and dimension of FAIC available in the laboratory	47
Figure 2.3: Photograph of FAIC (external).	48
Figure 2.4: Photograph of FAIC (internal).	48
Figure 2.5: Mercury thermometer.....	49
Figure 2.6: Aneroid barometer.....	49
Figure 2.7: Block diagram for experimental setup of Fluorescence measurement.....	53
Figure 2.8: Internal view of Radiator setup.	53
Figure 2.9: Radiator (external view)	53
Figure 2.10: Exradin A4 ionization chamber.....	54
Figure 2.11: Schematic diagram of Exradin A4 ionization chamber.	54
Figure 2.12: Photograph of 600 cc thin window ionization chamber.	56
Figure 2.13: Schematic diagram of HVL measurement setup.	58
Figure 2.14: Measured spectrum of N-15, N-40 and N-60 beam qualities using NaI based spectrometer.	62
Figure 2.15: Measured spectrum of N-60, N-80, N-100, N-120, N-150 and N-250 beam qualities using CZT based spectrometer.....	63
Figure 2.16: Spectrum of F-Mo, F-Cd and F-Sn measured using NaI based spectrometer.....	65
Figure 3.1: Photograph and schematic diagram of the developed 135 litre ionization chamber.....	76
Figure 3.2: Photograph of 600 cc thin window ionization chamber showing internal dimensions	79
Figure 3.3: Sketch showing points of non-uniformity measurement.....	80

Figure 3.4: Schematic of measurement setup for 135 litre IC at 500 cm distance.	81
Figure 3.5: Schematic image of a transmission type X-ray based WBHS	84
Figure 3.6: Measurement of half value layer at low dose mode.	86
Figure 3.7: Measurement of half value layer at high dose mode.	87
Figure 3.8: Photograph and scanned image of 135 litre chamber during measurement.....	88
Figure 4.1: Schematic diagram of plane wall 900 cc ionization chamber.....	102
Figure 4.2: The plane wall ionization chamber and the PMMA buildup cap.	103
Figure 4.3: Variation of collection efficiency with air kerma rate for 900 cc ionization chamber.....	104
Figure 4.4: Air kerma rate based calibration coefficient, N_K , of 900 cc ionization chamber at various energies and wall thickness.....	107
Figure 4.5: $H^*(10)$ rate based calibration coefficient of 900 cc ionization chamber at various energies and wall thickness.....	108
Figure 4.6: DDE rate based calibration coefficient of 900 cc ionization chamber at various energies and wall thickness.....	110
Figure 4.7: DDE rate (skin dose) based calibration coefficient of 900 cc ionization chamber at various energies and wall thickness.	112
Figure 4.8: Schematic diagram of developed 225 cc ionization chamber.	116
Figure 4.9: Photograph of 225 cc, 10 mm thick cylindrical ionization chamber.....	116
Figure 4.10: Thickness uniformity check (angular response) at N-15 beam quality.....	117
Figure 4.11: Energy response of the developed 225 cc ionization chamber for side-on geometry.	119
Figure 5.1: Photograph of four element plastic card	125
Figure 5.2: Experimental setup showing OSLD cards under copper filters, placed on water phantom.....	126

Figure 5.3: Whole body dose based energy response of α - $\text{Al}_2\text{O}_3\text{:C}$ OSL dosimeter under different thickness of Cu filters.....	128
Figure 5.4: Ratio of α - $\text{Al}_2\text{O}_3\text{:C}$ OSL dosimeter under 0.1 mm Cu and open window.....	129
Figure 5.5: Fitted curve between ratios of open to 0.1 mm Cu discs.....	129
Figure 5.6: $H_p(10)$ based energy response of α - $\text{Al}_2\text{O}_3\text{:C}$ OSL discs (relative to ^{137}Cs).....	131
Figure 5.7: Personal dose equivalent based response and fitted curve.	131

LIST OF TABLES

Table 2.1: Parameters of FAIC available in laboratory.....	47
Table 2.2: Technical specification of electrometer (PTW UNIDOS).....	48
Table 2.3: Characteristics of narrow series beams	51
Table 2.4: Specification of Exradin A4chamber.....	54
Table 2.5: Air kerma based calibration co-efficient (N_K) of Exradin A4 ion chamber at different K-fluorescence X-rays.	55
Table 2.6: Specification of 600 cc thin window ionization chamber.....	55
Table 2.7: Narrow series beam qualities generated and used for measurement.....	57
Table 2.8: Measured HVL's of generated narrow series beam qualities.....	60
Table 2.9: HVL's of generated customized X-ray beams.....	60
Table 2.10: Analyzed parameter of narrow series X-ray beam qualities using CZT and NaI based spectrometers.....	61
Table 2.11: Analyzed parameter of fluorescent X-ray beams using NaI based spectrometer.....	61
Table 2.12: Beam output of generated customized X-ray beams.....	67
Table 2.13: Beam output of generated customized X-ray beams.....	67
Table 2.14: Fluorescence X-ray beam output for different radiators at 100 cm from box.....	67
Table 2.15: Uncertainty in conventional true value of narrow series and customized X-ray beam qualities.....	68
Table 2.16: Conversion coefficients to operational quantities (ISO X-ray beams).....	70
Table 2.17: Conventional true value of operational quantities (ISO X-ray beams).....	71
Table 3.1: Dosimetric specification of 600 cc thin window ionization chamber.....	78
Table 3.2: Energy response of 600 cc thin window ionization chamber.....	79

Table 3.3: Measured field non-uniformity at different heights.....	80
Table 3.4: Sensitivity of 135 litre chamber for various X-ray customized beam qualities.....	82
Table 3.5: Linearity response of 135 litre Ionization chamber at 400 V applied potential.....	83
Table 3.6: Technical specification of whole body human scanner.....	84
Table 3.7: Result of HVL measurement at low and high dose mode.	87
Table 3.8: Dosimetric measurement of WBHS using 600cc ionization chamber.....	89
Table 3.9: Dosimetric measurement of WBHS using 135 litre ionization chamber.....	89
Table 3.10: Effective dose per scan as per measurements done by 600 cc ionization chamber.	91
Table 3.11: Average effective dose per scan as per 135 litre ionization chamber.....	92
Table 3.12: Reference effective dose per scan as per 600 cc ionization chamber.....	93
Table 3.13: Average reference effective dose per scan as per 135 litre ionization chamber.	93
Table 3.14: Ambient dose equivalent per scan as per 600 cc ionization chamber.....	94
Table 3.15: Average ambient dose equivalent per scan as per 135 litre ionization chamber.	95
Table 3.16: Maximum dose as measured by 600 cc ionization chamber at height of 100 cm.	95
Table 3.17: Average dose per scan as measured by 135 litre ionization chamber at 30 cm.	95
Table 4.1: Collection efficiency and air kerma rate linearity response of 900 cc ionization chamber.	106

Table 4.2: Calibration coefficients for 900 cc ionization chamber for 10 mm PMMA buildup cap.	109
Table 4.3: DDE based calibration coefficients for 900 cc ionization chamber for 4 mm PMMA wall buildup cap.	111
Table 4.4: DDE (skin dose) based calibration coefficients for, mylar wall, 900 cc ionization chamber.	113
Table 4.5: Energy response of 225 cc ionization chamber.	119
Table 5.1: Properties of α -Al ₂ O ₃ :C.....	124
Table 5.2: ISO 4037-1 X-ray beam qualities used for irradiation.....	125
Table 5.3: Deviation of estimated WBD from delivered WBD for various photon energies.....	130
Table 5.4: Deviation of estimated H _p (10) from delivered H _p (10) for various photon energies.....	132

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