Dose Optimization in Diagnostic Radiology

Thulani Nyathi

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ABSTRACT

Medical X-ray imaging is nowadays ubiquitous in healthcare. International studies have shown that patient doses during both diagnostic X-ray examinations and fluoroscopically guided procedures from one clinic to another can vary by a factor of up to 100. Such a variation in patient doses offers an opportunity for dose – image quality optimization. Given this background, every radiology clinic which wants to use X-ray imaging ethically and efficiently should have in place ways of optimizing the patient dose – image quality relationship. One generally accepted tool in the optimization process is diagnostic reference levels (DRLs). Currently in South Africa there are no established DRLs and there is no systematic patient dose data collection by the either the national regulator or any competent authority. The main purpose of this thesis was to quantify patient doses for patients undergoing diagnostic examinations and fluoroscopically guided procedures, educate radiation workers on typical patient doses, develop effective methods in quality control of radiographic and fluoroscopic equipment and evaluate radiographer familiarity with digital radiography technology within the context of a typical university teaching South African hospital. The present thesis comprises of seven studies, all carried out at Charlotte Maxeke Johannesburg Academic Hospital (CMJAH), formerly Johannesburg Hospital:

Study I: In this investigation the luminance level of X-ray viewing boxes and ambient lighting levels in reporting rooms were measured as a quality assurance procedure and compared with the recommended values by the Directorate of Radiation Control (DRC) of South Africa, European Commission (EC) and Nordic Radiation Protection Co-operation (NORDIC). Results from this investigation showed that the mean average luminance was 1027 cd m^{-2} and 3284 cd m^{-2} at the Division of Radiology and Division of Radiation Oncology respectively. The Division of Radiation Oncology had an average viewing box uniformity 7.14% compared to 27.32% at the Division of Radiology. The average ambient lighting was found to be 66 lux for both Divisions. The radiograph viewing conditions variably comply with guidelines. The radiographic imaging chain can only be as strong as its weakest link, thus this study underscores the need of implementing quality control and quality assurance standards in radiographic image viewing. Based on the practical experience of this investigation it is recommended that the DRC test criteria be adopted, in light of the varied recommendations worldwide.

Study II: This study aimed to develop, implement and evaluate a software program which can be used in a radiology quality control program. A Microsoft Excel™ based software program was developed for use in quality control: tests data collection, analysis and archiving of the tests done on general radiography equipment, fluoroscopy equipment and film processors. Validation of the software application in terms of usability, user-friendliness was done by an experienced radiographer. This software provides an easier and efficient way of recording quality control data, analysis and archiving.

Study III: This study retrospectively analyzed the radiation doses delivered to patients undergoing fluoroscopy guided procedures in terms of the *skin dose*[1] and the kerma-area product readings. A total of three hundred and thirty one fluoroscopically guided procedures were analyzed. In agreement with other published studies, a weak correlation was shown between *skin dose* and screening time, while a poor correlation was shown between KAP reading and screening time. There was a wide spread in the radiation doses registered for any one given type of examination, which shows that there is room for dose optimization. From the lessons drawn from this study it is practically feasible to record the KAP, fluoroscopy time and number of images routinely. The usefulness and potential use of KAP meters with regards to dose optimization in radiology was confirmed.

Study IV: This investigation aimed to assess the feasibility of fabricating in-house the clinical dosimetry radiology phantoms. A total of six patient dose assessment phantoms were fabricated of which four phantoms were as per American National Standards Institute (ANSI) specifications and the other two as per Centre for Devices and Radiological Health (CDRH) specifications. This study proved that the phantoms can be fabricated cost-effectively in-house in a hospital with a mechanical engineering workshop using materials which are locally available. In addition, this study determined radiation doses received by patients undergoing six general radiography examinations. The feasibility of both direct and indirect methods of patient dosimetry was studied. Patient dosimetry based on indirect measurements was the method of choice. Patient data and technical parameters related to the X-ray examinations were collected. The study involved the following examinations: chest posterior-anterior (PA), chest lateral (LAT), pelvis anterior-posterior (AP), abdomen AP, lumbar spine AP and thoracic spine AP. Entrance surface air kerma was calculated based on the X-ray tube

[1] See Section 8.3 on the use of the term *skin dose*

output of the unit used and the exposure parameters used for the actual examination. Based on the mean entrance surface air kerma (ESAK) values from the individual rooms, the following DRLs were established: 0.10 mGy for chest PA, 0.22 mGy for chest LAT, 2.98 mGy for pelvis AP, 4.19 mGy for abdomen AP, 5.30 mGy for lumbar spine AP and 3.28 mGy for thoracic spine AP. The calculated mean ESAK values were compared with previously published mean values from other countries. For the first time, a baseline for potential dose reference levels (DRLs) in South Africa was established for the selected examinations. The results of this snapshot audit serve as a benchmark for future dose optimization attempts in South Africa. Feasible and practical dose saving measures are presented and discussed based on the experience of the present patient dose audit carried out.

Study V: A replica of the CDRAD phantom was successfully fabricated in-house for use as an image quality test object. It has been shown that the phantom when fabricated in-house is inexpensive and can be made from materials that are readily available locally. Furthermore the utility of the replica phantom as both an acceptance testing and routine quality control tool has been demonstrated. The replica phantom proved effective for purpose and user-friendly.

Study VI: The purpose of this study was to assess radiographer familiarity and preferences with digital radiography and thereafter make recommendations in line with the migration from screen film to digital radiography in South Africa. A questionnaire was designed to collect data from either qualified or student radiographers from four teaching hospitals. From the four teaching hospitals there were a total of 205 potential respondents. Among other things, responses regarding experiences and preferences with digital radiography, quality control procedures, patient dose, advantages and disadvantages of digital radiography were sought. The information collected was based on self-reporting by the participants. Sixty-three out of 205 (31 %) radiographers from all the four radiology centres responded to the circulated questionnaire. The participants of this survey showed familiarity with digital radiography and have embraced this relatively new technology as shown by the fact that they can identify both its advantages and disadvantages as applied to clinical practice. However, there are minimal quality control procedures specific to digital radiography being undertaken and there is need for formal education, continuing education and manufacturer training with

respect to quality control as institutions make the transition from conventional screen film radiology to digital radiology.

Study VII: An investigation into the amount of scattered radiation from the couch during under-couch procedures was carried out. Of dosimetric concern are the forward scattered photons from the couch which contribute in principle to patient dose. Measurement of the amount of scattered radiation off the patient couch was accomplished by using an ionization chamber. The results of the investigation showed that for field size of dimensions, 10 cm * 10 cm, the scatter contribution is approximately 12 % of the total radiation reaching the patient surface. In addition the scatter contribution varies by ±2% across field sizes ranging from 8 cm * 8 cm to 20 cm * 20 cm, with the 10 cm * 10 cm field size taken as a reference field. This study underscores the need to account for the forward scattered radiation so as to improve the accuracy of clinical patient dosimetry.

Programs of continuing education and training of radiological personnel in appropriate radiological technique need be actively implemented in order to maintain a high level of awareness of the factors that determine the diagnostic quality and dose to the patients. In line with efforts to optimize dose from diagnostic radiography examinations it is recommended that national DRLs be established in South Africa for the most frequent examinations in general radiography and fluoroscopy. It is recommended that the South African national regulator endeavour to implement or facilitate implementation of a national patient dose database. In summary, this thesis indicates the possibility of dose reduction in diagnostic radiology through optimization of radiographic process.

Key Words: ***diagnostic radiology, fluoroscopically guided procedures, optimization of protection, image quality, dose reference levels, quality control, digital radiography***

DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Furthermore, I certify that this research work has the approval of the Human Research Ethics Committee at the University of the Witwatersrand. (Protocol Number M071032)

Thulani Nyathi

19th day of November 2012
Johannesburg

DEDICATION

In the memory of my father John Kwerepu Nyathi. Lomhlaba unzima, lomhlaba[1].

To my mother and wife for their consistent support and love. Intandane enhle ikhothwa ngunina[2].

To my son Thamsanqa "Thami" Olebogeng Nyathi.

He only half dies who leaves an image of himself in his sons[3].

And to the rest of my family and friends who have sustained me throughout.

[1] Zulu Tribe Proverb translated as " this world is a harsh place, this world"
[2] Ndebele Tribe Proverb translated as "a good orphan is the one licked by the mother".
[3] Quote from Carlo Goldoni an Italian playwright and dramatist.

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Disclaimer

Any opinions, findings, conclusions, or recommendations expressed in this thesis are those of the author and do not necessarily reflect the views of the Division of Medical Physics, CMJAH.

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2. **Nyathi T**, Nethwadzi LC, Mabhengu T, Pule ML and van der Merwe DG and Rapoho SP. Patient dose audit for patients undergoing six common radiography examinations: Potential dose reference levels. *The South African Radiographer Journal* ***2009; Vol 47(2): 9 -13***
3. **Nyathi T**, Pule ML, Segone P, van der Merwe DG and Rapoho SP. A dose audit of fluoroscopy examinations at Charlotte Maxeke Johannesburg Academic Hospital: Analysis of preliminary results. *South African Journal of Radiology*.***2009; Vol 13 (2): 24 - 28***
4. **Nyathi T**, Mwale AS, Segone P, Mhlanga HS, Pule ML. Radiographic viewing conditions at Johannesburg Hospital. *Biomed Imaging and Interv J* ***2008; Vol 4 (2): e17***

LIST OF PRESENTATIONS

1. **Nyathi T.** (2008). Reduction of doses in radiology and possible effects of high exposure to soft rays. Glynnwood Hospital. South Africa. 30 May 2009.

* At the time of submission this thesis had 5 citations in peer reviewed journal publications.

CHAPTER ONE

INTRODUCTION

1.1 An Overview

In November 1895, Professor Wilhelm Conrad Röentgen of the University of Wurzburg, Germany discovered X-rays in his laboratory[1-5]. It is reported that to demonstrate the properties of X-rays in a public lecture, Röentgen asked a prominent Swiss professor of anatomy by the name Rudolf Albert von Kölliker to put his hand in the beam and thus produced the first publicly taken radiograph clearly showing the bony structures of the hand and a ring on the finger[6]. From the very onset of Röentgen's discovery, X-rays were immediately applied to medical imaging.

Radiography as practiced then was immediately followed by fluoroscopy. Fluoroscopy is the method that provides real-time X ray imaging that is especially useful for guiding a variety of diagnostic and interventional procedures. The early equipment consisted of a tube with a fluorescent screen at one end and an eyepiece at the other. A body part placed in between the X-ray tube and the screen produced an image even in a lighted room.

In modern day society, diagnostic radiology is of paramount importance at any level of healthcare, be it in public health or preventative medicine or curative medicine[7]. Diagnostic radiology examinations can be used either solely or in conjunction with expert clinical judgement to diagnose or confirm disease processes. Medical X-ray examinations have empowered medical professionals to study physiology and view human anatomy non-invasively, leading to the elimination of some exploratory surgery[8].

In the year 2000, medical imaging was listed as one of the top 11 inventions for the past 1000 years, which is a clear indicator of the importance of this modality to humanity[8]. Mankind has gained a lot from the use of ionizing radiation, however the use of ionizing radiation poses some risk to the population. However, in general the risk posed by medical X-ray examinations is assumed to be outweighed by the derived benefit. An increase in the availability of medical X-ray imaging equipment in developing countries has led to an increase in the frequency of X-ray examinations[9].

Medical ionizing radiation sources give by far the largest contribution to the population dose from man-made sources and most of this contribution comes from diagnostic X-rays[10 -13]. The UNSCEAR 2008 Report mentions that the worldwide total number of diagnostic medical examinations (both medical and dental) per year is estimated to have risen from 2.4 billion in the 1991 - 1996 survey to 3.6 billion in the 1997 – 2007 survey, representing a 50 % increase[14]. Following the trend over the past couple of decades there is reason to assume that the use of X-rays for medical purposes is going to continue to increase. For example for the population of the United States of America the dose budget is as shown below[15].

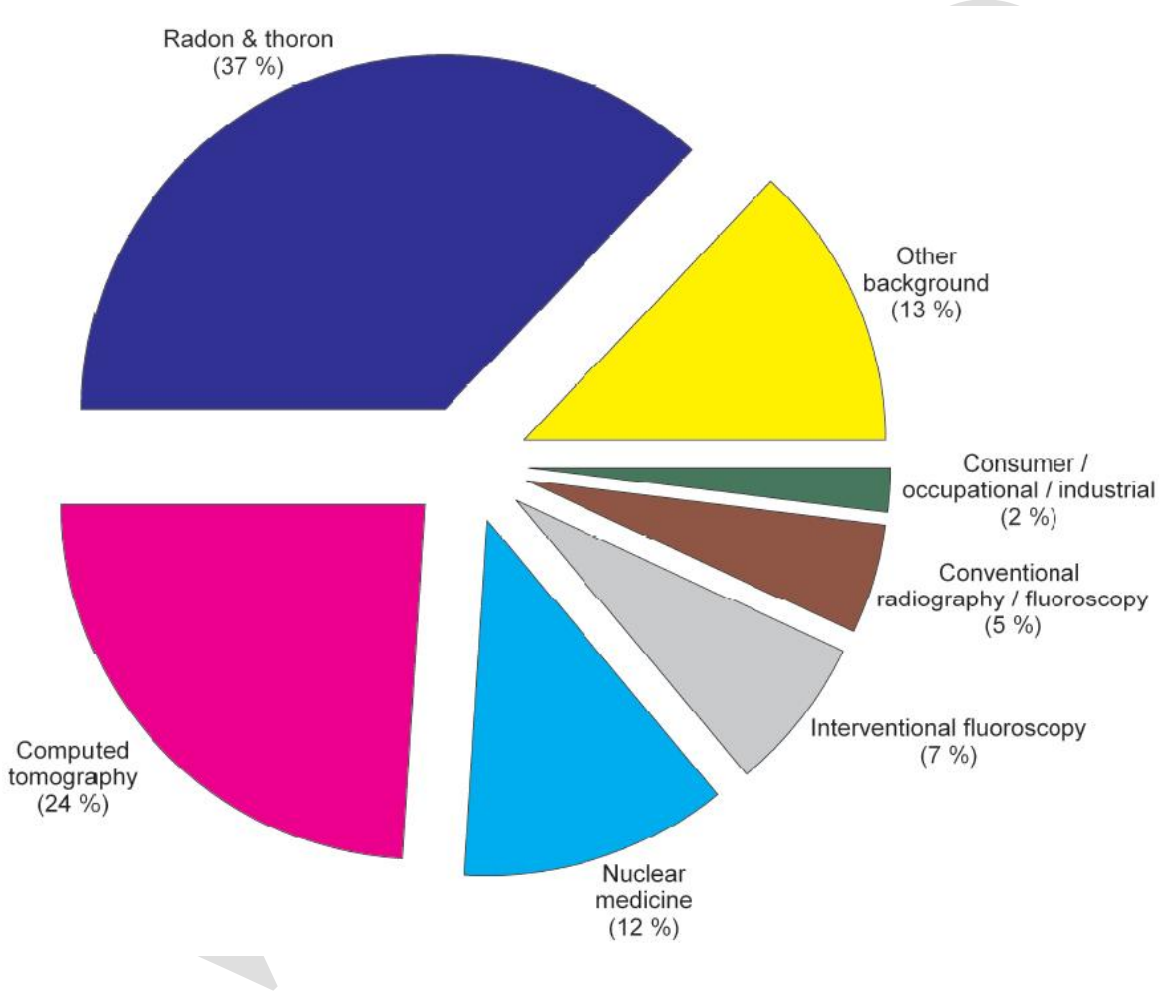


Figure 1.1: The pie chart shows sources of radiation exposure in the United States of America in 2006 [15].

When considering radiation dose due to medical applications it is worthwhile to mention the contribution by computed tomography (CT). From Figure 1.1 CT is clearly the largest dose contributor from medical use of ionizing radiation. The UNSCEAR 2008 Report noted that 34 % of the collective dose from medical exposures was due to CT procedures [14]. There has

been a remarkable increase in the use of CT since its clinical introduction in the early 1970s [16,17]. In 2004 CT examinations per thousand population per annum were as follows: 30 in Australia, 35 in Germany, 50 in Belgium and 97 in Japan [16]. For example as of 2008 the use of CT had increased by approximately 12 fold in the UK and by more than 20 fold in the US[18]. In the UK, CT contributes the bulk of the collective dose[18]. It is the opinion of the author that the use of CT is not as prevalent as that of general radiography in South Africa thus the deliberate choice to investigate the high frequency general radiography examinations. Nonetheless it is appreciated that CT is a high dose modality which deserves to be investigated.

South Africa is a healthcare level II country according to the UNSCEAR definition which is based on physicians per head of population [19]. This healthcare level classification translates to 332 diagnostic X-ray examinations per 1000 population per annum based on the 1997 –2007 survey [14]. Given this relatively high frequency of X-ray examinations, it will be a disservice to the population for the scientific community to not investigate radiography practice with the aim of optimising practice.

The detrimental effects of ionizing radiation are well documented[20]. Given the self evident increase in global usage of X-rays coupled with the increase in frequency of use, it becomes imperative for the medical physics community to explore ways of efficient and optimum usage. In simple terms, optimization in diagnostic radiology means producing an image with all the relevant diagnostic information for the least radiation dose. In practice application of optimization principles is not as easy as it might seem since the two quantities dose and image quality are intimately connected. In most cases better images need an increase in dose and the reverse is normally true. In a clinical set-up for any given patient the radiographer/ radiation technologist, in an effort to optimize dose has to make decisions with regard to the exposure parameters (kVp, mAs, use of grid, filtration and focus to film distance). All these parameters have an influence on both image quality and radiation dose to the patient. Having multiple parameters to choose from when taking a radiograph further complicates the optimization process, as the parameters are not necessarily complementary.

1.2 Status of Radiology in South Africa and Legislature

Within sub Saharan Africa, South Africa enjoys comparatively better radiology facilities. The radiology community is regulated by a directorate under the Department of Health, namely, DRC. The DRC's mission is to promote and maintain health within the framework of the National Health Plan and specifically the protection against injury or disease caused by technological devices, including hazardous sources of radiation, by furthering the safe and legal use of such devices. Currently there are 12602 medical X-ray units and 289 CT units licensed by the DRC. From the DRC listing of licensed medical devices it is evident that the technology in use varies from very old to the latest state of the art equipment[21]. The DRC stipulates the types of quality control (QC) tests and their frequency.

The mainstream radiology department professionals, namely radiologists, radiographers and medical physicists have voluntary professional societies which represent them. Radiologists have the Radiological Society of South Africa (RSSA) which represents radiologists and nuclear medicine physicians in South Africa and Namibia. The professional society for radiographers is called the Society of Radiographers of South Africa (SORSA), it represents radiographers practising in diagnostic radiology, nuclear medicine, radiotherapy and ultrasound. The South African Association of Physicists in Medicine and Biology (SAAPMB) represents medical physicists. All the mentioned societies are at liberty to make representations on issues affecting their practice to the Health Professions Council of South Africa (HPCSA) or the national government or any relevant statutory body.

The Hazardous Substances Act, (Act 15 of 1973) governs the safe use of medical x-ray equipment in South Africa [22]. Licensing X-ray emitting devices for use in South Africa is the sole responsibility of the DRC. The DRC has a mandate to enforce the Hazardous Substances Act, for example to ensure that appropriate quality control procedures are being undertaken for every installed unit [22]. The current official position in South Africa is that quality control procedures in radiology should be done by South African National Accreditation Agency (SANAS) accredited companies or organizations. However the SANAS accreditation is modality specific and as of July 2010 there are 14 organizations approved by the DRC to perform radiology quality control procedures [23].

South African radiology departments have not been spared from staff shortages. There is a general shortage of radiographers in the health sector and moreover the situation is worsened by labour migration to the private sector and overseas. As of June 2008 there were 4 medical physicists with a primary or sole responsibility in diagnostic radiology, otherwise the rest of the medical physics community provided service to the radiology community on a consultative basis. The current number of diagnostic radiology medical physicists' falls way short for optimum staffing levels, particularly worrying is that even some university teaching hospitals have vacant posts. The SAAPMB officially endorsed the use of the IAEA-TRS 457 protocol for radiology dose measurement in 2008 [24].

1.3 Problem Statement

Despite the fact that in general the benefits derived from medical radiation exposure outweighs the associated risks to the patients, there is a growing concern among the patients, public and the scientific community about the ill-effects of radiation. An interrogation of the google search engine on the internet reveals the scale of the radiation concerns the public has through the various published media articles. The first step in allaying the radiation effects phobia is to accurately quantify the risk of these procedures. Currently in radiology the risk metric of choice is effective dose, which can only be derived from the knowledge of patient doses in a population. Patient doses can be determined through carrying out dose audits in clinics, which evaluate patient dose, image quality and technique. Currently there is sparse literature on patient doses in South Africa and such lack of information reinforces fears about radiation. The problem can be summed up as a process optimization problem and thus the objective of this work to identify feasible ways of lowering patient doses.

1.4 Motivation for Research Work

The Government Gazette No. 14596 of 26 February 1993, made further specific regulations with regards to use of Group IV Hazardous Substances. The major theme of the mentioned Government Gazette was radiation protection of the patient, radiation workers and the general public. Of interest is Section 29, Part 2 of the Gazette which reads

"A holder shall ensure that any equipment or apparatus under his control

(a) that contains a Group IV hazardous substance and that is used for medical exposure; or

(b) that is intended for use with such substance.

is of such design or construction and is installed and maintained and calibrated in such a way that the exposure to ionizing radiation of any person who is undergoing a medical exposure may, as far as is reasonably practicable, be restricted to a minimum that is reconcilable with the intended clinical purpose or research objective." [25].

Thus there is a statutory obligation to diagnostic radiology service providers to apply the ALARA principle without compromising the image quality. However for this to be achieved there ought to be measurable metrics for typical X-ray examination. This can be done by way of setting up DRLs as suggested by the International Commission on Radiological Protection (ICRP) [26]. It is envisaged that establishment of DRLs will shift from the retrospect approach of "what dose did I deliver" to a more prospective approach of "what dose should I deliver". No DRLs for radiography examinations have been established in South Africa[27]. Moreover patient dose data collated from international studies involving countries across the globe is mainly based on data from developed countries[14]. It should be appreciated that for fluoroscopy / screening procedures a reduction in patient dose will also result in a corresponding reduction in radiation workers dose [28].

In the United States of America all fluoroscopic equipment manufactured on or after 10 June 2006, should be able to display air kerma rate and cumulative air kerma[29]. The DRC in South Africa followed suit in 2007 and changed the license conditions for fixed fluoroscopy units to include the instalment of KAP meters[30]. As a result all facilities having fixed fluoroscopy X-ray units were instructed to have a KAP-meter installed and to record the KAP readings after each examination with effect from 01 January 2008. It would be unfortunate to have this depository of KAP meter readings without any meaningful scientific analysis of the data. It is the objective of this thesis to analyse the data depository with the intention of contributing to the knowledge of patient radiation doses.

1.5 Significance of Study

In modern day society, patients and members of the public have nearly unlimited access to information regarding their care-paths. The pitfalls of this readily available information sourced from internet search engines and media is that it often lacks context and is easily misinterpreted by the lay public. Presently there is no local knowledge base to inform on typical radiation doses in South Africa and thus dose optimization development process,

henceforth this thesis will provide baseline knowledge to inform optimization processes on a practical local clinical setting level.

Public hospitals in South Africa are migrating to digital radiography, for example in 2006 Charlotte Maxeke Johannesburg Academic Hospital (CMJAH) installed a total of 6 digital units of which 5 were general radiography digital units and 1 digital mammography unit. Research from overseas has shown that digital radiography has the potential to improve workflow and lower patient doses, however this hypothesis has not been tested and established in a South African public hospital setting where most of the staff were trained on and operate analogue units. This thesis through a questionnaire will capture the current digital radiography practice in a few select South African public hospitals with the aim of making recommendations for "best practice".

For radiation protection purposes to the radiologist or interventionist the fluoroscopy units are in most cases operated with the X-ray tube under the couch. In this configuration at typical radiology beam energies there is forward directed backscattered radiation which present industry preferred dosimetry systems do not account for in quantifying patient skin doses. This thesis will quantify the amount of the forward directed backscattered radiation which contributes to the patient's skin dose and therefore potentially lead to a more accurate quantification of clinical dosimetry, which informs associated radiation risks to the patient.

1.6 Objectives

This work will attempt to find solutions with specific attention to the challenges and knowledge gaps pertinent to the South African radiology community. The objectives of this work are, among others,

- Measure incident air kerma and calculate entrance surface air kerma from selected X-ray examinations.
- Retrospectively analyse patient doses from fluoroscopic examinations and procedures.
- Identify potential high dose fluoroscopic procedures.
- Deduce and establish preliminary local diagnostic reference levels for selected examinations.
- Identify the weakest links in the X-ray imaging chain and subsequently address the optimization strategies accordingly.

- Educate, advice, and sensitize the South African radiology community on patient doses.
- Provide information on patient doses to the South African radiology community.
- Provide information on patient doses in healthcare level II countries.
- Assess the familiarity radiographers to digital radiography.
- Design a simple spreadsheet based application to be used for recording quality control results.
- Investigate the amount of forward scattered radiation on under-couch KAP-meter installations.

Scientific methods will be applied to improve the clinical application of ionizing radiation. The study is designed around four major scientific challenges in diagnostic radiology, being the justification of X-ray examinations, the optimization of X-ray technology, assessment of patient exposure to X-rays and image quality assessment in diagnostic radiology.

1.7 Organization

The structural organization of this thesis is described in the following paragraphs. This present work comprises of eleven chapters and five appendices.

Chapter One gives an overview of the subject matter of this work. It gives a brief history of the field of radiology. Furthermore, it spells out the objectives of this work and at the same time gives the justification for engaging in this research.

Chapter Two is a brief literature review on the various subjects of this dissertation. It briefly details and acknowledges prior research which has been done on this subject by other scholars. The literature review is limited to the following general subjects: quality control and quality assurance programs in diagnostic radiology, radiographic viewing conditions in diagnostic radiology, use of custom made quality control software in radiology, fluoroscopy dose audits, radiography examinations dose audits, physical and clinical image quality assessments, issues related to migration from screen film technology to digital radiography and scattered radiation from under couch procedures. Pertinent results and lessons learnt from this literature review are spelt out.

Chapter Three deals briefly with the science and engineering behind the production of X-rays. In addition a brief synopsis in the relatively complicated science of image formation on a screen-film combination is also offered. Digital radiography and fluoroscopy are introduced in this chapter.

Issues relating to radiation dosimetry in diagnostic radiology are introduced in Chapter Four. Concepts of dose measurement are introduced in this section of the thesis. More importantly the principal subject of this thesis, that is, dose optimization is introduced. Issues like the biological effects of radiation and the associated radiation risk are also discussed.

The thesis includes a comprehensive chapter on image quality metrics. Image quality metrics is presented in Chapter Five. The phrase image quality is defined in this chapter and also factors that affect image quality are discussed. This chapter offers both quantitative and qualitative means of measuring image quality.

Chapter Six discusses the materials and methodology employed in this research. Methods employed in this work varied from experimental measurements, engineering fabrication, questionnaire based data acquirement and statistical data analysis.

Chapter Seven provides an in-depth analysis of the collected data. The results are presented in a number of forms, amongst others, graphs, histograms and tables.

Chapters Eight deals with discussions arising from this work and drawing from what other researchers have done. This chapter gives an insight on the strengths and weaknesses of this thesis. Some of the work presented in this thesis has been published in scientific journals.

Chapter Nine gives out the recommendations borne out of this work and conclusions that have been deduced from this dissertation.

Chapter Ten gives out the conclusions that have been deduced from this dissertation. The main findings of this work are spelt out in this chapter.

Chapter Eleven has suggestions for future work based on the knowledge gaps identified from this work.

After Chapter Eleven there are five appendices, namely, CD-ROM accompanying this thesis, the User's Guide for the QC software developed, the X-ray room data collection form, the patient data collection form and a Questionnaire used in this thesis. The CD-ROM contains this thesis and the QC software. All the references cited in this work are listed after the Appendices.

CHAPTER TWO

LITERATURE REVIEW

2.1 Prior Work

Dose audits involve assessment of all parameters that influence both patient dose and image quality of the radiographs. Thus a dose audit should consist of evaluation of the radiographic technique, patient dose and image quality. Patient dose surveys have reported wide variations in doses for patients undergoing the same type of X-ray examinations, at times by a factor of 100 [31 -35]. This wide variation in patient dose is an indication of room to further optimize the radiography process. In addition, there is evidence that substantial reductions in these medical exposures are possible without detriment to patient care[31]. The wide variation in doses led the Royal College of Radiologists (RCR) and the National Radiological Protection Board (NRPB) to recommend that regular patient dose monitoring should be an essential component of a quality assurance (QA) programme in diagnostic radiology [36].

The ICRP and the European Commission have recommended the use of DRLs as a quantity to aid dose optimization and a tool for patient dose audit and monitoring [26, 37]. DRLs are defined as dose levels in medical radio-diagnostic practices or, in the case of radiopharmaceuticals, levels of activity, for typical examinations, for groups of standard sized patients or standard phantoms and for broadly defined types of equipment[37]. The DRL should fulfil the following criteria:

- Be clearly defined and easy to measure or calculate.
- Directly indicate the dose delivered to the patient.
- Allow easy correlations with the technical parameters of the medical examination.
- Be adapted to all types of radiological equipment.

According to the ICRP, implementation of DRLS can lead to the following:

- Reduce number of high or low dose values in a regional, national or local dose distribution.
- Promote a narrower range of dose values that represent good practice for a particular examination
- Promote progression towards an optimum range of dose values for a particular examination.

DRLs should be determined from patient dose surveys and be representative of the region or country. In order to be a true reflection of radiology practice DRLs should be regularly updated as practice and equipment change in hospitals.

As a result of the concerns about the biological effects of radiation on patients receiving diagnostic radiology examinations there have been numerous patient dose audits conducted in various countries. The results of these patient audits have been compared nationally and internationally. For instance, in 1992 the NRPB established a National Patient Dose Database to collate the measurements made by X-ray departments across the UK of radiation doses to patients undergoing radiographic and fluoroscopic imaging procedures [38]. This led to the publication of representative patient dose values in 1992. The published dose values were from data accrued through the period 1982 to 1985. Subsequent dose survey reports in 1996, 2002 and 2007 showed a continued patient dose decrement [39-41]. It therefore stands to reason that introduction of DRLs helped lower patient dose. Studies by the NRPB are large scale in nature, the 2007 publication is based on data collected from January 2001 to February 2006, comprising of 23 000 entrance surface dose measurements, 57 000 kerma area product (KAP) measurements for single radiographs, 208 000 KAP measurements and 187 000 fluoroscopy time recordings [41]

In the United States of America (USA) a large scale dose survey called Nationwide Evaluation of X-ray Trends (NEXT) was established for the purposes of producing a snapshot in time of patient doses from a nationally representative number of radiology facilities. The program was conducted jointly by the Conference of Radiation Control Program Directors (CRCPD) and the Food and Drug Administration's (FDA) Centre for Devices and Radiological Health (CDRH). The NEXT program was started in 1973, assessing patient doses from twelve common medical and dental diagnostic examinations using manual techniques [42]. However in 1984 the NEXT program started using clinically validated standard patient equivalent phantoms for use with automatic exposure control (AEC) techniques [43]. There is a lot of practical experience to be derived from the NEXT program should the South African radiology community decide to establish national DRLs.

In 2008 the initial results from an IAEA project involving countries from Africa, Asia and Eastern Europe were published. In this project there were six African countries participating,

namely Tanzania, Sudan, Democratic Republic of the Congo, Zimbabwe, Madagascar and Ghana. The mean entrance surface air kerma values were as follows: 0.33 mGy for chest PA, 4.07 mGy for lumbar spine AP, 8.53 mGy for lumbar spine LAT, 3.64 mGy for abdomen AP, 3.68 mGy for pelvis AP and 2.41 mGy for skull AP [44]. This study concluded that patient doses were not higher than those in developing countries, however it pointed out that poor image quality was the major source of unnecessary radiation to patients in developing countries. Furthermore the study showed that introduction of quality control procedures led to patient dose reductions ranging from 25% to 85% depending on the type of examination.

A number of studies from Nigerian radiology centres have been published [12, 45, 46]. In general patient doses have been found to be comparable to data from both European and other African countries. In 2007, a study involving 9 hospitals in Southern Nigeria estimated entrance surface dose using standard exposure factors and a mathematical algorithm[47]. The estimated mean entrance surface dose were as follows: 0.4 mGy for chest PA, 1.7 mGy for chest LAT, 6.7 mGy for skull AP, 4.2 mGy for skull LAT, 5.4 mGy for abdomen AP and 6.9 mGy for pelvis AP. Studies from an African country make for meaningful comparison of radiology practice, because they are more or less equal in terms of resources and also they have mostly common challenges.

In recent years there has been data from the Islamic Republic of Iran which has been published. The Islamic Republic of Iran is a healthcare level II country like South Africa thus presenting meaningful comparisons. A nationwide survey was conducted in phases from 2003, involving 31 radiology departments spread across 21 cities, involving 14 X-ray examination projections[48]. From the collected data the following dose reference levels were established for the following projections: 4.06 mGy for abdomen AP, 1.83 mGy for cervical spine AP, 0.93 mGy for cervical spine LAT, 0.97 mGy for chest AP, 2.07 mGy for chest LAT, 0.41 mGy for chest PA, 3.43 mGy for lumbar spine AP, 8.41 mGy lumbar spine LAT, 3.18 mGy for pelvis AP, 2.85 mGy for skull AP, 1.93 mGy for skull LAT, 2.83 mGy for skull PA, 2.72 mGy for thoracic spine AP and 5.29 mGy for thoracic spine LAT [48].

Tsapaki V *et al* [49] compared entrance surface dose values from a couple of examination types, using a mathematical method and thermoluminescent dosimeters (TLDs). Their study found that the entrance surface dose values derived from the mathematical/ calculation method

based on the exposure parameters was close to the results from the thermoluminiscent dosimetry. Furthermore, the study concluded that the calculation method offered an easy, cheaper and faster way of performing patient dosimetry.

There are a number of things which can be done to minimize patient doses in general radiography examinations, for instance[50]:

- Use patient specific exposure parameters (kVp, mAs and filtration)
- Keep the number of views per examination to the minimum necessary.
- Consider alternative modalities e.g. ultrasound and MRI.
- Use the most efficient image receptor consistent with the diagnostic information sought.
- Avoid the universal use of anti-scatter grids.
- Always collimate the X-ray beam to the size of the image receptor and clinical region of interest.
- Optimize the processor performance.

Presently in South Africa there is no published work of DRLs for diagnostic radiology examinations thus the motivation to undertake this study. Published work in the field of radiology has been limited to fluoroscopically guided procedures and mammography examinations [51 -53]. It is well recognized and appreciated that fluoroscopically guided or interventional radiology procedures contribute significantly to the total collective dose due to medical exposure even if their frequency is relatively low [54]. In addition, it is widely appreciated that some procedures in interventional radiology carry greater radiation risks than many other radiological examinations. The fact that fluoroscopy is a high dose modality could be possibly the motivation for South African research having been in this specialty. One of the few South African studies was by Acho *et al* who employed TLD dosimetry to measure radiation doses to 27 patients undergoing fluoroscopically guided back pain management procedures [51]. A large variation in patient doses for the same procedure was reported in this study. Acho et al reported the following mean maximum skin doses: 20.2 mGy for epidural injections, 48.9 mGy for facet joint injections, 37.4 mGy for sacroiliac joint injections and 14.3 mGy for radiofrequency neurotomy.

Technically a DRL represents doses for a typical examination or procedure, however the concept of 'typical' procedures is not well defined in interventional radiology either as the procedures can vary greatly. Marshall *et al* cautions on the interpretation of DRLs from specific clinics in light of the skewed and dispersed DRL distributions encountered in interventional radiology [55]. For complex examinations they suggest setting up DRLs based on pooled size-corrected patient KAP distributions rather than distributions of average KAP per room. It has been shown that KAP values alone are not adequate indicators of skin dose, having shown poor correlation with skin dose[56]. However the KAP reading has been adopted by many as a quick indication of the radiation dose delivered. Some researchers have discredited this quantity due to its weak correlation with entrance surface dose, which is the quantity of interest given its intimate relation with deterministic effects.

Patient dose audits have also been conducted for fluoroscopy procedures. For example in 2004 the IAEA published the document IAEA-TECDOC-1423, which was a coordinated research project involving countries from Africa, Asia and Eastern Europe [57]. The countries involved can generally be classified as developing countries as such this data in valuable and applicable to the South African situation. Morocco was the only African country participating in this project. Information recorded included patient's age, weight, number of images, fluoroscopy time and KAP readings. The patient dose data was estimated from at least a patient sample size of five with an average mass of 70±10 kg for European countries and 60±10 kg for Asian countries. This multi-national study had a mean DAP value of 23.2 Gy cm^2 (3.5 - 84.5 $Gycm^2$) and an average screening time of 3.5 minutes (1.0 – 11.9 minutes) for a barium meal procedure[57].

There are a number of things which can be done to minimize patient doses in fluoroscopy procedures, for instance [58, 59]:

- The field size should be restricted to the region of interest.
- Keep the X-ray tube at the maximal distance from the patient while the image intensifier is kept as close as possible to the patient
- Keep beam ON time to an absolute minimum
- Operator reaction to the 5-minute time notifications.
- Use of the Last-Image-Hold facilities
- Keep the tube current as low as possible.

- Keep the kVp as high as possible bearing in mind the patient thickness, patient dose and image quality.
- Removal of the anti-scatter grid and use of screen-film combinations of a higher speed class.
- Minimize room lighting to optimize image viewing.
- Only justified examinations to be undertaken.

In as much as one would like to have the patient dose as low as reasonably achievable, the limiting factor is the diagnostic information derived from the particular image. The dilemma in many cases is that image quality improves with higher patient doses, albeit a violation of the ALARA principle. Image quality is affected by a number of factors, ranging from the acquisition process, image receptor device, image processing process and image display. A number of methods have been used to assess image quality in radiology, either using phantoms or patients. However, some researchers have questioned the use of phantom based image quality studies to make inferences to clinical image quality as the link with clinical image formation is neither well defined nor predictive. It is therefore important for image quality to be defined in terms of what is needed or supposed to be detected in a particular image. Krupinski *et al* has defined image quality as task based [60,61]. The subjective nature of image quality makes any objective assessment difficult.

Errors and variations in interpretation represent the weakest link in clinical imaging [62]. Among other things these errors are a result of poor technique. In 2007 Egbe *et al* did a retrospective study on assessing image quality of abdominal radiographs based on the Commission of European Communities image quality criteria [63]. In the study by Egbe, 53 % of the radiographs classified as good quality images. In such a scenario there is a need and scope for image quality improvement. In 2001 van Soldt *et al* performed a patient dose and image quality survey for patients undergoing PA chest radiography in 25 selected centres in Netherlands [64]. For image quality the study employed a contrast-detail phantom. A detailed description of the CD phantom is given in Chapter Five. Some researchers have gone further and investigated image quality based on clinical images. For example, in 2004 Tingberg et al studied the effect of the characteristic curve on the image quality of chest and lumbar spine radiographs based on the recommendations of the European Guidelines on Quality Criteria for Diagnostic Radiographic Images [65]. Image quality was evaluated by seven experienced

radiologists, both fulfilment of the European Image Criteria and visual grading analysis (VGA) were analysed.

Quality control and assurance in medical radiology is a legal requirement in South African. The International Organization for Standardization (ISO) defines quality assurance as all those planned and systematic actions necessary to provide confidence that a product or service will satisfy the given requirements of quality [66]. In everyday talk, quality control is often confused with quality assurance, however, quality control is defined as the process through which the actual quality performance is measured, compared with existing standards and the actions necessary to keep or regain conformance with the standards.

Implementation of a quality assurance program seeks to continuously improve performance of the workflow process. A quality assurance system should be designed in such a manner that it provides for the following:

- Provide routine and consistent checks to ensure compliance.
- Identify and address any deviations from compliance.
- Document and archive all QC activities.
- Obtain optimum diagnostic information at minimum cost and with minimum radiation dose.

The collection and analysis of data is very critical in a QA cycle as it leads to a robust and effective critique of the quality performance status of the system. As such ways need to be found which will lead to easier data collection, analysis and archiving. Presently most radiology departments use paper for both recording and archiving their QA records. Analysis of large records on paper is not only cumbersome but also prone to transcription errors.

Many medical physicists have developed spreadsheets to record, analyse and archive QA data. In most instances these spreadsheets have been developed by an individual, which is ineffective for implementation and use by others. The use of such software makes it possible to consolidate all the QA data in one repository which makes it easier for the medical physicists, field service engineers, radiographers and policy-makers to review the quality performance of any device. Langer and Kanal developed a library of spreadsheets to facilitate the performance of diagnostic radiology physics QA[67]. The spreadsheets were originally

posted on the now defunct world wide web (http://radweb.mcis.washington.edu/~sglanger) for use by anyone. The spreadsheets were later posted on http://diag-medphys.nfinite-horizons.org/ , however for some reason these spreadsheets are no longer accessible. For any QA software to be effective it should have a way of immediately display the trend in the QA results with respect to the reference or baseline results as on acceptance testing. Despite its advantages, software programs have the potential to suffer from systematic programming errors, data corruption and there needs to be a learning curve as users move from hardcopy to softcopy systems.

Performance of the reporting radiologists depends on a host of factors of which viewing conditions is one of them. The resolution of the eye is strongly dependent on image brightness so for the purposes of accurate film reading it is desirable to have optimum radiograph viewing conditions. At a luminance value of approximately 1300 cd m^{-2} the maximum resolution of the eye is approximately 12 lp/ mm at a viewing distance of 25 cm, which is grossly reduced in darker viewing conditions[68]. A dark radiograph of film density over 2.5 or dim viewing conditions can result in a human being's eyes' resolution to drop to less than 4 lp / mm[68]. Optimum viewing conditions have been suggested by organizations like World Health Organization (WHO) [69].

The computer industrial technology revolution has not spared radiography. For example, conventional screen-film radiography is being replaced by digital technology based radiography. Fuji Photo Film Co were the pioneers of digital radiography systems, they introduced what they called computed radiography (CR) in the 1980s[70]. The CR system consisted of an europium-activated barium fluorohalide imaging plate and a laser readout system. Early CR images were of poorer quality than screen-film, however the general image quality of CR systems has since then improved drastically[70]. The major disadvantage of CR is the time lag between exposure of the imaging plate and subsequent display of the image. The remedy to this disadvantage was the design and implementation of flat panel detectors (FPDs). FPDs are self scanning, two dimensional solid state imaging devices Passage of time and further improvement in technology led to the capability of viewing images instantaneously through the application of flat panel detector technology.

Digital radiography if well optimized has the potential to reduce patient dose, however transition to this modality has not necessarily lead to a reduction in the radiation burden to the patients. In some cases it has been found to lead to an increase in patient doses, for example a study by Vano *et al* showed an increase of between 40% and 103% in patient entrance doses [71]. Radiology department have to go through a learning curve as they transit from screen-film technology to digital radiography. At times this process takes long as the radiographers would not have been adequately trained in the digital modality. Another challenge with digital radiography is that often the energy response of digital detectors is different from film. AEC calibration in digital radiography demands and deserves an alternative parameter to optical density [72]. Some traditional quality assurance aspects in radiology have been affected by the introduction of digital radiography. For instance, image display has also been affected by the migration to digital radiology as such optimum viewing conditions of soft copy images demands changes in traditional image display quality control and assurance.

For under-couch installations, KAP dosimetry is complicated by the presence of attenuation and scatter from the couch [73]. In 1965 Carlsson measured KAP calibration factors for both over-couch and under-couch installations for X-ray beams having HVLs ranging from 3mm Al to 8 mm Al [74]. The quotient between over- and under-couch installations ranged from 1.28 (for 3 mm Al) to 1.12 (for 7 mm Al) [74]. The influence of scattered radiation has implications on KAP calibration dosimetry. The amount of forward scattered photons from the couch to the patient was investigated in this work.

2.2 Rationale of Study

The aim of this work was to investigate current radiological practice in a typical South African public hospital and subsequently suggest and recommend dose optimization measures. This thesis is made up of seven studies and below the rationale of the studies is explained:

Quality control of radiography viewing conditions: One of the ways of obtaining accurate diagnosis depends on the radiologist being able to see all the radiographic detail on the film. Much effort has been invested in dose reduction and image quality improvement, however all this is futile if the radiograph viewing conditions are sub-optimal. Prior to this study there were no tests on viewing conditions were being performed at the radiology department at CMJAH. The trend for radiology departments to transit to digital radiography has been discussed in Chapter One, the importance of viewing conditions cannot be overemphasised in digital radiology. An

ongoing quality control program to ensure optimal viewing conditions in-line with international recommendations will be established as a result of this study.

Custom made quality control software: It is not enough to do quality control procedures without proper recording. The designed software makes it possible for soft copy recording and archiving and in addition it lends itself for trend analysis. The software in its present form captures all the tests required by the DRC and thus practical experience from its use will inform

The DRC states the quality control tests to be conducted in a radiology department without providing the test procedures, this approach works in a situation where there is adequate medical physics staffing. In the South African situation where there is a lack of medical physics staffing in radiology departments and quality control tests are done by non-medical physicists it is prudent to provide work instructions for the tests and this will be provided as an appendix to this thesis.

Fluoroscopy procedures and general radiography examinations dose audits: The first step to dose optimization is to undertake a dose audit, as such this study reviewed the doses received by patients who underwent some fluoroscopy procedures and radiography examinations. Fluoroscopy procedures are usually patient dose intensive, while the investigated general radiography examinations are frequent leading to a significant high collective effective dose thus the choice to analyse these two modalities. All fluoroscopy units in South Africa are by law required to have KAP meters installed, whose readings provide dosimetry metrics which have potential in dose optimization. Results of these dose audits will provide baseline values for comparison with international dose values. Furthermore these studies provide preliminary dose reference levels, of which the dose reference levels concept has been proven to be effective in bringing down patient doses in radiology. Radiological procedures and examinations which can benefit from further dose optimization will be identified from these studies.

Non-clinical image quality assessment: The dose optimization process is not a monotonic pursuit of reduction of patient doses, however it takes into consideration the image quality. An image quality assessment phantom was fabricated in-house phantom to assess non-clinical image quality. This phantom can be used to evaluate changes in image quality as parameters of the imaging chain are changed in a dose optimization process. Furthermore this phantom can be used to evaluate the consistency in the image quality derived from an X-ray machine over its lifespan.

Digital radiography practice and technique: If the full advantages of digital radiography are to be realised the end-users should understand and appreciate the modality's capabilities and functionalities. Traditional quality assurance practice need be modified when digital radiography is adopted. This study was in the form of a questionnaire which interrogated the radiographer's appreciation of the capabilities of digital radiography with particular bias to its dose optimization potential.

Forward directed backscatter from under-couch procedures: For procedures where the X-ray tube is under-couch, there is some forward backscatter radiation from the couch to the the patient. Currently the detector of choice in fluoroscopy units is the KAP however it has no capabilities of measuring this backscatter contribution to the patient's dose. From the literature review and the current industry standards there is a knowledge gap with regards to the inclusion of the forward directed backscatter in patient dosimetry. This study enables more accurate quantification of the forward directed radiation backscatter and thus provides for more meaningful determination of patient skin doses.

CHAPTER THREE

PHYSICS OF RADIOLOGY

3.1 Introduction

Anatomic imaging is governed by the physics of interaction between energy and matter. Diagnostic radiology comprises of a couple of imaging modalities. The commonly used modalities are X-ray radiography, computed tomography (CT), ultrasound (US), magnetic resonance imaging (MRI), nuclear medicine (NM) and positron-emission tomography (PET). Each modality has its advantages and disadvantages depending on the anatomy or physiology being subject to examination. Ultrasound is based on differential reflection and refraction of high frequency sound waves by matter of different densities. On the other hand MRI uses a combination of magnetic fields and radio waves in order to produce images. The obvious advantage of US and MRI is that they do not use ionizing radiation given the fact that ionizing radiation has the potential to induce carcinogenesis. Nuclear medicine and PET involve the administration of radioactive nuclide tracers whose distribution in the human body is detected by appropriate cameras, eventually giving an indication of the metabolism. Nuclear medicine is primarily used to investigate physiological function of organs. X-ray radiography and CT utilise ionizing radiation in the process of image production. Only X-ray radiography will be discussed in depth in this present study.

The radiographic process is largely made possible and effective owing to the fact that different types of anatomy (materials) present with different attenuation properties to the radiation beam. In practice, an X-ray machine directs ionizing radiation to a region of interest in the body, this radiation tends to pass through less dense tissue or organs in the body but is attenuated by denser structures. In analogue radiography radiation which has passed through a patient will strike a cassette containing a fluorescent phosphorous screen and subsequently expose the X-ray film. The areas on the film which were exposed to the light coming from the fluorescent phosphorous screen (created by the X-rays striking the screen) will be blackened after the development of the film and the unexposed areas will remain white. The degree of blackening on the developed film thus depends on the amount of exposure to radiation. In the text below various key concepts of the physics of radiology are dealt with superficially as these are dealt with at depth in standard radiology textbooks.

3.2 X-ray Production

X-rays are produced as a result of interactions between electrons of a specific kinetic energy and an appropriate target material. X-rays are produced inside a glass envelope called an X-ray tube. The X-ray tube houses among other components two electrodes namely, a cathode and an anode. The cathode is connected to the negative pole of a high frequency generator which generates or supplies a steady supply of direct current. The anode is connected to the positive pole of the generator. Below is a simplified schematic diagram of a typical X-ray tube[75].

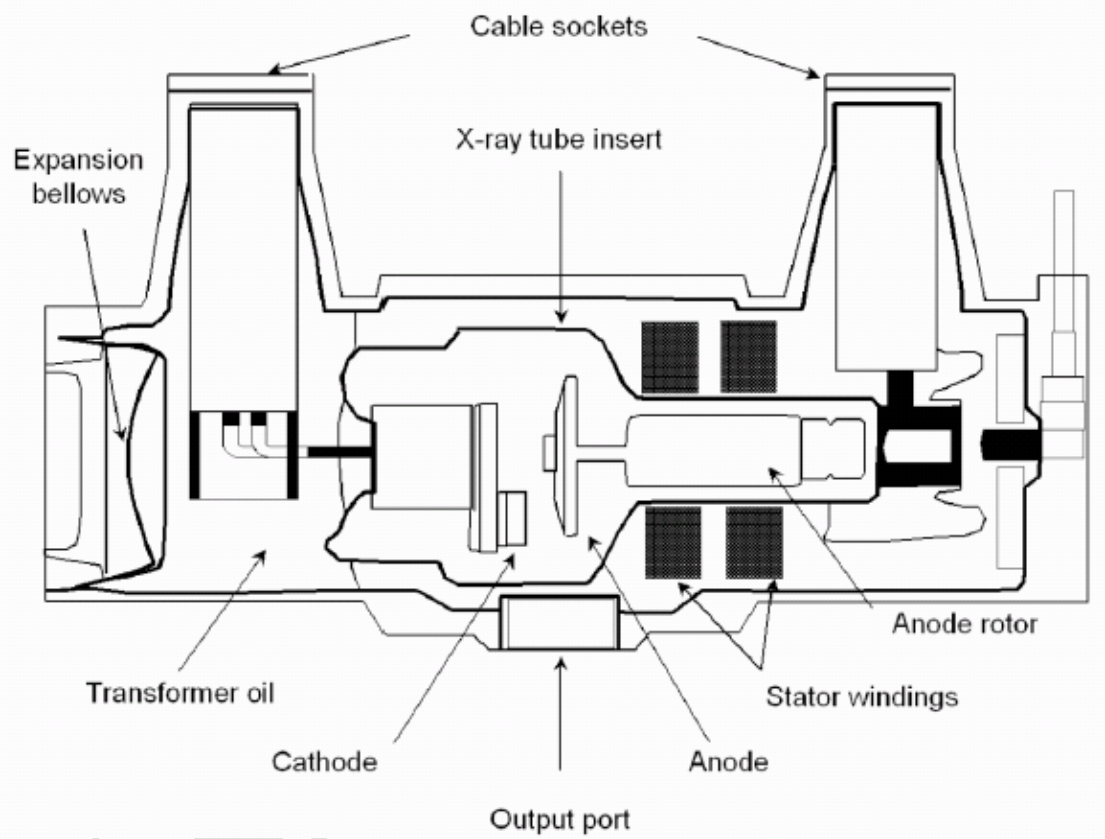


Figure 3.1: A schematic diagram of an X-ray tube [75].

The cathode consists of a coiled resistive wire commonly called a filament. Most filaments are made up of tungsten. As a result of the large current the cathode emits electrons as a result of thermionic emission. Due to a large potential difference between the cathode and anode the electrons are immediately accelerated to the anode. The kinetic energy of the electrons is converted to other forms of energy upon interacting with the anode. The X-ray production process is highly inefficient with 99% of the electron's energy being channelled to heat production and a meagre 1% for radiation production [76].

In most general radiography units, the anode is made up of tungsten or alloys of tungsten. Below are some of the desired properties of an anode material [77].

- High atomic number which in turn favours electron to photon conversion efficiency.
- A high melting point.
- A high heat conductivity
- A low vapour pressure.

As the electrons impinge on the target they undergo a couple of possible interactions of which two modes of interactions lead to the production of two types of radiation namely, bremstrahlung and characteristic radiation. Bremstrahlung radiation is a result of the electron interacting with the nuclear forces (intra-nuclear interaction) while the characteristic radiation is a result of the electron interacting with another electron(s) in orbit of the target material nucleus. The radiation from the target is then filtered and collimated before being directed to the patient. A suitable detector is used to capture the radiation which comes out of the patient. Ultimately a radiologist or any competent person in the field of radiology should analyse and interpret the images.

3.3 Image Formation

The X-ray beam emerging from the patient is incident on a radiation detector, normally a radiographic film. The emergent radiation will expose the radiographic film. The radiographic film is relatively insensitive to radiation but sensitive to light thus it is normally used in conjunction with an intensifying screen. In the case whereby an intensifying screen is used then both the film and two intensifying screens are housed in a cassette, with the film being sandwiched between two intensifying screens. A schematic diagram of an X-ray cassette is shown below.

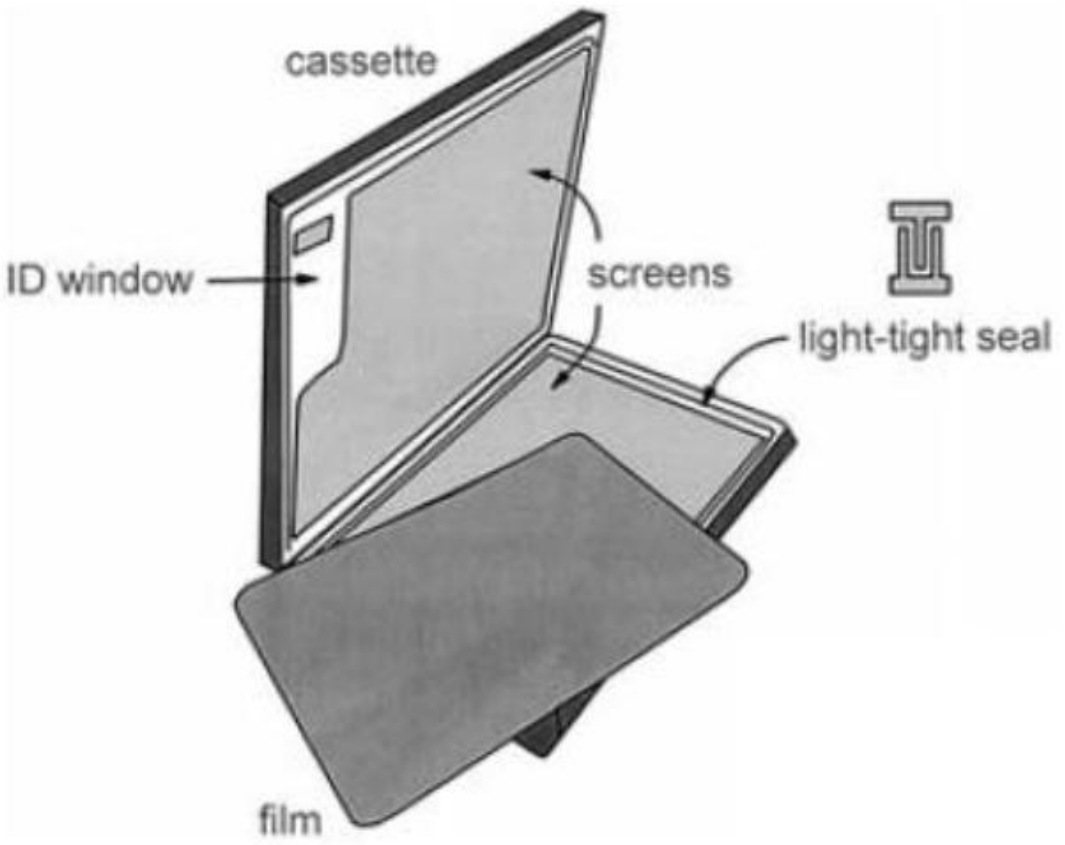


Figure 3.2: A schematic diagram of an X-ray cassette and film [78] .

The net result of radiation interacting with the intensifying screen is the emission of light photons which will in turn expose the X-ray film. Thomas Edison is credited with being the first one to use calcium tungstate as an intensifying screen [75]. However the first screen film image was by Mihajlo Idvorski Pupin [79]. The use of calcium tungstate as a phosphor in the intensifying screens demised in the 1970s with the introduction of rare earth phosphors[75]. Some examples of rare earth phosphors are gadolium oxysulfide, lanthanum oxybromide and yttrium tantalite. The principal attraction and advantage of a screen-film combination is that it uses less radiation compared to direct exposure to the film to yield the same film optical density. In addition screen film technology reduced exposure times, thus removing a lot of movement blur from images. However the introduction of intensifying screens degrades the near perfect spatial resolution of film.

The X-ray film consists of a transparent base which is made out of non-flammable polyester. The base acts as a supporting medium for other layers. The base should be strong, flexible, waterproof and stable dimensionally such that it is suitable for automatic processing.

Immediately after the base there is a subbing layer which acts as glue or a binder between the base and the emulsion. The emulsion is the light sensitive part of the film. The image formation process takes place in the emulsion. The emulsion consists of silver halide compounds suspended in gelatine. The emulsion is protected from mechanical damage by the outermost layer called the supercoat. The supercoat should be pervious to processing chemicals and also possess surface characteristics which make it appropriate for transportation by the rollers of the processor. The basic structure of a duplitised film is shown in Figure 3.3 below [80].

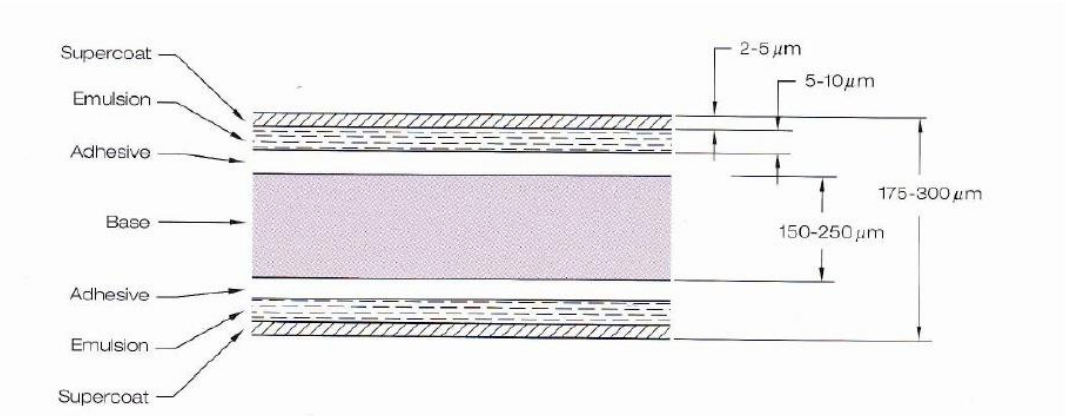


Figure 3.3: The basic structure of a duplitised film[80].

The emulsion has the silver and bromide ions in a cubic lattice. In a pure crystal the cubic lattice is electrically neutral. The presence of impurities will lead to creation of a spot on the surface of the crystal called a sensitivity speck, which has a tendency of attracting any free electrons in the crystal. X-ray exposure of the emulsion leads to the production of free electrons as a result of both photoelectric and Compton interactions. In addition in the case of using intensifying screens, the light photons will also further dislodge electrons from the bromide (halide) ion.

$$Br^- + h\nu \longrightarrow Br + e^- \qquad \textbf{3.1}$$

The bromine atom is absorbed by the subbing layer. The electrons produced will eventually be trapped by the sensitivity speck. Once an electron is trapped on the sensitivity speck it will then attract a positively charged silver ion. The interaction between an electron and the silver ion leads to the formation of a neutral silver atom. Repetition of this process will result in an area of the crystal with a number of neutral silver atoms and thus a latent image.

During the development process, crystals containing a latent image allow the rest of the silver ions present to be reduced to silver atoms. The silver atoms give a dark colour on the film. The film is then fixed using a weakly acidic solution. The crystals which did not contain a latent image are washed off at the fixation stage leaving a light area on the film.

3.4 Digital Radiography

Most radiology departments in South Africa are making a transition from screen-film technology to digital radiography. In the case of digital X-ray imaging the incident X-ray photons either undergoes intermediate conversion to secondary quanta before an electrical signal is generated and further processed to give an image or the electrical signal arises directly from the interaction of the X-ray photons with the detector. In broad terms digital radiography can be divided into two classes, namely, computed radiography which is photostimulable phosphor detector based and direct digital radiography which is flat panel imaging based. Digital radiography has its own advantages and disadvantages when compared to screen-film radiography, some of which are shown in Table 3.1 [81,82].

Table 3.1: Advantages and disadvantages of digital radiography over screen-film radiography [81, 82].

Advantages	Disadvantages
Increased dynamic range	Poorer spatial resolution.
Linear response of images	Artifacts due to the imaging plate, image processing algorithms etc
Availability of post-exposure processing functions	Poor techniques can be used as radiographers depend on post-exposure processing capabilities.
Easy to archive since images are in digital format	Increased sensitivity to scattered radiation.
Leads to a higher patient thorough-put	More expensive than screen-film radiography.
Separation of image capture, processing, storage and display processes which means they can be optimized individually	Lack of familiarity to radiologists and radiographers.

CR employs photostimulable phosphors as radiation receptors. The phosphors used are usually europium doped barium fluorohalides, for example, BaFBr and BaFI [83]. In computed radiography an imaging plate, which houses the photostimulable phosphor is placed in a light-tight enclosure, exposed to the X-ray image and then read out by raster scanning with a laser to release the photostimulated luminescence signal. The blue photostimulated luminescence signal is collected by a lightguide, which eventually feeds the signal to a photomultiplier tube (PMT). The PMT signal is then digitized to form the image on a point-by-point basis. CR has the advantage of having a workflow pattern which is very similar to

screen-film radiography. This similarity is very useful in the event of a transition from screen-film radiography to computed radiography. Figure 3.4 shows the workflow process in CR.

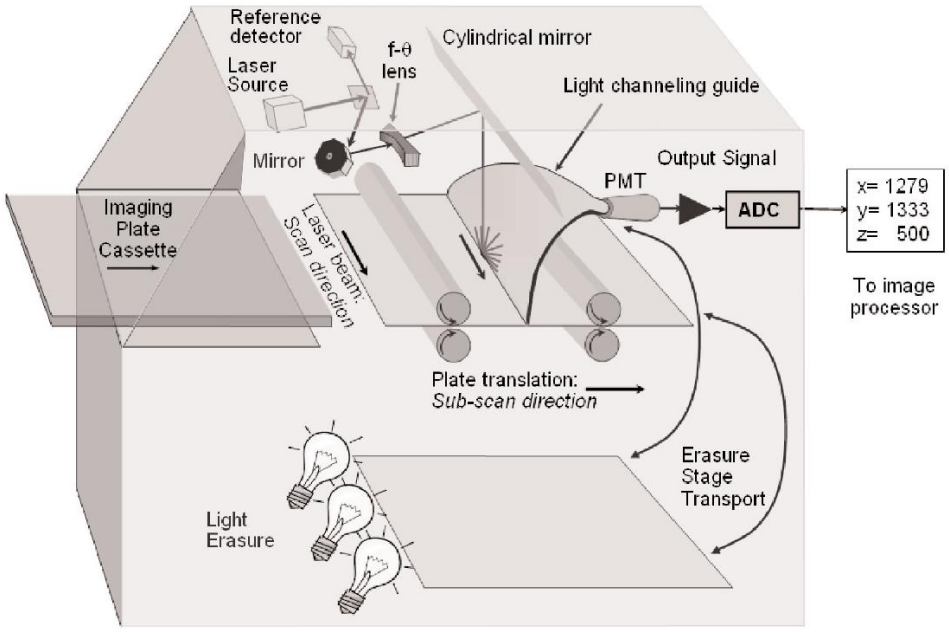


Figure 3.4: A representation of the CR imaging plate reading process workflow [84].

The comparatively time consuming read-out process in computed radiography is one of its major drawbacks.

Direct digital radiography on the other hand, does away with the read out process by providing for instantaneous display of images. In digital radiography the digitization of the X-ray projection image occurs within the image receptor. Detectors in digital radiography can be in the form of charged coupled devices (CCD) or flat panel imagers (FPI). Furthermore FPIs are generally of two types namely, direct detection or indirect detection flat panel imagers.

Indirect FPIs are only sensitive to visible light hence the necessity of using X-ray intensifying screens which will convert the X-rays into light energy which is readily detected by the FPI. Most indirect FPI systems use cesium iodide (CsI) or gadolinium oxysulphide (Gd_2O_2S) as the intensifying screen [71, 82, 85]. Each detector in the FPI is divided into two areas, a comparatively large area which is light sensitive and a small area housing the electronics. The light sensitive portion of the detector is a photoconductor, and electrons are released in the

photoconductor region on exposure to visible light. During exposure, charge is built up in each detector element and is held there by a capacitor. After exposure, the charge in each detector element is read out using the electronics system. Below is a schematic diagram of the indirect conversion system.

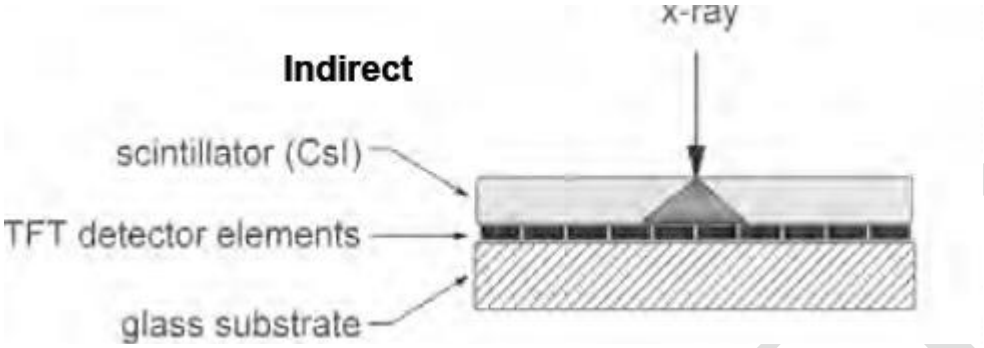


Figure 3.5: A layout of an indirect conversion digital radiography system [75].

Each detector element in an FPI has a transistor associated with it, and during exposure a negative voltage is applied to all gate lines, causing the transistor switches on the FPI to be turned off. As a result the charge accumulated during exposure remains stored in the capacitor of each detector element. During readout, positive voltage is sequentially applied to each gateline, the charge from each detector element is read out, digitized and stored forming a digital image.

In direct flat panel detectors are made from a layer of photoconductor material on top of a thin film transistor array. The photoconductor of choice is usually selenium. A negative voltage is applied to a thin metallic layer on the front surface of the detector and thus the detector elements are held positive in relation to the top electrode.

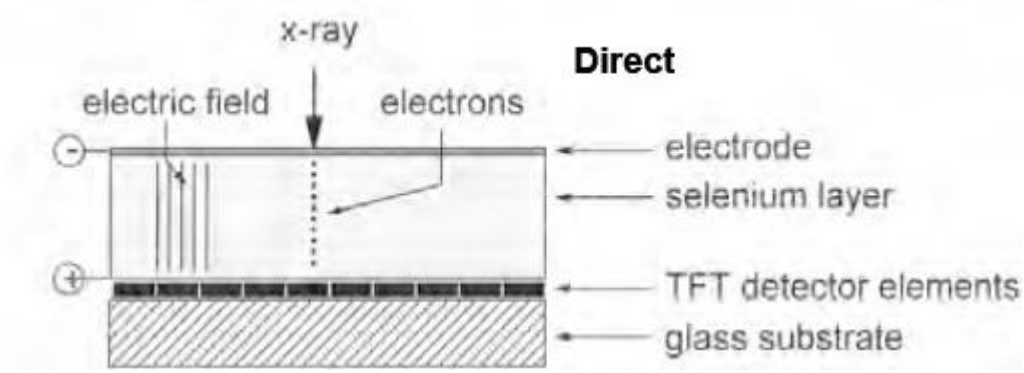


Figure 3.6: A layout of a direct conversion digital radiography system [75].

During X-ray exposure, X-ray interactions in the selenium layer liberate electrons that migrate through the selenium matrix under the influence of the applied electric field and are collected on the detector elements.

3.5 Fluoroscopy

Fluoroscopy provides real-time, X-ray projection imaging of dynamic processes as they occur. In general fluoroscopic procedures can be classified into two categories, namely, diagnostic imaging for visualization of patient anatomy and interventional procedures for therapeutic purposes. The essential main components of a fluoroscopic imaging system are shown in Figure 3.7.

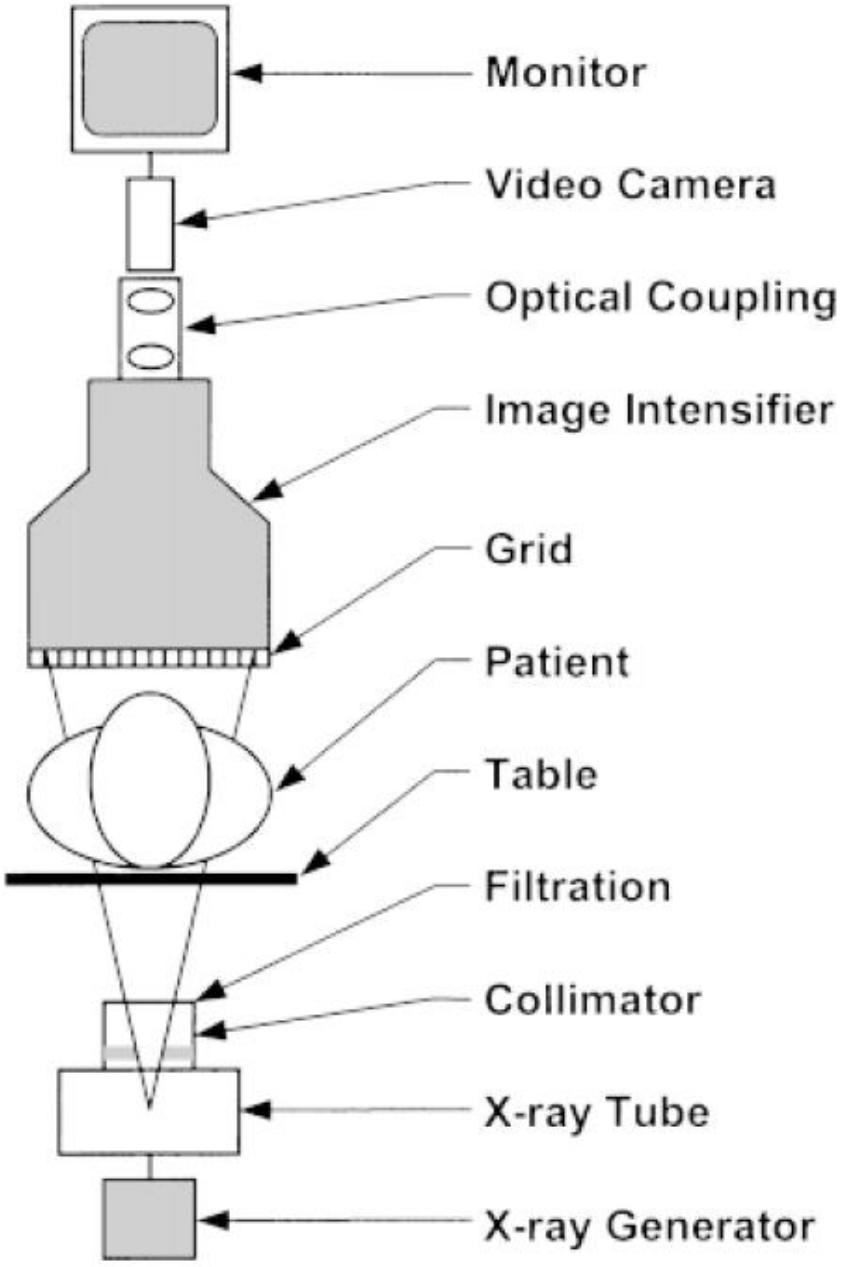


Figure 3.7: The components of the fluoroscopic imaging chain [86].

Fluoroscopic procedures are normally performed by using an image intensifier (II) to detect the x-ray pattern emerging from the patient after removal of scattered radiation by the anti-scatter grid. The II is coupled to closed-circuit television systems and it converts incident X-rays into a minified visible light image thus in the process significantly improving visibility of the image to the viewer. Within the II, the input phosphor, which is normally cesium iodide (CsI) converts the X-ray photons to light photons. The input phosphor in an II serves a purpose similar to the intensifying screen in screen-film radiography. Intimately attached to the input phosphor is the photocathode which converts the light photons to photoelectrons.

The electrons are accelerated under the influence of a large voltage in the range of 25 kV to 30 kV between the photocathode and the anode structure on the other side of the evacuated tube. Focussing electrodes are used to restrict the electron pathway and thus maintain the electron spatial distribution as they were released at the input phosphor. The electrons impact on the output phosphor made of zinc cadmium sulfide doped with silver (ZnCdS:Ag), and by virtue of the acceleration gain of the electrons and the geometric reduction of the electron distribution, the resultant light image is amplified [87]. The signal from the output phosphor is picked up by the camera system and finally displayed for viewing on a monitor.

The long fluoroscopy times particularly during interventional procedures may result in patient doses that cause deterministic effects of radiation in patients [10]. It is therefore necessary to optimize fluoroscopic guided procedures to keep the doses to both patients and medical staff as low as reasonably achievable consistent with the goal at hand.

CHAPTER FOUR

RADIOLOGICAL DOSIMETRIC QUANTITIES AND UNITS

4.1 Introduction

A number of organizations have put in place guidelines and recommendations with regards to the dosimetry and effects of ionising radiation. The ICRP is an international body responsible for informing and making recommendations on all aspects of protection against ionising radiation. On the other hand the International Commission on Radiation Units and Measurements (ICRU), develop and define dosimetric quantities and units. Also national bodies like the Health Protection Agency (HPA), National Council on Radiation Protection and Measurement (NCRP) and others have also made recommendations for radiation safety in their respective countries.

4.2 Dosimetry Quantities

Diagnostic radiology dosimetry quantities can be classified as either basic or application specific quantities[10]. Basic dosimetric quantities are fundamental quantities defined in ICRU Report 60 [88]. In the text below, dosimetry quantities relevant to radiological physics are discussed.

4.2.1 Basic Dosimetry Quantities

Basic dosimetry quantities are briefly discussed below.

4.2.1.1 Fluence (Φ)

Is the quotient dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da, thus:

$$\Phi = \frac{dN}{da} \qquad \textbf{4.1}$$

Fluence has the unit m^{-2}.

4.2.1.2 Energy Fluence (ψ)

Is the quotient dR by da, where dR is the radiant energy incident on a sphere of cross-sectional area da, thus:

$$\psi = \frac{dR}{da} \qquad \textbf{4.2}$$

Energy fluence has the unit J/m^2.

4.2.1.3 Kerma (K)

Kerma is defined as the quotient dE by dm, where dE is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in a mass dm of material[10].

$$X = \frac{dE}{dm} \qquad \textbf{4.3}$$

Kerma has the unit J/kg or Gray.

4.2.1.4 Mean Energy Imparted

The mean energy imparted, $\bar{\varepsilon}$, to a given volume of matter equals the radiant energy, R_{in}, of all the charged and uncharged ionizing particles which enter that volume minus the radiant energy, R_{out}, of all those charged and uncharged ionizing particles which leave the same volume, plus the sum, ΣQ, of all changes of the rest energy of nuclei and elementary particles which occur in the volume, thus:

$$\bar{\varepsilon} = R_{in} - R_{out} + \Sigma Q \qquad \textbf{4.4}$$

For the diagnostic radiology energy range, ΣQ is zero. Mean energy imparted has the unit J.

4.2.1.5 Absorbed dose (D)

Absorbed dose, D, is the quotient $d\bar{\varepsilon}$ by dm, where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm, thus:

$$D = \frac{d\bar{\varepsilon}}{dm} \qquad \textbf{4.5}$$

This quantity applies to all types of ionizing radiation and to any absorbing medium.

The Gray or J/kg is the unit used for absorbed dose. Whenever secondary electron equilibrium is established kerma is numerically equal to absorbed dose[10]. Since in the diagnostic range of energies the production of bremstrahlung with low atomic number materials is negligible, the dosimetric quantity of choice is kerma instead of absorbed dose.

4.2.2 Application Specific Dosimetry Quantities

Only application specific quantities relevant to general radiography and fluoroscopy will be discussed below. Air kerma instead of absorbed dose is used as the basis of all directly measured application specific quantities [89]. Figure 4.1 demonstrates the various application specific dosimetry quantities and their position with respect to the geometry of an imaging system.

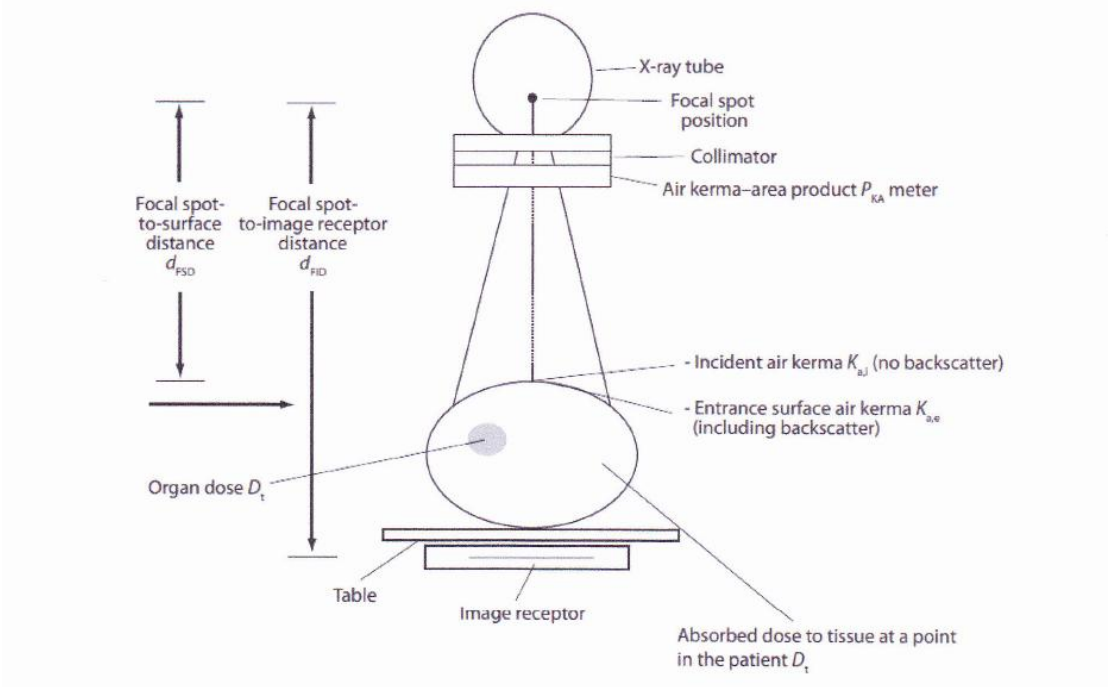


Figure 4.1: A diagram showing various patient related dosimetric quantities[14].

4.2.2.1 Incident air kerma (K_i)

The incident air kerma, K_i, is the kerma to air from an incident X-ray beam measured on the central beam axis at the position of the patient or phantom surface. This quantity does not include backscattered radiation. The unit for incident air kerma is the Gray.

4.2.2.2 Entrance surface air kerma (ESAK)

The entrance surface air kerma, ESAK, is the kerma to air measured on the central beam axis at the position of the patient or phantom surface. This quantity includes both radition incident on the patient or phantom and backscattered radiation. The unit forESAK is the Gray.

The ESAK is related to the incident air kerma through the backscatter factor, B:

$$ESAK = K_{i*} B \quad \textbf{4.6}$$

The imparted energy on the patient or effective dose to the patient can be derived from ESAK values[73].

4.2.2.3 X-ray tube output (Y(d))

The X-ray tube output is defined as the quotient of the air kerma at a specified distance, d, from the X-ray tube focus by the tube current-exposure time product, P_{It}, thus:

$$Y(d) = \frac{K(d)}{P_{It}} \quad \textbf{4.7}$$

The unit for X-ray tube output is J kg^{-1} C^{-1} or Gy A^{-1} s^{-1}.

4.2.2.4 Kerma Area Product

The kerma area product (KAP) is the integral of the air kerma over the field area (x by y) at a plane perpendicular to the beam axis. KAP is measured using a transmission type ionization chamber, namely KAP meter which is mounted on the collimator housing of the X-ray unit. In mathematical terms KAP is given by the relation[73]:

$$P_{KA} = \int_A K(x,y)_{c,air}\, dxdy \quad \textbf{4.8}$$

where A is the area of the beam in a reference plane perpendicular to the beam axis,
$K_{c, air}$ is the air collision kerma at the plane (x,y).

For field sizes where the heel effect can be neglected the air kerma is approximately constant over the field area (A) and can then be expressed as the product of the air kerma and area.

$$P_{KA} = K_{c,air} * A \quad \textbf{4.9}$$

Advantages of using this quantity are that it is easily measured, applies also to fluoroscopy measurements and it also takes into account the beam area. Effective doses can be derived from KAP values and it has been shown that KAP is more closely related to effective dose than ESAK[73]. For photon energies used in diagnostic radiology the air kerma is approximately equal to the absorbed dose, thus at times KAP is often erroneously called the dose-area product (DAP).

4.3 Kerma Area Product Meters

Basically KAP meters are large area, transmission ionization chambers with associated electronics. When in use the KAP meter is placed perpendicular to the beam central axis and in a location that completely intercept the entire beam area of the X-ray beam. An alternative to the transmission ionization chamber based KAP meter is the mathematical KAP meter which is based on a computer software program which utilizes information about the X-ray tube output to derive the KAP reading. The reading from a KAP meter can be changed by altering the X-ray technique factors (kVp, mA, time), varying the area of the field or both. The KAP reading for practical purposes can be considered as independent of the distance between the X-ray focus and patient.

KAP is a measure of the total energy imparted to the patient as ionizing radiation. The KAP reading can be converted to effective dose using appropriate conversion factors [90, 91]. KAP meters have the advantage of being universal, that is they can be used for any examination and patient. Compared to TLDs they can be used in fluoroscopy procedures which involve a variety of X-ray tube angulations and patient positions. The main drawback of KAP meters is that their readings do not include the backscatter component and thus do not indicate skin dose. Furthermore the interpretation of data from KAP meters is not without its challenges. KAP meters exhibit some energy dependence thus correction factors should be derived. The configuration of the KAP meter introduces some bias to the KAP value, for example, if there is some material or object in between the KAP meter and patient, the patient will receive less dose than what is implied by the displayed KAP value. This is particularly true with under couch KAP meter installations; different calibration coefficients should therefore be derived.

4.4 Patient Risk Related Quantities

The ultimate aim of dosimetry in radiology is to quantify the radiation risk posed on the patient as a result of the particular examination.

4.4.1 Dose Equivalent (H)

Dose equivalent is defined as the product D, the absorbed dose and Q the quality factor[92].

$$H = D^* Q \qquad \textbf{4.10}$$

where D is the absorbed dose.

Q is the quality factor which accounts for linear energy transfer (LET) dependence.

The quantity dose equivalent applies to a point in tissue. The SI unit for the dose equivalent is the sievert (Sv) and the rem is an alternative unit.

4.4.2 Equivalent Dose (H_T)

The average absorbed dose in the tissue or organ (T) due to radiation of type R, weighted by a radiation weighting factor w_R is defined as the equivalent dose (H_T)[10, 26, 92, 93].

$$H_T = w_{R*} D_{T,R} \quad \textbf{4.11}$$

where $D_{T,R}$ is the average absorbed dose in tissue T.

w_R is the radiation weighting factor for radiation R

The radiation weighting factor accounts for the differences in the relative biological effects of different types of radiation in producing stochastic effects at low doses. In the diagnostic radiology energy ranges the radiation weighting factor is assigned a value of unity. When the radiation consists of components with different w_R, the equivalent dose in tissue T is given by summing all contributing radiation types.

$$H_T = \sum_R w_R * D_{T,R} \quad \textbf{4.12}$$

The ICRP Report 103 of 2007 revised and updated the radiation weighting factors which were previously in the ICRP Report 60 [26, 92]. The differences in the radiation weighting factors from the two reports are shown in Table 4.1 [26, 92].

Table 4.1: Updated radiation weighting factors for different radiation qualities according to ICRP [26,92].

Radiation type	Radiation weighting factor w_R	
	ICRP 103	ICRP 60
Photons	1	1
Electrons and Muons	1	1
Protons and charged pions	1	5
Alpha particles, fission fragments and heavy ions	20	20
Neutrons	Continuous function of neutron energy	Step and continuous functions of neutron energy

For X-ray energies used in diagnostic radiology, the radiation weighting factor is taken to be unity.

4.4.3 Effective Dose (E)

The effective dose expresses the relative detriment associated with each irradiated tissue or organ and it is expressed as if the whole body were irradiated [10,26,92,93]. The tissue weighting factor (w_T) is obtained by expressing the detriment of each tissue-specific cancer or hereditary disease relative to the total aggregated detriment.

$$E = \sum_T w_T * H_T \qquad \textbf{4.13}$$

The effective dose concept allows for the summation of doses from different sources of radiation and subsequent comparison with dose limits that relate to whole body radiation exposure. Effective dose has the unit J/kg, however the most commonly used special name is the sievert (Sv). Effective dose provides an indication of the potential detriment of radiation and thus can be used to evaluate the appropriateness of an examination using ionizing radiation.

The tissue weighting factors have also changed with the publication of ICRP 103. The updated tissue weighting factors are shown in Table 4.2 [92].

Table 4.2: Updated tissue weighting factors for the different organs according to the ICRP [26, 92].

Organ / Tissue	Tissue weighting factor w_T	
	ICRP 103	ICRP 60
Gonads	0.08	0.20
Red bone marrow	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.04	0.05
Breast	0.12	0.05
Liver	0.04	0.05
Oesophagus	0.04	0.05
Thyroid	0.04	0.05
Skin	0.01	0.01
Bone surface	0.01	0.01
Remainder	0.12	0.05[12]

4.4.4 Collective Effective Dose

It is defined as the product of the effective dose and the number of individuals exposed. It gives an indication of the overall population radiation risk in terms of the number of radiation induced cancers or hereditary effects as a result of the exposure [92]. The unit for collective effective dose is the person-sievert or man-sievert.

4.5 Biological Effects of Ionizing Radiation

The fact that radiation will be attenuated as it traverses through tissue leads to the biological effects associated with radiation. The interaction between radiation and human cells triggers a chain of events, some of the possibilities being[94]:

- Cells receive no damage to critical sites and thus are unaffected.

[11] There are 14 organs / tissues in ICRP 103 compared to 12 in ICRP 60.

- Some cells will accumulate enough damage to be lethal and will die in their next attempt to divide.
- Some cells accumulate a degree of damage that is however not lethal, which if given enough time gets repaired.

It is a widely accepted tenet that ionizing radiation has the potential of inducing carcinogenesis in tissue. The probability of causing biologic damage in tissue by ionizing radiation is not only restricted to high doses but exists even at low dose levels. A great deal of information concerning biologic effects of radiation has been gathered from Japanese atomic bomb survivors, Chernobyl accident survivors, medical exposures and occupational exposures[6]. The data is extrapolated to lower doses, which brings some uncertainty but nonetheless gives an insight into the biological effects of ionizing radiation.

The biologic effects of ionizing radiation on humans can be broadly classified into two categories, namely deterministic – and stochastic effects. Deterministic effects are characterised by radiation effects which manifest themselves once a well defined radiation dose has been absorbed. Examples of deterministic effects of radiation are skin erythema, epilation, death as a result of acute exposure, cataract formation. In addition deterministic effects can be thought of as acting at a tissue level. Some of the deterministic effects on skin as a function of dose are given in Table 4.3 [95].

Table 4.3: Deterministic effects for skin as a function of dose and their onset time.

Deterministic Effect	Dose Threshold (Gy)	Onset time	Peak time
Early transient erythema	2		~ 24 hours
Temporary epilation	3	3 weeks	
Main erythema	6	10 weeks	~ 2 weeks
Permanent epilation	7	3 weeks	
Dry desquamation	10	4 weeks	~ 2 weeks
Invasive fibrosis	10		
Dermal atrophy	11	>14 weeks	
Telangiectisia	12	>52 weeks	
Moist desquamation	15	~4 weeks	~5 weeks
Late erythema	15	~6 – 10 weeks	
Dermal necrosis	18	>10 weeks	
Secondary ulceration	20	>6 weeks	

Radiation injuries or burns are not uncommon in interventional radiology. Koening *et al* has reviewed the types of radiation induced injuries after fluoroscopically guided procedures [96]. Figure 4.2 shows one example of a radiation injury on a 69 year male patient with a history of angina who had undergone two angioplasties of the left coronary artery within 30 hours. The patient later developed secondary ulceration over the left scapula. Figure 4.2 shows the radiation burn on the patient as a result of the procedures [96].

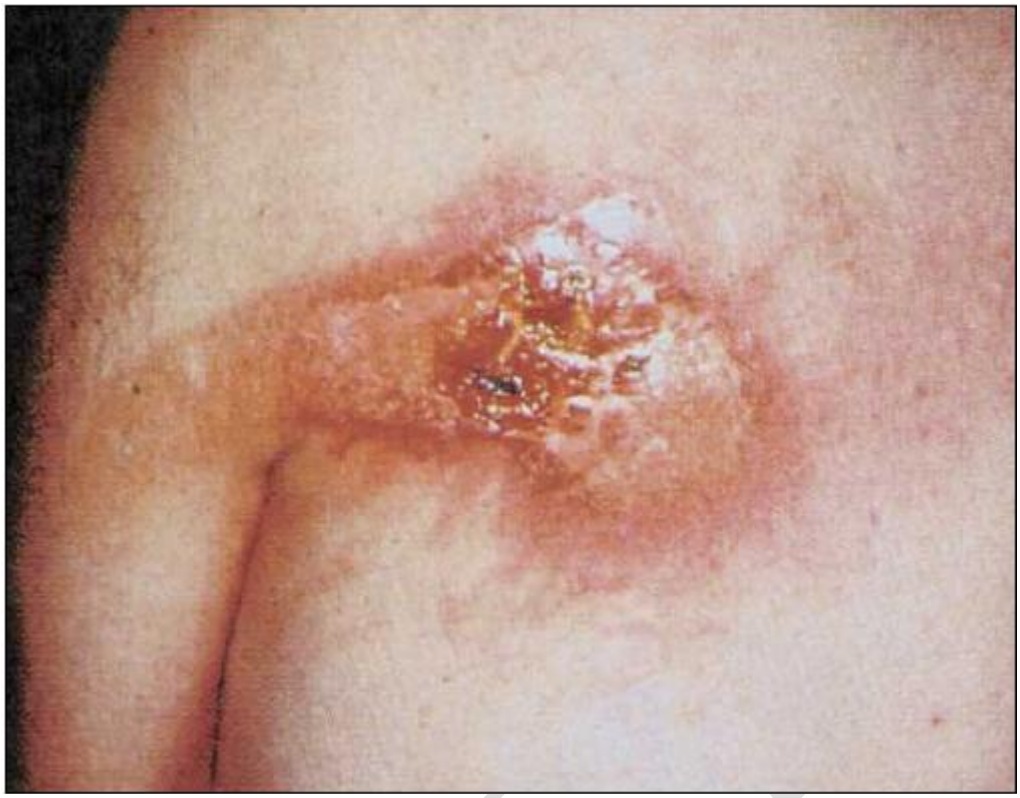


Figure 4.2: A picture from Koening TR et al showing a radiation injury on a patient after undergoing the two procedures [96].

Stochastic effects can be thought of as acting at a cellular level and they are basically governed by laws of probability or chance. Stochastic effects result in the modification of the genetic material of cells as opposed to killing of cells. The effects of ionizing radiation are often difficult to distinguish from other forms of trauma[94]. Generally the level of doses associated with general radiography is not high enough to cause deterministic effects, however the doses encountered in interventional radiology can cause deterministic effects.

4.6 Radiation Risk Assessment Models

Ionizing radiation has been associated with inducement of cancer in the exposed population, therefore it becomes imperative for the scientific community to be able to both qualify and quantify the radiation risk involved. Radiation risk estimates are based on the increased rates of cancer, not on death directly from the ionizing radiation [97]. Risk estimates are influenced by the radiation characteristics (dose, dose rate, fractionation, radiation quality), biological

characteristics (age, sex, genetic background, and nature of tissue or organ) and the approach to the analysis (dose response model, projection model and risk model).

Mathematicians and epidemiologists have developed radiation risk models of the relationship between radiation and the associated risk (causation of fatal cancer). The five radiation risk models which have been developed over the years will be discussed below. For comparison purposes the risk models are presented on a common set of axis in Figure 4.3 [98].

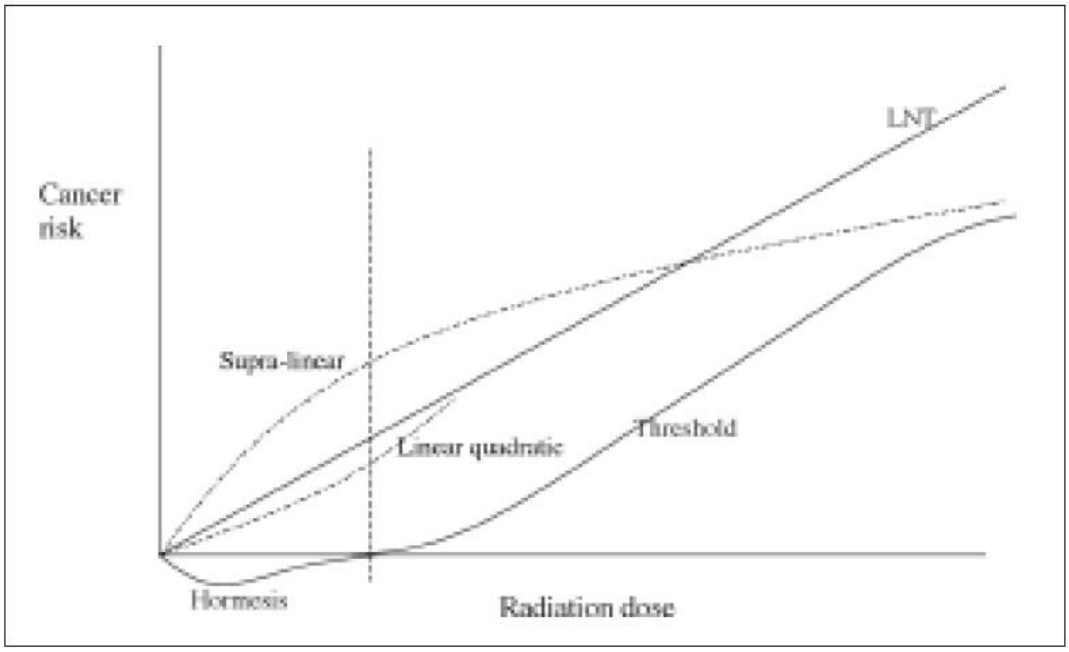


Figure 4.3: The relationship between the radiation dose and the associated risk as predicted by the different models: supra-linearity, linear no threshold, linear-quadratic, threshold and hormesis.

4.6.1 The Linear No Threshold (LNT) Risk Model

This model assumes that the radiation risk is directly proportional to the amount of radiation dose absorbed in tissue[99 -101]. The LNT model assumes that any exposure to radiation in excess of the usual background level poses an additional risk of cancer. In theory damage to DNA at a single point has a potential to induce cancer. Application of this model has not been without controversy, however the NCRP Report 136 states: " Although other dose-response relationships for the mutagenic and carcinogenic effects of low-level radiation can not be excluded, no alternate dose-response relationship appears to be more plausible than the linear non-threshold model on the basis of present scientific knowledge"[102]. This model has found

widespread application in radiation protection where the premise is "better play it safe" rather than underestimate the risk. In addition it has been used to assess the net benefit from collective X-ray examinations.

4.6.2 The Linear Quadratic Model

This model is a variant of the LNT model, proposing that any amount of radiation dose poses a risk of cancer. The linear quadratic dose-response model predicts a lower incidence of cancer than the linear model at low doses and a higher incidence at intermediate dose. The BEIR V committee recommends the linear quadratic model for prediction of leukaemia and bone cancer [75].

4.6.3 The Supra-Linear Model

This is another variant of the LNT model, it assumes that any dose of radiation possess a risk of inducing a cancer. One of the explanations of this dose-effect relationship has been the existence of a small subpopulation of individuals within the total population who are hypersensitive to radiation [100]. Compared to the LNT model the supra-linear model can lead to an overestimation or underestimation of the radiation risks depending on the level of radiation dose.

4.6.4 The Threshold Value Model

This model is based on the reasoning that below a certain level of radiation dose there is no risk of causation of fatal cancer. Researchers behind this model argue that the body has the capability and mechanisms to repair radiation damage to the tissues[103-105]. To further support their model they argue that the level of cancer prevalence is not significantly higher in areas where the background radiation is above average. The main weakness of this model is that it has failed to come up with a threshold radiation dose value below which radiation can be classified as posing no risk.

4.6.5 The Hormesis Model

This model is premised on the fact that *any* substance which is introduced into the body in large amounts (overdose) has harmful effects yet small amounts of the same substance are beneficial[106 -110]. The relationship between radiation dose and risk as proposed by the hormesis model is shown in Figure 4.2.

4.7 Dose measurement methods

Patient dose assessments are conducted in order to estimate the radiation risk associated with the X-ray examination, thus the reason for dose optimization is to minimize this risk. In patient dose assessment it is important to define the site at which the dose is to be estimated. The dose to the skin surface is a useful parameter because it is comparatively easy to measure and it is useful as a starting point for estimating dose to the underlying organs.

The radiation dose to patients who have undergone diagnostic radiology examinations can be determined by two general methods, namely, direct and in-direct measurement methods.

4.7.1 Direct Methods

Direct measurements involve the placement of a suitable dose measuring device (a dosemeter) on the patient's skin or close to the organ of interest prior to the examination. The dose measurement done during an examination at the site of interest is the easiest and often the most accurate method of determining patient dose. TLDs have been used for this purpose in a number of patient dose surveys[111 -117]. After irradiation and with appropriate calibration, this method yields the entrance surface air kerma at the point of application resulting from the examination. Strictly no X-ray parameters need to be recorded, although in practice beam quality and field size need to be known if internal doses are to be calculated from the initial TLD measurement. TLDs have the advantage of being small, enabling them to be stuck on a patient without causing image artefacts for general radiography examinations. The disadvantage of this technique includes the inevitable delay between exposure and readout of the dosemeter and the inability to perform retrospective dose estimates. Also the execution of a survey involving several thousand individual exposures brings about a considerable increase in workload. In addition the calibration process of TLDs is time consuming. Alternatively dose assessment can be done using phantoms, i.e. an artificial object simulating a patient.

Other forms of dosimeters have also been used for patient dosimetry. Film dosimetry has been used with success to quantify patient doses in interventional radiology[118,119]. In addition, metal-oxide semiconductor field effect transistors (MOSFETs) have also been used for patient dosimetry in interventional radiology [120,121]. Novel applications of scintillators have also been applied to measure patient doses in radiology with success[122, 123]. Diamond

detectors have also been used to measure patient doses successfully [124]. It should be appreciated that all forms of dosemeter need to be calibrated and their dosimetry characteristics like linearity, beam quality dependence and directional dependence need to be established.

4.7.2 Indirect Methods

These types of measurement involve prior measurement of X-ray exposure or exposure rate usually made in the un-attenuated beam for a range of radiographic parameters. These measurements together with the radiographic factors used in the particular examination and published X-ray interaction data, allow the calculation of the entrance surface air kerma, ESAK (Gy) and kerma area product, KAP (Gy cm^2) and subsequent calculation of the effective dose. For these indirect methods, no beam measurements are needed during the examination itself.

Dose assessment can also be done by computer simulations. One popular method is the Monte Carlo simulation. In radiation physics simulation of a virtual image of the exposure conditions is modelled to a computer program, which then creates virtual particle tracks followed from the source to their final absorption. Possible interactions with matter are induced with random numbers and known probabilities of each interaction type. Monte Carlo simulations provide a safe, reliable, inexpensive and flexible tool for complicated studies in medical radiation physics[125]. The Monte Carlo simulation can be verified by use of TLDs or measurements in phantoms. The disadvantage of Monte Carlo simulation is that it is time consuming.

4.8 Dose Optimization in Radiology

Optimization can be defined as the process of finding the best compromise among several often conflicting requirements [126]. In business optimization is associated with improvement of the efficiency of a production process. However in the radiology context, it is the process of determining what level of protection and safety makes exposures and the probability and magnitude of potential exposures, 'as low as reasonably achievable', economic and social factors being taken into account. Optimization will therefore involve input from the radiologist, radiographer and medical physicist. In radiology the aim of optimization is to achieve an adequate diagnosis through the attainment of sufficient image quality yet using the

least possible radiation. The optimization process in a radiology clinic involves the following steps, in order of execution:

- Initial preparation: establish an agreement of the optimization process in the radiology clinic.
- Dose and image quality assessment: performance of patient dose audit in conjunction with an assessment of clinical image quality.
- Review of current status of procedure: compare patient doses with appropriate benchmarks
- Intervention: recommend changes to the radiography protocol.
- Verification of the effect of optimization process: record results and make available to all stakeholders.
- Monitoring: Process to be continually monitored with a view of further adjustment and improvement.

Practical implementation of optimization is more often an iterative process with the aim of lowering the dose to image quality ratio.

CHAPTER FIVE

IMAGE QUALITY IN RADIOLOGY

5.1 Background

The quality of a medical image is determined by the imaging method, the characteristics of the equipment and the imaging variables selected by the operator. Thus the definition of quality for the resultant image in practical terms depends on the information sought from it. For example in some instances spatial resolution is a priority yet in another instants, contrast is the priority. Variations in image quality can also be caused by changes in X-ray output and film processing techniques. The change in X-ray output may be due to aging of the X-ray tube, variation in electricity supply or in the X-ray machine parameters (kVp, mA and timer calibration) or due to operator error. Improper image quality is a composite result of both equipment failure and human error. It has been shown that for optimally performing equipment, poor image quality is predominantly due to improper choice of technique factors leading to under- and over-exposure and positioning errors[127]. Poor image quality can also be due to old (expired) or a wrong concentration of the processing chemicals, the development time and the processing temperature. Acceptable X-ray image quality is maintained by using a comprehensive quality assurance program.

5.2 General Image Quality Metrics

The aim of imaging is to create an accurate, high quality imagery which faithfully represents the physical object. There should be both quantitative and qualitative methods to ascertain the faithfulness and representativeness of the image to the object. There are several quantities which can be used to assess image quality, broadly falling in two categories, either objective or subjective. Image quality can not be completely quantified by a single metric. In 1960 Linfoot suggested that the similarity of image and object be assessed by comparison of the spatial intensity of the actual image g(x,y) with the spatial intensity of the ideal image g'(x,y). To define similarity between the image and object Linfoot used three quantities, namely, image fidelity, relative structural content and correlation[128].

5.3 Primary Image Quality Metrics

Any meaningful judgement of image quality should be based on measurable quantities. The three primary image quality indicators are contrast, resolution and noise[129]. A variation in any one of these metrics should translate to a change in perception of image quality.

5.3.1 Contrast

This quantity shows how well two adjacent objects can be distinguished as separate entities. Contrast can be said to show the differences in the attenuation properties of objects. The diagram below illustrates the concept of contrast.

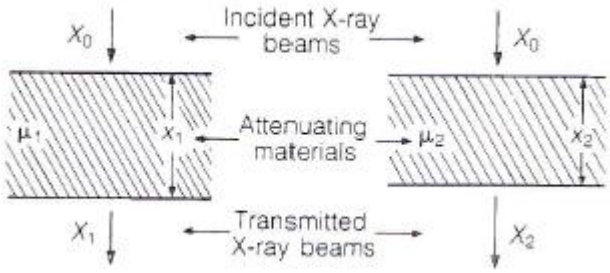


Figure 5.1: A schematic diagram illustrating the concept of contrast [77].

Any perception of contrast will be due to the difference in the transmitted intensities through the attenuating materials. The transmitted intensities X_1 and X_2 are related to contrast through the relationship[77]:

$$\text{Contrast} = \log_{10} \frac{X_2}{X_1} \qquad \textbf{5.1}$$

As beam energy increases, the Compton effect becomes predominant, leading to increased scattered radiation which will ultimately reduce the contrast. In simple terms contrast is a measure of the difference between densities on an exposed detector.

5.3.2 Resolution

This is the capability of an imaging system to distinguish between two adjacent structures as separate entities[75, 77]. The spatial resolution of an X-ray unit can be measured using bar patterns. It is measured in line pairs per millimetre. The higher the number of line pairs per millimetre the superior the resolution of the system. Resolution is affected by a number of factors which include the following, focal spot size, motion unsharpness.

5.3.3 Noise

Noise degrades image quality and limits the ability to visualize low contrast objects[130]. In screen-film technology noise can be thought of as the random fluctuation of film density about some mean value following uniform exposure. In digital technology it can be defined as the optical density variation in the pixel values across an image of a uniform object. The major source of noise is radiographic mottle, which has three components namely, screen mottle, film mottle and quantum mottle[131]. Screen mottle is caused by the non-uniformities in the screen construction, yet film mottle is caused by the graininess of the film. Quantum mottle is a result of the random nature of the interactions involved in the production and detection of X-ray photons. As a result of quantum mottle there is a random variation in the number of photons incident on a detector.

5.4 Overall System Performance

If dose optimization is to be successful in diagnostic radiology then image quality should be explicitly defined. Most of the time clinical image quality refers to a subjective judgement based on an impression of quality of clinical radiographic images in which case the assessment's usefulness is questionable[132]. However when image quality is judged by task based criteria the assessment is more relevant.

There are a number of ways of classifying and quantifying X-ray image quality which are useful in comparing imaging systems. The quality of an image should be assessed in relation to the imaging capability of the device that produces it. However, it should be appreciated that when an image is assessed subjectively, the use made of the diagnostic information is dependent on the observer, in particular his or her visual response system. Below is a discussion on various methods of assessing image system performance.

5.4.1 Signal-to-Noise Ratio (SNR)

Every imaging system aims to have a high object signal compared to the background signal and minimal noise in order to produce high quality images. The two mentioned properties of images are important, however, their ratio is the most significant indicator of image quality[133]. The SNR of a radiographic system describes the ability of the system to reproduce low-contrast objects. Signal-to-noise ratio is defined as

$$\text{SNR} = \frac{\overline{s_1 - s_2}}{\sigma(s_1 - s_2)} \quad \textbf{5.2}$$

$$= \frac{\overline{s_1 - s_2}}{(\sigma^2(s_1) + \sigma^2(s_2))^{1/2}} \quad \textbf{5.3}$$

where $\overline{s_1}$ and $\overline{s_2}$ represent the mean signal intensity in background and signal regions of the image respectively

$\sigma(s_1)$ and $\sigma(s_2)$ are the standard deviation in the mentioned regions respectively.

It has been shown that to have reliable detection by human observers, the SNR should at least have a value equal to five.[134].

5.4.2 Noise Equivalent Quanta

For an ideal imaging device, the measured SNR in the final image is proportional to the square root of the number of photons in the region of interest.

$$SNR_{meas} \propto \sqrt{N_{meas}} \quad \textbf{5.4}$$

However, in reality there are various sources of noise in the imaging device which are not related to the Poisson-distributed x-ray flux. As a result the real SNR is less than the ideal SNR.

$$SNR_{real} < SNR_{ideal} \quad \textbf{5.5}$$

If the noise from the real-world imaging device is fed back to the input stage one gets an indication of the effective number of incident photons had the device been an ideal imaging device. Thus a number of quanta N′ can be related to the measured real SNR.

$$N' = SNR_{real}^2 \quad \textbf{5.6}$$

N′ is the noise equivalent quanta (NEQ), it gives the effective number of quanta used by the imaging device based on the measured SNR[133]. Dividing the NEQ with the incident number of quanta gives an indication of the efficiency of the imaging device. The NEQ describes the image collection and storage stage of the imaging chain[135].

5.4.3 Detector Quantum Efficiency

The detector quantum efficiency (DQE) is a metric used to describe the performance of X-ray imaging systems expressed as a function of spatial frequency[136]. It is a measure of how the available signal-to-noise ratio is degraded by the imaging system.

DQE can be determined from the following relationship:

$$DQE = \frac{SNR_{out}^2}{SNR_{in}^2} \qquad \textbf{5.7}$$

This is simply the ratio of the output signal-to-noise ratio to the input signal-to-noise ratio of the imaging system. DQE is also related to the NEQ and incident quanta through the relation:

$$DQE = \frac{NEQ}{N} \qquad \textbf{5.8}$$

The quantity DQE is a rigorous, quantitative and transportable concept for objectively evaluating the performance of an X-ray detector. It should be noted that while DQE is usually defined for an image detector, it is not restricted to such. Since DQE does not include the observer/ radiologist it therefore lacks the possibility to describe the effects of the image processing and display stages of the imaging chain[136].

5.4.4 Modulation Transfer Function

Imaging systems are normally assessed by way of their resolving power. Unfortunately radiology imagers are complex devices and many factors contribute to their resolution capabilities. Some of the factors can not be readily expressed in terms of resolution and might not be related to one another. The concept modulation transfer function (MTF) is one way of combining these factors. At any stage in the imaging process, the available information can be represented in terms of a spectrum of frequencies. The most detailed specification of spatial resolution is provided by the modulation transfer function[137]. The idea of spatial frequency can be understood by considering two ways of describing an object consisting of a set of equally spaced parallel lines. Instead of saying the object consists of lines equally spaced 0.2 mm apart, one can say that the lines occur with a frequency in space (spatial frequency) of five per millimetre.

Fourier analysis provides a mathematical method for relating the description of an object or image in real space to its description in frequency space. For a true image of an object to be

produced the imaging system should be able to transmit every spatial frequency in the object with 100 % efficiency. The MTF of the imaging system is the product of the MTFs of the respective subcomponents.

Thus the MTF of the system at any spatial frequency, υ, is that the product of the MTFs of all the components at spatial frequency υ. The advantage of the MTF methodology is that it is conceptually easy to understand, besides it is much more difficult to work in real space. In addition, by examining the MTFs of each component it is possible to determine the weakest link in the imaging chain and also the MTF can be used to analyze the effect of varying singular imaging conditions on image quality. In general screen-film systems which require a low dose, show a decreased MTF and increased noise compared to systems requiring high dose.

5.4.5 Noise Power Spectrum

The noise power spectrum (NPS) can be thought of as the variance of the image intensity divided among the various frequency components of the image or as the variance of a given spatial frequency component in an ensemble of measurements of that spatial frequency. NPS is related to MTF and two dimensional DQE through the relationship[138].

$$DQE_{(u,v)} = \frac{d^2 MTF^2_{(u,v)}}{qNPS_{(u,v)}} \qquad \textbf{5.9}$$

where the average pixel value in an image, $MTF_{(u,v)}$ is the two-dimensional system modulation transfer function, q is the average density of X-ray quanta incident on the system while the image is being acquired, and NPS is the noise power spectrum which is a measure of the radiographic mottle.

5.5 Physical/ Physiological Assessment

It is useful to assess image quality in terms of both physical image quality parameters and observer's perceptual response. The MTF is very useful in assessing the physical performance of an imaging system, but its major shortfall is that interpretation of images using this quantity remains obscure. Thus it is of great relevance to involve the observer in analysis of image quality, because images are then judged on clinical merit. A simple method of assessment is to detect a detail of interest in the presence of noise. A major weakness of this type of assessment method is that visual thresholds at which objects can be (a) detected,

(b) recognized and (c) identified are not the same. This means that results can not be simply extrapolated from studies on test objects to clinical images[77].

5.5.1 Receiver Operator Characteristic Curves (ROC)

Expression of image quality by way of using exclusively physical properties of the imaging system suffers from two major disadvantages:

- The derivation of one all-embracing measure of image quality is extremely difficult, and
- Such attempts do not include the observer of the image in the imaging system chain.

It is widely accepted that ROC analysis is the most complete way of quantifying and reporting accuracy in two-group classification tasks. ICRU Report 54 states that the ROC methodology is the only method which allows for an imaging system performance evaluation without observer bias[139].

The concept of ROC analysis was introduced in medicine by Lusted who postulated that a radiologist could achieve different combinations of sensitivity and specificity by consciously changing the "threshold of abnormality" or "critical confidence level" which are used to differentiate between nominally positive images from nominally negative ones[132]. The ROC methodology acknowledges that accurate image interpretation by an observer does not only depend on the physical imaging system or the pathology but also on the perceptual characteristics of the observer and the "critical confidence level" the observer assumes in distinguishing between nominally positive images and nominally negative images.

For a ROC study a set of images are obtained using different imaging systems or techniques, to be tested. In ROC studies the correct status of the image must be known. Phantoms using simulated lesions or abnormalities can be used, but it is also possible to use actual clinical images. In most cases the problem in diagnostic imaging can be simplified to the detection or non-detection of an abnormality in the image. Thus in the simplest approach, each image contains either one or no abnormality. The former are called "positive" images and the latter are called "negative" images. The images are given to an observer who is asked to indicate whether an abnormality/ lesion is present or absent in each image, as well as where it is and his or her confidence that it actually is present. There are usually four confidence levels:

- 1 = certainly present
- 2 = probably present
- 3 = probably not present
- 4 = certainly not present.

For each confidence level the following parameters are calculated:

- True positive fraction (TPF) which is the fraction of positive images correctly identified as positive by the observer.
- False positive fraction (FPF) which is the fraction of negative images incorrectly identified as positive by the observer.

The TPF is sometimes called the sensitivity and (1 – FPF) the specificity of the test or observer. An additional two parameters can also be calculated: true negative fraction, TNF = (1 – FPF) and the false negative fraction, FNF = (1 – TPF). The ROC curve is the obtained by plotting the true and false positive rates[140]. Figure 5.2 shows an example of a ROC plot.

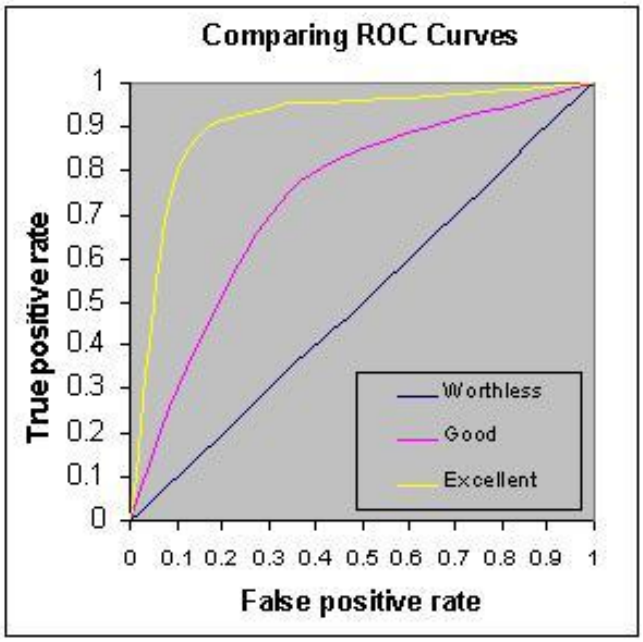


Figure 5.2: An example of a ROC curve [141].

The ROC curve should lie above the ascending 45° diagonal which would represent "guessing", i.e. equal probability of true and false positive detection. The further the curve lies above the 45° line and the greater the area under the curve the better the performance of

the imaging system and/ or observer[132]. The red and yellow curves are typical ROC curves. As the test accuracy improves, the curve moves towards the top left-hand corner of the plot, which means in Figure 4.0 the yellow line represents superior test accuracy. The area under the curve indicates the accuracy of the imaging technique, with an area of 1.0 representing a perfect diagnostic test, having 100% sensitivity and specificity.

ROC methodology is widely accepted as the gold standard of image quality assessment. However the use of the ROC methodology is limited in use for routine quality control and assurance because it takes time calculating, drawing and analysing. There are variants of the ROC methodology which aim at increasing the statistical power of the evaluation in comparison to pure ROC methodology. A detailed review of the different variants of the ROC method is given elsewhere[142]. For example, in the free response forced error (FFE) experiment described by Chakraborty and Winter which is a variant of the ROC method, the observer's task is to correctly localise multiple lesions in an image and to rank them in order of confidence[143]. In this method lesions are marked in ascending numerical order according their apparentness in the image until an error is committed, i.e. a false positive image has been created. The FFE score, A_1 is calculated using the relation:

$$A_1 = \frac{\sum_{i=1}^{I}\sum_{o=1}^{O} TPF_{o,i}}{I * O} \qquad \textbf{5.10}$$

where $TPF_{o,i}$ the quotient between the number of correct findings (m) before observer o makes an error and the total number of lesions (n) in image i.

I is number of images

O is number of observers

5.5.2 Contrast Detail Tests

ROC analysis is relatively time consuming and alternatively psychophysical techniques are desirable. One such alternative technique that has been used for assessing observer performance of a system is contrast detail analysis. Contrast detail tests can be performed for a particular imaging device at a given dose and subsequently compared to another imaging system at the same dose or the same technique can be applied over a range of doe exposures. There is a variety of contrast-detail phantom designs on the market however all these

phantom designs have in them objects of varying diameter and varying levels of subject contrast. The subject varying contrast in these phantoms is normally achieved in two ways either by utilising holes of different depth or having circular objects made up of objects of different attenuating properties.

Low contrast detectability can be measured using phantoms or viewing the clinical images by the eye. There are a couple of low contrast detail phantoms available on the market. One of the popular test objects on the market are the Leeds test objects which is marketed by Leeds Test Objects Limited, Boroughbridge, United Kingdom. The original design concept was done by Hay et al[144]. Leeds Test Objects Ltd offers a range of test objects: TOR CDR, TO 10, TO 12, TO 16, TO 20 and TOR 18FG[145]. The test objects are imaging modality specific, being used for either radiography or fluoroscopy units. Figure 5.3 is a photograph of the commercial Leeds test object TOR 18 FG for use in fluoroscopy examinations.

Figure 5.3: A photograph of the Leeds Test object.

This particular test object consists of eighteen circular discs of 8 mm diameter. For the purposes of image quality assessment the observer under a predetermined set of imaging conditions will determine how many discs are visible in the image and this is compared with tabulated data, which relates the number of objects seen to threshold contrast for the particular X-ray beam quality. The apparent advantage of this kind of test is that it is easy and quick to perform. It can be applied to track changes in system performance and also rank X-ray units according to their contrast and noise characteristics. Since this is a subjective test its greatest weakness is that it depends on the observer and there is bound to be a wide variation in assessment from one observer to another. In addition over time observers become familiar with the expected image making the test lose its objectivity.

5.5.3 Forced Choice Experiments

The motivation behind this class of tests is to eliminate observer bias in assessment. For each detail size and contrast the observer is presented with an example of a detail and then asked to identify the location of a similar detail in a given fixed number of possible locations.

The CDRAD phantom is one popular phantom for performing forced choice experiments. The CDRAD phantom is manufactured by Artinis Medical Systems B.V., Andelst in the Netherlands[146]. This phantom consists of a 10 mm thick block of perspex measuring 265 mm X 265 mm. It is composed of 15 rows and 15 columns , with only the top three rows having one hole drilled, while the other remaining rows have two holes, one drilled in the centre and the other in a randomly chosen corner. The phantom is designed in such a manner that within a row the hole diameter is constant, with exponentially increasing hole depth and within a column the hole-depth is constant while the diameter decreases exponentially. One of the variants of the pattern of the CDRAD phantom is as shown below[146].

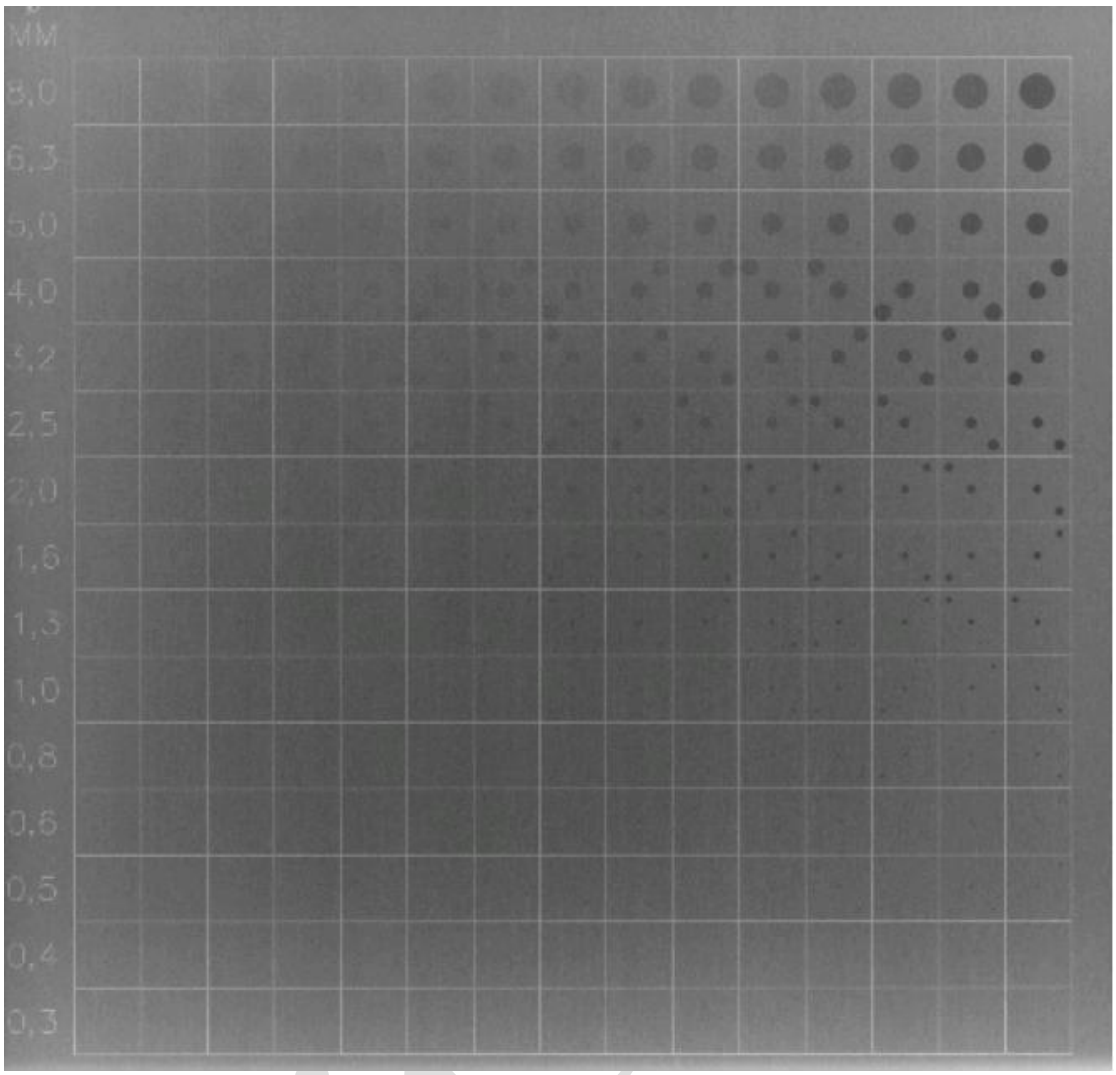


Figure 5.4: A radiographic image of a CDRAD phantom[146].

There are four patterns available for the phantom to avoid observers memorizing location of holes as they gain experience with usage of the phantom. However, the arrangement of the test details is irregular thus the observer can not intuitively predict the location of a detail. The assessment then involves the observer identifying the location of the detail, upon which the image quality factor will be calculated based on the correct responses.

$$\text{Correct observation ratio} = \frac{Correct\ observations}{Total\ number\ of\ squares} \qquad \textbf{5.11}$$

Alternatively the image quality factor (IQF) methodology can be used:

$$IQF = \sum_{i=1}^{15} C_i * D_{i,th} \qquad \textbf{5.12}$$

where i denotes the contrast column

C_i denotes the contrast

$D_{i,th}$ denotes the threshold diameter in contrast column i

A plot of the smallest visible diameter and contrast is called the contrast- detail (CD) curve. The CDRAD phantom can be used across all the X-ray imaging devices in diagnostic radiology. Furthermore the CDRAD phantom can be used to compare imaging systems and observers.

In addition to commercially available phantoms there is also the TRG- Phantom on the market courtesy of ALVIM Research and Development Ltd of Israel[147]. Most image quality phantoms have test objects arranged in a permanently fixed configuration that can possibly be retained in the observers' memory and thus lead to a false evaluation. TRG is a statistical contrast-detail phantom consisting of a polyvinylchloride body with two groups of six columns. Each column consists of 10 discs, 5 of which have holes drilled into them. Pathology simulating test objects are eccentrically located in the tissue equivalent disks, which can be displaced within sockets numbered by X-ray opaque material. Below is a picture of the TRG phantom.

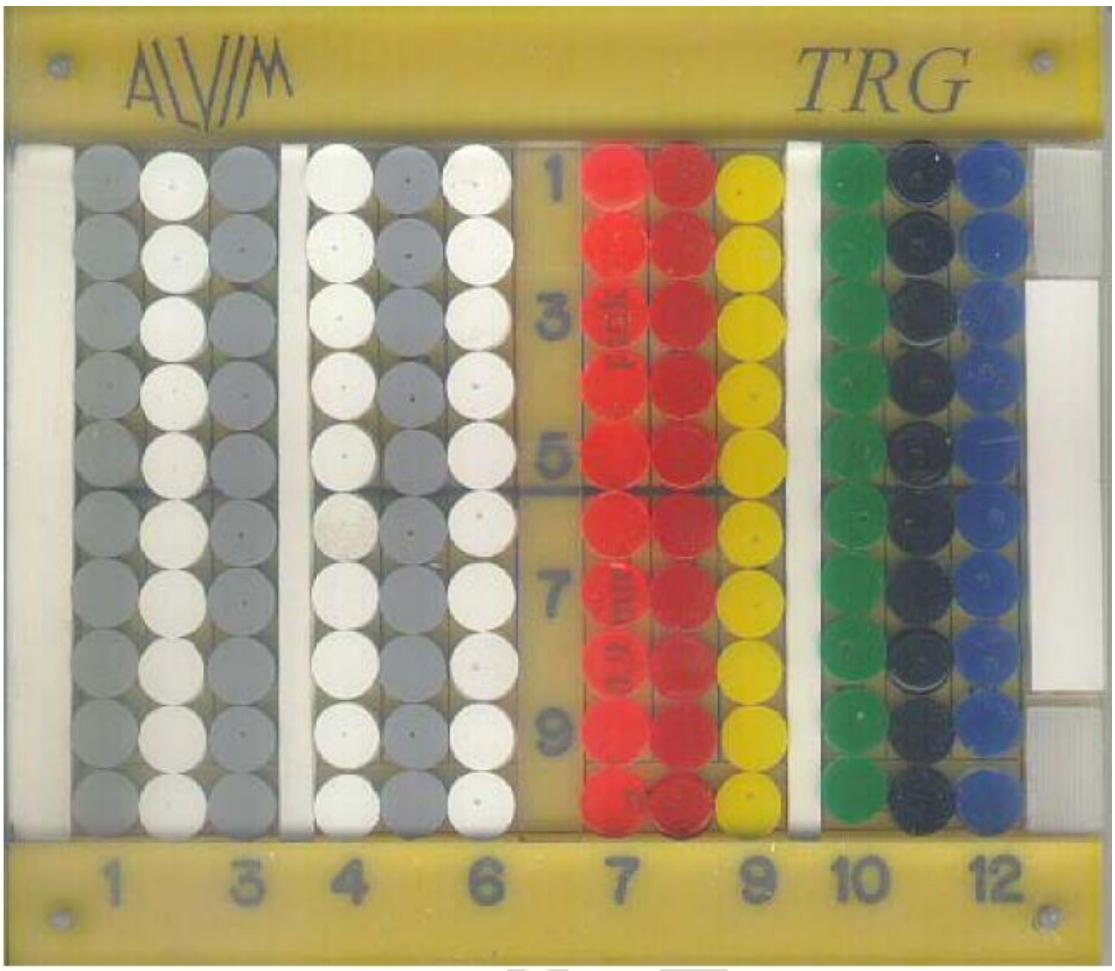


Figure 5.5: A picture of the TRG phantom[147].

Each test element can be displaced independently from the others. Columns 1 -6 includes polyvinylchloride plates to simulate high contrast while columns 7 -12 has PMMA plates for low contrast. Half of the plates have a small hole drilled somewhere in the middle and these holes vary in depth and in diameter. The size of the hole varies from 0.5 mm to 1.0 mm in the polyvinylchloride plates and from 0.9 mm to 2.0 mm in the PMMA plates. The depth of each hole is the same as its diameter. A distinct advantage of this phantom is that it has a provision to move the test objects from one position (location) to another, and the observer cannot know or predict their locations during the experiment.

5.5.4 Visual Grading Analysis

Visual grading analysis (VGA) has established itself as a strong, reliable alternative to the ROC methodology[148]. A number of reasons have been put forward to support the establishment of VGA as a consistent alternative to ROC methodology. Firstly in VGA the

quality criteria are based on clinically relevant structures. In addition, VGA has shown to generally agree with the ROC method, which is considered as the gold standard of image quality assessment. In comparison with the ROC method, VGA has proved to be easy to conduct and is less time consuming. In the VGA approach to image assessment the image or a feature of the image is given a relative score, which reflects how well that image or feature can be visualised. Any set of clinical images can be used in a VGA study. An in-depth description of the VGA methodology is given elsewhere[149]. VGA can either be conducted in an absolute or relative manner. The two methods are briefly discussed below.

The relative approach involves a comparison between the clinical test images and a reference image. Subsequently the observer gives a score or rates the clinical images with respect to the reference image. An image quality criteria for chosen anatomy/ structures is used in such studies, the European Quality Criteria is one such criteria that has been widely used. Typically four to five grading scales are used, for example,

- Much poorer than the reference image
- Slightly poorer than the reference image
- Equivalent to reference image
- Slightly better than the reference image
- Much better than the reference image

The absolute method grades images according to visibility of particular anatomy/ structures in the image. The point scale is based on the following:

- Excellent
- Good
- Moderate
- Poor
- Very poor

To proceed with any meaningful analysis of VGA studies the scale steps used have to be converted into numerical values. One example of such a scale that can be used in a clinical situation is as shown in Table 5.1 below.

Table 5.1: A typical VGA relative rating scale.

Relative Rating	Meaning
	The structure in the image is
-2	Clearly inferior to
-1	Slightly inferior to
0	Equal to
+2	Slightly better to
+1	Clearly better to
	Structures in the reference image

Results of the VGA study are then used to calculate the visual grading analysis score, which is defined as the mean of all the ratings when the numerical representations of the scale steps are used. The normalised visual grading analysis score (VGAS) can be calculated from

$$VGAS = \frac{\sum_{i=1}^{I}\sum_{s=1}^{S}\sum_{o=1}^{O} G_{i,s,o}}{I * S * O} \qquad \textbf{5.13}$$

where G is the relative ratings of the images are summed over a number of observers (o), images (i), and structures (s).

I is the total number of images per technique

S is the total number of structures

O is the total number of observers

The VGA results are dependent on the reference image. VGA is very much a subjective test thus it can be improved by having multiple observers and averaging their scores.

5.5.5 Image Criteria Score

An alternative to VGAS is image criteria score (ICS). This image assessment tool is based on visualization of defined anatomic structures. The concept of image quality criteria was introduced by the Radiation Protection Programme of the Commission of the European Communities. After extensive clinical trials in Europe, image quality criteria were established for a number of radiological examinations[150 -152]. A criteria based on visualization of particular anatomy is established, and an image taken under particular radiographic conditions is assessed on fulfilment of the criterion using either a “YES” or “NO”. For a number of images taken using the same radiographic technique, the fraction of fulfilled criteria, ICS, is calculated as below:

$$ICS = \frac{\sum_{i=1}^{I}\sum_{s=1}^{C}\sum_{o=1}^{O} F_{i,c,o}}{I * C * O} \qquad \textbf{5.14}$$

where F is fulfilment of criterion c for image i, by observer o.

I is the total number of images

C is the total number of criteria

O is the total number of observers

Each anatomical examination has its own image criteria depending on the pathology of interest.

5.6 Weaknesses of Observer Based Studies

The greatest weakness of observer based studies is both intra-observer and inter-observer variation in reporting the same images. The decision taken by an observer is influenced by his or her experience, perceptions, expectations and preferences. The lack of consistency in interpretation of images has been shown in studies whereby observers were asked to re-evaluate images after a certain interval of time and their interpretations were shown to vary from the initial by up to 20% [153].

To reduce observer variability the following can be implemented in observer studies: use of multiple observers, averaging observer scores, observers should be familiar with images to be studied and a reasonable period of time should be allowed to elapse before the next reading session so as to reduce memory bias from the observers.

5.7 Image Artifacts

An artifact is an optical density on film or image that is not due to the anatomy being radiographed. Artifacts can be due to the acquisition device, patient related factors and processing devices. In general an artefact is an acknowledged image imperfection that does not hamper clinical image interpretation. The presence of numerous artifacts can lead to reduced observer confidence[153]. In screen film radiography artifacts can be as a result of the following[154, 155]:

- Poor screen-film contact
- Improper use/positioning of a grid

- Blurred images due to patient motion
- Poor patient preparation
- Artifacts due to inappropriate patient clothing during exposure, e.g. jewellery, glasses, belts, etc
- Chemical fog artifacts due to improper or inadequate chemistry, resulting in a dull gray haze on film.
- Processor rollers can be a cause of artifacts on images. Scratches on film can be as a result of rollers not turning smoothly or be due to chemical buildup on the crossover guide. Dirty rollers can make deposits on the film.
- Film fogging can be a result of use of an incorrect safelight, film cassette or darkroom not being light-tight. Fogging can also occur from the close proximity of the safelight.
- The static artifact is caused by buildup of electrons in the emulsion, usually as a result of an electric discharge from the finger to the film. Other possible causes could be that the darkroom humidity is too low, processor feed tray not electrical grounded or screens were not cleaned with an antistatic screen cleaner.

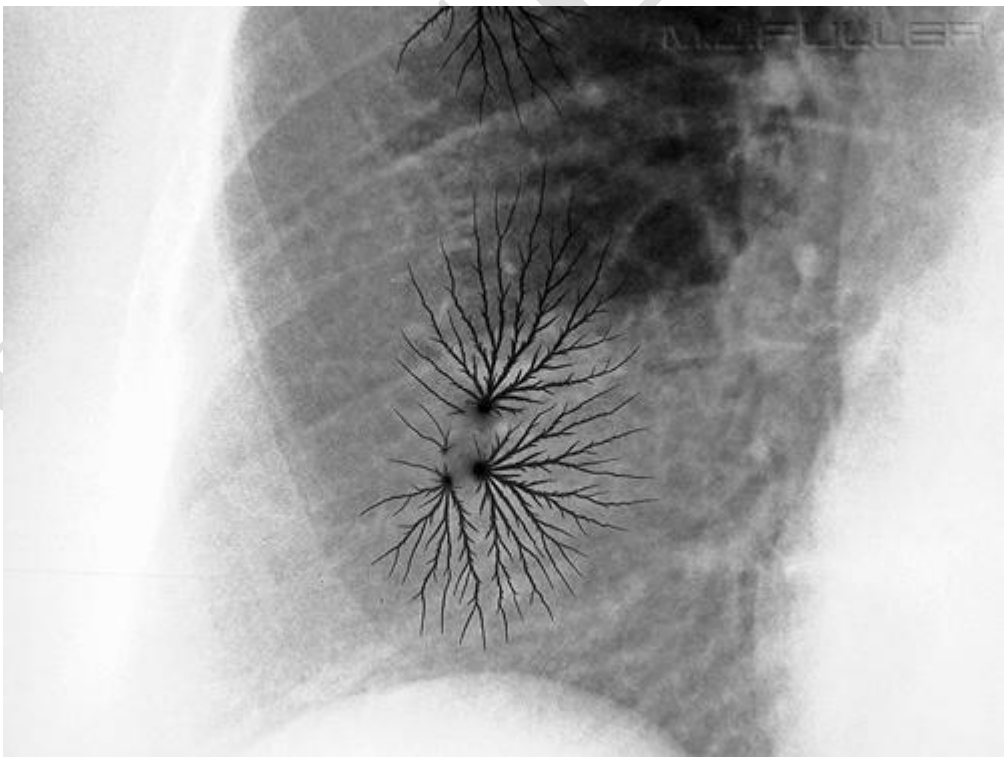


Figure 5.6: A radiograph exhibiting the static artifact [155].

Remedies to static are grounding one's hand on a metal object before handling the film, installation of a humidifier or use of an antistatic cleaner at the recommended frequency.

- Smudge manifests as a yellowish stain on a finished radiograph. This can be due to inadequate film washing or remaining thiosulfate from the fixer solution.

For digital units utilizing an image intensifier, image artifacts can be experienced from pincushion distortion, magnetic field distortion and vignetting[133]. For laser scanning based systems one of the most common artifacts is banding or shading perpendicular to the direction of the laser scan[133]. Banding or shading can be as a result of dust accumulating in the scanning optical mirror[133]. Scratches on the CR imaging plate can cause image artifacts as shown below[155].

Figure 5.7: A radiograph showing scratch artifacts on a CR image [155].

The remedy to scratch artifacts is to replace the photostimulable phosphor plate. In addition caution should be taken when cleaning imaging plates as improper cleaning can lead to image artifacts. Only manufacturer recommended cleaning agents should be used for cleaning CR plates.

Grids are equally relevant to digital radiography as they are to screen film radiography, however, the grid should be used with the correct orientation. An example of an artefact due to incorrect grid orientation is shown below[155].

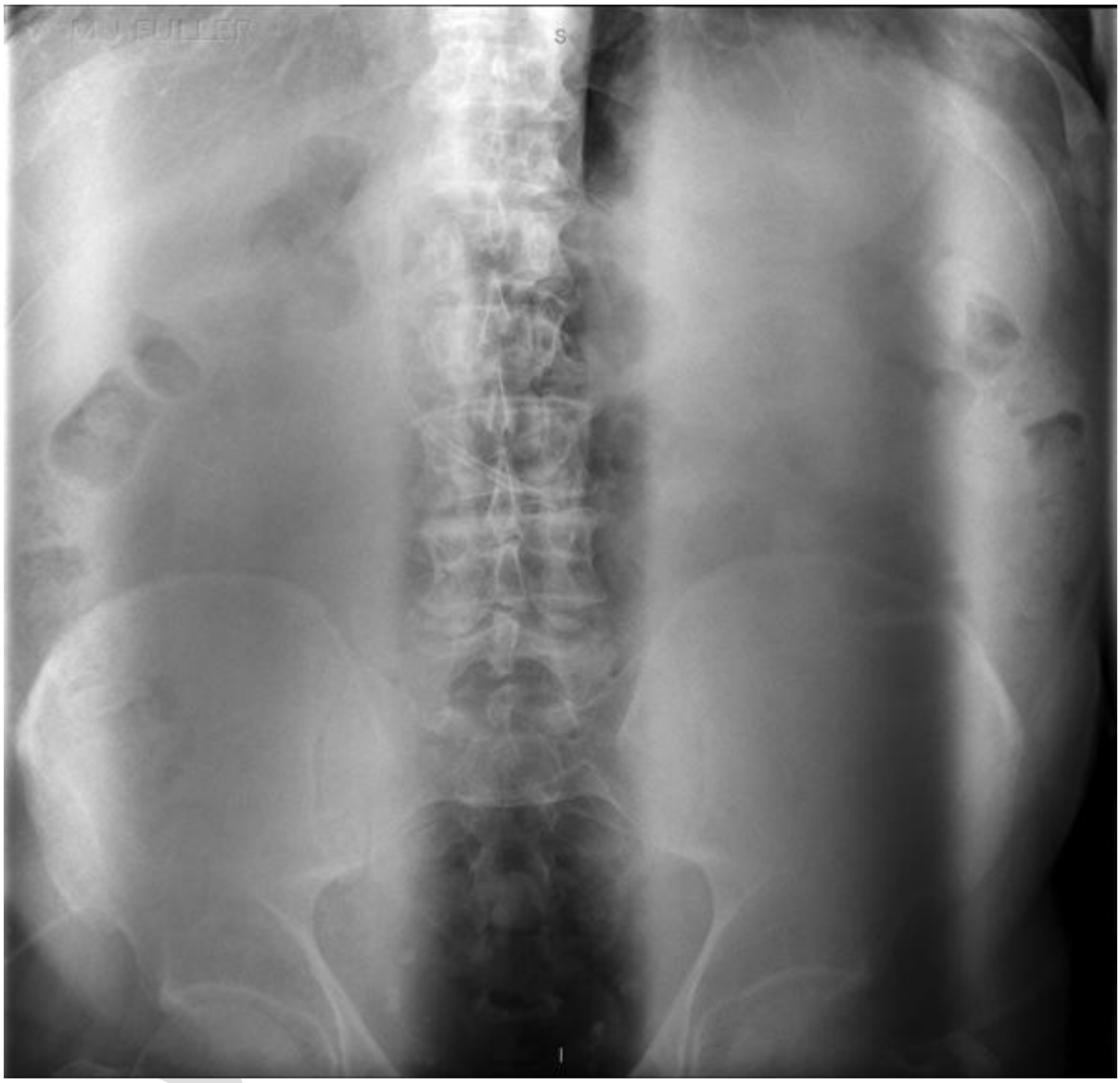


Figure 5.8: A radiograph showing artifacts due to incorrect orientation of grid [155].

A robust quality control program would easily pick up artifacts before they influence the accuracy of diagnosis in the clinic.

CHAPTER SIX

METHODS AND MATERIALS

6.1 Quality Control of Radiography Viewing Conditions

This study was conducted at the Divisions of Radiology and Radiation Oncology of CMJAH. All the conventional viewing boxes and radiograph viewing areas/ reporting rooms in these two divisions were subject to assessment. A calibrated Nuclear Associates Precision Photometer, Model 07-621 was used for measuring the viewing box luminance, viewing box luminance uniformity and the viewing area ambient lighting (illuminance).

For consistency in the experimental measurement set-up, a distance of 30 cm was maintained between the photometer and the viewing box. The choice of this measurement distance was motivated by the fact that it approximates the distance between the viewer and the viewing box in a typical clinical setting. There was a time lag between switching ON a viewing box and measurement of its brightness to ensure that the light output stabilises. Ambient lighting was measured from a distance of 30 cm away from a switched off viewing box[156-157].

For the purposes of measuring luminance the view box was divided into four quadrants such that five measurements were taken namely at the centre of the view box and also at the centre of each quadrant. The partitioning pattern used for the viewing boxes is shown in Figure 6.1.

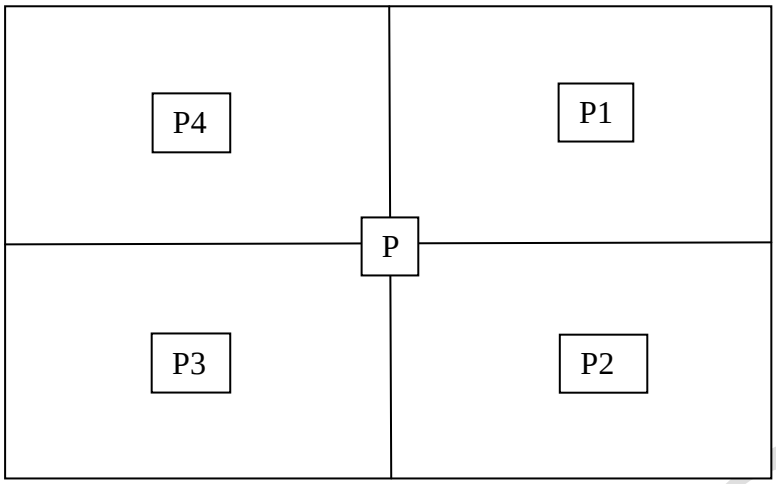


Figure 6.1: Partitioning of the viewing box for the purposes of measurement.

These measurements were taken with the photometer positioned flush on the view box. The luminance of the particular viewing box was then calculated as the average of the five measurements. Viewing box luminance uniformity was determined using the relationship below[156]:

$$Uniformity(\%) = \frac{P_{max} - P_{min}}{P_{max} + P_{min}} * 100 \qquad \textbf{6.1}$$

where P_{max} is the maximum luminance measured and

P_{min} is the minimum luminance value measured on the viewing box.

Assessment of fulfilment of viewing conditions and ambient lighting conditions was based on guidelines from the DRC, European Commission (EC) and the NORDIC countries [158-159]. These guidelines for the parameters viewing box luminance, uniformity of viewing box and ambient lighting are shown in Table 6.1.

Table 6.1: Tabulation of published guidelines.

Organization	Luminance of viewing box (cd m^{-2})	Uniformity of viewing box (%)	Ambient lighting (lux)
DRC	≥ 1500	≤ 20	≤ 100
NORDIC	1500 – 3000	≤ 15	≤ 100
EC	≥ 1700	≤ 30	≤ 50

6.2 Custom Made Quality Control Software

A list of required quality control tests for general radiography units, fluoroscopy units and processors was drawn up based on the DRC requirements. The document is not prescriptive on how to do the tests, however it references the Institute of Physics and Engineering in Medicine (IPEM) Report 91 and the British Institute of Radiology (BIR)[160 -161]. The frequency of tests and the pass/ fail criteria adopted were primarily as recommended from the DRC website.

A personal computer-based, user-friendly computer program has been developed by the author for the purposes of recording, analysis and archiving relevant quality control test results for general radiography, fluoroscopy and processor units. The spreadsheet program was implemented as an Excel 2003 Workbook which requires information from the QA / QC tests. To ensure an efficient and reliable application package, the following design criteria were applied:

- Cell and worksheet protection was used to ensure that fixed data can not be accidentally changed.
- Creation of pull down menus was used to limit permissible entries.
- Exclusivity of worksheets was maintained as much as possible so as to avoid a cascade effect in the event of corruption of one worksheet.
- Hardwiring of factors in formulas was avoided.

The Excel workbook was designed so as to afford easy access to the relevant worksheets. The main menu of the workbook should present the user with the following broad options:

- General Radiography QA
- Fluoroscopy QA

- Processor QA
- Repeat Analysis

Within each equipment class, worksheets are grouped according to frequency of testing, namely, daily, weekly, monthly, 3 monthly, bi-annually and annually. Cells that require data entry or direct user input are left un-shaded (white background). All cells populated with a calculation formula are locked to avoid corruption of the data. In general the colour green represents satisfaction of the pass criteria while the colour red represents satisfaction of the fail criteria. For easy monitoring of data use of control charts is used. An in-depth description of how the software operates is given in Appendix A and B.

6.3 Fluoroscopy Procedures Dose Audit

Patient and dosimetric data was collected retrospectively on patients who had undergone fluoroscopy based examinations or procedures between the period 14 August 2007 and 26 March 2008 at the Division of Radiology, CMJAH. Patients who had either the screening time or KAP readings not recorded were excluded from this study. Another criteria for study eligibility was that the patients ought to have been 18 years and above at the time of the procedure. The following patient related parameters were collected from the record books, namely: name and surname of the patient, sex of the patient, age of the patient, type of examination, contrast agent used, clinician(s) performing the examination, radiographer(s) performing the screening, total screening time, total KAP reading for examination/ procedure and duration of the procedure. The following procedures were analyzed namely barium swallow, barium meal, barium enema, hexabrix swallow, gastrografin meal, voiding cystourethrogram, fistulogram, myelogram, nephrostomy and loopogram.

All the examinations were performed on a Philips Medical Systems multi-purpose C-arm MultiDiagnost Eleva unit. Figure 6.2 is a photograph of the unit used in this study.

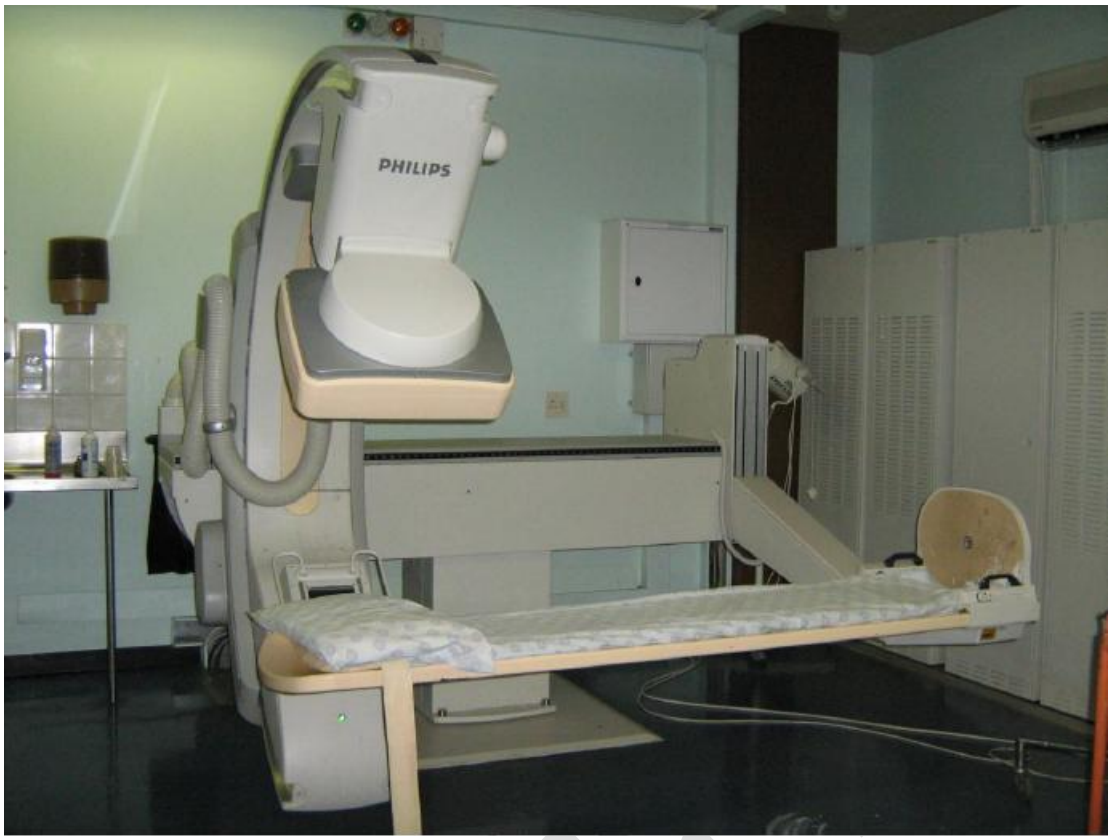


Fig 6.2: A photograph of the Philips MultiDiagnost Eleva C-arm unit.

The MultiDiagnost Eleva unit is capable of performing a wide range of examinations. The unit is driven by a high frequency Optimus TC generator. The accelerating potential can be varied from 40 kVp to 150 kVp in the radiographic mode and between 40 kVp and 125 kVp in the fluoroscopy mode. The unit provides:

- Nominal diameter of field sizes: 17 cm, 20 cm, 25 cm, 31 cm and 38 cm
- Fluoroscopic modes: low, normal and high dose rate
- 0.5 to 30 pulses per second range
- 0.1 mm Al added filtration
- Focus to detector distance ranges from 95 cm to 125 cm

In addition the MultiDiagnost Eleva unit has a mathematical built-in KAP-meter installed from which the *skin dose*[1] and KAP reading are derived. The mathematical KAP meter uses data from the generator and the positions of the jaws to calculate the *skin dose* and KAP

[1]The unit displays skin dose on the console which in actual fact should read as air kerma instead of skin dose. See Section 8.3 for more detail.

values. The *skin dose* was displayed and recorded in mGy while the KAPs were recorded in μGym^2. Both the KAP and *skin dose* reading are displayed on the X-ray unit control console and there is a facility to make a printout of these readings. The unit is periodically serviced and the appropriate quality assurance performed.

The KAP meter reading was validated using an ionisation chamber (PTW Type TM77334) with a calibration certificate traceable to German standards for air kerma. The ionization chamber was positioned 75 cm from the focus. The field size at the point of measurement was confirmed using radiographic film. The validation geometry minimized scattered radiation from the KAP meter, collimator housing and surrounding objects reaching the reference ionization chamber. A working tolerance of ± 25% was considered acceptable for agreement between the KAP reading and the product of the ionization chamber reading and beam area [162].

Descriptive and summary statistics were generated. Some data manipulation was performed with Microsoft Excel™ 2000. In addition, Microsoft Excel™ was used for all graphing, generating scatter plots, trend lines and linear regression. The relationship between the various dosimetric quantities was sought and expressed in terms of the coefficients of correlation[163]. There were clearly transcription errors in the original record books as such the Chauvenet's criterion test was used to exclude exceptionally out of trend values (either too low or high) [164].

6.4 Radiography Examinations Dose Audit

A prospective patient dose audit requires detailed planning and organization for it to be meaningful. Decisions need to be taken with regards to the dosimetry method to be used, phantoms, what data need to be collected and responsibility for data collection. The following sub-sections detail what was done in preparation for the patient dose survey at CMJAH.

6.4.1 Phantoms

Diagnostic radiology phantoms were fabricated in-house at the Division of Medical Physics, CMJAH as per ANSI and CDRH specifications [10, 166,167]. Only clear acrylic and type 1100 aluminium was used to fabricate the phantoms. A total of four phantoms (ANSI specifications) were fabricated for the following anatomical sites, namely, chest, abdomen-lumbar spine, skull and the extremities. In addition two phantoms (chest and abdomen lumbar spine) were fabricated according to the CDRH specifications. The materials required for the fabrication are given in Table 6.2.

Table 6.2: List of ANSI and CDRH phantoms fabrication requirement list.

ANSI PHANTOMS	
Five sheets	260 mm X 260 mm X 25.4 mm Acrylic
One sheet	260 mm X 260 mm X 1 mm Aluminum
One sheet	260 mm X 260 mm X 50.8 mm Acrylic
One sheet	260 mm X 260 mm X 2 mm Aluminum
One sheet	80 mm X 260 mm X 4.5 mm Aluminum
One square tubes	20 mm X 20 mm X 250 mm Acrylic
CDRH ABDOMEN/ LUMBAR SPINE PHANTOM	
Five sheets	270 mm X 270 mm X 30 mm Acrylic
One sheet	270 mm X 270 mm X 20 mm Acrylic
Two sheets	270 mm X 270 mm X 12 mm Acrylic
Two sheets	270 mm X 80 mm X 2 mm Aluminum
CDRH CHEST PHANTOM	
One sheet	270 mm X 270 mm X 30 mm Acrylic
Two sheets	270 mm X 270 mm X 12 mm Acrylic
Two sheets	270 mm X 270 mm X 10 mm Acrylic
Two sheets	360 mm X 280 mm X 10 mm Acrylic
One sheet	300 mm X 20 mm X 6 mm Acrylic
One sheet	270 mm X 270 mm X 2.5 mm Aluminum
One sheet	270 mm X 270 mm X 1.6 mm Aluminum

6.4.2 TLD Dosimetry

Measurement of radiation doses using TLDs requires that they be calibrated. A Toshiba Medical Systems Corporation radiotherapy simulator unit was used as the X-ray source in this investigation. The unit uses a model KXO-50XM diagnostic X-ray high voltage generator and has an inherent filtration half value layer of 1.8 mm Al at 70 kVp. In addition this unit offers both radiography and fluoroscopy functions. Quality control tests like reproducibility, linearity, and field light – radiation field congruence, and timer accuracy, were performed on the unit to establish compliance of the unit to the specifications of the DRC. The unit passed the reproducibility, linearity and field light – radiation field congruence tests as per DRC criteria. Timer accuracy was measured using the PTW DiaVolt Universal and was found to be satisfactory.

A total of 78 LiF:Mg,Cu,P TLDs marketed as GR-200A were used in this study. The properties of GR-200A TLDs are shown in Table 6.3.

Table 6.3: The characteristics of the GR-200A TLD [165].

General Properties	
Material	LiF
Doping	Cu, Mg, P
Manufacturer	Fimel, France
Form	Circular chips
Dimensions	4.5 mm ϕ * 0.8 mm
Density	2.65 g per cc
Effective atomic number	8.2
Dosimetric Properties	
Fading at 20 °C	Negligible
Light dependence	Negligible
Photon energy dependence in the range of 30 keV to 1.25 MeV	< 20 %
Linear response range	1 μGy – 12 Gy
Pre-irradiation Annealing	
Temperature	240 °C
Heating rate	
Duration	10 minutes
Reading Cycle	
Preheating temperature	140 °C
Duration of preheating	7 seconds
Heating temperature	245 °C
Duration	10 seconds

The TLDs were prepared for dosimetry as per manufacturer instructions. The 75 TLDs were annealed using the cycle given in Table 6.3. The TLD annealing procedure was performed using a programmable TLDO™ oven controlled by the THELDO™ software. Rapid cooling

after the annealing was achieved by retrieving the TLD tray from the oven and immediately placing it on top of a copper block.

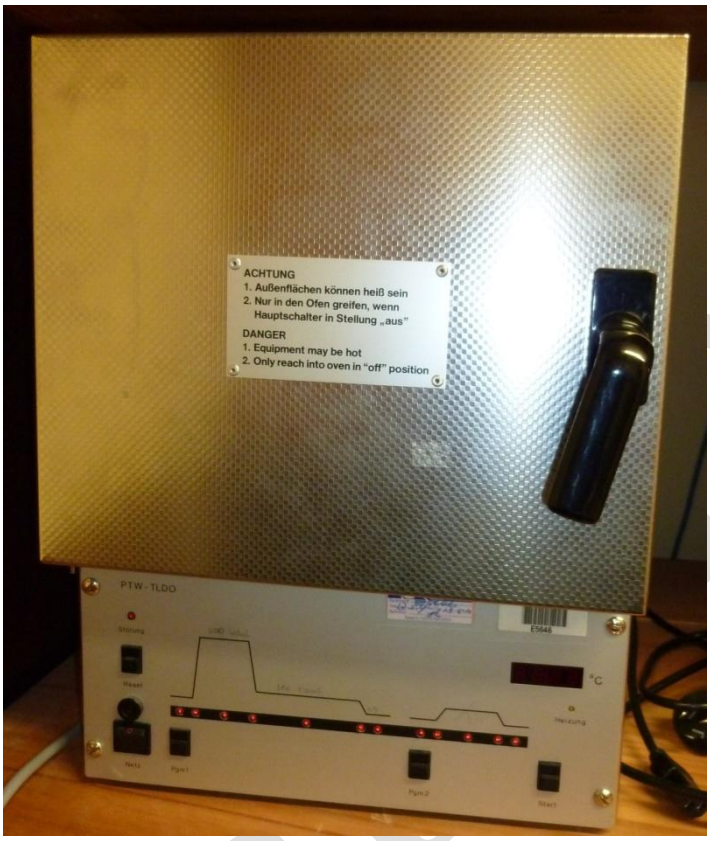


Figure 6.3: A photograph of the TLD annealing oven.

TLDs were calibrated against a calibrated PTW – Freiburg ionization chamber TM77334-2244 at various beam qualities. The long term stability of the ionization chamber was checked using a carbon -14 check source at regular intervals during the course of this work. The beam qualities ranged from 50 kVp (2.07 mm Al first half value layer (HVL)) to 150 kVp (5.8 mm Al first HVL). The TLD calibration set-up is as recommended in the IAEA TRS-457 diagnostic radiology protocol [10]. As an initial calibration process the TLDs were uniformly exposed to 1 mGy and subsequently the reader calibration factor (RCF) and the elemental correction coefficients (ECC) of the individual dosimeters were determined. Each TLD chip had its own unique identification number. Background radiation dose was considered to be negligible in this study.

The TLDs were read using a Harshaw Model 3500 manual TLD reader manufactured by Harshaw Bicron Radiation Measurement Products. The Harshaw 3500 operates

on WinREMS software, which runs under a Windows® platform on a separate computer, providing user interface while the reader control and the applications software. The reading cycle is shown in Table 6.2.

6.4.3 Frequency of Examinations

It is recommended that DRLs should initially be established for one or two of the more common X-ray examinations[168]. Based on this recommendation clinical records of general radiography patient examinations performed at the main X-ray department at CMJAH during the period 02 January 2008 to 31 December 2008 were analyzed to determine the frequency of examinations.

6.4.4 Patient Population

This was a descriptive quantitative survey in which patient doses were determined in terms of the entrance surface air kerma. Participation consent was actively sought from the patients. The patients mass was measured using a bathroom scale, while height was measured using a tailor's tape measure. For each participating patient, the following information was recorded: mass, height, exposure parameters (kVp, mAs), focus-film distance, use of grid and quality of the radiograph. A data collection form was designed to allow for all the necessary information to be recorded. A copy of the data collection sheet is given in Appendix C. All this information was collected over a period of one week. The body mass index (BMI) was calculated for each patient. Only adult patients undergoing the following examinations were eligible for the study: chest PA, chest LAT, pelvis AP, abdomen AP, lumbar spine AP and thoracic spine AP.

Dose has been shown to relate closely to the equivalent diameter of the patient [169]. Instead of measuring the patient's thickness at the relevant anatomical site, the equivalent diameter (ED) in centimeters was calculated using the relationship from Reay et al [170].

$$ED = 2\sqrt{\frac{w}{\pi * h}} \qquad \textbf{6.2}$$

where

w is the patient's mass in grams

h is the patient's height in cm

The above equation takes account of body shape by approximating the person to a cylinder with the same density as water.

The DRLs in this study were established from the calculated ESAK values, as advised in the IAEA Code of Practice[10]. ESAK calculations were done only for exposures which resulted in films of diagnostic quality. Through the use of published conversion factors, ESAK values can be converted to risk related quantities, such as organ dose and effective dose. However calculation of risk related quantities was not performed.

6.4.5 Computational Method

For this study the indirect dosimetry methodology used was as per IAEA TRS 457 protocol. The x-ray tube output from the units was measured using a calibrated 1 cm^3 PTW-Freiburg TM77334 ionization chamber connected to a PTW UNIDOS E electrometer. From the measurement of K(d) the x-ray tube output, Y(d) in Gy per mAs was then calculated as the quotient of K (d) by P_{It} where K(d) is the air kerma and P_{It} is the tube loading during the exposure in mAs.

$$Y(d) = \frac{K(d)}{P_{It}} \qquad \textbf{6.3}$$

The incident air kerma is calculated using the following relationship.

$$K_i = Y(d) * P_{It}\left(\frac{d}{FTD - t_p}\right)^2 \qquad \textbf{6.4}$$

where Y (d) is the output $(mGy(mAs)^{-1})$ of the X-ray tube at particular exposure settings

P_{It} is the tube loading during the exposure of the patient

FTD is the focus to table distance

t_p is the patient thickness at the irradiation site

The advantage of K_i is that it can be converted to patient risk related quantities like organ and effective dose. Furthermore, for the determination of ESAK, K_i is multiplied by an appropriate backscatter factor.

$$ESAK = K_i * BSF \qquad \textbf{6.5}$$

where BSF is the backscatter factor.

Backscatter factors are a function of the irradiated area and can be obtained from the appendix of the TRS 457 protocol. ESAK is used to evaluate skin doses, which is critical for management of deterministic effects.

6.4.6 Patient Dosimetry

A patient dose audit was undertaken to quantify the level of doses patients received from the various radiographic examinations. The study was done at the main x-ray department of CMJAH. The main x-ray department has five x-ray rooms of which two were used for this study. Two Philips Medical Systems units, powered by Optimus 50 high frequency generators were used for this study as the other two units were not used for the examinations being audited and the other unit was not functional at the time of the patient dose audit. Each unit had an inherent filtration of 2.5 mm of aluminum (Al). However, added filtration could be activated by setting the built-in rotatable filter disk to one of the filter values indicated on the disk, namely, 0 mm Al, 1 mm Al, 2 mm Al and 1 mm plus 0.1 mm Cu. In addition the units had moving anti-scatter grids of grid ratio 12:1. Information with regarding the technical aspect of the units was recorded in a data collection form, shown in Appendix B.

6.4.7 Ethics Approval

Ethical clearance was issued by the University of the Witwatersrand, Human Research Clearance Committee. In addition informed consent was obtained from each study participant.

6.5 Non-Clinical Image Quality Assessment

A patient dose audit in isolation from some form of radiological image quality assessment is not of much value. In situations where there is a trade-off between patient dose and image quality, both quantities need to be measured. As such radiograph image quality was done using phantom images. A contrast detail phantom was used to assess image quality. A contrast detail curve provides the best qualitative way of representing both the spatial and contrast capabilities of an imaging unit. The horizontal axis of the curve represents the size of the objects (detail) while the vertical axis corresponds to the contrast of the objects.

6.5.1 Fabrication of the CDRAD phantom

A replica of the commercial CDRAD contrast-detail phantom was fabricated in house for image quality studies [146]. Drill pattern number 2 was used to fabricate the phantom[146].

6.5.2 The Observers

Three medical physicists reported on the images. All the participating medical physicists were fully employed at CMJAH. Scoring of images was as per the CDRAD manual [146].

6.5.3 Image viewing conditions

The radiographs were viewed by the observers on conventional viewing boxes. The room luminosity in the room was constant throughout the experiment. The observers could take as much time as they wanted viewing the radiographs and could stand at any distance from the viewing box.

6.5.4 CDRAD Contrast-Detail Study

The CDRAD phantom was symmetrically sandwiched between 8.3 cm blocks of 30 cm X 30 cm PMMA sheets. The total thickness of the CDRAD phantom plus the PMMA sheets is 17.6 cm which is equivalent to 20 cm of water. This phantom – PMMA blocks arrangement gives scatter conditions representative of an average adult patient.

The experimental set-up for acquiring images of the CDRAD phantom sandwiched by the Perspex sheets is shown below.

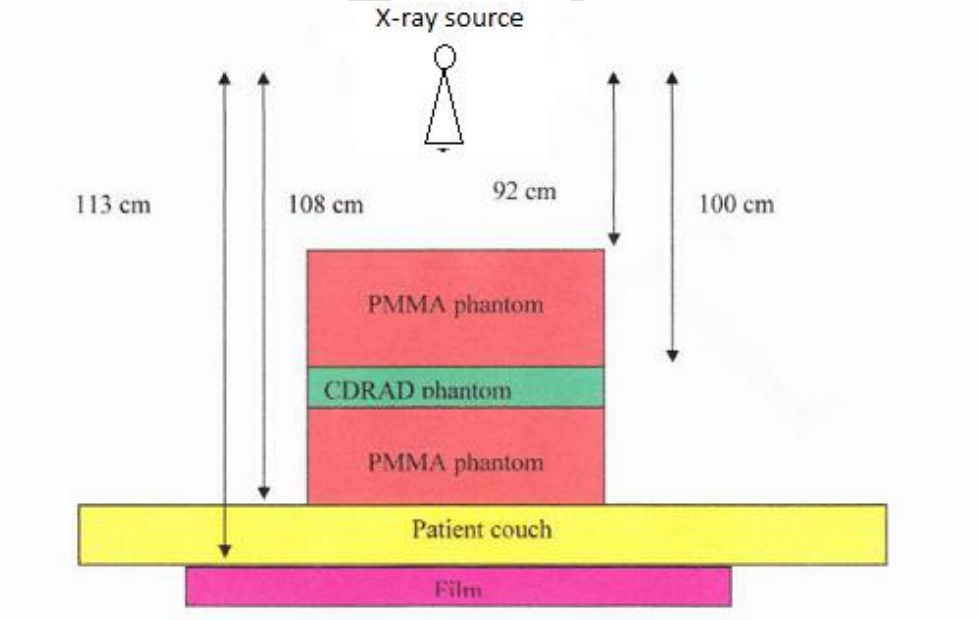


Figure 6.4: The experimental set up for imaging the CDRAD phantom.

A focus to proximal surface of the CDRAD phantom distance of 100 cm was maintained throughout the experimental study. The effect of the following parameters on the threshold-contrast detectability was investigated:

- variation of kVp
- variation of the thickness of PMMA sandwiching the CDRAD phantom
- variation in between imaging units

The observers had to identify in every square matrix the location of the holes drilled on the corner. Results were entered into a score sheet provided with the phantom manual. After comparing the score forms to the reference form (drill pattern) a correction scheme was used taking into account the four nearest neighbours, using the rules in the CDRAD manual[146]. The threshold contrast value was determined for each diameter.

6.6 Digital Radiography Practice and Technique

The aim of this investigation was to assess radiographer familiarity with digital radiography in four teaching hospitals. A cross-sectional study was designed in which a questionnaire was used to collect data from either qualified or student radiographers from four teaching university hospitals in South Africa. The questionnaire is provided in Appendix D. Only qualified radiographers or registered student (trainee) radiographers were eligible for inclusion in the current study. Student radiographers were included in the study because they would give an insight into the training programs and in some cases due to staff shortages they work under minimal supervision. Due to a request by one of the participating institutions, the hospitals will not be identified by name in this study.

The questionnaire used took a multiple format, i.e. it had closed and open ended questions. The information collected was based on self-reporting by the study participants. The questionnaire captured the participants' familiarity, preferences, knowledge and workmanship with regards to digital radiography. The participants in this survey were further asked questions relating to operation of their digital X-ray units, comparing digital radiography to screen-film radiography and their preferences when using digital radiography units.

A soft copy of the questionnaire was e-mailed to the radiotherapy medical physicist at the relevant teaching hospital, who made printouts and hand delivered them to the Assistant

Director of Radiography. The Assistant Director then asked the radiographers to respond to the questionnaire. Participation into the study was voluntary and no incentive for participation was offered. Furthermore data anonymity and confidentiality was assured.

Descriptive statistics were generated from the data using Microsoft Excel 2007 and StatsDirect software. Descriptive statistics included summary measures and frequency tables. In line with research ethics all the collected data was handled with confidentiality.

6.7 Scatter from Under-couch Procedures

An isocentric radiotherapy simulator unit manufactured by Toshiba Medical Systems Corporation was used for this study. The unit has a 4.4 cm thick carbon fibre couch, equivalent to 1.15 mm Al at 100 kVp. In under-couch system X-ray units, scattered radiation is generated from the couch. Before the scatter measurements were done, the X-ray transmission factor of the couch was measured. The couch transmission was determined across a range of tube voltages, from 40 kVp to 120 kVp in steps of 10 kVp. A field size of 10 cm * 10 cm at a focus-to chamber distance of 100 cm was used for the transmission measurements. A 1 cm^3 PTW-Freiburg TM77334 ionization chamber calibrated in terms of air kerma was used for the measurements. The couch was raised to its highest possible vertical position to be as close as possible to the focus so as to have minimal scattered radiation reaching the ionization chamber during the transmission measurements.

The experimental set-up during the scatter measurements always had slabs of PMMA slabs placed distal to the parallel plate chamber so as to simulate the amount of scatter generated by an average patient. One of the Perspex blocks had a notch carved at its centre so as to accommodate the plane parallel chamber used for the measurements. The focus to chamber distance was maintained at 100 cm for all the experimental measurements. The determination of scatter generated from the couch and directed to the patient involves two steps, namely,

- measurement of the *primary radiation*[2] (PR)beam
- measurement of the *primary plus scattered radiation* (PPS) beam.

The amount of *primary radiation* was measured from the experimental set-up shown in Figure 6.5. The couch was lowered to its lowest possible position, which was the closest to

[2] Strictly speaking this is not primary radiation however term is use to differentiate from scatter from the couch.

the X-ray tube. This arrangement rules out the possibility of any scattered radiation from the couch reaching the ionization chamber, thus provides a measurement of the *primary radiation* only.

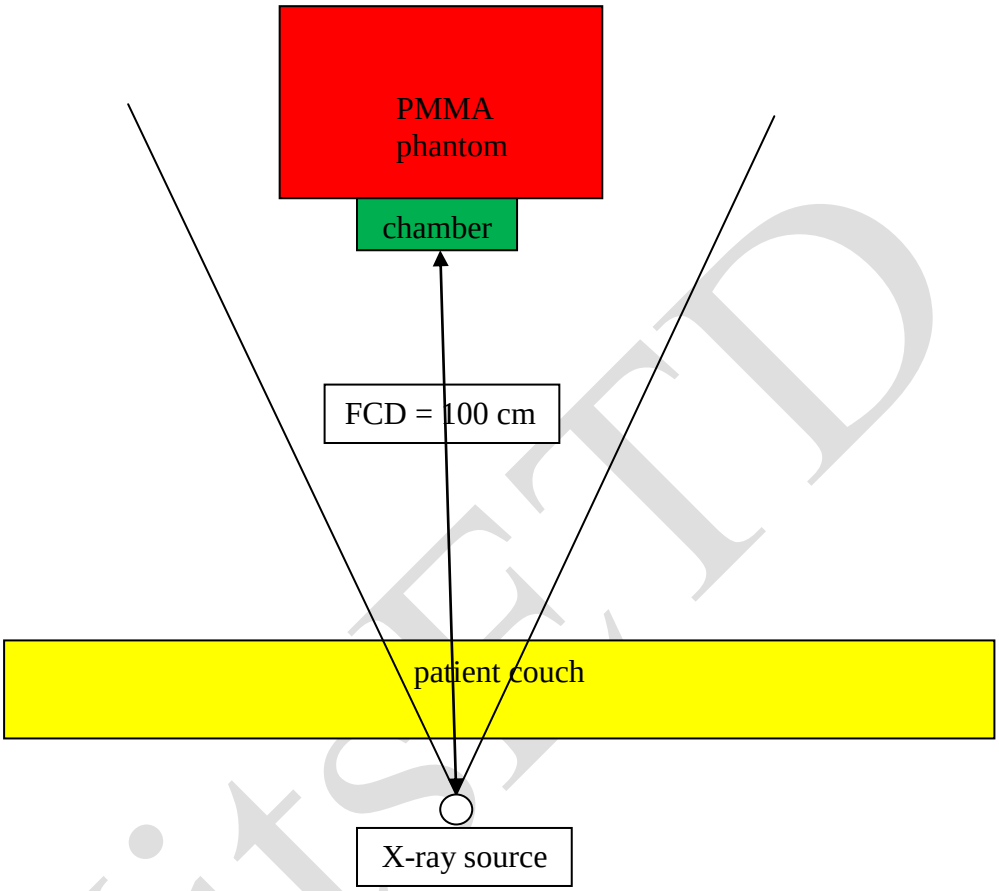


Figure 6.5: The experimental set-up for measurement of primary radiation from the source.

The *primary plus scattered radiation* beam is measured with the ionization chamber flush on the couch. The experimental setup is shown in Figure 6.6 below.

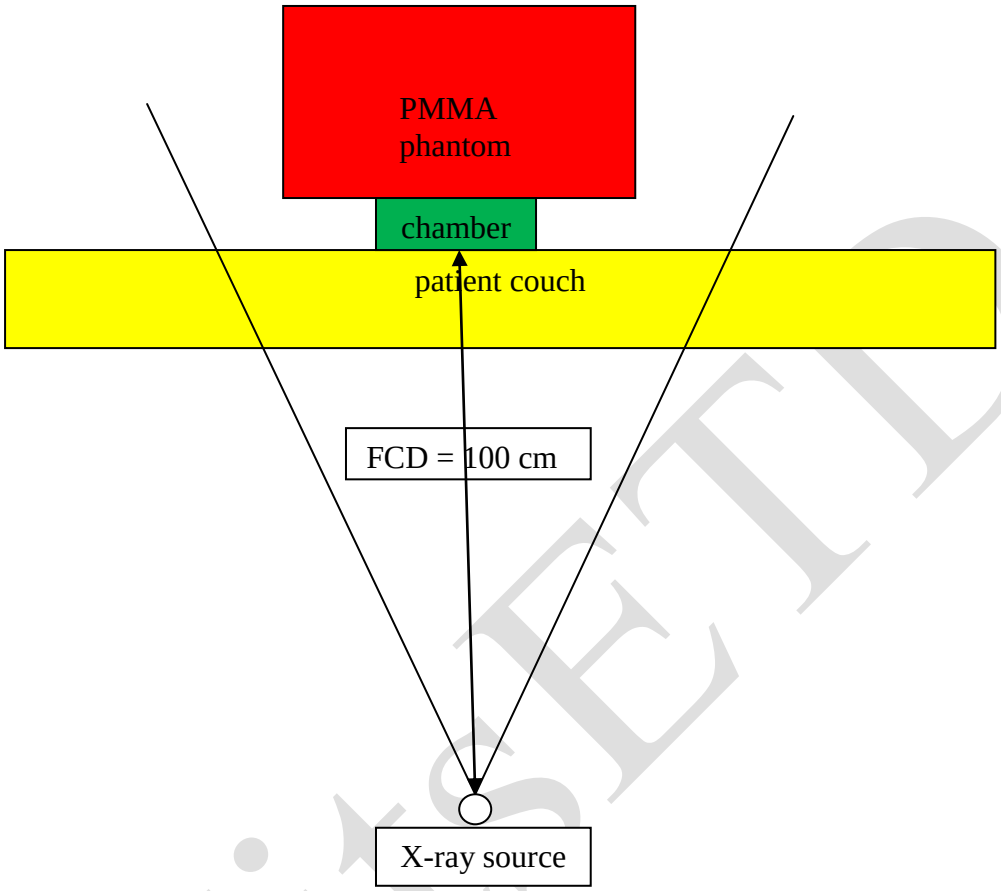


Figure 6.6: The experimental set-up for measurement of both primary plus scattered radiation from the source.

In this investigation the measured ionization charge was corrected for ambient conditions. The ratio of primary plus scattered radiation to primary radiation was calculated. This study investigated 60 kVp, 70 kVp, 90 kVp and 120 kVp beams.

CHAPTER SEVEN

RESULTS AND ANALYSIS

7.1 Quality Control of Radiography Viewing Conditions

A total of 47 viewing boxes had their average luminance, average central luminance, average uniformity measured in this study. From this total, 24 viewing boxes were located in various areas at the Division of Radiology and the remaining 23 were located at the Division of Radiation Oncology. Results of the investigation are tabulated in Table 7.1. Numerical figures are given to the nearest whole number.

Table 7.1: The mean luminance and luminance uniformity of the viewing boxes.[1]

Division	Mean Average Luminance (cd m^{-2})	Mean Central Luminance (cd m^{-2})	Average Uniformity (%)
Radiology	1027 [549]	1285 [666]	27 [13]
Radiation Oncology	3284 [328]	3305 [407]	7 [4]

In addition to the viewing box luminance measurements, the ambient lighting of the reporting rooms was measured. The results of these measurements are shown in Table 7.2.

[1] The standard deviation in the measured quantity is shown in square brackets.

Table 7.2: The average ambient lighting readings from the viewing stations in the two departments.[2]

	Radiology	Radiation Oncology
Average Ambient Lighting (lux)	66	66
Standard Deviation Average Ambient Lightining (lux)	25	32

The data in Tables 7.1 and 7.2 was compared with the published guidelines from the DRC, NORDIC and the EC as given in Table 6.1. Figures 7.1 and 7.2 below show the percentage of viewing boxes which were in compliance with the guidelines as set out by different organizations at the Divisions of Radiology and Radiation Oncology respectively.

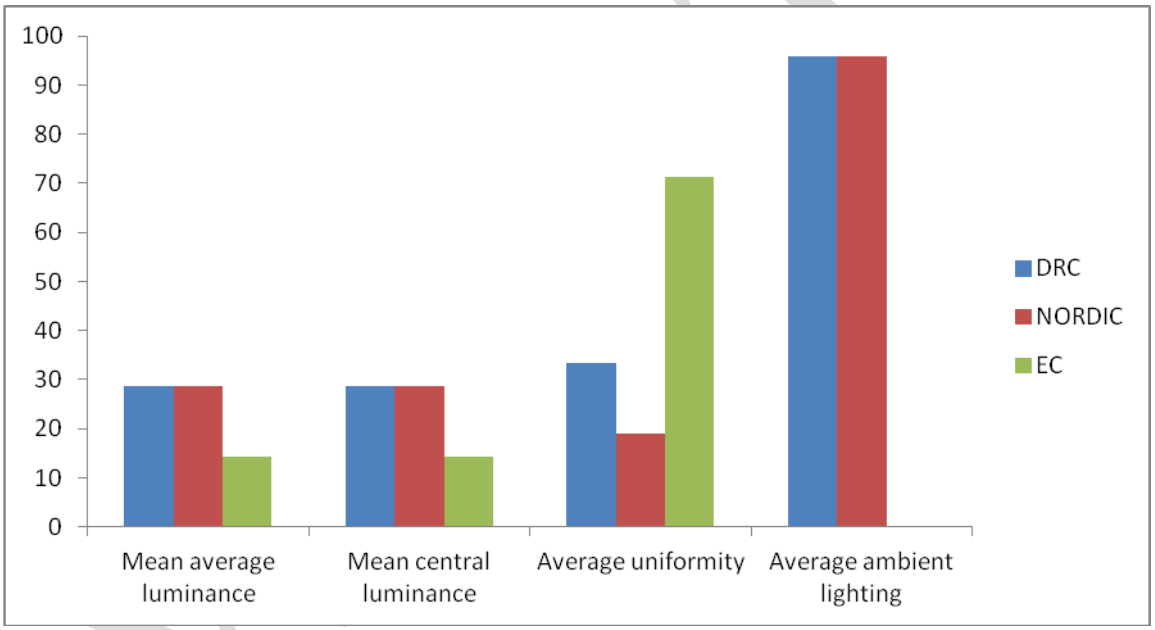


Figure 7.1: A bar chart showing the percentage of viewing boxes at the Division of Radiology which are compliant to the different guidelines.

[2] The standard deviation in the measured quantity is shown in square brackets.

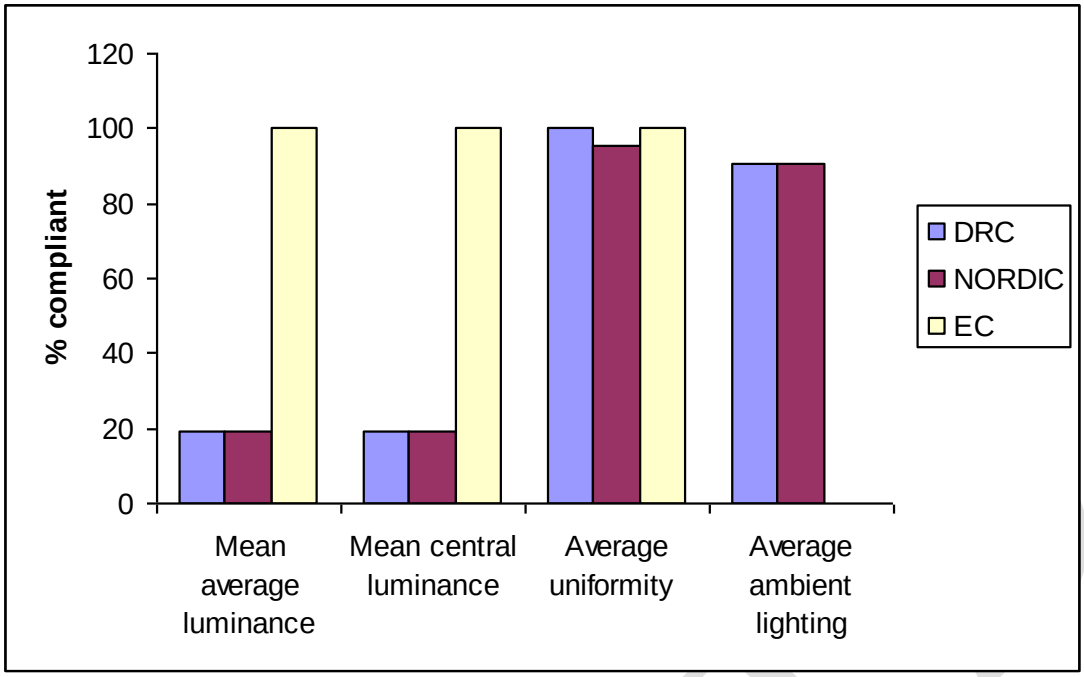


Figure 7.2: A bar chart showing percentage of viewing boxes at the Division of Radiation Oncology complying with different guidelines.

7.2 Custom Made Quality Control Software

An Excel based workbook has been developed to capture, analyse and archive QC results for the following equipment: general radiography units, fluoroscopy units and processors. In addition there is a provision to perform repeat analysis of any one imaging room. In total the workbook consists of twenty separate Microsoft Excel™ files some of whom comprise of more than one worksheet. A software package provides for the following:

- Increase reliability of QA evaluations
- Reduce use of paper documentation.
- Provide an automatic pass / fail criteria based on the DRC requirements.

At present, the program is a Microsoft Excel™ 2003 workbook which can be run on a common office PC with usual basic provisions. To facilitate easy use the software has a graphic user interface which utilises a click button, upon clicking it reveals the main menu of the program. Below is a screen shot of the graphic user interface.

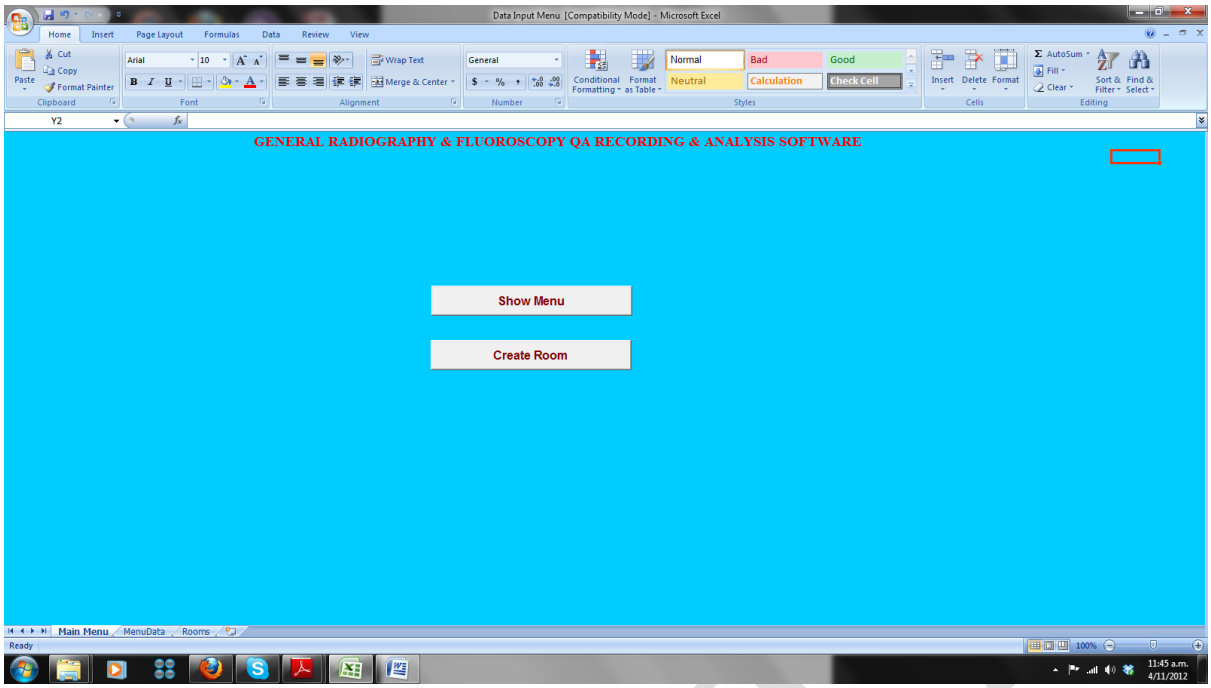


Figure 7.3: A screen capture of the graphic user interface.

When the user clicks the "Show Menu" button the computer screen is as shown below:

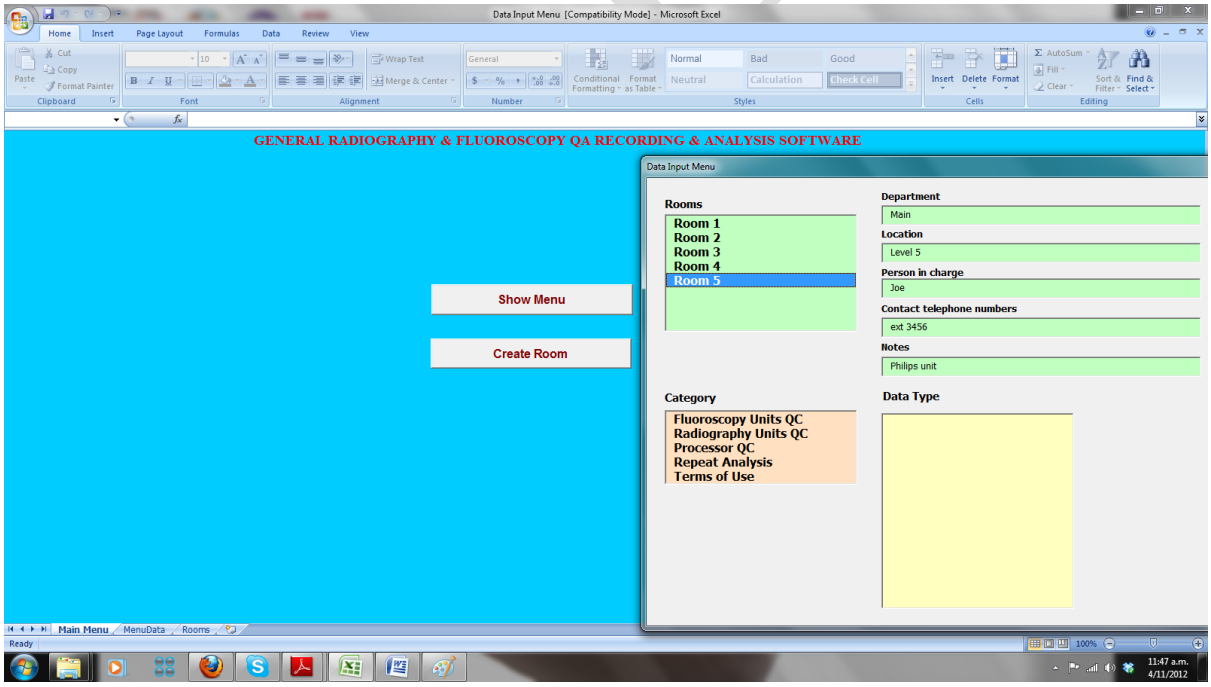


Figure 7.4: A screen capture showing the options presented to user according to equipment.

This screen "page" allows the user to select the relevant equipment that he/she wants to perform the tests on. Selection is made possible through clicking on the modality/ equipment of choice.

Furthermore under each equipment or modality the tests are sorted according to the recommended frequency of tests. The frequency options range from daily, weekly, monthly, quarterly, bi-annually and annually and selection is through clicking at the frequency of choice. An example of the frequency choices for the radiography modality is shown below in Figure 7.5.

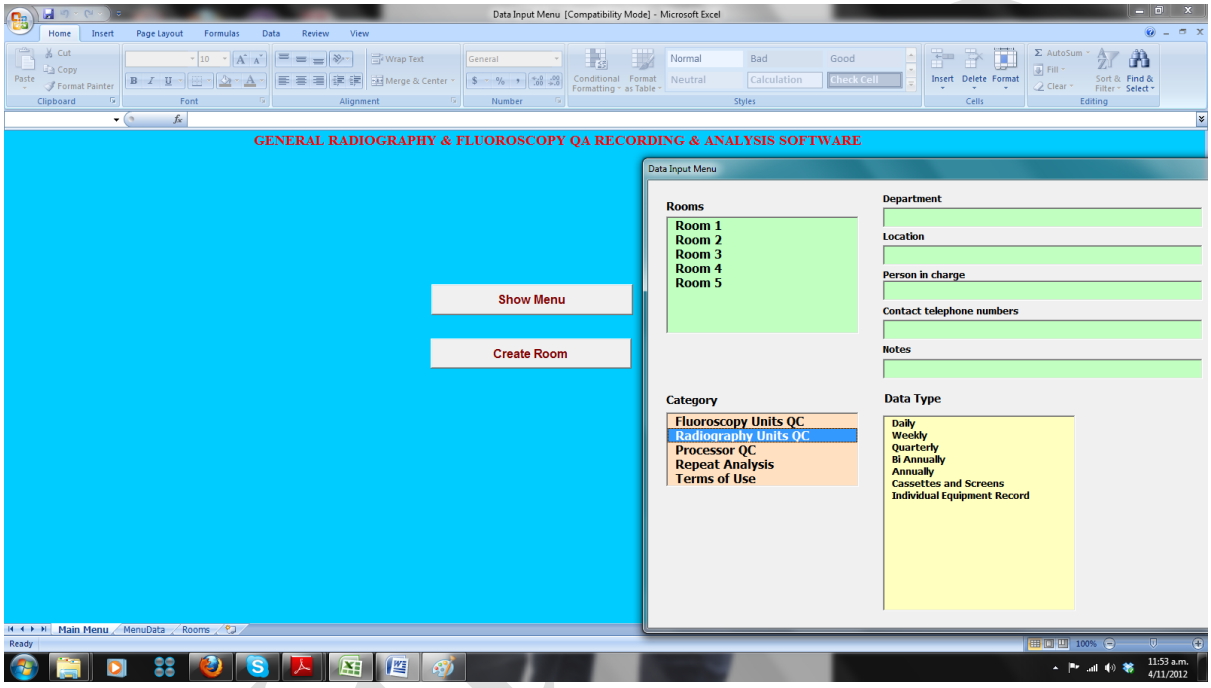
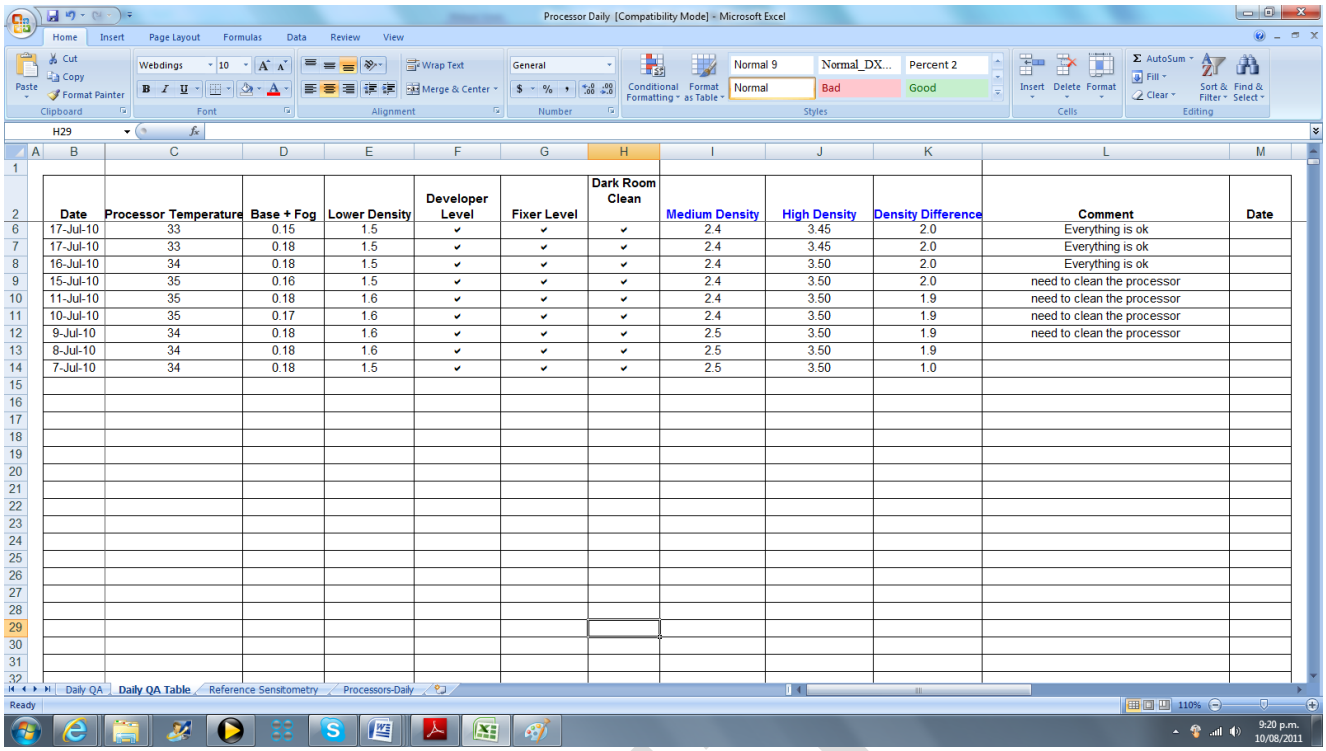


Figure 7.5: A screen capture showing the frequency of test options for the radiography modality.

The software presents graphical display facilities for the user to easily identify any trends. The daily processor test results are automatically archived in a table format for easier trending. A typical daily processor test output table is shown in Figure 7.6.



Date	Processor Temperature	Base + Fog	Lower Density	Developer Level	Fixer Level	Dark Room Clean	Medium Density	High Density	Density Difference	Comment	Date
17-Jul-10	33	0.15	1.5	✔	✔	✔	2.4	3.45	2.0	Everything is ok	
17-Jul-10	33	0.18	1.5	✔	✔	✔	2.4	3.45	2.0	Everything is ok	
16-Jul-10	34	0.18	1.5	✔	✔	✔	2.4	3.50	2.0	Everything is ok	
15-Jul-10	35	0.16	1.5	✔	✔	✔	2.4	3.50	2.0	need to clean the processor	
11-Jul-10	35	0.18	1.6	✔	✔	✔	2.4	3.50	1.9	need to clean the processor	
10-Jul-10	35	0.17	1.6	✔	✔	✔	2.4	3.50	1.9	need to clean the processor	
9-Jul-10	34	0.18	1.6	✔	✔	✔	2.5	3.50	1.9	need to clean the processor	
8-Jul-10	34	0.18	1.6	✔	✔	✔	2.5	3.50	1.9		
7-Jul-10	34	0.18	1.5	✔	✔	✔	2.5	3.50	1.0		

Figure 7.6: A screen capture showing the daily processor quality control test results archive.

The daily radiography room QC tests are binary in nature, either the equipment passes or fails the test, thus the user has to tick the check box if the equipment passes or leave un-ticked if the equipment fails the criteria. Figure 7.7 shows a screenshot of the radiography daily QC test worksheet.

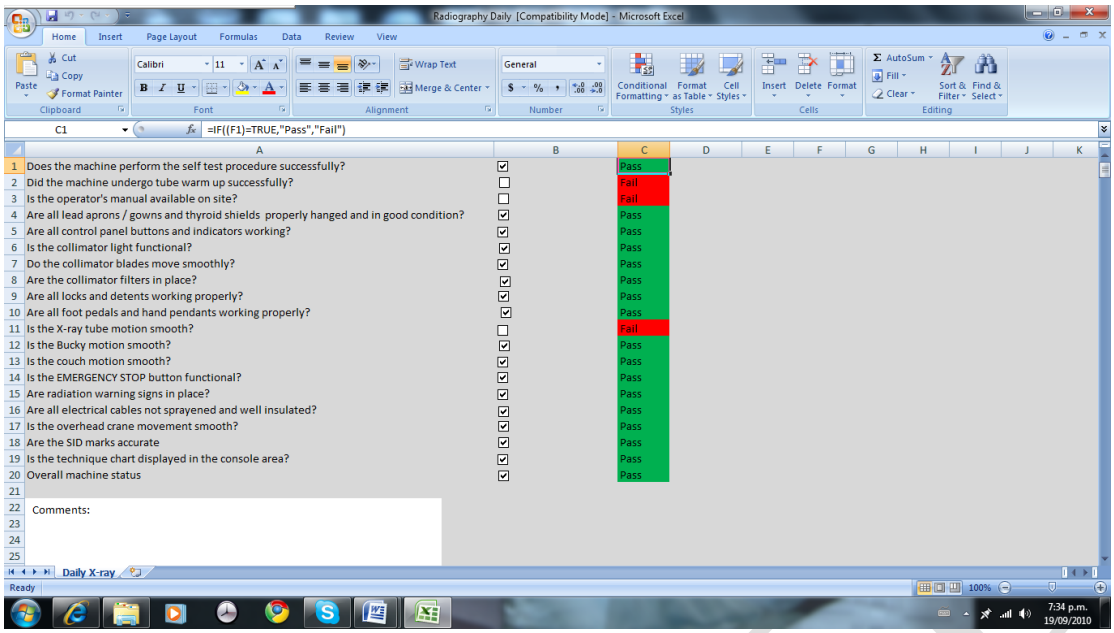


Figure 7.7: A screen capture showing the daily X-ray quality control test results page.

To further aid decision making with regards to fulfilment of criteria, a pass of fulfilment of criteria is shown under a green background yet a fail is shown under a red background. If the tolerance limits are not exceeded then the assumption that the unit is working properly can be made.

The data integrity of the software package is ensured through locking of cells which involve a calculation. Moreover the user has the option of protecting the worksheets by way of the use of a password should the worksheet need to be edited. After data entry and necessary calculations the output sheet has been optimized for black and white printing on an A4 size paper.

To evaluate the performance of the software application, an experienced diagnostic radiology radiographer with experience in quality control procedures, tested the functionality of the package. The validation process proved that the software can be used in a typical clinical setting.

7.3 Fluoroscopy Procedures Dose Audit

A total of three hundred and thirty one (331) patients were involved in this study, with patient age ranging from 16 - 88 years (mean age of 51.2 years). The patient population comprised of 159 males and 172 females. The distribution of examinations according to their type is shown

in Figure 7.8 below. The majority of the examinations were for the upper gastrointestinal tract.

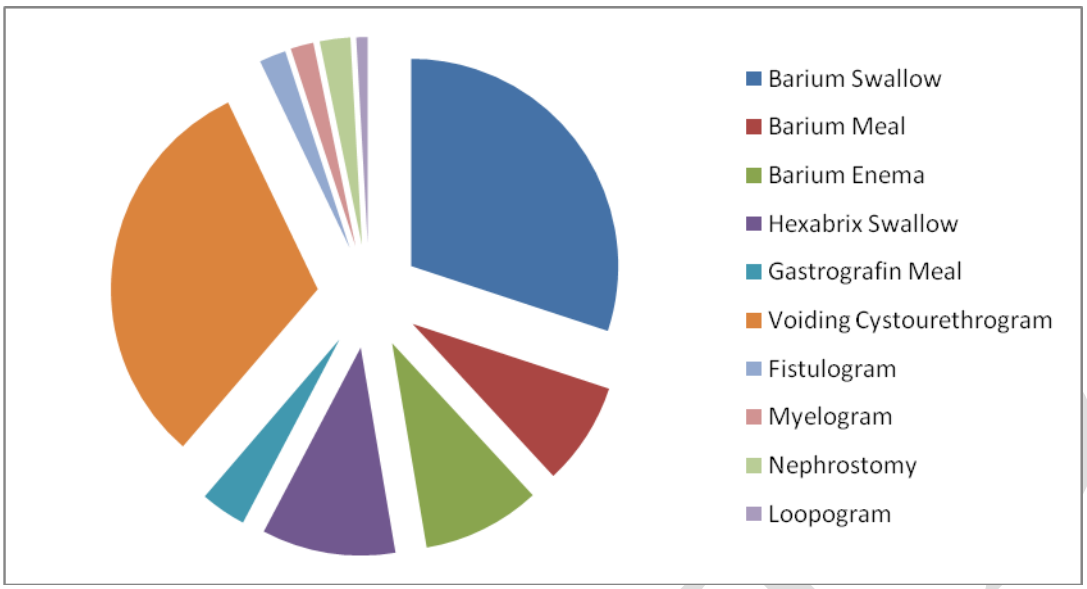


Figure 7.8: A pie chart showing the examination type distribution.

This review study involved forty eight clinicians and thirty seven radiographers of varying experience in their practice. The adopted technique for any particular examination was at the discretion of the radiologists.

The KAP readings from the unit was found to be within 10 % of the product of the X-ray field area and air kerma as determined by the reference ionization chamber. The mean, standard deviation, range, mean and 75 th quartile were calculated to the nearest whole number for each type of examination from the individual patient records of the *skin dose*[3] and KAP reading. The results are shown in Table 7.3 and Table 7.4.

[3] See Section 8.3 for further discussion on the use of the term *skin dose.*

Table 7.3: A tabulation of the mean, range, standard deviation and median in KAP values for various examinations[4].

Examination	Number of examinations	Mean KAP	Range	Standard deviation	Median KAP	Third Quartile
		µGym^2	µGym^2	µGym^2	µGym^2	µGym^2
Barium Swallow	101	1912	235 -7276	1482	1398	2477
Barium Meal	27	2343	47 - 6505	1819	2005	2654
Hexabrix Swallow	35	1643	241 - 9712	2336	723	1529
Gastrografin Meal	75	2689	167 - 6979	2283	2353	3942
Barium Enema	31	5062	519 – 20296	4285	4337	6846
Voiding Cystourethrogram	106	1560	130 – 9419	1658	1007	1868
Fistulogram	7	1320	154 – 2559	971	1483	2068
Myelogram	6	1821	14 – 5266	2335	596	3405
Nephrostomy	8	1458	161 – 2559	794	1468	2070
Loopogram	3	810	746 - 910	88	774	842

[4] Calculated quantities are given to the nearest whole number

Table 7.4: A tabulation of the mean, range, standard deviation and median in skin dose values for various examinations[5].

Examination	Number of examinations	Mean skin dose	Range	Standard deviation	Median skin dose	Third Quartile
		(mGy)	(mGy)	(mGy)	(mGy)	(mGy)
Barium Swallow	101	78	62 -347	55	59	108
Barium Meal	27	127	38 - 395	101	94	149
Hexabrix Swallow	35	57	7 - 242	60	35	56
Gastrografin Meal	75	75	10 - 131	43	74	121
Barium Enema	31	177	55 - 487	99	154	210
Voiding Cystourethrogram	106	63	7 - 579	51	53	86
Fistulogram	7	71	9 - 155	57	50	105
Myelogram	6	117	1 - 292	112	104	171
Nephrostomy	8	38	7 - 179	63	11	25
Loopogram	3	31	22 - 49	16	22	36

Analysis of the range of both the skin doses and KAP meter readings shows a wide variation within one examination. The third quartile KAP values from this study were compared with the DRLs from the UK data as shown in Figure 7.9 [38].

[5] Calculated quantities are given to the nearest whole number

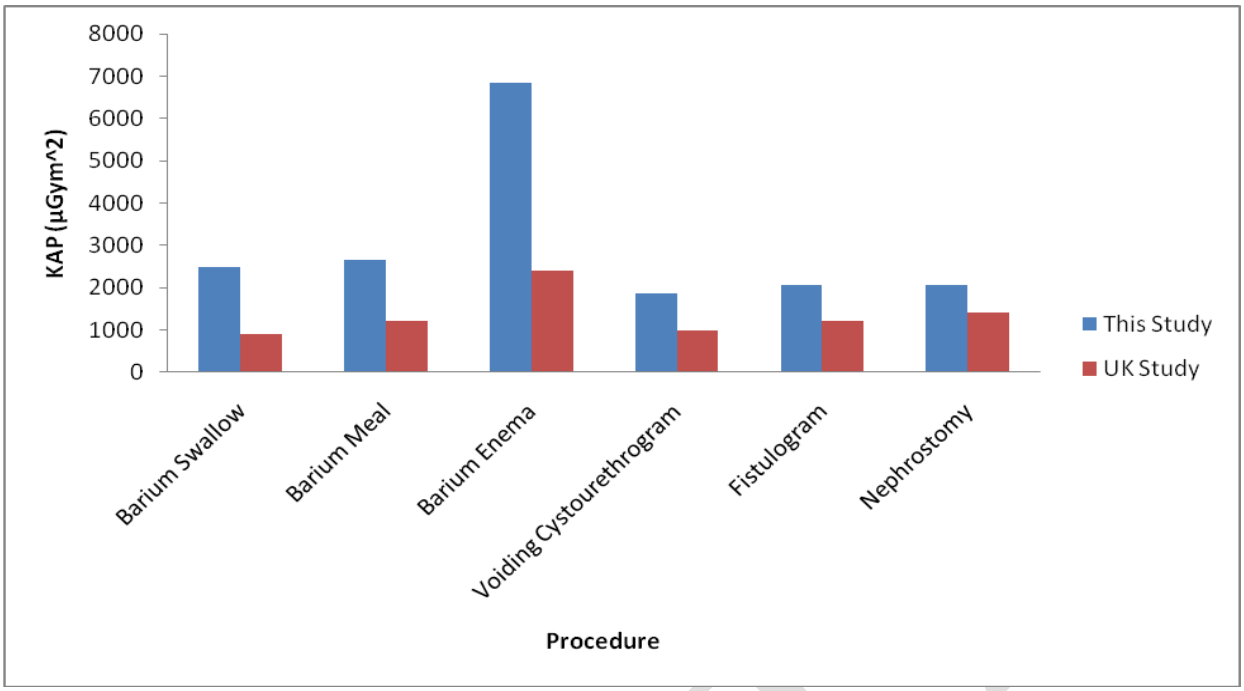


Figure 7.9: A bar chart showing a comparison of the third quartile KAP values from this study and the DRLs from the UK study.

Figure 7.9 shows that the third quartile values from this study are higher than the data from the UK. However it should be borne in mind that this is data from a single centre as opposed to the multi-centre study of the UK.

In this study KAP values were not converted into a patient risk related parameter but the influence of the various parameters on it was analysed. Time in terms of the screening time and the duration of the whole procedure have an impact on the patient dose. The mean screening time, mean procedure duration and number of radiographs taken per procedure were documented and are given in Table 7.5.

Table 7.5: The mean screening time, mean procedure duration and number of films taken per examination type[♦].

Examination	Mean screening time (minutes)	Mean procedure duration (minutes)	Mean number of films taken
Barium Swallow	4	27	4
Barium Meal	7	43	5
Hexabrix swallow	3	24	4
Gastrografin Meal	4	47	3
Barium enema	10	54	4
Voiding Cystourethrogram	4	41	2
Fistulogram	3	34	2
Myelogram	54	55	2
Nephrostomy	8	93	2
Loopogram	2	22	2

Furthermore the recorded screening times from this study were compared to the data from the UK study. The comparison of these two studies is shown in Figure 7.10.

♦ Values of screening time and duration of fluoroscopy are quoted to the nearest integer

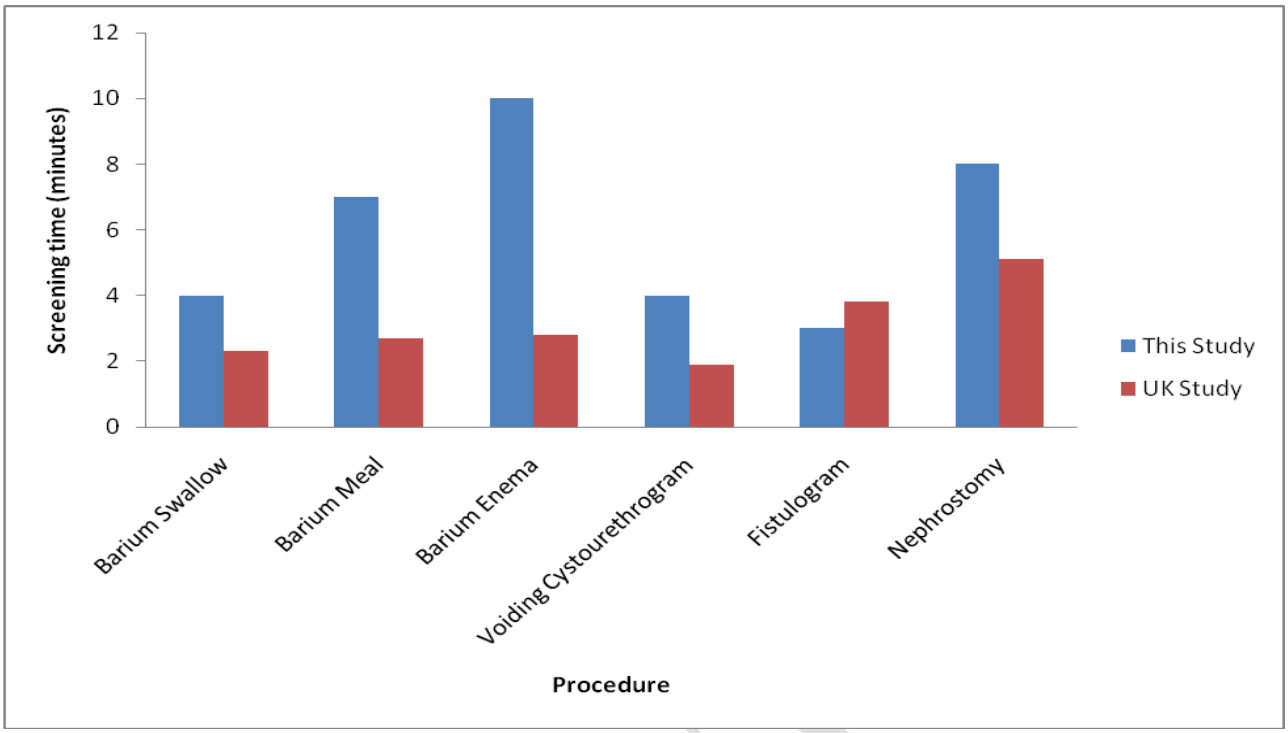


Figure 7.10: A bar chart showing a comparison of the third quartile screening times from this study and those from the UK study.

The relationship between dosimetry quantities and/ or dose influencing quantities needs to be known for any attempt to optimize patient doses. The relationship between screening time and skin dose and between screening time and KAP was evaluated in terms of coefficients of correlation. Table 7.6 shows the coefficients of correlation between the evaluated dose metrics and the tests of correlation were shown to be of moderate correlation.

Table 7.6: Coefficients of correlation between the different dosimetry influencing quantities.

Relationship	Coefficient of Correlation	Coefficient of determination
Screening time vs *skin dose*	0.6474	0.4196
Screening time vs KAP	0.3959	0.1567
KAP vs *skin dose*	0.4787	0.2291

Furthermore this work tested the relationship between the number of films/ radiographs taken per procedure and the two dosimetry quantities, KAP and *skin dose*. Results of this

investigation showed that the correlation was statistically insignificant between the number of films taken and the two dosimetry quantities. Results of the coefficient of correlation tests are shown in Table 7.7. The results show a weak correlation between the number of films taken and the dosimetry quantities: KAP and *skin dose*. Based on Table 7.7 it can be concluded that an increase in the number of films taken during a procedure does not necessarily translate to high patient doses.

Table 7.7: Coefficients of correlation between numbers of films used per examination and other dosimetry quantities.

Relationship	Coefficient of Correlation	Coefficient of determination
Number of films Vs KAP	0.4918	0.2418
Number of films Vs *skin dose*	0.4533	0.2055

The frequency of the various dose related parameters is shown in Figures 7.11 – 7.13.

The descriptive statistics for patient KAP, *skin dose* and screening times showed an asymmetrical distribution.

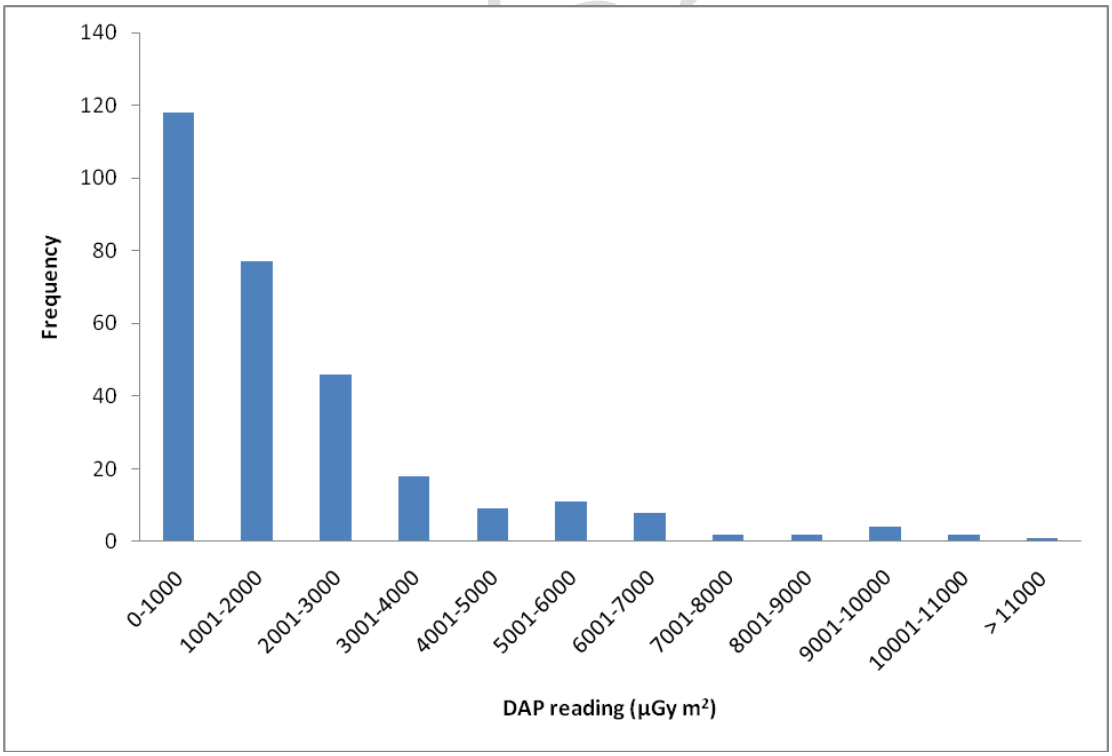


Figure 7.11: A skewed frequency distribution of the KAP readings.

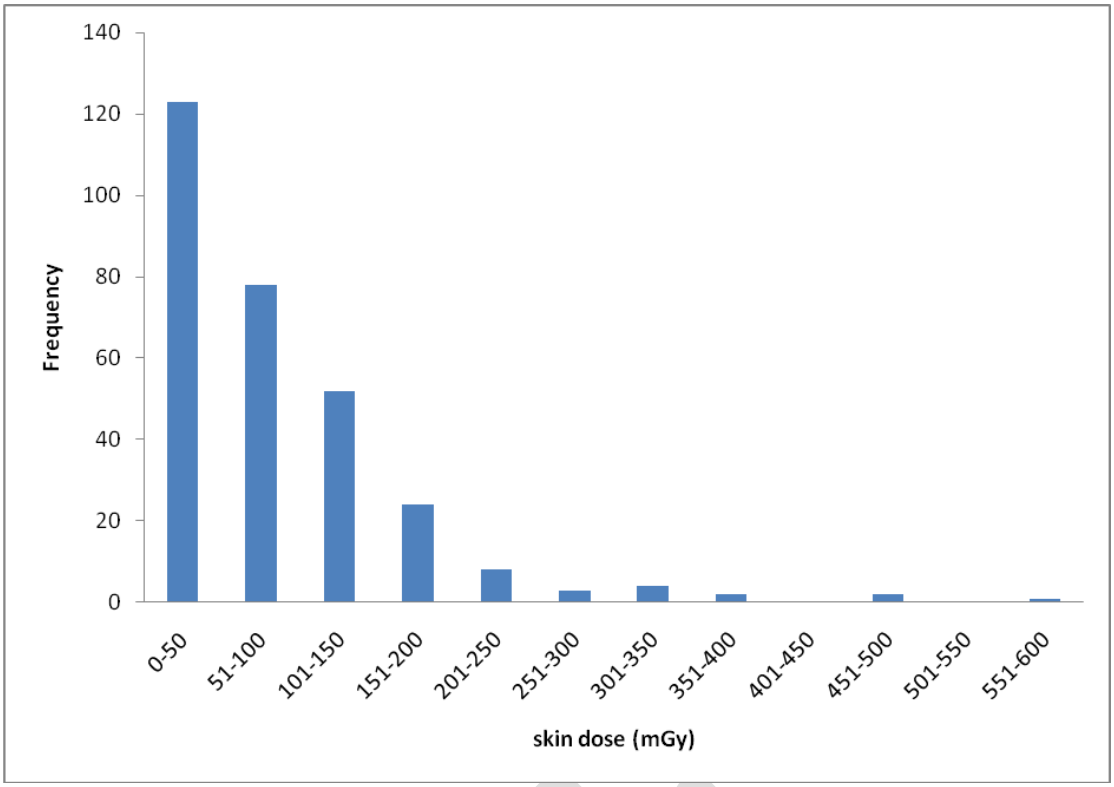


Figure 7.12: The frequency distribution of the recorded skin doses.

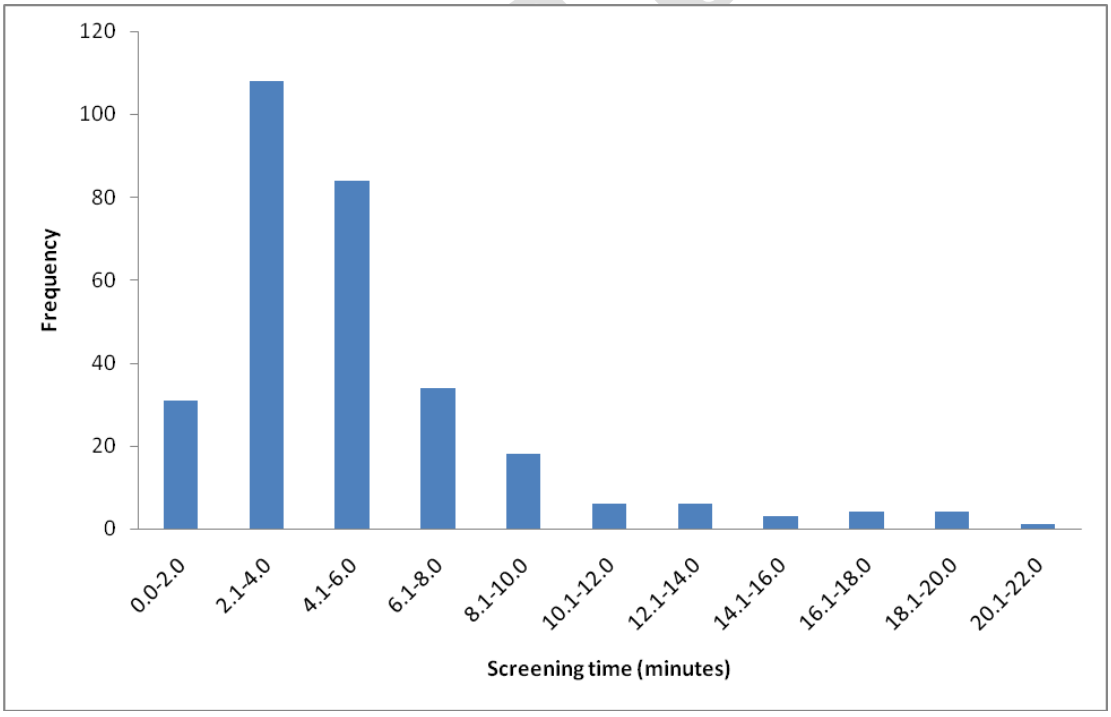


Figure 7.13: The frequency distribution of the screening time.

The left asymmetry in the distribution is welcome in terms of the patient radiation protection perspective since the majority of patients would have received less than the mean dose.

7.4 Radiography Examinations Dose Audit

Feasibility of the both the direct and indirect dosimetry methods was conducted in a clinical setting.

7.4.1 Phantoms

Four ANSI phantoms were fabricated as per recommended specifications. Figures 7.14 – 7.17 are photographs of the fabricated phantoms. Materials from the phantoms can be used interchangeably between the four types of phantoms. As of January 2009, it cost R1871.19c to buy the phantom material to be used across the four types of phantoms, yet if each phantom had material exclusively bought for it the total cost of materials would have been R4864.18c. The AAPM Report No. 31 recommends that the ANSI phantoms have the dimensions 305 mm * 305 mm (length * width) but it further states that a reduction in dimensions to 250 mm * 250 mm does not affect the entrance surface air kerma measurements. As a result the smaller dimensions were used to fabricate the phantoms.

Figure 7.14: A photography of the fabricated ANSI abdomen phantom.

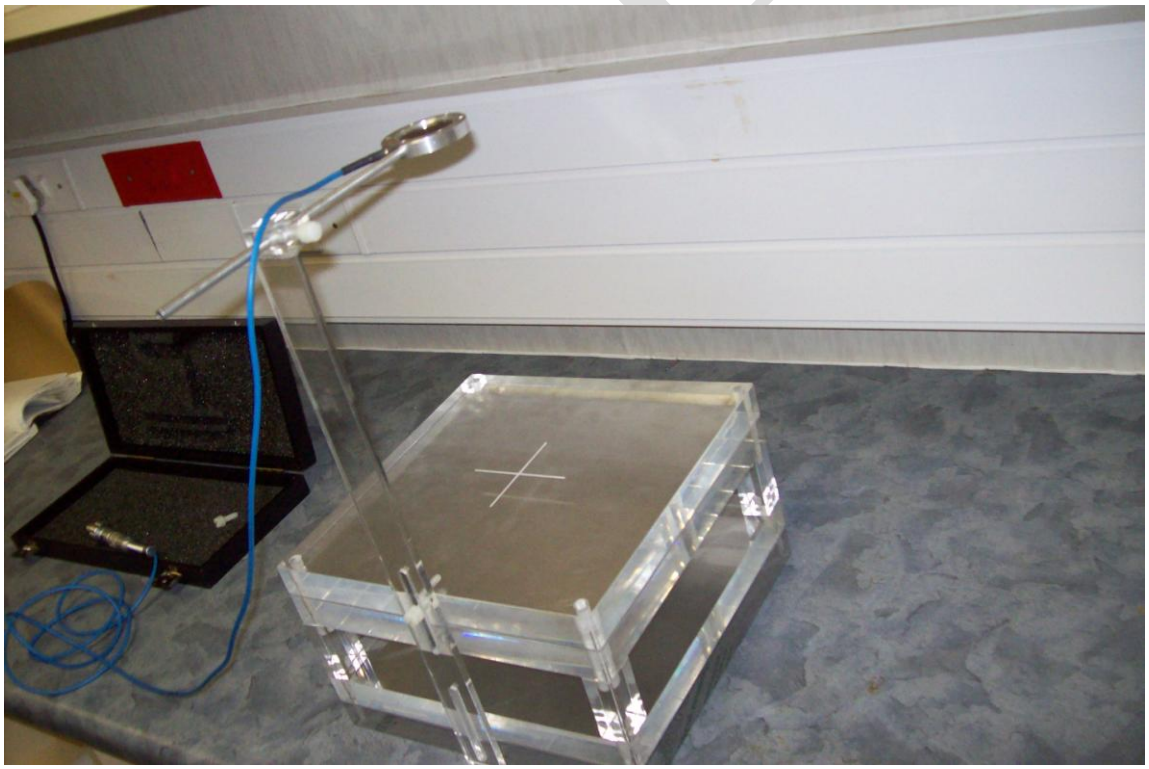


Figure 7.15: A photography of the fabricated ANSI chest phantom.

Figure 7.16: A photography of the fabricated ANSI extremity phantom.

Figure 7.17: A photography of the fabricated ANSI skull phantom.

The different phantoms were compared in terms of their mass, the cost of material, the time taken to fabricate them and level of their complexity in terms of fabrication. The level of complexity was classified into three categories, namely, low (easy to fabricate), fair and high (challenging – demanding a relatively high level of machining). Only the cost of materials is accounted for because the machining was done by people employed full-time by the hospital. Table 7.8 shows a comparison of the phantoms based on these criteria. A quotation was obtained from a local agent that sells these phantoms and prices are indicated in Table 7.8. The quoted prices from the vendor are exclusive of value added tax and are subject to the prevailing foreign currency exchange rate.

Table 7.8: A comparison of the physical properties of various ANSI phantoms[6].

Phantom	Mass (±0.25kg)	Cost of Material (ZAR)	Cost of phantom from vendor (ZAR)	Level of Fabrication Complexity[7]	Time taken to fabricate (hours)
Chest	7.0	977.20	8600.00	Fair	4
Abdomen/ Lumbo-Sacral Spine	12.0	1812.69	11100.00	Fair	6
Skull	10.7	1603.04	10600.00	Low	4
Extremity	3.5	471.25	3500.00	Low	2

In addition to the ANSI phantoms, the chest CDRH and abdomen/ lumbo-sacral spine CDRH phantoms were fabricated as per design specifications.

[6] Quoted prices are as of January 2009.
[7] Subjective assessment of fabrication process by fabricator

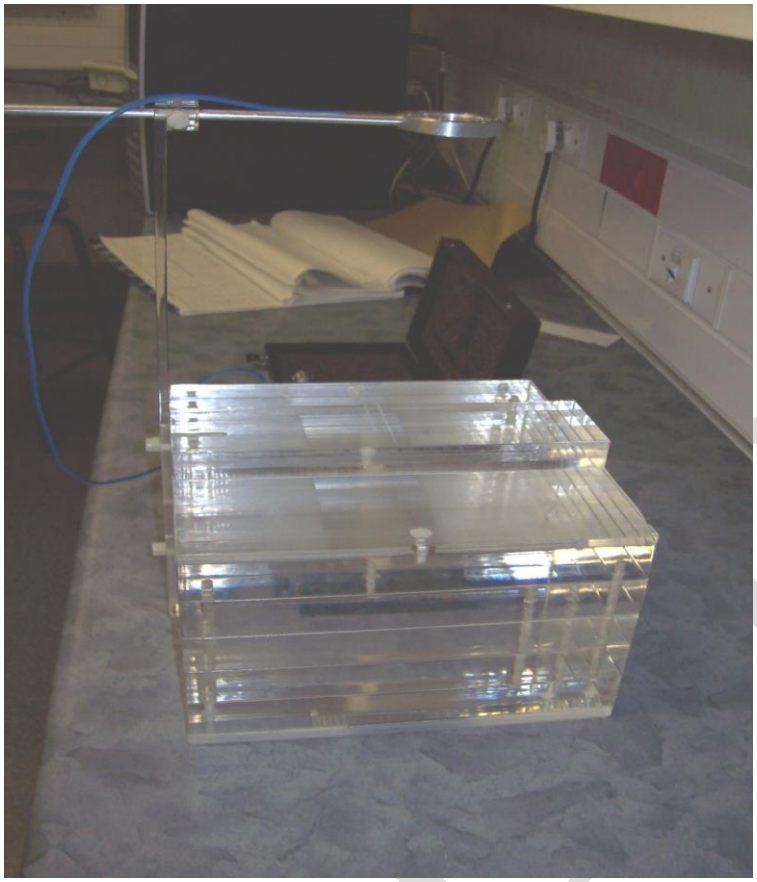


Figure 7.18: A photography of the fabricated CDRH abdomen phantom.

Figure 7.19: A photography of the fabricated CDRH chest phantom.

The fabrication process of the phantoms was evaluated subjectively. The design properties of these phantoms is shown in Table 7.9.

Table 7.9. Fabrication details for the two CDRH phantoms.[8]

Phantom	Mass (kg)	Materials	Cost of Material (ZAR)	Level of Fabrication Complexity[9]	Time taken to fabricate (hours)	Patient Equivalence
CDRH Chest	8.7	PMMA, Al, Air gap	2534.36	High	8	Established
CDRH Abdomen/ Lumbo-Sacral Spine	13.6	PMMA, Al	1166.67	High	10	Established

[8] Quoted prices are as of January 2009.
[9] Subjective assessment of fabrication process by fabricator

In terms of representing how radiation interacts with the patient and scatter generation from the patient CDRH have been shown to be more realistic [172 -173] . However the ANSI chest phantom proved to be easier to fabricate. In addition to satisfying radiation dosimetry requirements, the fabricated phantoms satisfy the health and safety requirements as they have the following properties:

- Toxicity: all materials used are non-carcinogenic and hypo-allergenic.
- Handling: phantoms are composed of individual slabs thus there is no need to carry the whole mass at once.
- Fire risk: no flammable products have been used.
- Mechanical properties: phantoms have sufficient mechanical strength.

7.4.2 TLD Dosimetry for Patient Dose Auditting

A total of seventy-eight TLDs were used in this study of which seven of them were classified as reference dosimeters and the remaining were classified as field dosimeters from which the presented results are based on. It was established that the Harshaw 3500 TLD manual reader had a reader calibration factor (RCF) of 0.511 nC/ μGy. Each TLD was characterized in terms of its element correction coefficient (ECC). It took an average of 78 seconds to read one TLD.

An initial attempt to use a single ECC factor for an individual TLD across the whole range of the available kVp proved to give unsatisfactory results, as there was a large discrepancy between the TLD measured incident air kerma and the calculated incident air kerma. Results of this initial investigation are given in Figure 7.20.

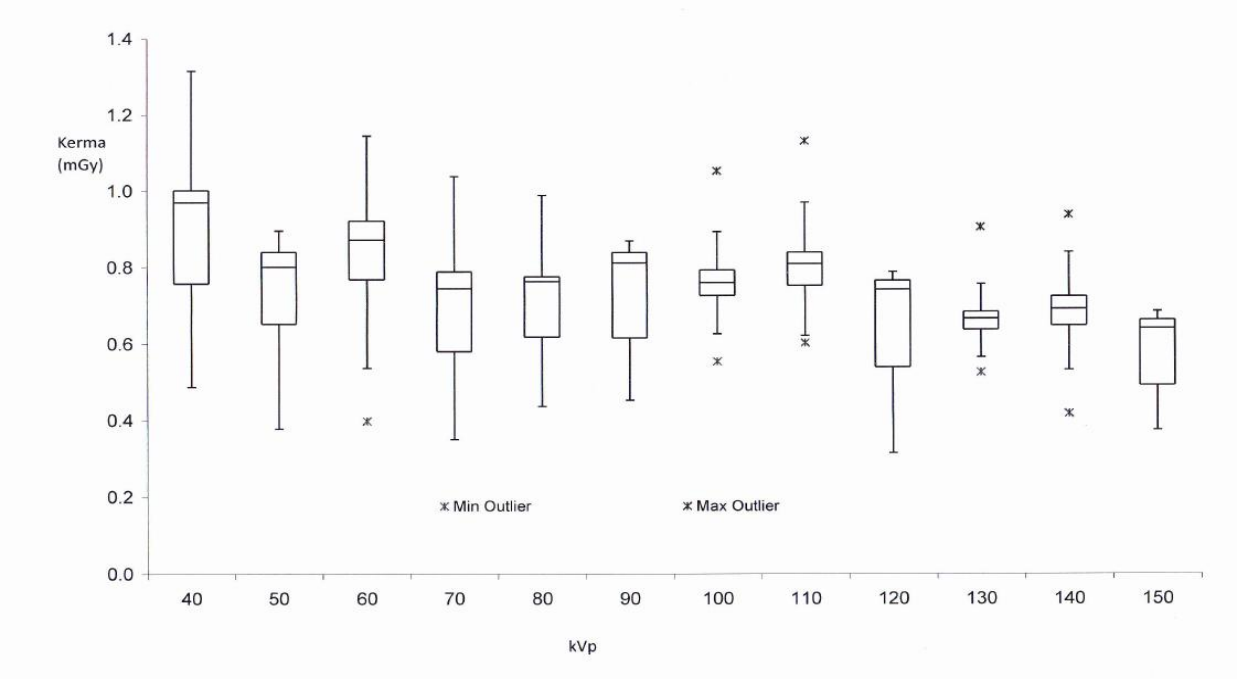


Figure 7.20: 78 TLD readings obtained after exposing dosimeters to a dose of 1.00 mGy over a range of tube voltages using a single ECC for each TLD chip.

Figure 7.20 shows that most of the TLD chips had a deviation of more than 20% from the expected reading. To improve the agreement between the TLD readings and expected reading, ECCs were established for each TLD at 10 kVp intervals from 50 kVp to 140 kVp. Figure 7.21 below shows the subsequent response of the TLDs to an incident air kerma of 1.0 mGy across a range of kVp.

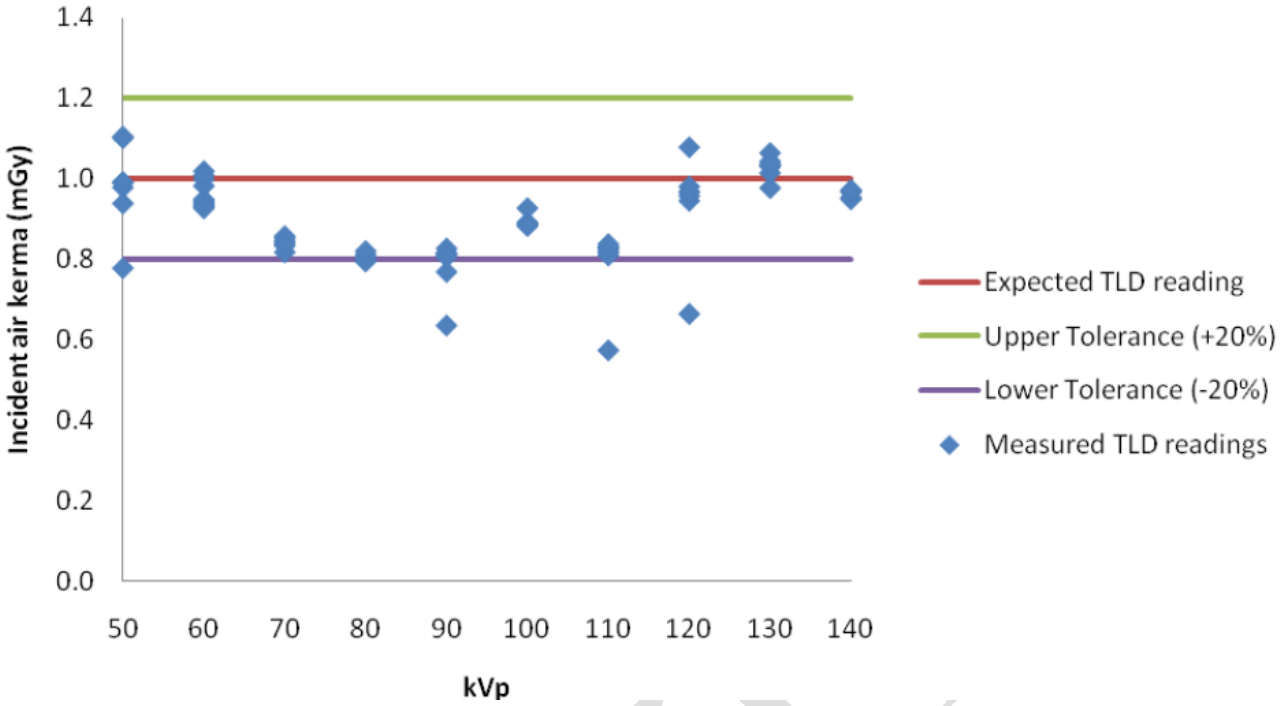


Figure 7.21: TLD readings obtained after exposing them to a dose of 1.00 mGy over a range of tube voltages.

Results of this current investigation agree with a study by Akpochafar which established that TLD GR200A response at diagnostic energies was significantly energy dependent.[171]

To further test the accuracy of TLDs, they were exposed to doses ranginging from 0.6 mGy to 17 mGy. The TLD reading was compared to the expected reading based on knowledge of the X-ray tube output obtained from ionization chamber measurements. Figure 7.22 summarises the relationship between the two methods employed.

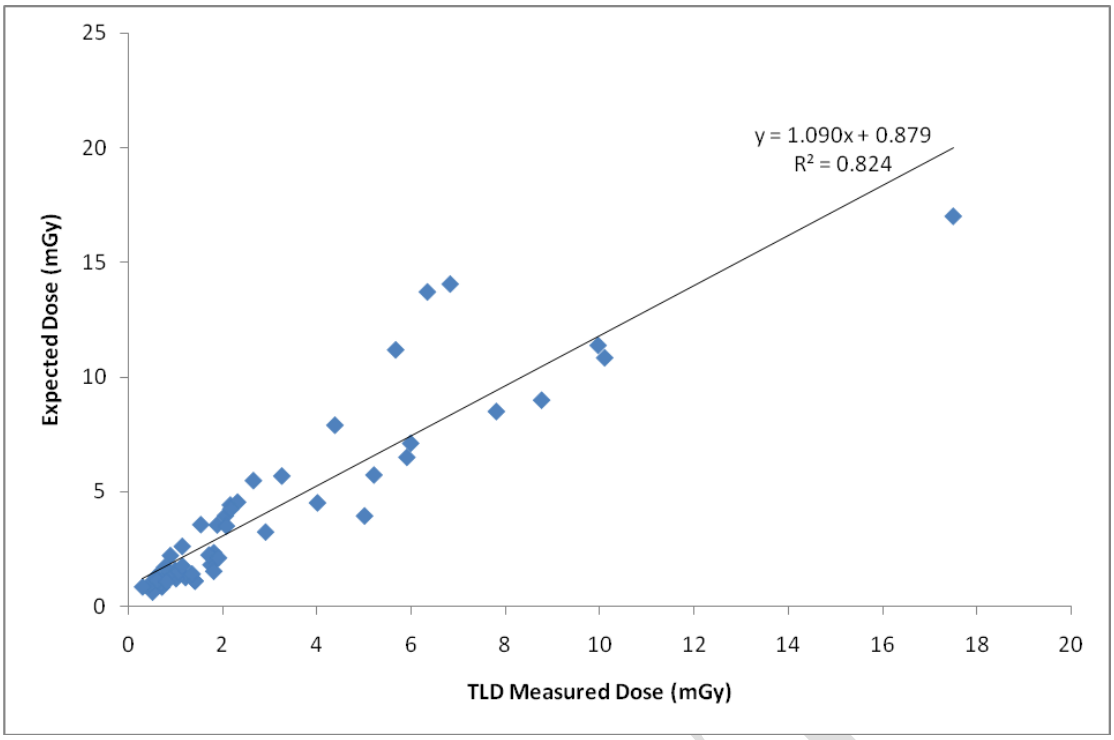


Figure 7.22: A plot of the measured TLD doses against the expected doses.

A direct proportional relationship is expected between the TLD response and the dose. Based on Figure 7.22 the use of TLD dosimetry was not pursued further as a direct method in this work. Therefore the practical approach of this work was to adopt the ionization chamber as the gold standard dosimeter. This choice was based on the fact that the ionization chamber used had a calibration traceable to the German standards of air kerma. Moreover the agreement between the expected doses and measured doses were not satisfactory, since the TLDs under-responded in most cases. In a developing country set-up where TLD facilities are not readily available to most radiology departments, thus the ionization chamber based dosimetry was adopted as a method of choice.

7.4.3 Frequency of Examinations

A survey of adult radiography examinations performed at the main X-ray department of CMJAH was conducted. A total of 14753 radiography examinations were performed during the period 02 January 2008 to 31 December 2008. The frequency distribution of the examinations is shown in Figure 7.23.

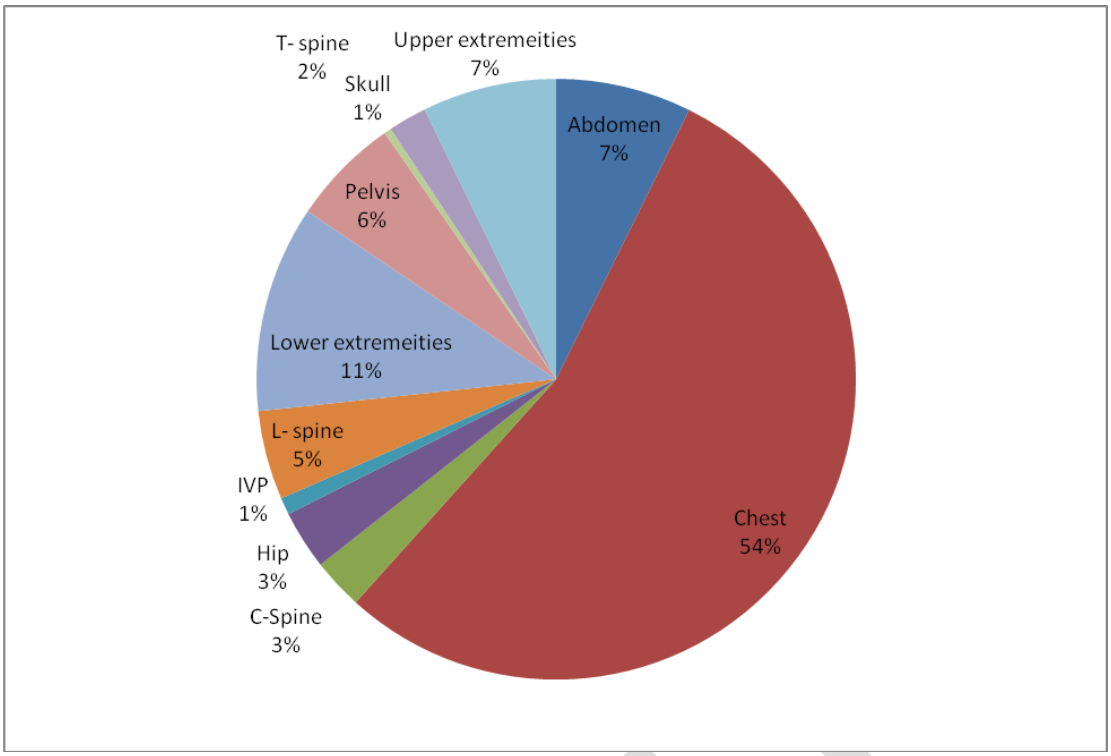


Figure 7.23: The frequency distribution of the examinations.

7.4.4 Patient Dosimetry

An analysis was done on the patient attributes who presented at the two general X-ray rooms. The mean of patient mass, height and BMI are shown in Table 7.11. Super HR – U30 orthochromatic X-ray films from FUJIFILM Corporation were used for all examinations. In addition only Agfa Curix Ortho Regular screens were used. The X-ray units used have an automatic exposure control (AEC) facility, however this facility was not used. Each room has a technique chart (exposure chart) displayed for a variety of examinations which can be performed on the X-ray unit. During the period of the dose audit the departmental combined repeat / reject rate was 1.3 %. The descriptive statistics related to the patient attributes and exposure parameters are shown in Table 7.10.

Table 7.10: Summary of the patient attributes and typical exposure parameters used.

Examination	Chest PA	Chest LAT	Pelvis AP	Abdomen AP	Lumbar Spine AP	Thoracic Spine AP
Room A1						
Number of patients	27	27	5	19	10	*****
Mean mass (kg)	75.0 (56.0-127.0) [29.6%]	75.0(56.0-127.0) [29.6%]	63.2 (60.0 – 64.0) [2.5%]	75.8 (56 - 105)[16%]	66.9 (61.0 - 74.0) [8.3]	*****
Mean height (m)	1.70 (1.52 - 1.92) [5.6]	1.70 (1.52 - 1.92) [5.6]	1.57 (1.56 - 1.62) [1.7%]	1.70 (1.56 - 1.86) [5.7%]	1.63 (1.56 – 1.70) [3.8%]	*****
Mean BMI (kg/m^2)	25.7	25.7	25.6	26.5	25.3	*****
kVp	125(109-125)[3%]	125(117-125)[2%]	63(60-64)[4%]	60(60-66)[3%]	66(60-77)[9%]	*****
mAs	1 (1.0 – 3.2) [48%]	3 (2.0 -6.3) [38%]	40 (50-63) [15%]	40 (32-100) [47%]	40 (40-100) [52%]	*****
Screen film speed	400	400	400	400	400	*****
Film size	35cm X43cm	35cm X43cm	30cm X40cm	30cmX40 cm	18cmX 43cm	*****
FFD (cm)	180	180	100	100	100	*****
Room A2						
Number of patients	22	22	8	7	8	11
Mean mass (kg)	68.1 (41.0 – 100.0) [21.4%]	68.1 (41.0 – 100.0) [21.4%]	68.1 (50.0 - 75.0) [12.6%]	67.4 (50.0-88.0) [20.3%]	56.9 (50.0 - 61.0) [2.0%]	65.8 (50.0 - 95.0) [20.6%]
Mean height (m)	1.68 (1.51 - 1.75) [3.8%]	1.68 (1.51 - 1.75) [3.8%]	1.76 (1.70 – 1.85) [4.4%]	1.60 (1.42 – 1.73) [6.1%]	1.70 (1.60 – 1.70) [1.5%]	1.68 (1.60 - 1.81) [3.6]
Mean BMI (kg/m^2)	24.1	24.1	22.1	26.5	19.7	23.2
kVp♣♦	125(109 - 125)[5%]	125(109 - 125)[3%]	63(57 - 66)[5%]	60(60 - 81)[11%]	66(60 - 90)[15%]	60 (55 - 66)[8%]
mAs♣♦	1 (1.0 – 2.25) [39%]	3 (1.6 – 4.0) [19%]	40 (22 - 40) [17%]	40 (40 - 100) [56%]	40 (32 -80) [52%]	40 (40 -100) [62%]
Screen film speed	400	400	400	400	400	400
Film size	35cm X43cm	35cm X43cm	30cm X40cm	30cmX40 cm	18cmX 43cm	18cm X43cm
FFD (cm)	180	180	100	100	100	100

***** Data not available

♣ Ranges are shown in parentheses ( )

♦ Coefficients of variation are shown in brackets [ ]

The frequency distribution of patient mass is shown in the bar chart in Figure 7.24.

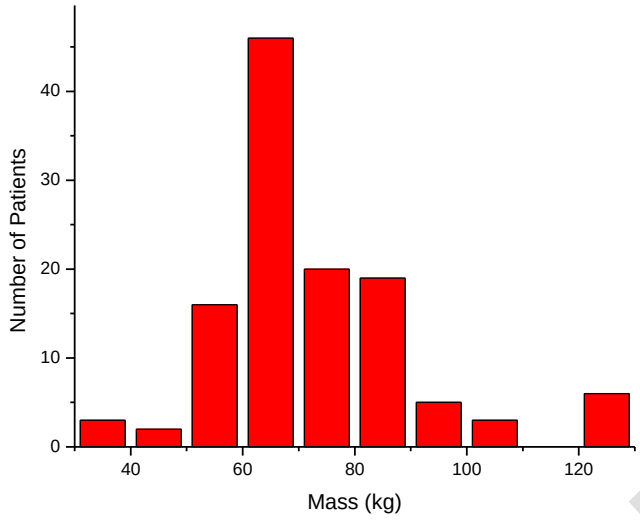


Figure 7.24: The frequency distribution of patients' mass.

Patient mass varied from 38 kg to 127 kg while patient height fluctuated from a minimum of 1.42 m to a maximum of 1.92 m. In comparison to the mAs coefficient of variation, the kVp coefficient of variation was narrower. The wide variation in mAs used for the examinations subsequently leads to wide variations in patient ESAK. Consistent with good radiographic practice a high kVp technique is being used for chest examinations. Furthermore the frequency of examinations during the period under review is shown in Figure 7.25.

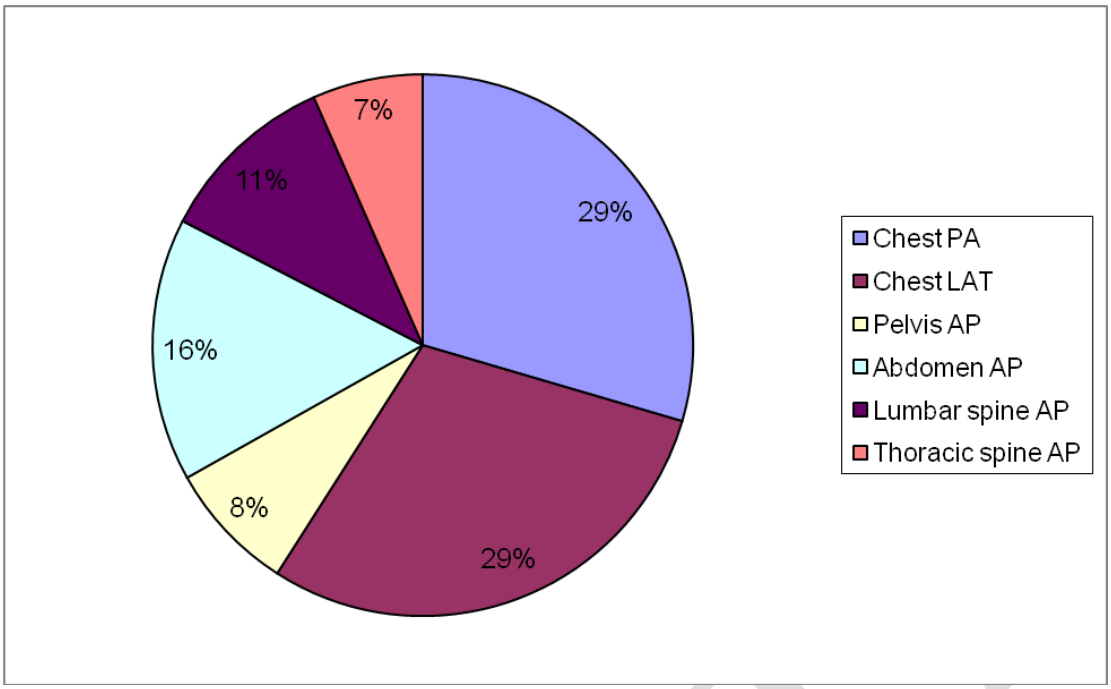


Figure 7.25: A pie chart showing total number of examination investigated according to anatomical region.

As in most radiology clinics, chest examinations were the most frequent of all the performed examinations.

7.4.4.1 X-ray tube Output

The X-ray tube output across the clinically used kVp range was calculated from the measured air kerma (K(d)) using equation 6.2. The x-ray tube output at 125 kVp was calculated as 0.0991 mGy/mAs and 0.0997 mGy/mAs for the A1 and A2 units respectively. The x-ray tube output was measured at 100 cm from the X-ray source and for an added filtration of 1 mm Al.

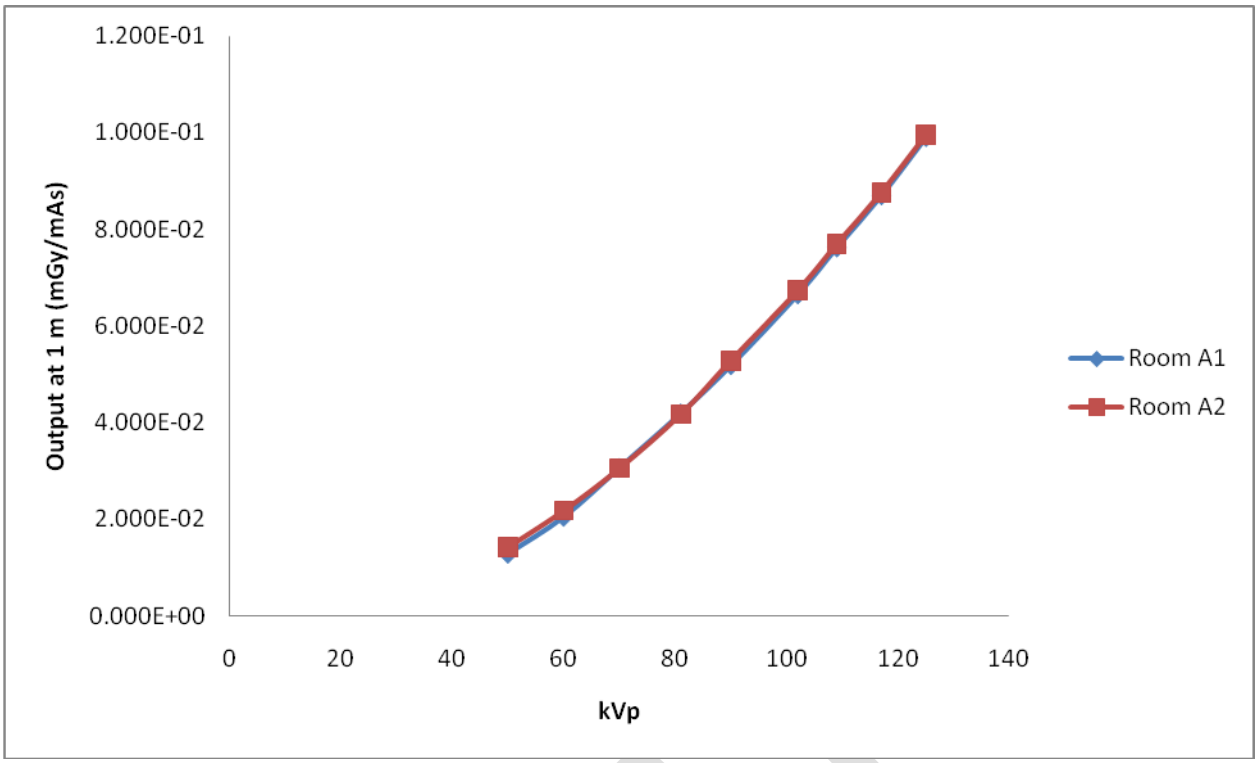


Figure 7.26: The X-ray tube output from the two imaging rooms.

During the period of collecting the data, the X-ray tube output constancy check was done prior to data collection and was found to be within ± 5% of its baseline value (first day output).

7.4.4.2 ESAK Measurements and Calculations

A total of 166 ESAK calculations were done based on the exposure parameters used for the particular examination and on the measured x-ray tube output. The descriptive statistics (mean, minimum, maximum, median e.t.c.) of the ESAK values from the two x-ray rooms are given in Table 7.11.

Table 7.11: Distribution of ESAK values in mGy for the different examinations.

Examination	Chest PA	Chest LAT	Pelvis AP	Abdomen AP	Lumbar Spine AP	Thoracic Spine AP
ESAK						
Room A1						
Minimum	0.05	0.12	3.16	1.58	2.20	*****
Mean	0.10	0.23	3.73	2.98	5.63	*****
Median	0.08	0.20	3.51	2.72	4.78	*****
Maximum	0.20	0.44	5.16	5.43	11.22	*****
Max/Min ratio	4	3.7	1.63	3.4	5.1	*****
Standard deviation	0.03	0.08	0.83	1.16	3.15	*****
Room A2						
Minimum	0.05	0.07	1.25	2.36	1.75	2.33
Mean	0.09	0.19	1.84	4.59	4.32	3.28
Median	0.08	0.20	1.90	3.14	4.16	2.99
Maximum	0.15	0.26	2.50	13.78	8.31	4.91
Max/ Min ratio	3.0	3.7	2.0	5.8	4.7	2.1
Standard deviation	0.02	0.04	0.40	4.07	2.43	0.90
Mean Room A1 ESAK / Mean Room A2 ESAK	1.11	1.21	2.02	0.65	1.30	*****

***** Data not available

In comparison with other published studies, the ratio of the maximum ESAK to minimum ESAK is moderate, having a maximum of approximately 6 for the patient examinations studied. Despite the two rooms having x-ray units of the same make and same technique

chart, there was a significant variation in the mean ESAK particularly for pelvis AP and abdomen AP examinations.

From these ESAK values the global mean was established based on the mean ESAK values per examination from each room. The mean ESAK values were compared with results from international studies as shown in Table 7.12 [38,44,45,48,174].

Table 7.12: Established mean from this study compared with results from national and international recommendations.

Examination	This study	Brazil[174]	UK[38]	Iran[49]	IAEA [175] ♠	IAEA[45]
mGy						
Date of study		2009	2005	2008	2004	2008
Chest PA	0.10	0.35	0.15	0.41	0.40	0.33
Chest LAT	0.21	0.96	0.60	2.07	1.50	[10]
Pelvis AP	2.79	[11]	4.00	3.18	10.00	3.68
Abdomen AP	3.79	[12]	4.00	4.06	10.00	3.64
Lumbar spine AP	4.98	6.60	5.00	3.43	10.00	4.07
Thoracic spine AP	3.28	[13]	4.00	2.72	7.00	[14]

♠ DRLs based on a screen film relative speed of 200. To compare with this study, values should be multiplied by 2.

[10] No data available
[11] No data available
[12] No data available
[13] No data available
[14] No data available

Furthermore, based on the mean ESAK values the DRLs were established at a third quartile level. The established DRLs from this study are given in Table 7.13.

Table 7.13: Established DRLs from this study.

Examination	DRL (mGy)
Chest PA	0.10
Chest LAT	0.22
Pelvis AP	2.98
Abdomen AP	4.19
Lumbar spine AP	5.30
Thoracic spine AP	3.28

7.4.4.3 Potential Dose Saving Practices

There are a number of changes, which can be implemented in practice to further decrease the dose to the patient. Patient dose is influenced by a host of factors: exposure factors, technique, FFD, film-screen speed, equipment type and age, film processing equipment and patient size[176]. In this study possible optimization strategies were not implemented but were however highlighted to management at the Division of Radiology. The possible options are discussed below:

Introduction of filters into the X-ray beam will lead to absorption of the low energy photons in X-ray spectrum, which would have nonetheless not reached the detector and thus give unnecessary dose to the patient. During the dose audit all examinations were currently being taken with a 1 mm Al filter, yet the units provide a range of filters. The effect of different levels of added filtration is shown in Figure 7.27.

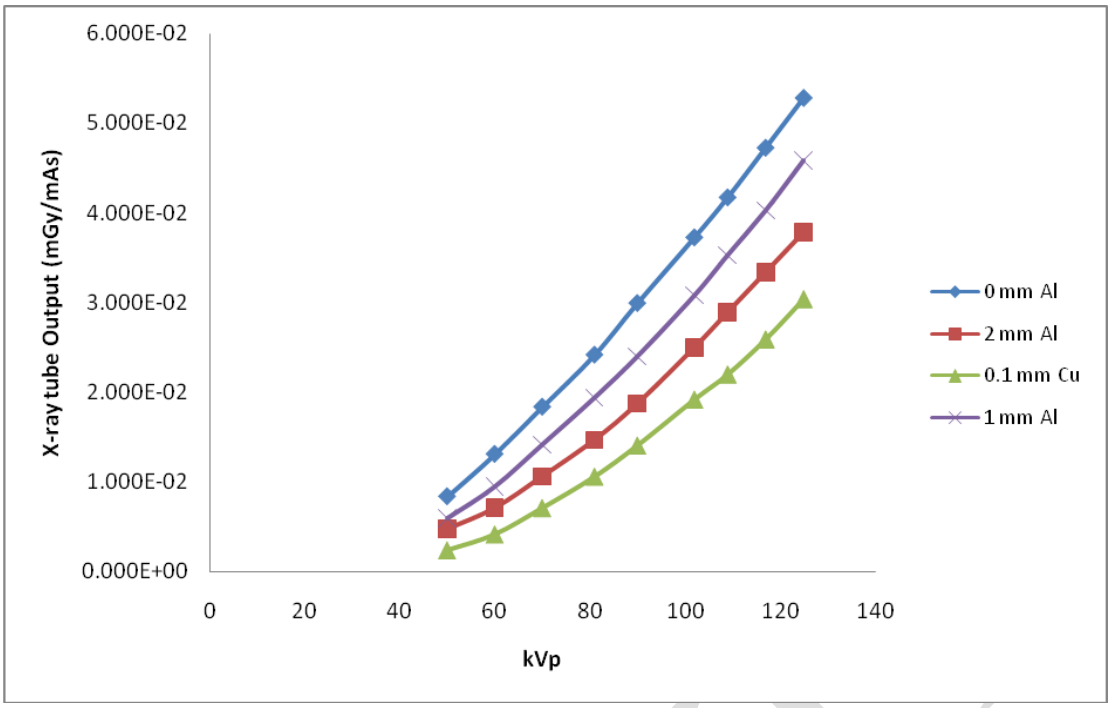


Figure 7.27: A comparison of the X-ray tube output for various filters.

For example, in Figure 7.27 the use of say a 0.1 mm Cu filter instead of the 1 mm Al filter at 125 kVp proved to deliver less dose, as it reduces the X-ray tube output by a factor of one-and-half without necessarily degrading image quality. A 1 mm Al filter does not electrically burdern the X-ray tube and thus does not shorten the tube's life span.

Furthermore the effect of beam filtration can be demonstrated by use of the software SpeckCalc[177-178].

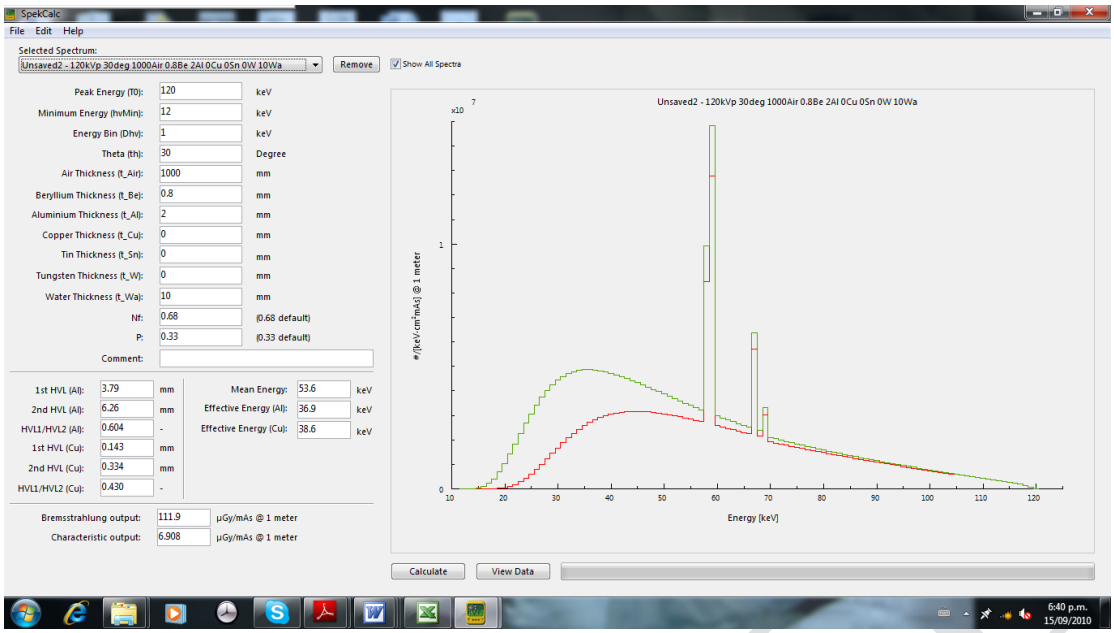


Figure 7.28: A demonstration of the use of the SpeckCalc software to show the effect of filtration on the X-ray spectrum.

For example in Figure 7.30 the green line represents a 120 kVp beam with 0.8 mm beryllium and 2.0 mm aluminium added filtration while the red line is from the same beam with the following added filtration, 0.8 mm beryllium, 2.0 mm aluminium and 0.1 mm copper. From the Figure 7.28 it is clear that the 0.1 mm Cu filter significantly decreases the amount of the low energy photons. This software can be used to pedagogically demonstrate the effect of filtration and thus be used as a workplace training tool.

Evaluation of radiographic exposure parameters is part of the dose optimization process. The imaging protocols have to be compared with other protocols which have proved to have less dose for optimum image quality. The tube potential used for the various examinations was compared with those recommended by the EU and New Zealand National Radiation Laboratory (NRL) [150,179]. Table 7.14 compares the kVps used in this study to those recommended for general good practice.

Table 7.14: A comparison of kVp used at CMJAH with those recommended by EU and NRL [150, 179].

Examination	This study	EU	NRL
	kVp	kVp	kVp
Chest PA	125	125	100 – 150
Chest LAT	125	125	100 – 150
Pelvis AP	63	75 – 90	70 – 90
Abdomen AP	60	*****	*****
Lumbar spine AP	66	70 -90	70 – 90
Thoracic spine AP	60	*****	*****

High kVp techniques can lead to use of low mAs and thus effectively reduce patient doses. Furthermore the focus to film distance according to the departmental technique chart used for the various examinations was compared with those recommended by the EU and New Zealand National Radiation Laboratory (NRL)[150, 179].

Table 7.15: A comparison of the focus film distance at CMJAH with those recommended by EU and NRL.

Examination	This study	EU	NRL
	cm	cm	cm
Chest PA	180	180 (140 -200)	180 (140 - 200)
Chest LAT	180	180 (140 -200)	180 (140 - 200)
Pelvis AP	100	115 (110 -150)	115 (100 – 150)
Abdomen AP	100	115 (110 -150)	115 (100 – 150)
Lumbar spine AP	100	115 (110 -150)	115 (100 – 150)
Thoracic spine AP	100	*****	*****

A change of the FFD from 100 cm to the recommended 115 cm brings about a change in the ESAK by nearly 20%. However, the significant reduction of the ESAK does not necessarily translate to a considerable reduction in effective dose to the patient[176]. In addition any change in FFD should be done in consideration of the grid being used, as this can lead to image artifacts as discussed in Section 5.7.

One of the easiest ways of reducing patient doses is to use low mAs techniques. For consistent image quality the automatic exposure control (AEC) chambers should be well calibrated. The radiographers' generally preferred to manually set the mAs. Therefore the use of the AEC facility is highly recommended.

7.5 Non -Clinical Image Quality Assessment

A replica of the CDRAD contrast-detail phantom (Artinis Medical Systems BV, Netherlands) was fabricated in-house. Drill pattern number 2 was used for this phantom[146]. All the drill bits below a diameter of 1 mm had to be purchased from the local hardware supplier. Lead ball bearings were used to mark the boundary of each individual square element making up the phantom.

The fabricated CDRAD phantom consists of a 10 mm thick and 265 * 265 mm^2 PMMA tablet in which cylindrical holes are drilled of varying depths (0.3 -8.0 mm) and diameters (0.3 – 8.0 mm). The phantom consists of 15 rows and 15 columns in which rows contain holes of constant diameter but exponentially increasing depth and columns contain holes of identical depth and exponentially decreasing diameter.

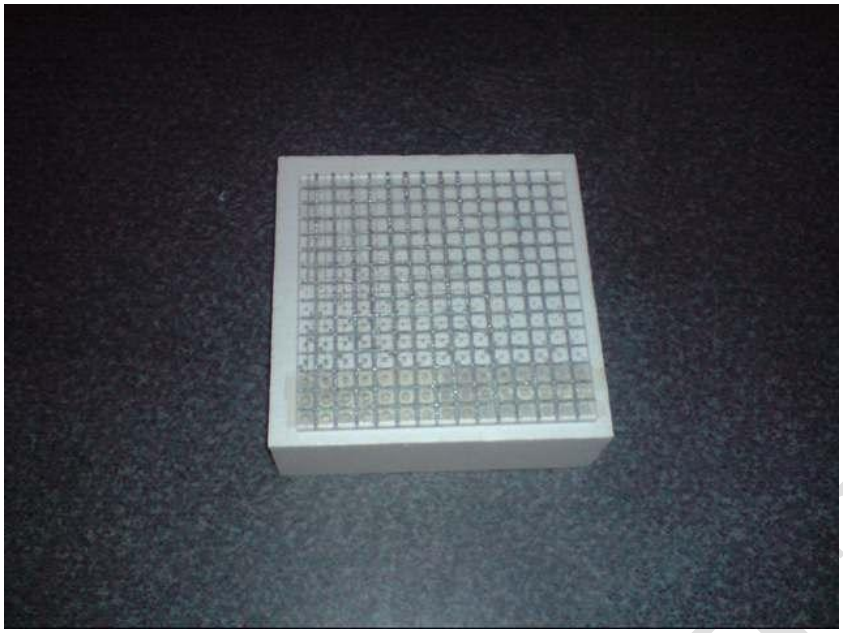


Figure 7.29: A photography of the fabricated CDRAD contrast-detail phantom placed on top of a polystyrene foam block.

The first three rows have only one hole at the centre of each individual square element. The remaining rows have one hole at the centre and another one at a randomly chosen position in one of the four corners of the square element.

The fabricated replica of the CDRAD phantom was used to assess the following aspects of image quality in a radiology department:

- comparing different radiographic techniques
- comparing image quality from different X-ray units

7.5.1 CDRAD Contrast –Detail Study

This study aimed to show typical application of the CDRAD contrast detail phantom in the clinical setting as a proof-of-principle. A couple of parameters which influence image quality as assessed by use of a contrast detail phantom were investigated. Every image acquired was read by 3 independent observers. Contrast detail curves were computed and plotted for each investigation.

7.5.1.1 Evaluation of Image Quality as a Function of kVp

In general a high tube voltage technique is advisable, however the choice has to be judicious as the tube voltage affects image contrast. Figure 7.30 below shows the mean contrast detail curves of images taken using 60 kVp and 80 kVp.

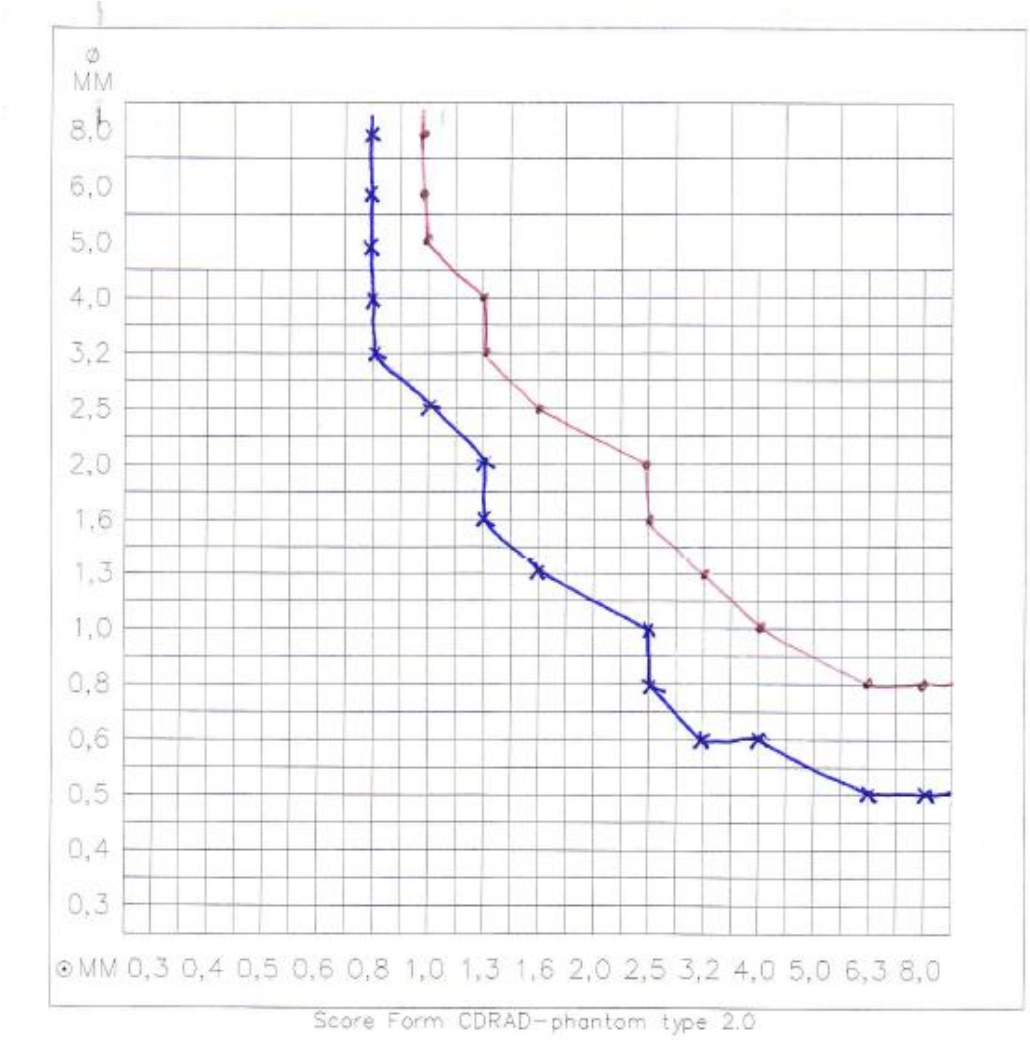


Figure 7.30: A contrast detail curves at 60 kVp (blue) and 80 kVp (red).

The images taken at 60 kVp showed more detail in comparison to those taken at 80 kVp.

7.5.1.2 Evaluation of Image Quality as a Function of Phantom Thickness

Patient or object thickness has an effect on image contrast. The effect of phantom thickness obtained by sandwiching the CDRAD phantom was investigated. The PMMA blocks sandwiching the CDRAD phantom were symmetrically distributed around it. Three phantom thicknesses were investigated, namely 16 cm, 14 cm and 12 cm. In addition the phantom

arrangement was imaged using 60 kVp. Figure 7.31 demonstrates the general loss of contrast as the phantom thickness decreases for the same tube voltage.

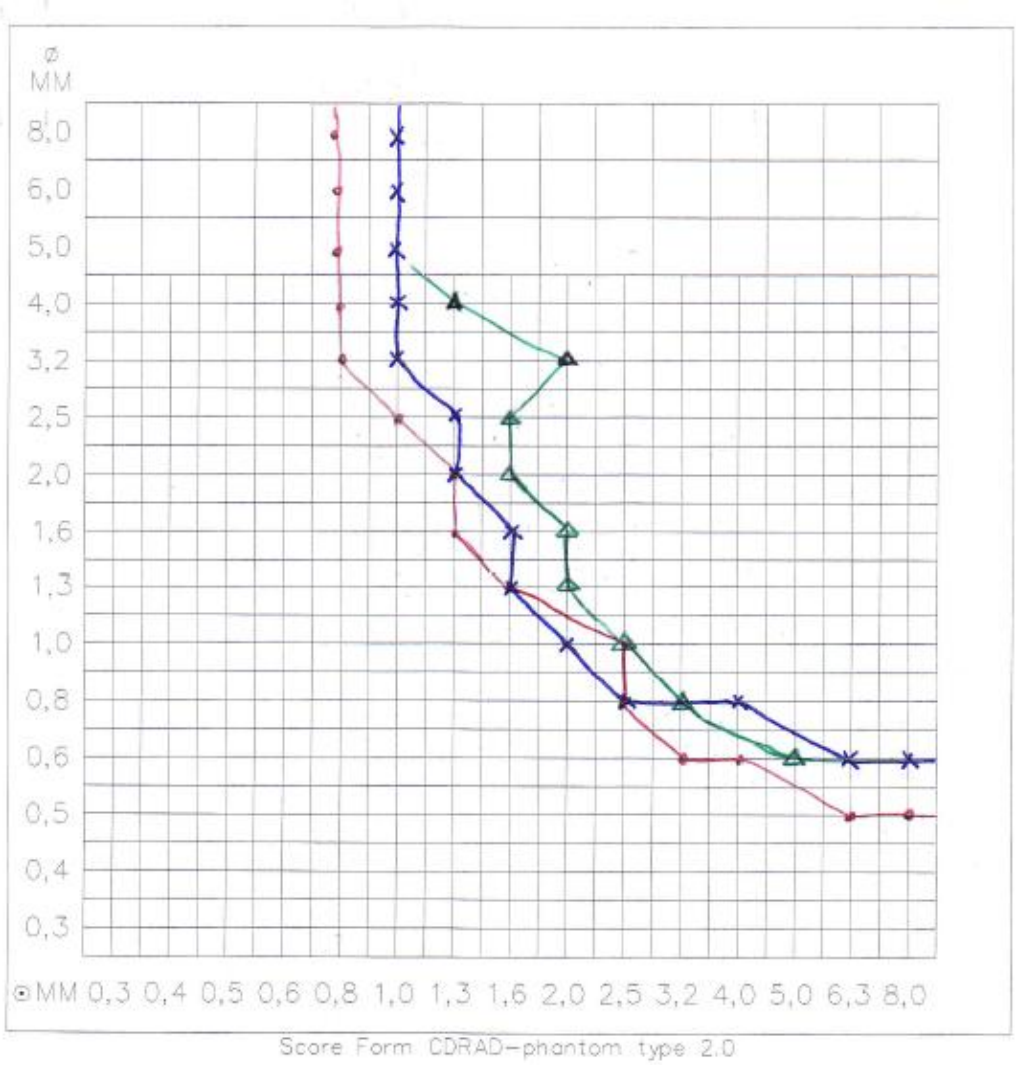


Figure 7.31: A contrast detail curves for different phantom thickness: 16 cm (red), 14 cm (blue) and 12 cm (green).

7.5.1.3 Evaluation of Image Quality Between Different X-ray Units

Different imaging units will have different image quality as a result of the engineering make-up. As an example the CDRAD phantom was imaged using two X-ray units and the resulting images were compared using contrast-detail curves. The same exposure parameters were used across the two units.

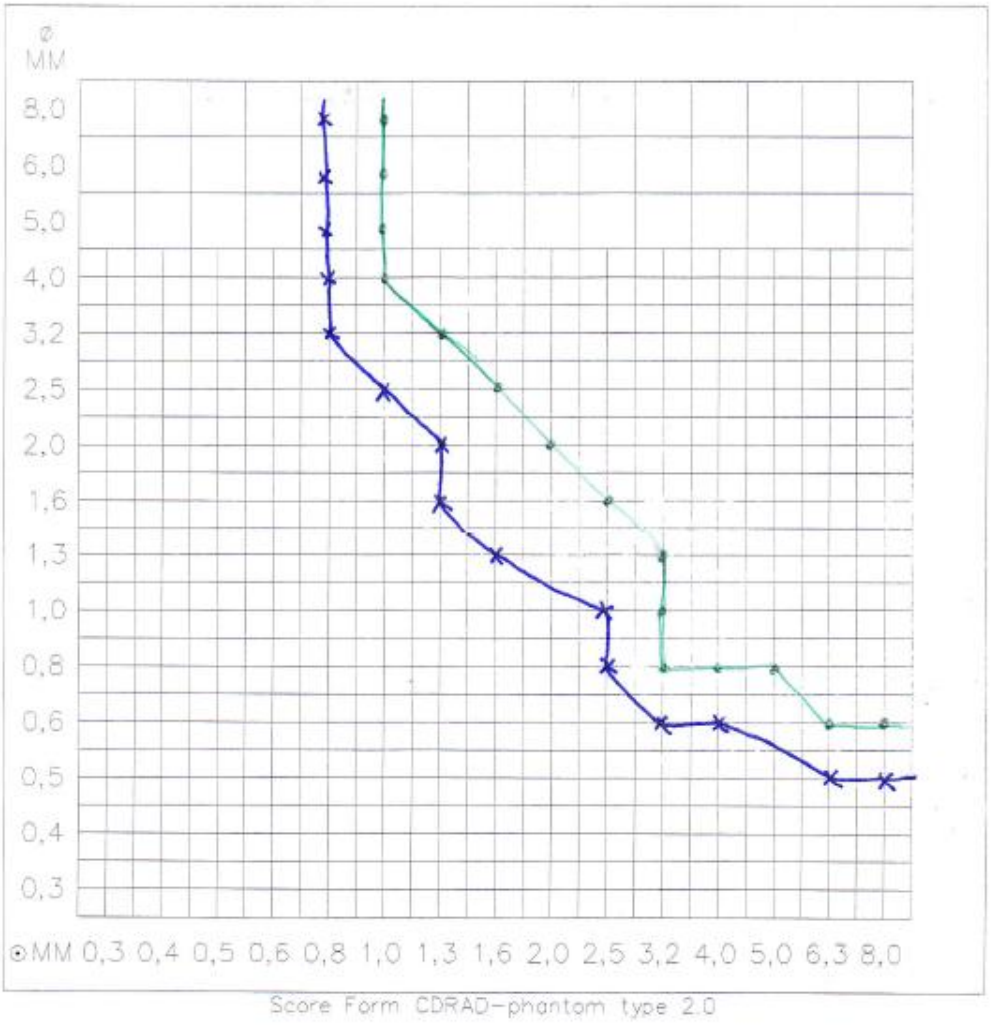


Figure 7.32: A contrast detail curves at Unit 1 (blue) and Unit 2 (green).

Based on Fig 7.34 Unit 1 has superior image quality in comparison to Unit 2. This reinforces the use of the CDRAD phantom for monitoring image quality performance of X-ray units.

7.6 Digital Radiography Practice and Technique

Sixty-three out of 205 (31 %) radiographers from the four public radiology centres responded to the circulated questionnaire. Among those who responded were ten student radiographers and fifty three qualified radiographers employed on a full-time basis. Because of the small numbers, student radiographers participating in the survey from each hospital were combined with qualified radiographers as shown in Table 16.

Table 7.16: Response rate based on returned questionnaires according to hospitals.

Hospital	Radiographers who participated in the study			Total
	Qualified Radiographers	Student Radiographers	Total participating (%)	
A	8	3	11 (15)	73
B	21	0	21 (41)	51
C	10	1	11 (28)	39
D	14	6	20 (48)	42
Total	53	10	63 (31)	205

Hospital D had the greatest response rate among the participating hospitals. Despite the poor response in some hospitals, the data collected provided some insights and lessons and was nonetheless useful. As such interpretations from this study should be viewed as exploratory and illuminative. Radiography techniques were not compared between the participating institutions.

In terms of modalities Hospitals A and D currently use flat panel based digital radiography units whereas Hospital B uses both computed radiography and flat panel based digital radiography units while Hospital C is currently using computed radiography units only. The equipment manufacturers are varied and included Philips Medical Systems, Siemens Medical, GE Medical Systems, Toshiba, Agfa, Fuji, Kodak and Konica Minolta. However, the interest of this present study was not to compare manufacturers.

All the qualified radiographers had post qualification experience ranging from 1 year to more than 5 years. Post qualification experience was further stratified by whether such experience included digital radiography technology. Figure 7.33 shows the distribution of post qualification experience according to the radiography modality.

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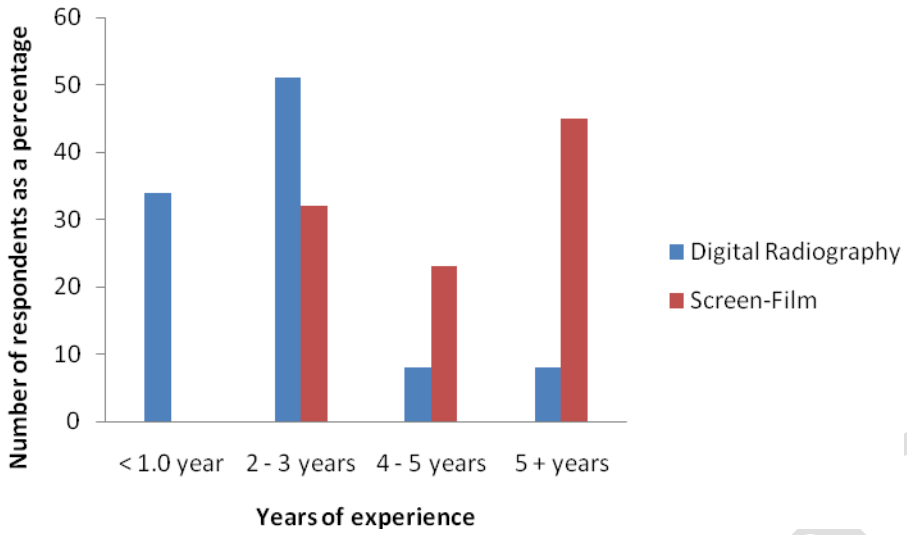

Figure 7.33: A bar chart showing post qualification experience stratified by imaging modality.

The above distribution confirms the fact that digital technology is still a relatively new technology to the South African radiography workforce public hospitals, only 15 % (8) of the qualified radiographers had 4 years or more of experience with digital radiography compared to 68 % (36) for the same amount of experience with screen-film radiography.

Table 7.17 provides a summary of key responses from radiographers based on the questionnaire administered. This has not been broken down into qualified and student radiographers because of the small number of students involved.

Table 7.17: Summary of key responses from study by participants.

Factor of interest		Number (%)	Total*
Training in digital radiography (DR)			
	Had formal education on DR	38 (61)	62
	Had formal training on DR quality control	10 (16)	61
	Thourough reading of the digital unit's manual	14 (23)	60
	Easier to perform retakes in DR	33 (55)	60
Comparison between digital and screen-film radiography based on participants opinion			
	Has superior spatial resolution	43 (71)	61
	Has superior image quality	45 (74)	61
	Gives relatively more radiation dose to the patient	30 (51)	59
	Has a wider dynamic range	50 (91)	55
Preference in digital radiography			
	Collimate rather than crop image	55 (89)	62
	Use grids	63 (100)	63

Note: *Total – varies because some few participants did not provide responses to specific questions.

Presently radiography training in South Africa involves academic teaching at a university and clinical practice at a university hospital. Sixty-one percent (38) of the participants had been exposed to digital radiography during their lectures while at university. A small proportion, 16 % (10) of the respondents underwent formal training in quality control procedures on the digital X-ray units they were using. The training was conducted by the relevant manufacturer's representative. However, none of the surveyed departments had or were following a particular written protocol on quality control procedures, although there was a designated radiographer responsible for quality control. Twenty-three percent of the respondents had managed to read the manual of the digital X-ray unit they were operating. Slightly more than half (55 %) of the participants felt it was easier for them to retake an

image in digital radiography than in screen film radiography. Fifty-five percent of the respondents preferred to collimate to the region of interest instead of cropping the image after acquisition.

In an open-ended section of the questionnaire, participants were asked what they thought the advantages of digital radiography were. The responses varied, but some reported advantages were common to most participants. Table 7.18 shows the five most popular advantages cited by the respondents.

Table 7.18 The most commonly cited advantages of digital radiography over screen-film radiography (n=63).

Cited advantage	Number of respondents (%)
More patients treated	34 (54%)
Post processing capabilities	18 (29)
Reduced radiation dose	18 (29)
Superior image quality	17 (27)
No wet processing	12 (19)
Other	34 (54)

One of the commonly cited advantages of digital radiography is the increase in patient throughput. In response to the question of how many patients they could image, a median of 20 patients and 50 patients could be imaged per eight-hour shift in screen-film radiography and digital radiography with inter-quartile ranges of (15-45) and (25 – 108) respectively.

Consistent with the fact that the participants are from public teaching hospitals the most commonly cited disadvantage of digital radiography was its "press button" approach. The digital radiography user interface takes away the fundamental radiography technique training i.e. exposure settings, which is core to the art of screen-film radiography.

Some of the participants' responses were not reported on because the response rate to the particular question was poor. Inclusion of all responses would have introduced attrition bias to the study.

7.7 Scatter from Under-couch Procedures

A Toshiba Medical Systems Corporation radiotherapy simulator unit was used for this study. The unit uses a model KXO-50XM diagnostic X-ray high voltage generator and has an inherent filtration half value layer of 1.8 mm Al at 70 kVp.

Prior to the scatter measurements, the percentage transmission of the couch was measured using an ionization chamber for a 10 cm X 10 cm field. The percentage transmission was measured over a range of kVps (50 – 125 kVp) in steps of 10 k Vp in between the range. Over the range of kVps an average percentage transmission of 78% (standard deviation 3%) was calculated for the couch.

The PPS to PR ratio was defined as the ratio of the charge collected using the experimental set-up in Figure 6.6 to that collected using the experimental set-up shown in Figure 6.5. A scatter plot of the measured ratio of the total scatter beam to the "primary" beam is shown in Figure 7.34.

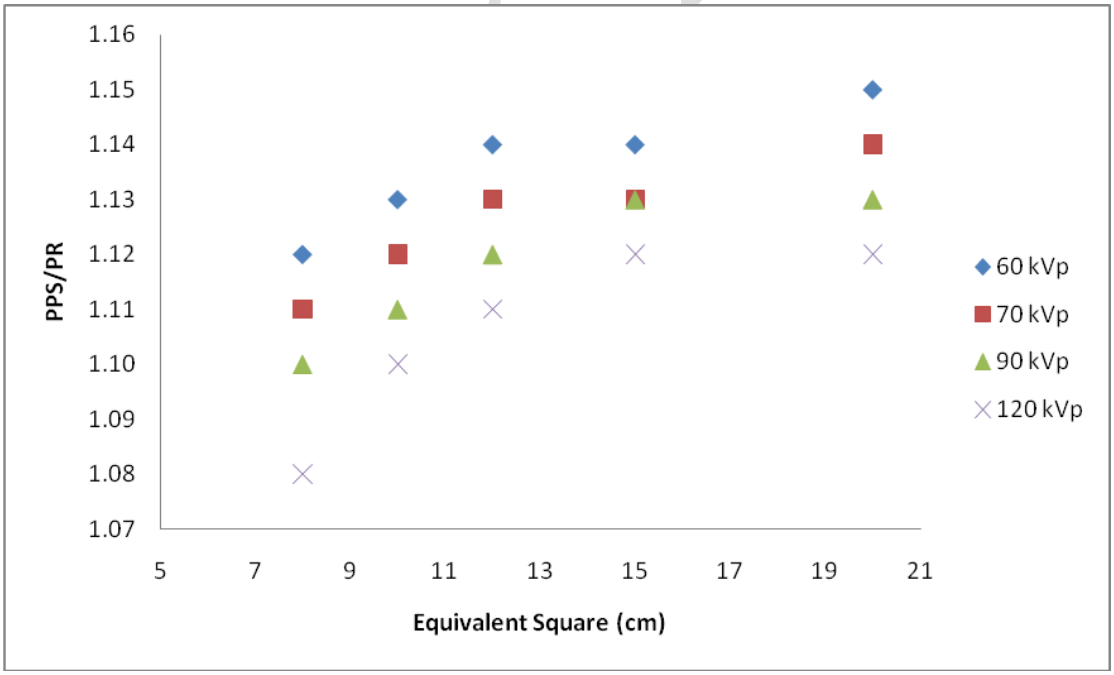

Figure 7.34: The ratio of the measured primary radiation to the total (primary plus scattered) radiation plotted against field size for different beam kilovoltages.

From Figure 7.34, the scatter contribution ranges from 8% to 15 % depending on the beam kilovoltage and field size. As expected the scatter component increases with field size. Furthermore the measured ratios of PPS to PR were normalised to the 10 cm * 10 cm field size SPR. A scatter plot of the normalised PPS/ PR is shown in Figure 7.35.

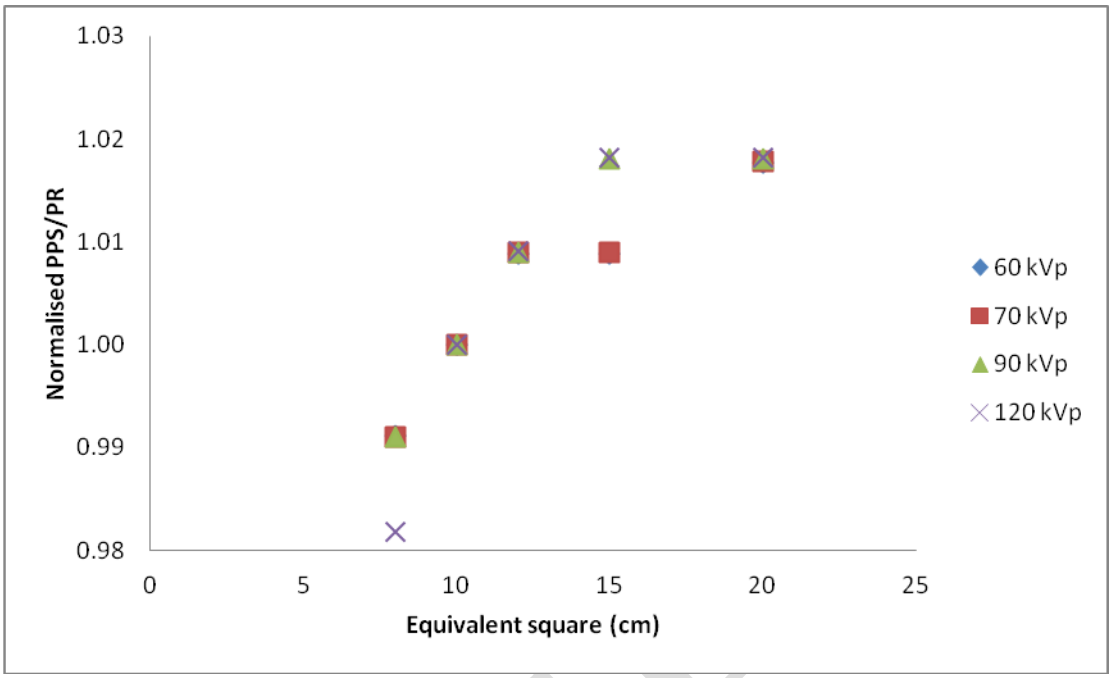

*Figure 7.35: The ratio PPS/ PR at different beam kilovoltages normalised to a 10 cm * 10 cm field size.*

Scattered radiation is inevitably generated within the patient support system. Figures 7.34 to 7.35 demonstrates the contribution of scattered radiation as a result of having a carbon fibre patient support in the way of the X-ray beam. From Figure 7.35, for a reference field size of 10 cm * 10 cm, the scatter contribution varies by a maximum of ±2% with field size. Thus for accurate clinical dosimetry the effect of forward scattered radiation from the couch needs to be factored into the patient skin dose.

CHAPTER EIGHT

DISCUSSIONS

8.1 Quality Control of Radiography Viewing Conditions

If the whole radiographic process chain is to be fully optimized it becomes imperative for viewing box luminance and ambient lighting to be optimal. The viewing box luminance, ambient lighting, viewing distance will to some degree influence what the radiologist perceives. The DRC, NORDIC and EC recommendations on the measured quantities in this study are not in total agreement and it would be a good idea for the radiology community to harmonize these guidelines worldwide or alternatively adopt one set of guidelines from one organization[180]. From the practical experience of this work it is recommended that the DRC criteria be adopted by radiology clinics in South Africa.

After 2000 hours of use the luminance of fluorescent tubes decreases by approximately 10%[181]. The American College of Radiology (ACR) recommends replacement of fluorescent tubes after every 18 to 24 months. This could explain the high level of viewing box luminance uniformity at the Division of Radiation Oncology as the division was opened in 2006. To improve the viewing box uniformity at the Division of Radiology it was suggested that the viewing boxes be cleaned and the fluorescent lamps be replaced regularly. The effect of the continual use of non-compliant viewing boxes can be determined by conducting observer performance studies.

The EC recommends that the ambient lighting be measured at a distance of 1 m, thus compliance with the European guidelines was not analyzed since we measured the quantity at a distance of 30 cm, this being premised on the assumption that a distance of 30 cm approximates the distance between the viewer and the viewing box in most clinical settings.

The average luminance is a better indicator of the viewing box luminance than the central luminance. This is confirmed by the greater standard deviation in the mean central luminance than the standard for the mean average luminance as shown in Table 7.0. It is thus recommended that the average luminance be used as a quality control metric for viewing box luminance.

Despite the widespread use of screen-film technology in developing countries there is a gradual shift to digital X-ray systems and this could be ultimate solution to viewing box luminance which is non-optimal and having a detrimental effect on radiograph reporting. The use of digital systems opens way for other viewing options like use of video monitors, printing the image on paper and the use of picture archiving and communication systems (PACS) which have the advantage of doing away with the cost of film, chemicals and processor equipment, but which also has its quality control demands. A study by Goo *et* al showed that monitor luminance and ambient light had little effect on observer performance in soft-copy reading of digital chest radiographs provided adequate windowing and levelling was used [182]. The quest for optimal viewing conditions is not only restricted to viewing box performance but should be extended to ensure adequate ergonomics at workstations, as human factors like fatigue have been shown to lead to diagnosis inaccuracy.

8.2 Custom Made Quality Control Software

The software program developed promotes data collection for quality assurance and serves as a database for easily identifying and managing trends and subsequent corrective measures. In the present South African scenario where there is a shortage of medical physicists who would otherwise be in-charge of the quality assurance programs, a computer program which can be used for collection, analysis and archiving of data is helpful. In most cases the QA would be done by someone who is not necessarily trained in that aspect or lacks the in-depth understanding of the results and analytical skills. Use of a computer program allows for data collection, archival and subsequent analysis by a medical physics expert. For any meaningful long term deductions on the performance stability of a piece of equipment to be made, there needs to be an archive of test results which can readily be captured for analysis, and this application package offers that by virtue of being digital in nature. Furthermore recording and archiving of QC results implies a level of evidence based practice.

Use of the graphical display, the green and red flag system on the results makes decision making on the suitability of equipment for clinical use easy. In addition software has the advantage of minimizing transcription errors. Furthermore the software's capability to rapidly retrieve QC related information allows the user to assess the data rapidly and efficiently.

Softcopy data collection lends itself to a possibility of further data analysis which could be potentially utilised by institutions like the DRC in multi-centre QA data analysis. Instead of sending loads of hard copy QC results to the DRC for annual inspection, potentially one can email the Excel files, which is comparatively easier, faster and user-friendlier.

Argus ™ software is one example of the commercial radiological QA software packages which can be purchased from vendors[183]. Despite the fact that these software packages are not affordable to most clinics, their test criteria is not necessarily designed to the fulfilment of national requirements. Therefore the "home-grown" package is a realistic alternative to a commercial software packages.

Over the years medical physicists have written computer software to support their scientific, educational and clinical endeavours. Writing any software for use in the clinic poses a number of challenges given the potential devastating effects of any malfunctioning computer program[184]. As such all potential users of this software are welcome to identify any bugs and make suggestions for potential improvements in its design.

8.3 Fluoroscopy Procedures Dose Audit

X-ray examinations involving fluoroscopy and interventional examinations contribute significantly to the total collective dose due to medical exposure even if their frequency is relatively low[185]. Given this background, fluoroscopic examinations and procedures deserve aggressive dose optimization methods. The legal requirement by the DRC to have KAP meters installed on all fixed fluoroscopy units lends itself to real time monitoring of patient doses and routine patient dose recordings during fluoroscopically guided procedures. Recording of KAP values make dose watching possible, for example an expected band of KAP values can be established for each procedure. For example, should KAP values consistently exceed this band, an investigation needs to be done, however, if the KAP values are consistently below the band at optimum image quality then the band needs to be updated.

During the period under review, some patients did not have their KAP reading or skin dose recorded after an examination. However, the recording process has significantly improved since then. The documentation process was still in its initial phase for the period under review so it was assumed that some radiographers were not yet used to recording the data and would

tend to forget. The division's decision to start recording KAP readings on 14 August 2007 paid dividends as by 01 January 2008 the process was fully compliant to the DRC's requirements, presumably radiographers were used to the workflow process. In addition, it is good workmanship to document all the patient examination related parameters for the purposes of comparison with other radiology departments and also as a quality control measure with the aim of continuously improving the process. In addition the referring physician can be notified on those patients with a high KAP or *skin dose* reading for further long-term monitoring and follow-up.

The Philips MultiDiagnost Eleva unit displays the KAP and *skin dose*. However what the manufacturer calls *skin dose* is actually air kerma. Skin dose would need to include backscatter factors and the unit does not have a bank of the appropriate backscatter factors. The displayed air kerma is referenced to the interventional reference point (IRP) which is a point 15 cm from the isocenter towards the focal spot[186]. The position of IRP depends on the height of the couch, the angulations of the beam and the size of the patient. Depending on the geometry, the IRP may lie outside or inside the patient, or may coincide with the patient skin surface. Since the IRP moves relative to the patient as beam angulation changes, the cumulative air kerma is usually an overestimate of skin dose. However for situations where the IRP is at the skin or closer to the skin, the cumulative air kerma will be a good approximation of skin dose.

The calculated KAP DRLs from this study are considerably higher than the published UK DRLs [38]. UK DRLs are from a wide range of centres, whereas these results are from a single referral university teaching hospital which arguably does complicated procedures. Some of the procedures were done by registrars, since they are still learning this may explain the generally higher doses delivered to patients. However some studies have reported KAP values higher than those presented here, for example a nationwide Swiss study established 60 Gy cm^2 and 150 Gy cm^2 as DRLs for barium meal and barium enema respectively compared to 27 Gy cm^2 and 70 Gy cm^2 for the same procedures as established from this study [54]. Despite the use of a single dedicated fluoroscopy suite there was a wide variation in measured skin doses and KAPs within any type of examination. CMJAH is a training institution and this variation could be a result of a difference in experience of both radiographer and radiologist. In addition relatively high doses were recorded, this could arise

from the fact that the current survey is for a university hospital where the proportion of complicated cases might be relatively high and where there is a high number of junior radiologists undergoing their training. Doses are likely to be higher when these procedures are performed by a radiologist not adequately trained on technical details of the equipment [189, 190]. This can be ameliorated by teaching radiation safety and dose optimization at medical school and vigorous on-job training. Monthly audits of doses by physicians and their subsequent display can lead to reduction in doses as no doctor would want to always top the list for unjustified reasons.

The simplest and most widely available dosimetry quantities in fluoroscopy are fluoroscopy time and number of fluoroscopic images. These are analogues of dose, i.e they do not measure dose directly and by themselves are insufficient to determine patient dose[187 -188]. In general fluoroscopy time has a poor correlation with peak skin dose (PSD), however if it is the only measurement available, it is better to record it than not monitoring at all. In this investigation, an analysis of the screening time for the various examinations showed a moderate correlation (r = 0.65) between screening time and *skin dose*, while a weak correlation (r = 0.40) was deduced between screening time and KAPs. This is can be explained by the fact that a KAP meter reading includes the dose contribution from the digital acquisitions which contribute a significant amount to the total dose but not to the screening time. The poor correlation should be interpreted cautiously as the fluoroscopy screening time is of limited use as it makes no allowance for the influence of dose rate or field size.

KAP has been proven to be a good indicator of stochastic risk, and correlates with operator and staff dose, however it is not an ideal indicator of deterministic risk. KAP does not correlate well with skin dose, however it is a useful surrogate measure of skin dose. The most optimal quantity which needs to be measured in fluoroscopy patient dosimetry is the PSD. PSD may be measured with a computerised analysis tool integrated into the fluoroscopic unit. The likelihood and severity of radiation induced skin injury to the patient as a whole are functions of the highest radiation dose at any point on that patient's skin i.e. the PSD. PSD and KAP are the most useful predictors for deterministic and stochastic injury, respectively[187 -189]. The RAID-IR study established the following approximate conversion relationship between PSD and KAP [189].

$$PSD\ (mGy) = 249 + 5.2 * KAP\ (Gy*cm^2) \quad \textbf{8.1}$$

Such formulas are strictly applicable to a particular clinic and its procedures, as such caution needs to be exercised if they are to be adopted in other clinics. However in those situations where there is lack of dosimetry support they can be used as a rough guide.

The ICRP has recommended the use of DRLs as a first step in the optimization of radiology procedures. However, in a British Journal of Radiology commentary Dr Dendy asks the question whether the principle of DRLs can be used in interventional radiology (IR) and would such a move aid optimization[191]. He alludes to the variability of the procedures and therefore suggests that if DRLs are to be adopted for IR procedures, then they have to be graded for each type of procedure, according to simple, medium and complex. However he claimed the starting point was to collect detailed information on a wide range of procedures from a number of different centres. However, Miller et al have successfully proposed initial DRLs for fluoroscopically guided procedures in the USA successfully [192].

The KAP meter reading has been criticised as being ambiguous, for example a high reading can be as a result of a big area being exposed (less dose) or a high dose on a small area. However KAP readings are still relevant for purposes of radiation protection of the patient and as a potential predictor of stochastic effects. In addition the clinically available dose and KAP measurements ignore the effect of backscatter from the patient. Backscatter can increase skin dose by 10% -40%, depending on the beam area and energy [10]. However, since the KAP reading is directly related to the beam area, it therefore shows the level of beam collimation and monitoring of these readings can lead to patient dose reduction.

Fast changing technology has made physicians to be forever on the learning curve. Before physicians master a technique on any equipment, a new advanced model is on the market and at times using a different detector combination which demands its own optimization process. It should be understood that for any dose optimization process to be successful in any clinic it should include all the professional groups working in the clinic, i.e. the radiographers who record the dose descriptors; the radiologists who carry out the procedures, the referring physicians who give patient care after the procedure and the medical physicist who is in-charge of the dosimetry, and liases with the equipment engineers.

The present South African statute makes it mandatory for patient record keeping for 5 years post-procedure. In terms of the dosimetry is it mandatory to keep a record of the fluoroscopy time, however the KAP reading can be recorded if applicable. The ICRP Report 85 recommends recording of dose parameters for two groups of patients, namely,

- Those who have undergone procedures with entrance skin dose above 1 Gy and they are likely to have repeat procedures.
- Those who have undergone procedures with entrance skin dose above 3 Gy and they are unlikely to have repeat procedures.[193].

Table 8.1below shows dose metric recommendations from other organizations and individuals.

Table 8.1: Existing recommendations for recording patient dose[188].

Reference	Reference type	Procedures for which dose to be recorded	When dose should be recorded	Dose metrics recorded
ICRP [193]	International guideline	Determined by dose	PSD > 1 Gy if procedure likely to be repeated; PSD > 3 Gy if procedure not likely to be repeated	PSD and location, skin dose map
Spanish statute [194]	National law	Mandatory for all interventional procedures	Always	KAP (minimum requirement), fluoroscopy time and number of images
FDA Advisory [195]	FDA advisory (US)	To be decided by each facility	If skin dose equals or exceeds threshold dose set by each facility (1 -2 Gy suggested)	Skin dose, skin dose map or verbal description of site
ACR [196]	ACR technical standard (US)	Determined by fluoroscopy time or expected skin dose	Fluoroscopy time > 10 minutes or expected skin dose > 2 Gy	Fluoroscopy time, location of skin areas receiving dose > 2 Gy
CRCPD (2001) [197]	CRCPD resolution (US)	Procedures with a potential for producing radiation induced injury	Not specified	Not specified
CRCPD (2003) [198]	Suggested state regulations for radiation control (US)	All	All	Fluoroscopy time, number of images
Faulkner [199]	Review	All	Always	PSD and KAP
O'Dea et al [200]	Observational study	Greater than 0.01% chance of exceeding 6 Gy PSD if study not likely to be repeated; > 5% chance of exceeding 1 Gy PSD if study likely to be repeated at the same skin site	All procedures meeting criteria	PSD
Waite and Fitzgerald [201]	Observational study	FGIPs	Always for cerebral embolization, for all cases if easily available, otherwise periodic check for FGIPs.	PSD and KAP for cerebral embolization and for all cases if easily available
Miller et al [189]	Observational study	All	All if integrated dosimetry available, otherwise procedures with known potential for high dose	PSD, CD, KAP, fluoroscopy time acceptable only if other metrics not available
Miller et al [202]	Observational study	All	All if integrated dosimetry available, otherwise procedures with known potential for high dose	PSD, CD, KAP

Clearly from Table 8.1 there is no world-wide consensus on which dosimetry metrics should be recorded for interventional studies. This scenario presents an opportunity for the South African radiology community in liaison with the DRC to formulate a policy stipulating the

dose metrics to be recorded and at what level. However the from the lessons drawn from this study it is practically feasible to record the KAP, fluoroscopy time and number of images, similar to the Spanish statutes.

Fluoroscopy machines have a dose alarm, which would alert the operator after screening for a certain preset time. The physician would be expected to respond to this alarm accordingly without compromising patient care. There are other metrics which can be used to alert physicians on the patient doses delivered during procedures. Table 8.2 shows the level of notification for the various surrogates of patient dose used in the clinic.

Table 8.2. Summary of radiation monitoring dose notification thresholds [188].

Parameter	First notification	Subsequent notification	Threshold
Peak skin dose	2000 mGy	500 mGy	3000 mGy
Reference point air kerma	3000 mGy	1000 mGy	5000 mGy
Kerma area product*	300 Gycm^2	100 Gycm^2	500 Gy cm^2
Fluoroscopy time	30 minutes	15 minutes	60 minutes
*Assuming a 100 cm^2 field at patient skin.			

Furthermore Table 8.2 gives the threshold values upon which the patient must be actively followed up after a procedure. Establishment of threshold values should take into consideration factors like: what is the appropriate threshold level, what data analysis is expected to be done and who does the analysis. A balance has to be struck between having thresholds low enough to capture all real events and also high enough to keep the workload within reasonable limits.

This investigation had some limitations which deserve to be mentioned. Some of the procedures had limited number of patients (<10). Such low patient numbers are expected in non-specialist hospitals, the remedy is to collect data over a very long period which is not always practical. This study involved 48 clinicians and 37 radiographers which is a relatively big number, of which some are students in training. Such a big group makes any efforts to narrow patient doses difficult as it is difficult to achieve consistency in such a large group of

varying clinical experience. KAP values are procedure specific and may be department specific, therefore it is difficult to use KAP trigger levels for skin dose estimated for one procedure, for another procedure, or even in another place performing the same procedure, however at times it may well be the only indicator available.

8.4 Radiography Examinations Dose Audit

For a hospital equipped with a mechanical engineering workshop it is cheaper to fabricate the recommended radiology phantoms in-house. The phantoms which are recommended by the DRC are cost effective and relatively easy to build. Phantoms are useful in the dose optimization process, having the advantage that unlike patient studies there is no need for seeking consent and ethics approval in order to perform dose measurements. However their major limitation is that they fail to indicate the dose variations evident in the clinic due to differences in patient size and tissue composition.

The indirect measurement method based on X-ray tube output measurements is ideal for large patient populations. TLD dosimetry can be used as a stand-alone system or in conjunction with indirect measurement dosimetry methods [203]. One of the disadvantages of TLD dosimetry is its large start-up capital investment and is thus not a cost-effective option for a small radiology department. In the South African situation TLD dosimetry would be ideal for those hospitals with radiotherapy centers where TLDs are being used for patient *in-vivo* dose verification. In this work the TLDs used generally gave lower doses than the expected calculated dose based on the X-ray tube output. TLD dosimetry was found to be labour intensive and time consuming as a manual TLD reader was used. TLD response is beam quality dependent which implies that they should be calibrated across the beam quality spectrum in radiology, which further reinforces the fact that their use is labour intensive. Perhaps use of three TLD chips to measure a single exposure would yield improved results through averaging or rejection of an extremely out of trend reading. Some researchers have labelled TL dosimetry as a ‘black art’ due to the fact that it yields inconsistent results at times[171, 204]. Furthermore in comparison to ionization chamber dosimetry, TLDs have a higher uncertainty. In addition, TLDs can only be used for examinations which don’t seek fine detail as they can easily present as an artefact.

Entrance surface air kerma is one of the dose indicators which can be used in clinical patient dosimetry. There is an alternative formalism to equation 6.4 which has been published. Some researchers have used the relationship [47, 205, 206, 207]:

$$K_e = Output * (\frac{kVp_{ex}}{kVp_{ref}})^2 * (\frac{FSD_{ref}}{FSD_{ex}})^2 * mAs * BSF \qquad \textbf{8.2}$$

where Output is the X-ray tube output at reference kVp_{ref} and at a reference distance of FSD_{ref}

kVp_{ex} is the tube potential used for the particular examination.

mAs is the product of the tube current and the exposure time.

FSD_{ex} is the focus to skin distance for the particular examination.

BSF is the backscatter factor

The assumption in equation 8.2 is that the X-ray tube output is proportional to the square of tube potential (kVp^2). This is not a universal truth as shown in Figure 8.1, where the output was a function of $kVp^{2.061}$.

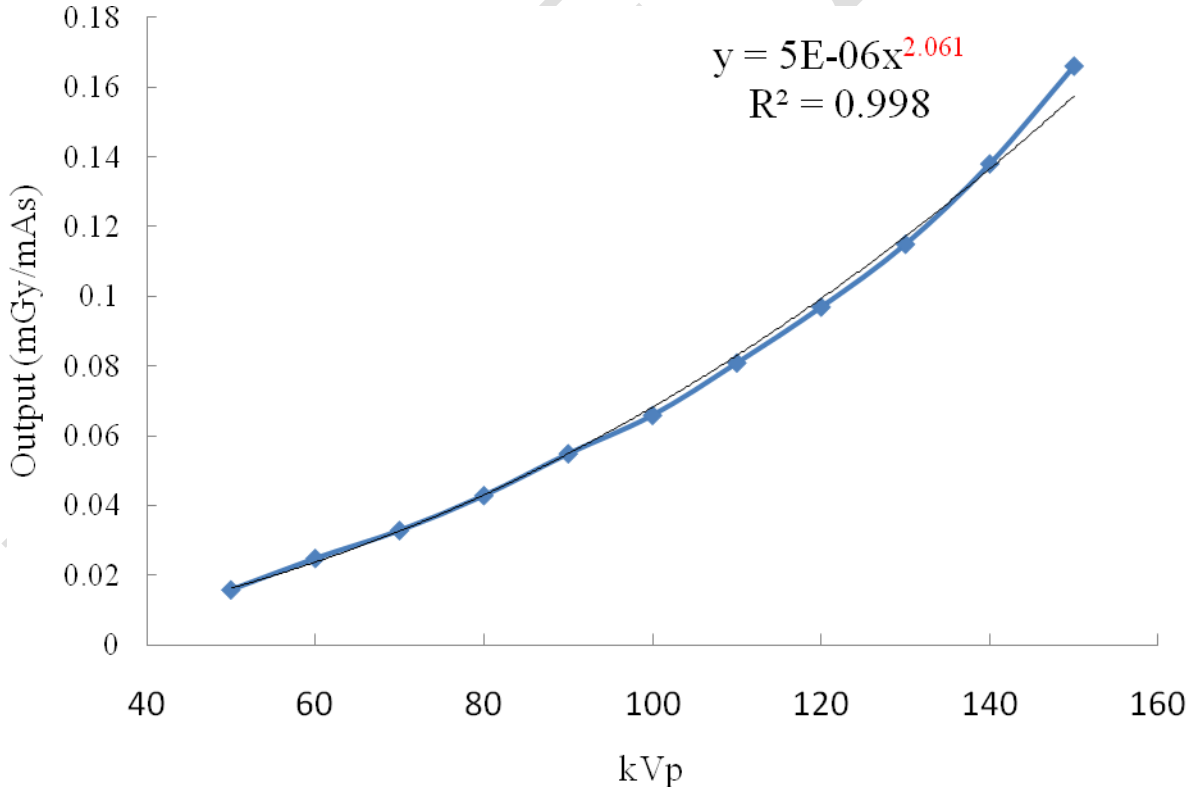

Figure 8.1. The variation of X-ray tube output with kVp.

It is therefore recommended that beam output be measured across a reasonably representative spectrum of kVps instead of measuring it at one reference kVp as suggested by equation 8.1.

Calculation of entrance surface air kerma has proven to be a suitable and reliable alternative to TLD measurements. The present study did not show a good correlation between doses as calculated from exposure parameters and doses from TL dosimetry. Despite the poor correlation of this study some studies elsewhere have shown agreement between computational and TL dosimetry methods [208]. However the computational method is a cost effective method of conducting representative patient dose estimations and is ideal for dose audits involving a large number of patients.

Most European countries have established and published their own DRLs but adopting a DRL from another country is not advisable given the variation in radiography practice, state of equipment and technique throughout the world. Once the local DRLs are established they have to be compared with the national DRLs or international DRLs and this comparison provides an opportunity for continuous dose optimization improvement. To the best of the author' knowledge no DRLs based on clinical data have been established in South Africa for general radiography examinations. Establishment of local DRLs will allow comparison of practice with other centres or other countries.

The DRLs from this study are comparatively lower than those set up by most countries. This could be a result of the fact that the DRLs from international studies are established from several x-ray rooms in different hospitals and therefore radiography practice and technique varied widely. In addition, in some cases, authors setting up DRLs do not report on the patient dose influencing factors like added filtration, screen-film speed, generator type, use of AEC or manual method, and image receptor technology. For instance, the DRLs from this study are based on a screen-film speed of 400 compared to 200 used in the IAEA study [175]. As hospitals migrate to digital technology, patient dose audits must be carried out and DRLs representative of this technology established.

There is a danger that medical physicists can invest a lot of effort in attaining the levels of published or legislated DRLs which on its own will be antithetic to the principle of dose and image quality optimization, as this could divert the medical physicist from the search for the best or optimum combination of patient dose and image quality. Patient doses that are far lower than DRLs need to be investigated. Dose optimization in the clinic should not

necessarily end with complying with regulatory DRLs, physicists should continue seeking ways to optimize systems which already meet regulatory guidelines.

In this study the author was actively responsible for the data collection as the radiographers felt it would be an extra work load to them, being short-staffed. From our experience, this indirect method of assessing patient doses introduces minimal inconvenience to the running of an x-ray department. However, for large scale studies it would be much easier and less disruptive to the patients for the radiographers working on the X-ray units to collect the data required for entrance surface air kerma calculation. In addition, direct involvement of radiographers in the measurement process would improve their awareness of patient doses and the effectiveness of radiation protection measures.

Since all the dose influencing parameters are to be recorded when setting up DRLs, it makes it easier to pinpoint parameters leading to higher doses and thereafter optimize the process. Although DRLs are not applicable to individual patients, their establishment is based on knowledge of the x-ray tube output, which means queries from patients regarding their personal doses can be answered with confidence.

In compliance with the DRC quality control and quality assurance requirements it is assumed that most suites know the x-ray tube output from their units. It is possible that most radiology centers have indeed been conducting patient dose audits in an effort to optimize their examinations. Should this be the case then it is suggested that a national database be established in the mould of the National Patient Dose Database (NPDD) of the United Kingdom (UK), in which measurements of radiation doses to patients are collated[38]. Trends could then be monitored and reliable national DRLs could be developed and refined. The DRC is best suited to set-up such a database given that annual quality control returns from all licensed radiation users in the country are collated by them.

In comparison patients in Room A1 received more dose than those in Room A2, despite Room A2 having a higher X-ray tube output. This could be a result of different patient sizes, Room A1 having larger patients as shown by the fact that for the same type of examinations the average patient mass was 70.2 kg in Room A1 compared to 67.4 kg in Room A2. The very existence of differences in mean entrance surface air kerma values between the two

examination rooms shows that there is potential for further optimization of the radiography process at CMJAH. The two units were using an added filtration of 1 mm Al, thus an appropriate change to use other available filter thicknesses should lead to dose reduction. Furthermore, adoption of the radiography techniques suggested in the document *European Guidelines on Quality Criteria for Diagnostic Radiographic Images* for instance, could further decrease patient doses while maintaining good image quality[150].

Training and continuous professional development is crucial in the effort to optimise doses, for example, the dose optimization concept should be taught to radiology registrars and radiography students as they train such that as they graduate into full professionals they are fully conscious of the need to strike a balance between dose and image quality. For this to succeed it would entail changes in curricula being taught at training institutions and having relevant societal scientific meetings putting emphasis on the concept.

Patient thickness has an influence on the dosimetry and therefore it is important to record patient height and mass during a patient dose audit. It is recommended that at least 10 patients per x-ray room be used in the establishment of DRLs [36,168]. In this study this was not always possible, however, since the data collection was spread over a week it can be argued that a true reflection of radiographic practice and technique was captured. The use of such a low number of patients has a disadvantage in that one or two individual patients may influence the mean value significant. This can be minimized by accepting patients within a certain mass range (60 kg – 80 kg) into the survey. However this concept leads to exclusion of a significant patient population from the study, thus decreasing the statistical power of the survey. However Miller et al in a study for fluoroscopic guided procedures concluded that patient body habitus did not significantly affect the 75th percentile dose [192].

The importance of imaging continues to increase for both radiotherapy planning and radiotherapy treatment delivery [209]. As such patient dose monitoring is potentially useful for not only diagnostics, but also therapy, especially with increasing introduction of image guided radiation therapy related techniques to clinics around the world [209]. Dosimetry techniques used in radiology can be used potentially with or without changes by the radiation oncology physicists in the dosimetry of imaging modalities as applied to radiotherapy. The

optimization of process principles used in radiology imaging can be applied in radiotherapy portal verification procedures.

Effective dose has been used to quantify patient radiobiological detriment, its advantage being that it facilitates a comparison of the risks associated with different spatially-inhomogeneous exposures. However the effective dose has its own weaknesses, with some researchers calling for its scrapping off [210 - 213]. Some of the disadvantages of the effective dose concept are that it was introduced by the ICRP as a way of quantifying occupational exposures, and thus can not be used to determine individual risk, it is age and sex average, which thus brings about the inherent uncertainties in this quantity. Therefore, it would be meaningful to ultimately quantify risk of radiation induced cancer death. The PCXMC Monte Carlo based computer program that has been developed by the Finnish Radiation and Nuclear Safety Authority (STUK) has the capability of calculating organ doses and subsequently perform cancer risk assessments based on the Biological Effects of Ionizing Radiation (BEIR) VII committee models [214]. The PCXMC offers tissue weighting factors from ICRP Publication 60 or 103 and it incorporates adjustable-size paediatric and adult patient models. However this software due to its cost would be generally out of reach for most of the developing world potential users. There is one freely available computer program, CALDose_X which calculate incident air kerma and entrance surface air kerma based on the output of the X-ray equipment. In addition, the software uses conversion coefficients (CCs) to assess absorbed dose to organs and tissues of the human body, the effective dose as well as the patient's cancer risk for radiographic examinations. [215]

This work had some significant limitations, which deserve discussion. Data could have been collected over a longer period of time and in turn have an increased number of patients. Use of the concept of equivalent diameter for patient thickness tends to underestimate the FSD for the AP and PA projections while overestimating the FSD for the lateral and oblique projections. In addition the use of body mass index has limitations since it does not make any differentiation between body type e.g ectomorph or endomorph or mesomorph. Also the use of phantoms of fixed dimensions present inherent limitations since patients are of various sizes and shapes.

8.5 Non –Clinical Image Quality Assessment

It has been demonstrated that in a hospital equipped with a mechanical engineering workshop it is cheaper to fabricate the CDRAD phantom in-house. The dose optimization process should involve measurement of appropriate dose and image quality metrics [216, 217]. Dose metrics are fairly well established and standardised in comparison to the image quality metrics. Any image quality metric should be able to both qualitatively and quantitatively describe the fulfilment of medical purpose of that image.

The fabricated CDRAD phantom is easy to use and being a phantom it spares patients from unnecessary dose. Vano *et al* demonstrated that the image quality from the phantom has a good correlation with clinical images [218]. In addition the CDRAD phantom has a distinct advantage in that it evaluates the whole imaging system, that is both the imaging system and the observer.

Use of phantoms for image quality assessment has the advantage of getting rid of the inhomogeneity and variability inherent in any patient population. However use of phantoms is without its disadvantages as questions have been raised about the subjectivity of these tests over time if the same phantom is used and the clinical relevance of the tests. In general image quality phantoms evaluate the imaging system performance under ideal set-up conditions. To improve the simulation of clinical conditions (X-ray spectrum and scatter contribution), the CDRAD phantom was sandwiched between 16cm of PMMA which provide full scatter conditions.

In an era where most university teaching hospitals in South Africa are acquiring digital radiography units, the CDRAD phantom is an asset in image quality assessment and dose optimization. The CDRAD phantom has been used to determine the optimum beam energies in chest images using screen-film and computed radiography [219 - 220].

8.6 Digital Radiography Practice and Technique

The study undertaken was exploratory and illuminative for other teaching hospitals, however it showed some very interesting results worthy of further exploration. This study allowed the evaluation of the opinion of radiographers on digital radiography. The study also presents a potential area of collaboration with other teaching hospitals in South Africa for further

studies based on lessons learned from this study, with particular emphasis on setting up technical and clinical protocols.

Among the four institutions surveyed, only Hospital B had a picture archiving and communication system (PACS) implemented in its radiology department. Some experts have suggested that in order to reap the full benefits of digital radiography, one needs to implement PACS [221]. It is, therefore, recommended and encouraged that institutions eventually implement PACS as they migrate from film to filmless radiography if they are to fully realize the benefits of digital radiography. Studies have shown that implementation of PACS has led to increased radiographer productivity and overall efficiency of radiology departments [222 -225].

There is a large gap in the number of radiographers with at least four years of experience with digital radiography in comparison to screen-film radiography. This could be explained by the fact that most radiographers were only exposed to digital radiography post qualification. This becomes a challenge since in most cases it is the more qualified radiographers who are tasked with training students and supervising newly-qualified radiographers. Thus, it becomes imperative for them to be subjected to formal education in this modality.

Quality control procedures and quality assurance are equally important in digital radiography as they are in conventional screen-film radiography. However, it must be appreciated that the workflow process and operational nature of digital radiography directly affects traditional quality assurance practice [226]. For example, how does a radiology department implement an accurate film reject analysis in digital radiography, given the fact that radiographers can readily delete images on the workstation? It is recommended that quality control procedures required for digital radiography be included in radiography undergraduate and postgraduate programs. To further improve service delivery, radiology departments should implement formal in-house quality control training to members of staff.

Radiographers should be encouraged to read the operator's manual of the X-ray units they are using. Reading the manual would empower the operator to realize the most out of the unit, particularly post processing functionality. Since the majority of the participants (84%) alluded to the fact that they never had formal quality control training of the units they are using, it is advisable that they at least consult manuals available to them.

All the hospitals who participated in this study did not have a full-time medical physicist in their radiology departments. This is owing to a nationwide shortage of medical physicists in South Africa, and as a result of this critical shortage, most institutions have medical physicists working in their radiotherapy department full-time and their service to diagnostic radiology departments is limited to a consultative basis. Furthermore, the regulations governing licensing and operation of radiology departments do not stipulate the minimum medical physics staffing levels consistent with the type of equipment. The advent of these new technologies should encourage participation of medical physicists who would be responsible for performing acceptance testing, patient dose measurements, objective image quality assessments, setting up of quality control programs, annual quality assessment of all the X-ray units in their departments and quality control review programs[81, 82 , 227].

In dealing with radiation dose issues, it should be appreciated that digital radiography has a wider dynamic range than screen-film systems and overexposures or underexposures can yield quality images, because post processing adjustments can be made[85]. In digital radiography, a higher patient dose would usually translate into an improvement in image quality as the images have less noise. In comparison to screen-film technology, digital radiography systems do not give an immediate feedback to radiographers concerning the radiation dose and as a result, there is a potential risk for dose creep[85, 228, 229]. Although digital radiography has the potential to achieve dose reduction in a number of examinations, patient dose increments in the range of 40–103% have been reported in the process of migrating from screen-film to digital radiography [71, 230]. Thus, the unnecessary pursuit of beautiful images would violate the ALARA principle. There is also a risk that if the X-ray generator AEC develops a fault or the output calibration drifts, the dose increase or decrease can go unnoticed because of the wide exposure dynamic range of digital systems. In addition, the wide exposure dynamic range means that there is significant potential for the initial set-up of the system to be non-optimized, which further motivates for having medical physics staffing in radiology departments.

Digital radiography has post processing functions, for example, images can be cropped to show only the region of interest. It is bad radiography practice to rely on cropping images instead of collimating the beam as this leads to unnecessary radiation dose burden to the

patient. In addition, proper collimating will lead to noise reduction in images, which will potentially result in lower reject rates.

Digital radiology presents cost benefit advantages to developing countries. In comparison to film processors the use and maintenance of phosphor based imaging plates and accompanying computer system is easier [231]. In the event where there is a lack of funds to finance installation of a PACS and associated network system, users can burn images on CD-ROMs. CD-ROMs have an advantage of being portable and easily transported from one imaging department to another.

For any digital radiology department to be successful in terms of keeping patient doses as low as reasonably achievable it needs to adopt and implement a well structured quality control program. Key to the success of a digital radiology program is the training of radiographers as they make a transition from film / screen technologies. However it must be acknowledged that public hospitals have had challenges when it comes to establishment of quality assurance teams. For example appointment of dedicated quality assurance radiographers has been frustrated by staff shortages, whereby the quality assurance radiographer has to abandon his/ her duties to do clinical duties.

The ease of digital radiography poses a risk of an increased number of unnecessary exposures. It has been shown that in as much as digital radiography can potentially lead to a 50 % dose reduction, this is offset by a almost doubling of the number of procedures. Furthermore, in general for digital radiography the image quality increases (noise decreases) as the dose in increased. As such for any procedure the image quality needs to be well defined for the specific task at hand. There has been a proposal to classify digital radiography into three image quality bands, namely, low, medium and high.

Although this is the case, caution is needed with the interpretations as the present sample size is relatively small given the number of radiology centers in South Africa having both conventional screen film and digital radiography. Further face-to-face interviews rather than mailed questionnaires would have improved participation. However, it stands to reason that since these surveyed institutions are teaching hospitals, their radiography practice culture cascades to a number of other centers.

8.7 Scatter from Under-couch Procedures

KAP meters offer the possibility of online measurement of patient doses and subsequent recording of these doses have been widely used for patient radiation dose assessment. As such the regulatory requirement of having KAP meters on every fixed fluoroscopy unit is welcome and will help in the dose optimization efforts.

The backscatter from couch and patient to the KAP meter is in most cases negligible given the distance between the KAP meter and the patient and couch. However of dosimetric concern are the forward scattered photons from the couch which contribute in principle to patient dose. The couch generated scattered photons will therefore increase the patient's skin dose without any contribution to diagnostic image quality. This component of patient dose is not accounted for by the KAP reading.

Attenuation properties of the patient couch and the mattresses have to be factored in when reporting KAP readings for under-couch procedures. For under-couch installations, the calibration factor needs to be modified to take into account attenuation in the couch. Some manufacturers use a calibration factor which is a weighted average of the over-couch configuration and the under-couch configuration. This can only be accurate if spectral changes are negligible, thus the calibration factor would need to be decreased in value in proportion to the attenuation of the couch. The backscatter from couch and patient to the KAP meter is in most cases non-existent to negligible given the distance between the KAP meter and the patient and couch. However of dosimetric concern are the forward scattered photons from the couch which contribute in principle to patient dose. Furthermore it should be appreciated that foam type mattress can lead to patient dose reduction as they approximate an air gap.

CHAPTER NINE

RECOMMENDATIONS

9.1 Recommendations

Below are recommendations drawn from the practical experience of this work, whose aim is to further optimise radiology practice.

- It is recommended that the light box lamps be purchased in bulk to avoid batch variations in terms of colour and intensity. Furthermore as a measure to improve uniformity, should there be a need to replace a lamp in a viewing box, all the lamps should be replaced.
- This study has shown the feasibility of measuring patient doses and establishment of DRLs in a radiology department. It is therefore recommended that multi-centre studies be conducted in an effort to establish national DRLs. It has been shown in the UK that implementation of DRLs have progressively led to a reduction in patient doses.
- Equipment dose saving capabilities should be used to their fullest by operators. Examples of such are different filtration and AEC capabilities.
- The South African medical health community, society at large and in particular the radiology community needs to be educated and alerted on dose optimization options for patients through awareness campaigns, training curricula, continuing education programs. One simple and straight forward way of reducing the radiation burden to patients is to reduce the frequency of examinations and procedures. Over-utilization has been cited as one of the major causes of the dramatic increase in radiation doses in American patients [232]. Hendee *et al* report on ways of avoiding over-utilization of ionizing radiation as suggested by participants of the American Board of Radiology Foundation summit on causes and effects of over-utilization of imaging [232]. As such relevant professional and scientific societies in South Africa have the responsibility to educate and encourage their membership on alternative imaging modalities which do not use ionizing radiation. Physicians can use the ACR Appropriateness Criteria® and ICRP guidelines on appropriate imaging examinations for their patients and radiation protection of the patient respectively [233, 234]
- For radiology clinics without medical physics support, as a first attempt to optimize radiography practice it is recommended that the European Union radiography practice

guidelines be adopted. The patient dose reducing measures mentioned in Chapter 2 are effective in optimizing practice.

- The ACR guidelines on DRLs has offered guidance on the roles of medical physicists and physicians in the effort of patient dose-image quality optimization, however it does not offer any guidance on the role of radiographers. South African radiology community, which need include but not limited to the following organizations, South African Association of Physicists in Medicine and Biology, Radiological Society of South Africa, Society of Radiographers of South Africa and DRC, should discuss and provide guidelines on the roles of radiographers in dose optimization.
- For fluoroscopically guided procedures it is recommended that protocols be set –up to decide which dosimetric parameters need to be recorded, guide patient counselling and post-procedure after-care for those patients who would have received doses beyond the set threshold. If there is no local data available then as an initial step to optimization of protection, consistent use of any of the dosimetry parameter thresholds in Table 8.2 would be appropriate. Based on results of this study it is recommended that at least KAP and screening time be recorded for each procedure.
- Migration from screen-film to digital radiography presents challenges to radiology clinics. In this work most radiographers claimed to have never had a formal training in digital radiography, therefore it is recommended that radiology departments adopt the ICRP Report 93 recommendations on digital radiography training [235].
- In light of a general medical physicists shortage in South Africa, having the medical physics support service provided for a district or province by a floating medical physicist would be an alternative.
- Results of this study have shown that the amount of scattered radiation from the patient couch to the skin is not negligible, thus for accurate patient dosimetry in under-couch procedures forward scattered photons from the patient support table should be included.

CHAPTER TEN

CONCLUSIONS

This study contributes to the development of DRLs in radiography/fluoroscopy in the context of a developing country and highlights the need for quality assurance in radiology and furthermore recommends the need of the establishment of a national patient dose database for the purposes of establishing South African DRLs. Any form of regulation or standardization begins with dissemination of information and this study attempts to do that. Furthermore, conclusions of the separate investigations comprising this work are discusses below.

10.1 Quality Control of Radiography Viewing Conditions

This study showed that the viewing conditions at CMJAH were variably in compliance with guidelines from international organizations. However it is suggested that the DRC recommendations be adopted by South African radiology clinics, as this would easily be used as proof of compliance for viewing conditions. Furthermore, this study underscores the need of implementing quality control and quality assurance standards in radiographic image viewing, in support of overall optimization of the radiographic process.

10.2 Custom Made Quality Control Software

The purpose of this work was the design and test of a software program to acquire, analyse and archive quality control test data. A PC-based user-friendly computer program capable of data entry, analysis and archiving was developed. The computer program is based on Microsoft Excel™ and can be used on any PC running on the Windows operating system and with the normal accompanying hardware and software provisions. In addition to being used for reject analysis the designed software can be used for a variety of QC tests on general radiography units, fluoroscopy units and film processors. This program offers a quantitative approach to gathering and generating statistics on equipment QC. This software supports radiology staff in performing QC and QA tests on radiology equipment. It is envisaged that the use of this computer program will help radiology departments achieve compliance with the regulatory authority. This computer program is freely available to any potential user.

10.3 Fluoroscopy Procedures Dose Audit

The presented patient dose data in this study represents practice at CMJAH. Data from 331 fluoroscopy examinations was collected and analyzed. Procedures resulting in higher patient radiation doses have been identified. The barium and myelogram studies contributed most to patient doses. There is a wide spread in the radiation doses registered for any one given type of examination. This large variability in the radiation dose delivered proves that the studied fluoroscopic examinations stand to gain from dose optimization. The 75-th percentile values established in this investigation were higher than the DRLs of the UK. In addition this study shows the usefulness of KAP meters in radiology with respect to dose optimization.

10.4 Radiography Examinations Dose Audit

The phantoms for patient dose measurements recommended by the DRC can be fabricated in-house in a hospital with a mechanical engineering workshop using materials which are locally and readily available. As part of ongoing QC and QA procedures of indirect patient dose assessment using phantoms should be encouraged in all radiology departments. A computational method based on exposure parameters for assessing patient dose in plain radiography was successfully used. It has been demonstrated how a patient dose audit could be performed in a large teaching hospital with minimal interference to practice. To the best of the authors' knowledge this is the first time patient doses for general radiography examinations have been audited and published in South Africa. The data presented in this study is an initial attempt at establishing local DRL values and the established DRLs are shown in Table 7.13. This study suggested dose saving measures which result in significant reduction of the patient radiation dose burden. Application of such measures can lower the collective effective dose from diagnostic radiology examinations, potentially leading to lower associated cancer risk. Furthermore, this study has an educational function to the radiology community and also provides a benchmark to assist any statutory organization to establish DRLs in South Africa.

10.5 Non-Clinical Image Quality Assessment

A replica of the CDRAD phantom was successfully fabricated in-house for use as an image quality test object. It has been shown that the phantom when fabricated in-house is inexpensive and can be made from materials that are readily available locally. Furthermore the utility of the CDRAD phantom as both an acceptance testing and routine quality control

tool has been demonstrated. The CDRAD contrast-detail phantom is easy to use, and the contrast-detail curves correlate with the subjective impression of image quality. This study will in future be expanded to involve clinical image quality using the CEC image quality recommendations: see Chapter Eleven.

10.6 Digital Radiography Practice and Technique

This investigation successfully evaluated opinion and knowledge among radiographers of digital radiography. The results of this survey showed that participants are familiar with digital radiography and have embraced this relatively new technology as shown by the fact that they can identify both its advantages and disadvantages as applied to clinical practice. There is however minimal quality control of digital radiography being done at the surveyed institutions. It is therefore recommended that users of digital X-ray units adopt comprehensive national or international protocols [81,84, 236]. As quality control becomes more important and technical in nature for digital radiography equipment the role of medical physicists becomes critical, thus, stakeholders in the South African diagnostic radiology community should establish the minimum staffing requirements for medical physicists particularly for teaching hospitals. Findings from this study suggest that there is need for formal education, continuing education and manufacturer training with respect to quality control as institutions make the transition from conventional screen film radiology to digital radiology.

10.7 Scatter from Under-Couch Procedures

The main motivation for this investigation was to quantify the amount of couch generated forward scatter and its implications to patient dosimetry. This study shows that the calibration factor for under-couch installations should not only take into account the attenuation properties of the patient couch but also include the effect of forward scattered photons to the patient. In the investigated under-couch irradiation geometry, the mean scatter radiation contribution was found to be approximately 12 % for a reference field of 10 cm * 10 cm. In addition the scatter contribution varies by ±2% across field sizes ranging from 8 cm * 8 cm to 20 cm * 20 cm, with the 10 cm * 10 cm field size taken as a reference field. This study underscores the need to account for the effects of forward scattered radiation for accurate clinical patient dosimetry.

CHAPTER ELEVEN

SUGGESTIONS FOR FUTURE WORK

11.1 Suggestions for future work

The major limitation of the patient dose data presented in this study was that it was representative of a single hospital, therefore it is suggested that for future work, a multi-centre investigation be conducted. It is envisaged that such a study would produce data that could be used to establish national DRLs for common radiography examinations. It is suggested that such a study be conducted in liaison with the DRC for the obvious reason that it would make it easier to regulate the established DRLs.

The effort of keeping patient doses as low as reasonably practicable consistent with the intended purpose must be extended to other imaging modalities, for example CT and dentistry radiography. CT is by its nature a high dose modality and deserves scrutiny and monitoring in the effort of dose optimization. For example in the USA, the largest contributor to the dramatic increase in population radiation exposure is due to CT scans [237]. As such it is suggested that multi-centre studies be conducted to ascertain the frequency of CT examinations and subsequent establishment of DRLs for the high frequency examinations.

Dentistry radiography is a low dose modality however, it is being used relatively more frequently and moreover by non-radiologists. Experimental and epidemiologic evidence has linked exposure to low-dose ionizing radiation with the development of solid cancers and leukemia [238]. Dental radiology consist of a series of radiation exposures that are partially superimposed, it is thus a target for dose optimization procedures. The use of teeth bracelets demands frequent X-ray imaging and this potentially leads to excessive exposure to the thyroid which is worrisome given the generally young age group which wear teeth bracelets. It is suggested that also DRLs also be established in dentistry radiography.

Fluoroscopic and digital radiographic imaging technologies are making it possible to accurately image and treat a wide range of conditions in both adults and children. However, radiographic examinations cannot be successfully conducted using a “one-size fits all” approach. Paediatric patients, whose tissues and organs are still developing, are significantly

more sensitive to radiation than adults and thus deserve special attention [239 -244]. In addition, the cancer risk for a given radiation dose is higher for children compared to adults, one reason for this is the longer life expectancy of children, which allows a latent cancer to develop [239]. The risk is approximately three times higher for newborns and declines to that of adults by the middle of the 3rd decade of life. Data published in the last decade suggest that even low levels of radiation exposure increases a child's risk of eventually developing a cancer by a small but statistically significant amount [239 -242]. The small but significant increased cancer risk associated with X-ray imaging studies in children highlights the importance of minimizing radiation exposure in paediatric patients. The number and frequency of paediatric imaging studies using ionizing radiation should be minimized and radiographic imaging conducted only when necessary. Paediatric patients are not simply small adult patients as established DRLs for adult patients can not be applied in paediatric radiology. The dose optimization effort in paediatric radiology should also involve ergonomics as cchildren may be fearful of medical equipment, unco-operative to instructions, need immobilization during examinations and need to see parents or caregivers throughout the examinations and procedures. Special attention should be given to adolescent patients, who have an adult sized body but possess children elevated risk coefficients. Adoption of optimized Image Gently® protocols would possibly lead to a reduction in doses [245]. Design of paediatric phantoms should be considered as the phantoms used in this work are for adults.

The natural step after phantom image quality studies is to do a study based on clinical images. A clinical image quality study based on the EC image quality criteria for both adult and pediatric patients is recommended for future work. Such a study will help put into perspective the entrance surface air kerma measurements and thus further strengthen the dose optimization effort. A computerised data collection database has already been designed by the author for future use in such kind of studies. In the designed database the radiologist makes the assessment on a soft copy. The program automatically saves the completed form for subsequent retrieval for analysis. Figure 11.1 shows a snapshot of the computer program homepage.

Figure 11.1 A screen-dump of the image quality score recording database graphic user interface.

The presented computer program can be used for data acquiring and archiving during clinical image quality studies utilizing the European Guidelines on Quality Criteria for Diagnostic Radiographic Images.

The replica of the CDRAD image quality phantom fabricated in this study will in future be benchmarked against a commercial version. It is anticipated that this would further give confidence on the utility of the in-house fabricated phantom.

The amount and nature of the scattered radiation from the patient couch and or mattress can be effectively be investigated using Monte Carlo simulations. Results of the Monte Carlo simulations can then be benchmarked against the presented experimental results.

NOMENCLATURE

AAPM	American Association of Physicists in Medicine
ACR	American College of Radiology
AEC	Automatic Exposure Control
AP	Antereo-posterio
Al	aluminium
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practical
ANSI	American National Standards Institute
BEIR	Biological Effects of Ionizing Radiations
BIR	British Institute of Radiology
CCD	Charged Coupled Devices
CDRH	Centre for Devices and Radiological Health
CEC	Commission of European Communities
CMJAH	Charlotte Maxeke Johannesburg Academic Hospital formerly Johannesburg Hospital
CNR	contrast to noise ratio
Cu	copper
CR	computed radiography
CRCPD	Conference of Radiation Control Program Directors
CsI	Cesium Iodide
CT	computed tomography
DAP	Dose area-product
DDI	Detector Dose Indicator
DRC	Directorate of Radiation Control
DRL	dose reference level
DDR	direct digital radiography
EC	European Commission
ECC	element correction coefficient
ESAK	entrance surface air kerma

ESD	entrance surface dose
FDA	Food and Drug Administration
FPD	flat panel detector
FPI	flat panel imager
FOM	figure of merit
FSD	focus to skin distance
FTD	focus to table distance
HPA	Health Protection Agency
HVL	half value layer
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
ICRU	International Commission on Radiation Units and Measurements
ICRP	International Commission on Radiological Protection
ICS	image criteria score
II	image intensifier
IPEM	Institute of Physics and Engineering in Medicine
IQF	image quality figure
IRP	interventional reference point
ISO	International Organization for Standardization
KAP	Kerma area-product
K_i	incident air kerma
kVp	kilovolt (tube voltage)
K_{tp}	temperature – pressure correction factor
LAT	lateral
LNT	linear no threshold
mA	milliampere
mAs	milliampere second
MRI	magnetic resonance imaging
MOSFET	metal-oxide silicon field effect transistor
MTF	modulation transfer function

N_k	chamber calibration factor
NEXT	Nationwide Evaluation of X-ray Trends
NEQ	Noise equivalent quanta
NM	nuclear medicine
NMISA	National Metrology Laboratory of South Africa
NORDIC	Scandanavian countries
NPS	noise power spectrum
NRPB	National Radiation Protection Board (UK)
PA	Postereo-antereo
PACS	picture archiving and communicating system
PMMA	polymethyl methacrylate
PMT	photomultiplier tube
PPS	*primary plus scatter radiation*
PR	*primary radiation*
PTW-FREIBURG	Physikalisch-Technische Werkstatten Dr. Pychlau GmbH
QA	quality assurance
QC	quality control
RCF	reader calibration factor
RCR	Royal College of Radiology
RSSA	Radiological Society of South Africa
ROC	receiver operating characteristics
SAAPMB	South African Association of Physicists in Medicine and Biology
SNR	signal to noise ratio
SORSA	Society of Radiographers of South Africa
STUK	Finnish Radiation and Nuclear Safety Authority
TCDD	threshold contrast –detail detectability
TLD	thermoluminescent dosimeter
TRS	Technical Report Series
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

UK	United Kingdom
US	ultrasound
USA	United States of America
VGA	visual grading analysis
VGAS	visual grading analysis score
WHO	World Health Organization

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APPENDIX A

RADIOGRAPHY AND FLUOROSCOPY QC SOFTWARE CD-ROM

The CD-ROM which comes with this thesis contains the following materials in appropriately named folders:

- A folder named **Software Suite**, which is a collection of Excel Microsoft ™ worksheets which make up software.
- A folder named **Thesis**, which contains the Chapters and Appendices which make up this Thesis.
- A folder named **User Guide**, which contains a detailed guide to the software user.

The methodology used to perform the QC tests has been adapted from practical experience, the CRCPD Quality control recommendation document or the University of Rochester Medical Centre Manual [250, 251]. As the test apparatus may vary, the setup procedures also vary, thus the suggested procedures must be used as a general guide, however the measurement metrics should essential be the same. Any mention of a particular test equipment is for illustrative purposes as any equivalent equipment can be used. A qualified Diagnostic Radiology Medical Physicist may be required to give specific instructions on setup relevant to that clinic.

All the contents of the CD-ROM are supposed to be used on any personal computer running on a Microsoft Windows platform. Instructions on how to install the software are given in Appendix B.

APPENDIX B

RADIOGRAPHY AND FLUOROSCOPY QC SOFTWARE USER'S GUIDE

B1.1 Structural Architecture Of Software

This document is a guide to the usage of the software program. A more detailed Use Guide can be found on the CD-ROM accompanying this thesis. This present software version supports QC tests on the following equipment: radiography units, fluoroscopy units, processors and repeat analysis. At present, the program takes the form of a collection of four workbooks of which each of the workbooks have a number of worksheets under it. The individual worksheets have been kept un-linked for simplicity of design and for easy troubleshooting should there be a bug. Each QC test is presented in a single worksheet which provides for data input, analysis and output.

The method to perform the tests presented herein is not prescriptive, however the required input data is the same. At present, the program is a Microsoft Excel 2003 application and so that it requires only a common office personal computer with usual provisions, as such Microsoft Excel Application (version 2003 or higher) must be installed on your personal computer. The application should work on computers running on any of the following operating systems: Windows 2000®, Windows XP® and Windows 7®. The program is available freely and can be requested from the author.

B1.2 Installation

The CD-ROM contains a folder named *Software Suite*. This folder contains the following 20 Microsoft Excel worksheets:

- *Data Input Menu*
- *Fluoroscopy Quarterly Tests*
- *Fluoroscopy Annual Tests*
- *Fluoroscopy Daily Tests*
- *Fluoroscopy IER*
- *Fluoroscopy Weekly Tests*
- *Processor Baseline Sensitometry Tests*

- *Processor Control Film CrossOver Tests*
- *Processor Daily Tests*
- *Processor IER*
- *Radiography Quarterly Tests*
- *Radiography Annual Tests*
- *Cassettes and Screen Tests*
- *Radiography Daily Tests*
- *Radiography Semi-Annual Tests*
- *Radiography IER*
- *Radiography Weekly Tests*
- *Repeat Analysis*
- *Terms of Use*
- *User Records*

In addition to the spreadsheets there is a folder named *Results* on which the results of the tests can be saved onto. Installation of the software is a one-step process where the *Software Suite* folder is copied from the *D-drive* to *My Documents*. Note that the software suite can only work if the all the worksheets are in one folder.

When the Data Input Menu workbook is opened a form with "*Show Menu*"and "*Create Room*" buttons pops up ready for user input. Clicking on the *Category* item will populate the *Data Type* list with the data types applicable to that category. When you know click on a *Data Type* the appropriate workbook will automatically open. Furthermore, for the application to work the user must enable macros in Excel.

B1.3 PROGRAM TOUR GUIDE

On opening the *Data Input Menu* worksheet the user is faced with the graphic user interface shown below. The *Data Input Menu* worksheet is the main worksheet of this workbook.

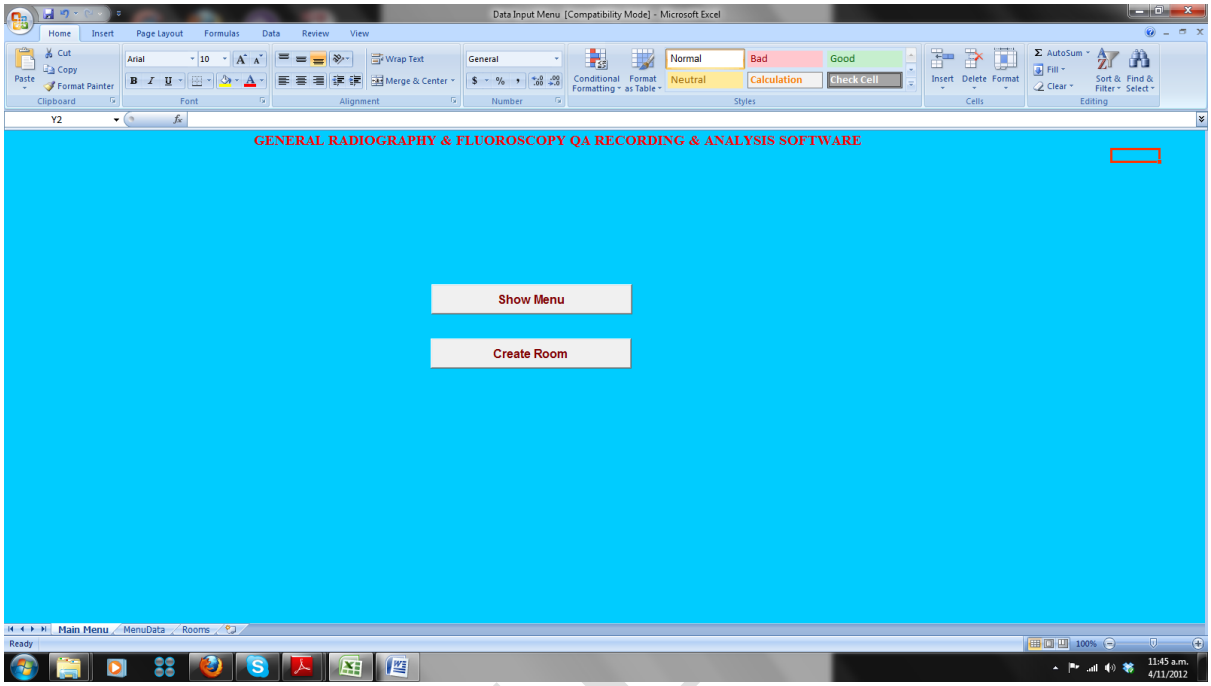

Figure B1: A screen dump showing the main menu worksheet.

The main worksheet has two buttons, namely, the "*Show Menu*" button and the "*Create Room*" button. The "*Show Menu*" button shows a list of rooms housing the equipment under the quality control program. In addition the various modalities under the quality control program are also shown.

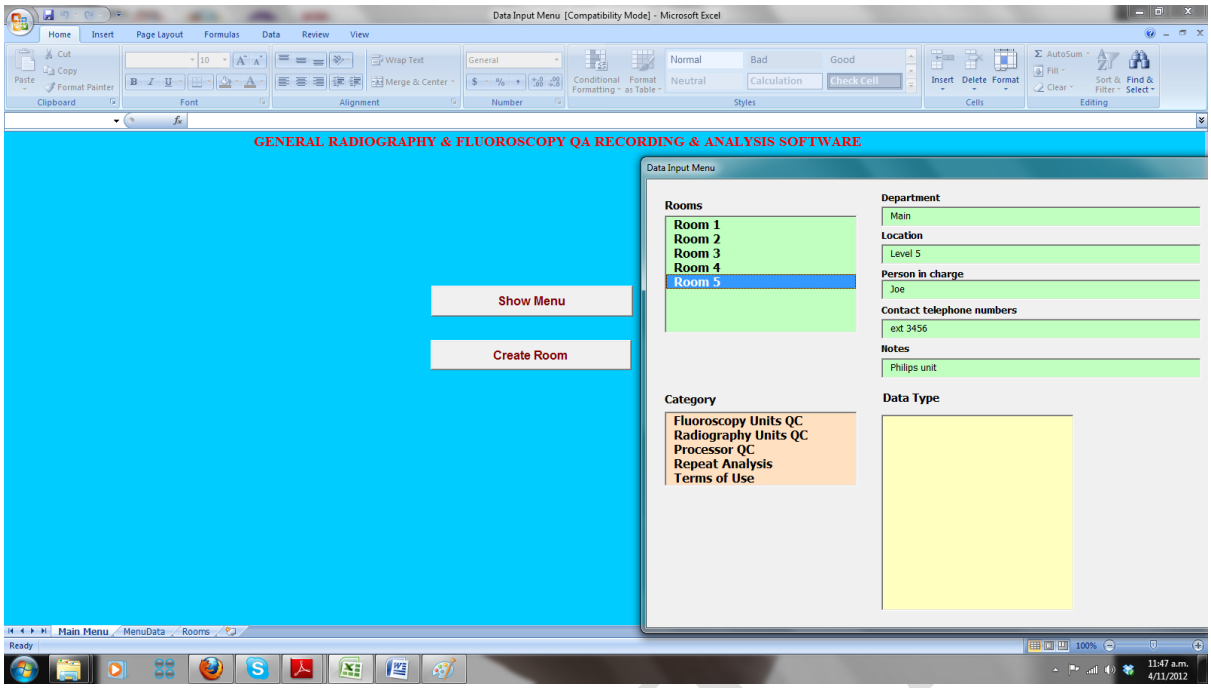

Figure B2: A screenshot after the "Show Menu" button has been pressed.

The "*Create Room*" button offers the capability of the user to add imaging rooms housing equipment under the quality control program. When the *Create Room* button is clicked the user will be presented with a form which will allow you to enter the room data. The graphic user interface looks as below after the *Create Room* button has been clicked.

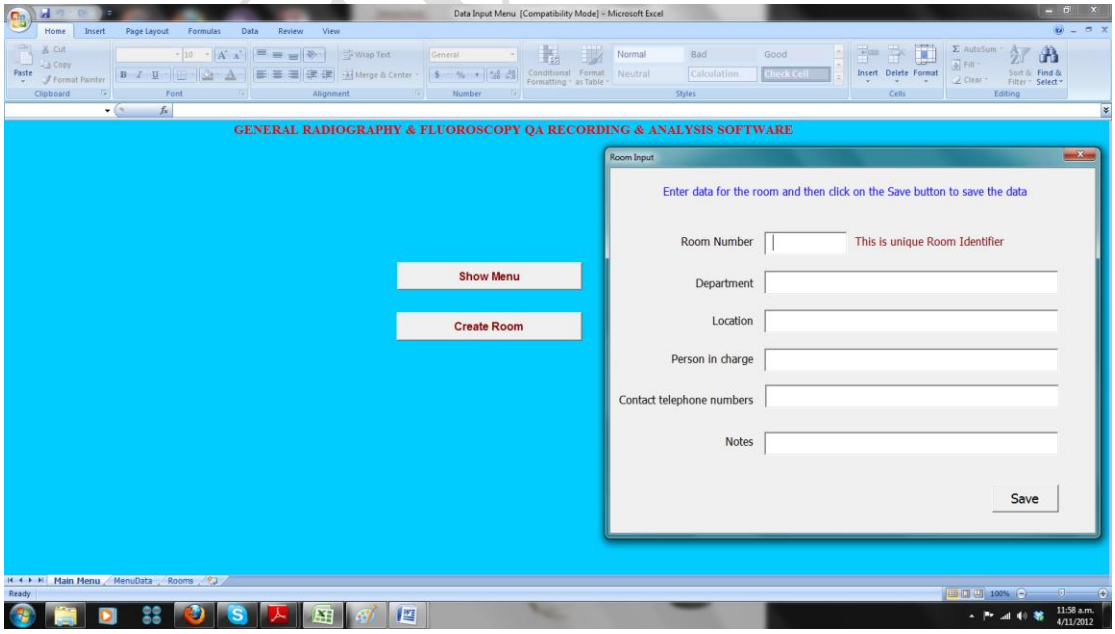

Figure B3: Shows the Create Room userform.

After populating the form the user can click the *Save* button to save the information and this information is automatically saved in the *Rooms* worksheet. As a precautionary measure when a user attempts to change data of an existing room a warning will be issued before the data is saved. Alternatively information about a room can be edited on the *Rooms* worksheet.

Navigation through the worksheets is made easier by grouping the tests according to both modality and their frequency. A certain security degree is maintained through sheet and cell protection, but the user is responsible to keep clean working habits.

The worksheets use the following unique coloured scheme. This makes it more user-friendly.

Table B1: The colour coding system used in this program.

Colour	Represents
Accent 6, Orange	Direct data input cell
Orange	Calculated value from another cell
Green	Pass / Yes criteria
Red	Fail / No criteria
Grey	Worksheet background

Results of the tests can be printed off and the print-outs are optimized to be one a single A4 size page and in black and white. Since the aim is to replace working with hardcopies, the print quality is set to low quality.

B2.1 Radiography and Fluoroscopy Daily Tests

Worksheets to perform daily tests are found on the worksheets: Radiography and Fluoroscopy Daily Tests. The daily tests on radiography and fluoroscopy units consist of visual checks on the equipment. These tests are to assure that all components of the radiographic x-ray system indicator lights, displays, and mechanical locks and detents are working properly and that the mechanical rigidity and stability of the equipment is optimum. The user has to confirm functionality of the various components, by ticking the check boxes on the worksheet. A tick resembles a Pass/ Yes/ Affirmative action whilst an un-ticked check box represents a Fail/ No.

B3.1 Radiography and Fluoroscopy Weekly Tests

The weekly step wedge test is found on the Radiography and Fluoroscopy Weekly Tests worksheets of the Main Menu. Analysis of the results is either visual inspection of the resulting step film (comparing to the reference / baseline film) or through measurement of the optical densities at each step using a densitometer. The optical densities for each step are plotted on a control chart. Each week the highest number of discernible steps on the step wedge should be recorded and any deterioration from the baseline value should be investigated.

B4.1 Radiography and Fluoroscopy Quarterly Tests

Worksheets to perform the three monthly tests are found on the worksheets: Radiography and Fluoroscopy Quarterly Tests. For fluoroscopy suites three monthly tests involve the check on the protective clothing and the HLC safety functionality. For radiography rooms the tests which are done on a three monthly interval are the light field –radiation field congruency, visual inspection on protective clothing, radiation field bucky alignment and the collimator alignment and checks on positive beam limiting devices.

B4.1.1 Light Field and Radiation Congruence Test

Aim:

- To determine if radiation is being delivered on the projected light field.

Procedure:

- Install a loaded 24cm X 30 cm cassette in the bucky and set an FFD of 100 cm.
- Adjust the field size such that its less than the film size.
- Place coins as shown below:

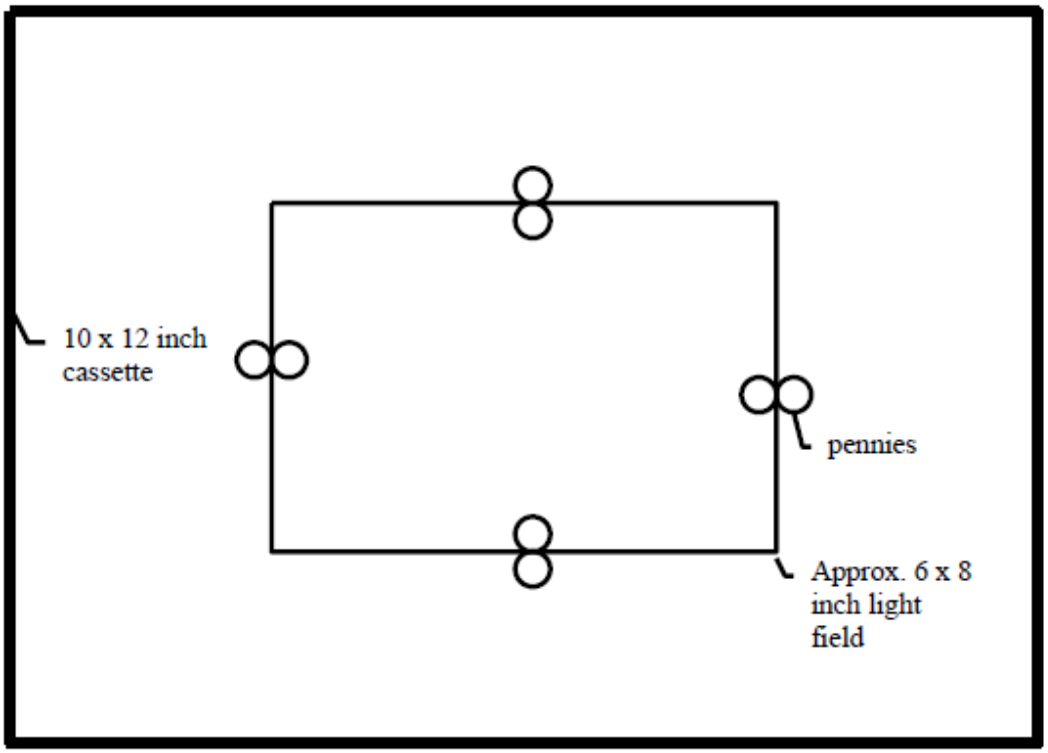

Figure B4: Set up for the light field and radiation field congruence.

- Expose the X-ray film to get sufficient darkening and subsequently develop.
- After developing the film measure the distances between the light (where coins touch) and radiation field for all coin locations.
- Enter the measured distance differences into the spreadsheet on cells **D12:G12.**

.

Results:

- The tolerance for this test is ±2% of the SID.

B4.1.3 Radiation Field and Cassette Holder Alignment Test

Aim:

- To assure that the light field accurately defines the x- ray field.

Procedure:

- Use the same exposed film from the Light Field and Radiation Congruence test.
- Determine the center of the x-ray field and also the geometric centre of the film using a ruler edge as shown in the worksheet (see Rad Field Cassette Alignment worksheet).
- Enter the measured distances on the spreadsheet cell **D13**..

Results:

- The tolerance for this test is ±2% of the SID.

B4.1.2 Protective Clothing Tests

Aim:

- Apron, gonad shield and gloves are screened periodically to determinate their function in blocking radiation passage.

Procedure:

- Each item is visually and manually inspected for holes and cracks. If notice suspicious then fluoro them.
- Screening maybe used to confirm holes and cracks.
- Lead shields found to be defective are discarded through the Radiation Safety Unit for proper disposal of lead.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Protective clothing with holes or breaks should be removed from use and be replaced.

B4.1.5 Positive Beam Limiting Device Test

Aim:

- To determine if the positive beam limiting device is operating correctly.

Procedure:

- Identify two cassettes of the same size.
- Insert one cassette on the cassette holder and the other on the patient couch, each time ensure that the cassettes are uniformly oriented.
- Determine if the collimator is adjusted to a field size smaller than the image receptor while the PBL system is activated, the light field should be slightly smaller than the size of the cassette on the patient couch.
- Determine if the PBL system responds correctly to different cassette sizes.
- Determine if X-ray production is not possible at an FFD outside the specified range for the PBL system.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Collimator should adjust to a field size smaller than the image receptor.
- PBL system should respond correctly to changes in cassette sizes.
- Radiation production should not be possible at an FFD outside the range of the PBL system.

B4.1.7 Radiography Dose Constancy Test

Aim:

- To determine if the X-ray tube radiation tube output is constant over a period of time.

Procedure:

- The baseline value for this set-up should be determined on an annual basis following the absolute dosimetry.
- Information will be recorded on the Dose Constancy worksheet under the Radiography Quarterly Tests workbook.
- The chamber must be at 80 cm from the source with at least 20 cm from the couch to avoid backscatter.
- Use the following exposure factors: **70 kVp** and **40 mAs**.

- Enter the ambient temperature and pressure on cells **D26:D27**.
- Make at least three exposures and record the measured charge on cells **D34:F34**.
- Compare the measured charge with the baseline value.

Results:

- The tolerance for this test is ±25%.

B4.1.7 Fluoroscopy Dose Rate Constancy Test

Aim:

- To determine if the X-ray tube radiation tube output is constant over a period of time.

Procedure:

- The baseline value for this set-up should be determined on an annual basis following the absolute dosimetry.
- Information will be recorded on the Dose Rate Constancy worksheet under the Fluoroscopy Quarterly Tests workbook.
- Set a distance of 100 cm from focus to image intensifier.
- Record the focus-to-image intensifier distance on cell **C24**.
- Position the ionization chamber on the **185 mm** thick PMMA phantom
- Use the following exposure parameters: **70 kVp** and **4mA**. Any other reference exposure parameters can be used as long consistent with the absolute dosimetry.
- Enter the ambient temperature and pressure on cells **D24:D25**.
- Make at least three exposures and record the charge measured over 1 minute on cells **C36:E36**.
- Compare the measured charge with the baseline value.
- Compare the measured charge with the baseline value.

Results:

- The tolerance for this test is ±25%.

B4.1.7 Fluoroscopy High Level Control (HLC) Test

Aim:

- To determine if the audible indicator of the HLC is functioning properly.

Procedure:

- Activate the HLC.
- Determine if the audible indicator sounds when the HLC is activated.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- The audible indicator should sound whenever the HLC is engaged.

B5.1 Radiography Semi Annual Tests

Worksheets to perform the bi-annual tests are found on the Radiography Semi-Annual workbook. The following tests are under this category: dark room fog test, room lighting, viewing box luminance and light field luminance.

B5.1.1 Dark Room Fog Test

Aim:

- To assure that the safelights and other potential sources of "unsafe" light will not fog the film being handled in the dark room.

Procedure:

- Turn off all lights in the dark room.
- After eyes have adapted to the darkness (about 5 minutes), check for light sources. Particular attention should be devoted to seals around doors, pass-boxes, processors, suspended ceilings, etc.
- Eliminate any light sources.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**
- Open a new box of film. This box film must be the same type that is normally used in the dark room.
- Load the film into the cassette in total darkness.
- Exposure the film using an X-ray technique to a density of film is approximately 1.0.

- Place the film on the counter in the darkroom with all of lights off.
- Cover the left half of the film with one opaque sheet of paper. Keep this half covered throughout the two steps.
- Turn on the safelights and all other indicator lights.
- Cover all but the upper quarter of the remaining portion of film with the second piece of the opaque paper and expose that portion for 2 minutes. Shift the opaque paper so that one-half of the film is uncovered and exposed 1 minute. Shift the paper again so that ¾ of the film is uncovered and exposed for another minute. This film has a total exposure of 4, 2, and 1 minutes in the three exposed areas.
- Determinate the density difference between the exposed areas and the corresponding unexposed areas using a densitometer.
- Enter the density difference on cell **D19.**

Results:

- The density difference between the fogged and unfogged portions of the film should not exceed 0.05 O.D. For the two minute exposure area and must not exceed 0.05 O.D. for the one minute exposure.

B5.1.2 Room Lighting Test

Aim:

- To assure that the room light conditions are adequate for optimal viewing of radiographs.

Procedure:

- Use a calibrated photometer for measurements.
- Measurements should be done 30 cm away from a switched off viewing box.
- Perform measurements on four different positions.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**
- Enter the photometer readings on cells **F15:F18.**

Results:

- The average light luminance shall be at equal to or less than 100 lux.

B5.1.3 Viewing Box Luminance Test

Aim:

- To assure that the viewing boxes provide for optimal viewing of radiographs.

Procedure:

- Use a calibrated photometer for measurements.
- Before starting measurements ensure that the viewing box has been ON for a reasonable time to ensure that the light output is stable.
- Partition the viewing box into four imaginary quadrants.
- Perform measurements on four quadrants and on the central position.
- Enter the photometer readings on cells **F16:F19.**

Results:

- The average viewing box luminance shall be greater than or equal to 1500 cd/m^2.
- Viewing box luminance uniformity should be less than 20%.

B5.1.5 Light Field Luminance

Aim:

- To assure that the luminance of the light field collimation indicator is sufficient to delineate the area being exposed and that the dial markings on the collimator are accurate.

Procedure:

- Place the photometer on the tabletop, 100 cm from the source.
- Partition the light field into four imaginary quadrants.
- Activate the collimator light with the room lights off and read the luminance shown on the meter.
- Repeat for the remaining quadrants.
- Enter the photometer readings on cells **F11:F14.**
- Also measure the background luminance and record it on cell **D14.**

Results:

- The light luminance shall be at least 160 lux at 100 cm SID.

B6.1 Radiography Annual Tests

Worksheets to perform the annual tests are found on the Radiography Annual Tests and Fluoroscopy Annual Tests workbooks depending on the modality you are testing. It is advisable to have a qualified medical physicist perform these annual tests.

B6.1.1 Tube Leakage Test

Aim:

- To assure compliance with the regulatory requirements.

Procedure:

- Use worksheet Tube Leakage found on Radiography Annually and Fluoroscopy Annually workbooks.
- Compliance is evaluated using the maximum X-ray tube potential and the maximum beam current at that potential for "continuous tube operation".
- Maximum tube potential and current ratings (kVp_{max} and I_{max} , respectively) are usually quoted as leakage technique factors. I_{max} depends on kVp_{max} and the values typically assumed for I_{max} are 3.3 mA, 4 mA and 5 mA for kVp_{max} of 1150 kVp, 125 kVp and 100 kVp, respectively.
- For Assessment of X-ray Tube Leakage Radiation Close the X-ray tube diaphragm and place the tube down on the X-ray table. Surround the X-ray tube with at least 6 big X-ray cassettes with films, forming a closed volume (cubicle) around the X-ray tube housing (number the films).
- Perform a heavy exposure (according to the X-ray unit possibilities kVmax) – for example 125 kVp/ 200 mA for 1 sec.
- Develop the films and identify the dark places on the films.
- Place a large volume ionisation chamber at the places, where the films are most dark, 0.1 metre from the tube housing.
- If highest kV is:
    - 150 kVp use 3.3 x (3600/100) = 118.8 use therefore 120 mAs.
    - 125 kVp use 4 x (3600/100) = 144 mAs or if not available use 150 mAs
    - 100 kVp use 5 x (3600/100) = 180 mAs
- Repeat the measurement at other places around the tube housing and record the chamber readings on cells **C15: E18**.

- Set at highest kVp $_{max}$ (e.g 125 kVp), lowest mA (e.g. 50 mA) longest exposure time (e.g. 5 seconds).
- Make exposure and perform measurement at 1 metre.
- Record the readings on cells **C29:E32.**
- Repeat to cover the whole tube and record highest reading.

Results:

- Leakage radiation should be equal to or less than 0.876 mGy/ h (0.876 mGy/ h = 1 mSv/ h = 100 mR/ h) at 1 m.

B6.1.2 KAP-meter Verification Test

Aims:

- To assure that the KAP meter reading is accurate.

Procedure:

- Mount the KAP meter on the tube housing.
- Collimate the X ray beam to the desired field dimensions.
- Use these exposure parameters: **70 kVp** and **10 mA**.
- Place the ionization chamber on the central axis at a position of 200 mm above the couch to avoid the influence of backscattered radiation.
- Expose the ionization chamber and record the charge readings on cells **D21:F21.**
- Note the average of the KAP readings and record it on cell **E26**.

Results:

- Agreement between the chamber and KAP should be within ±25 %.

B6.1.4 Output Reproducibility Test

Aims:

- To test if the radiation output from the X-ray tube is reproducible.

Procedure:

- Position the ionization chamber in air at 80 cm from the source and away from any surfaces that can contribute backscatter.
- Field size should be large enough to cover the ionization chamber.

- To avoid the heel effect, do not place the ionization chamber towards the anode side of the X-ray tube.
- Set the X-ray generator to technique factors commonly used in the clinic e.g. 80 kVp.
- Make 5 exposures and record the charge reading for each exposure on cells **C16:C20.**

Results:

- The coefficient of variation should be within ≤5 %.

B6.1.6 Timer Accuracy

Aim:

- To ensure that the console time display is accurate and correct.

Procedure:

- Use the worksheet Timer Accuracy under the Radiography Annual Tests workbook.
- Use the PTW DiaVolt or equivalent instrumentation.
- Set value of kVp most frequently used in the room.
- Make an exposure at selected time station.
- Enter the DiaVolt readings in cells **C12:C22.**

Results:

- Time accuracy should be ≤ 10 %.

B6.1.8 kVp Accuracy Test

Aim:

- To ensure that the X-ray generator is producing the kVp as selected on the control panel.

Procedure:

- Use the worksheet kVp Accuracy under the Radiography Annual Tests workbook or Fluoroscopy Annual Tests workbook depending on the modality you are working on.

- Use the PTW DiaVolt or equivalent instrumentation.
- Collimate the beam to the active area of DiaVolt.
- Make exposures and record the displayed kVp values on cells **D13:D20** of the worksheet.

Results:

- kVp accuracy should be within ≤ 10 %.

B6.1.6 Annual QA Checklist

Aim:

- To ensure that an up-to-date QA program in the clinic.

Procedure:

- This test is in the form of a checklist.
- Ideally this test should be discussed at the departmental QA Committee meeting.
- Any non affirmative responses to the checklist questions must be followed up with the QA committee.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Affirmative responses to the checklist questions indicate a relevant and up-to-date technique chart.
- A non-affirmative response must be followed up with the QA committee.

B6.1.7 Technique Chart Review Test

Aim:

- To ensure that an up-to-date technique chart is being used in the clinic.

Procedure:

- This test is in the form of a checklist.
- Ideally this test should be discussed at the departmental QA Committee meeting.

- Any non affirmative responses to the checklist questions must be followed up with the QA committee.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Affirmative responses to the checklist questions indicate a relevant and up-to-date technique chart. A non-affirmative response must be followed up with the QA committee.

B6.1.9 Source-to- Image Distance Indicator Test

Aims:

- To assure that the source-to-image distance (SID) is indicated accurately.

Procedure:

- Note the indicated SID from the distance indicator. This should be done for each clinically used SID.
- Measure the distance from the focal spot to the cassette.
- Enter the measured distance on cell **C10.**

Results:

- This distance should be within 2% of the indicated SID.

B6.1.10 mA Linearity Test

Aim:

- To assure linearity or consistency in mGy/mAs between mA stations to achieve uniform results for the same mAs.

Procedure:

- Use the worksheet mA linearity Accuracy under the Radiography Annual Tests workbook.
- Set kVp and time most frequently used in the room.
- Make exposures over a range of mA settings and record the measured charge on cells **E13: G18.**

Results:

- Any two consecutive tube current settings shall not differ by more than 0.1 times their sum. That is $(X1 - X 2) \leq 0.1 (X1 + X 2)$.

B6.1.11 Half Value Layer Test

To be determined using an appropriate dosimeter, with a reasonable stability over a range of beam qualities. Also high purity aluminium filters to be used.

Aim:

- To assure that the amount of filtration is in compliance with DRC regulations.

Procedure:

- Use the worksheets HVL under either Fluoroscopy Annual workbook or Radiography Annual workbook depending on the modality you are using.
- Experimental set-up is as in IAEA-TRS 457.
- Enter the absorber thickness in column cells **B13:B17.**
- Record the measured charge for each absorber thickness on cells **D13:F17.**
- Note the trend-line equation from the plot.
- Enter the slope and intercept values from the trend-line equation on cells **B19** and **C19** respectively.

Results:

- Calculated HVL is given in cell **F21**.
- Compare with Table 3 in the DRC QC document.

B6.1.12 Radiography Absolute Dose Measurement

Aim:

- To measure the X-ray tube radiation output.

Procedure:

- Information will be recorded on the Absolute Dose worksheet under the Radiography Annual Tests workbook.
- Enter the exposure parameters to be used for the absolute dosimetry.
- Set a distance of 100 cm from focus to the patient couch.

- The ionization chamber should be at least 25 cm away from the patient table to avoid influence of backscattered radiation influencing its signal.
- Enter the ambient temperature and pressure.
- Enter the beam quality factor on cell **C24**.
- Make at least three exposures and record the charge collected in cells **C29:E29.**
- The incident air kerma is calculated in accordance to the IAEA -TRS 457 formalism.

Results:

- After determining the incident air kerma immediately determine the baseline values for the quarterly output constancy tests.

B6.1.13 Fluoroscopy Absolute Dose Measurement

Aim:

- To assure that the output dose rate of the fluoroscopy unit is in compliance with DRC regulations.

Procedure:

- Information will be recorded on the Annual Absolute worksheet under the Fluoroscopy Annual Tests workbook.
- Enter the correct chamber calibration factor on cell **D36.**
- Set a distance of 100 cm from focus to image intensifier.
- Record the focus-to-image intensifier distance.
- Position the ionization chamber on the **185 mm** thick PMMA phantom
- Enter the exposure parameters and beam quality on the worksheet.
- Enter the beam quality factor on cell **D31.**
- Enter the ambient temperature and pressure in cells **D26:D27.**
- Make at least three exposures and record the measured charge collected over a period of **1 minute** in cells **D39:F39.**
- Based on your set field size and beam quality choose the appropriate water and PMMA backscatter factors as given in IAEA-TRS 457. These should be entered in cells **D33:D34.**

- Use the IAEA -TRS 457 formalism to calculate the entrance surface air kerma rate.

Results:

- Entrance surface air kerma rate must be ≤50 mGy/min for normal dose rate.

B6.1.14 AEC Consistency (kVp) Test

Aim:

- To check the reproducibility of all the AEC chambers with varying kVp.

Procedure:

- Place a total thickness of 14 cm of perspex slabs close to the image receptor.
- Install an X-ray film in the film holder.
- Perform three exposures with the same chamber selected.
- The three exposures should be at 60 kVp, 80 kVp and 100 kVp.
- Enter the density readings in cells **D11:F14.**
- Compare the net densities of the three exposed films.

Results:

- The net densities should be within 0.9 and 1.4.
- Net density variation between the 4 films should be less than 0.2.

B6.1.15 AEC Consistency (Thickness) Test

Aim:

- To check the consistency of all the AEC chambers at different object thickness.

Procedure:

- Place a total thickness of 5 cm of perspex slabs close to the image receptor.
- Install an X-ray film in the film holder.
- Perform three exposures with the same chamber selected.
- Repeat the three exposures using 10 cm and 20 cm total thickness of perspex.
- Enter the density readings in cells **D12:F15.**
- Compare the net densities of the three exposed films.

Results:

- The net densities should be within 0.9 and 1.4.
- Net density variation between the 4 films should be less than 0.2.

B6.1.16 AEC Chamber Consistency Test

Aim:

- To check the consistency in response between all the AEC chambers.

Procedure:

- Place a total thickness of 20 cm of perspex slabs close to the image receptor.
- Install an X-ray film in the film holder.
- Select one chamber at a time and subsequently make three exposures.
- Repeat exposures for the other 2 chambers.
- Enter the density readings in cells **D13:F16.**

Results:

- The net densities should be within 0.9 and 1.4.
- Net density variation between the 4 films should be less than 0.2.

B6.1.17 AEC Overall Reproducibility Test

Aim:

- To check the reproducibility of all the AEC chambers.

Procedure:

- Place a total thickness of 20 cm of perspex slabs close to the image receptor.
- Adjust the beam size such that all the ionization chambers are within the radiation field.
- Install an X-ray film in the film holder.
- Select all the AEC chambers to be operational during exposure.
- Expose at 80 kVp.
- Repeat the exposures 4 times.
- Enter the density readings in cells **D13:D16.**

Results:

- The net densities should be within 0.9 and 1.4.
- Net density variation between the 4 films should be less than 0.2.

B6.1.18 Fluoroscopy Spatial Resolution Test

Aim:

- To check the maximum spatial resolution of a fluoroscopic system using the X-ray line pairs per mm patterns.

Procedure:

- Use the test pattern tool composed of line pair (lp) with discreet line pair groups.
- The test pattern tool shall be placed on a 19 mm thickness of type 1100 aluminium.
- The aluminium plate shall be covered by useful beam completely.
- Distance between couch and Image Intensifier shall be 30 cm.
- If the system has variable source to image (SID) then SID should not exceed 100 cm.
- Record of the highest number of the test pattern that gives visible separation lines between of group.
- Repeat for all the magnification stations.
- Results are to be entered in **Column D** of the worksheet.

Results:

- The minimum spatial resolution at center of the beam for all FOVs is given in the DRC document.

B7.1 Cassettes and Screens Tests

The QC tests on cassettes and screens is found on the Cassette and Screens workbook.

B7.1.1 Visual Check, Identification and Cleaning of Cassettes

Aim:

- To ensure the cassettes are in good order, are clearly marked with the correct type and speed of intensifying screens, and are identified by number to enable any cassette causing a film fault to be easily traced.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Procedure:

- Clean external surfaces of cassettes with damp swabs and soap or spirit-based swabs, taking particular care to avoid spirit contact with intensifying screens.
- Inspect cassette for damage, particularly the edges, hinge and catches.
- Check that the type of intensifying screen is clearly marked.
- Check that the cassette is marked with a number, which corresponds to the number on the intensifying screen.

Results:

- Cassettes with damage to the hinge or catches should be sent for repair or discarded.
- Intensifying screen identification labels should be replaced if not clear. All cassettes should be marked with indelible marker with a number to correspond to the number on the intensifying screen.

B7.1.2 Cassette Light Tightness Check

Aim:

- To test for light leakage into cassettes causing film fogging.

Procedure:

- Load the cassette with a film
- Place the cassette with suspect area of cassette uppermost, next to light source.
- Leave for 15 - 30 minutes.
- Process the film.
- A **tick** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Any light leakage will cause fogging.

B7.1.3 Screen-Film Contact Test

Aim:

- To assure that optimum contact is maintained between the screen(s) and film in each cassette.

Procedure:

- Load cassettes to be tested and let rest for approximately 15 minutes to allow trapped air to escape.
- Place the cassette on the table and collimate the beam to the cassette size.
- Place the wire mesh on top of the cassette and expose the cassette.
- Suggested technique factors are: 5-10 mAs, 50 kVp; 2 mAs, 70 kVp; or 3-5 mAs, 60 kVp).
- Process the film. The optical density of the area between the wires of the mesh on the film should be between 1.5 and 2.0.
- View the film on a viewbox in a room with low ambient lighting.
- Areas of poor contact will appear as dark areas on the film.
- A **tick** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Large areas (>2 cm in diameter) of poor contact may indicate the need for corrective action.
- Areas of poor contact around the periphery of the cassette may indicate faulty latches or worn seals on the cassettes.
- If the area of poor contact is not eliminated by cleaning, consider replacing the cassette.

8.1 Processor Tests

Below are the required tests for wet processors.

8.1.1 Processor Baseline Sensitometry Tests

Aim:

- To establish baseline sensitometry values for the processor, when the quality control program is initiated or there is a significant change in the processing workflow.

Procedure:

- Select a new box of film to be used for quality control purposes.
- Drain the chemicals and flush the processor with water.
- Replenish the tanks with fresh chemicals.
- Set the temperature recommended by the film manufacturer.
- Set the chemicals' replenishment rates to those recommended by the manufacturer.
- Expose and immediately process a sensitometric strip.
- Repeat this for five consecutive days.
- Read and record the densities from the sensitometric strip, including the density from the unexposed part of the film.
- The densities are to be entered in cells **D14:H35** of the worksheet.
- The average density for each step from the 5 sensitometry strips done over 5 consecutive days is given in **Column I.**
- Determine which step has a density closest to 1.20, and this corresponds to mid-density (MD).
- Determine which step has a density closest but less than 2.20, and this corresponds to high-density (HD).
- Determine which step has a density closest but not less than 0.45, and this corresponds to low-density (LD).
- The difference between HD and LD is the difference density (DD).
- Determine the average of the densities from the unexposed parts of the films, this is base-plus-fog density (B+F).

Results:

- Results of this test become baseline values of the processor sensitometry.

8.2 Processor Daily Tests

The daily test on the processors combines general functionality tests and particular processor parameters to be recorded and monitored every day. The daily tests have been split into two, namely quantitative and qualitative tests.

8.2.1 Qualitative Daily Processor Tests

Aim:

- To make sure on a day to day basis that all photographic processor is running optimally and producing consistent, high quality film.

Procedure:

- This test is in the form of a checklist.
- Answer the listed questions on the worksheet, ***a tick*** on the tick box indicates **pass** of criteria while if the tick box is **left un-ticked** that represents a **fail.**

Results:

- Affirmative responses to the checklist questions indicate a relevant and up-to-date technique chart.
- A non-affirmative response must be followed up for corrective action.

8.2.2 Quantitative Daily Processor Tests

Aim:

- To make sure on a day to day basis that all photographic processor is running optimally and producing consistent, high quality film.

Procedure:

- Expose the control film with the sensitometer.
- Develop the control film.
- Measure and record the base + fog optical density.
- Measure and record the optical density at the mid-density step.
- Measure and record the optical density at the high-density step.
- Measure and record the optical density at the low-density step.

- Calculate the difference density.
- Measure and record the developer temperature.
- Confirm that the levels of the chemicals are optimum.
- This information is to be entered on the **Daily QA** worksheet form under the **Processor Daily Tests** workbook.
- Type **a** for a tick to indicate a pass and **r** for a cross to indicate non-compliance.
- To archive the data click on the **Tabulate Morning Processor Check** button.

Results:

- Baseline Processor performance indicators would have been previously determined using the procedure **Processor Baseline Sensitometry Tests** described in **3.7.1.**
- If the MD and DD are within ±0.15 of their respective operating levels, and the B+F is within ±0.03 of its operating level, the processor is in control, and no further action is required.
- If the MD or DD exceeds the control limit of ±0.15, the source of the problem should be determined and corrected before clinical films are processed. Likewise, if the B+F exceeds +0.05, corrective action should be taken before clinical films are processed.
- The developer temperature should be as advised by the chemistry supplier/ manufacturer.
- An archive of all the tests is found on the **Daily QA Table** worksheet on the **Processor Daily Tests** workbook.

B8.3 Control Film Cross-Over Test

Aim:

- When one nears the end of the box of film that has been used for processor monitoring, crossover testing should begin with the new box of film.

Procedure:

- With 5 films remaining, select a new box of film for processor quality control.
- Assure that the processor is in control.

- Expose and immediately process 5 sensitometric strips each from the old and new boxes of film.
- For the old box of films enter the densities on cells **E13:I17.**
- For the new box of films enter the densities on cells **E22:I26.**
- Determine the average of the steps previously identified for processor quality control for MD, DD, and B+F from the 5 films from the old box and from the 5 films from the new box.
- Determine the difference in the average values between the new and old boxes of film.
- Adjust the old operating levels for MD, DD, and B+F by this difference to establish the new operating levels. This is accomplished by adding the difference (new-old), including the sign, to the old operating level. If the difference (new-old) is positive, the new operating level is increased. If the difference (new-old) is negative, the new operating level is decreased.
- Record the new operating levels with their new control limits on a new control chart. Record the complete emulsion number of the new box of film on the new processor control chart. If the new box of film produces step densities that are so different from the old that the monitored steps are no longer the best choices, then new operating levels need to be established. (The best choices are the step with densities greater than or equal to 0.45 for the low-density step, closest to 1.20 for the mid-density step, and closest to but less than 2.20 for the high-density step.)
- Make a notation on the control chart in the remarks section of the date that a cross-over was performed.

Results:

- If the MD and DD are within ±0.15 of their respective operating levels, and the B+F is within ±0.03 of its operating level, the processor is in control, and no further action is required.
- If the MD or DD exceeds the control limit of ±0.15, the source of the problem should be determined and corrected before clinical films are processed. Likewise, if the B+F exceeds +0.05, corrective action should be taken before clinical films are processed.

B9.1 Repeat Analysis

This worksheet provides for repeat analysis. This test should be done every 3 months. The data is presented in the form of bar charts for easy visualization.

Aim:

- To provide a method for the analysis of the rejected radiographs will provide information concerning those aspects of radiological imaging that need the most attention.

Procedure:

- Start the test with an empty reject film container.
- Establish a method to accurately determine the amount of raw film consumed starting on the day that you clean out the reject films.
- Decide on the length of the survey period (such as a week). At the end of this period, collect all rejected radiographs and determine the actual number of radiographs exposed (i.e., the number of sheets of raw films consumed) during this period.
- Analyze all of the rejected films and determine the reason that they were probably rejected.
- Record the reasons for rejection in cells **D46 and above**, while the number of rejected films in that category is recorded in cells **E46 and above**.
- Determine the overall reject rate. For example, if there were 7 rejected films and a total of 122 films produced, then overall rate is:

$$\frac{7}{122} \times 100\% = 5.7\%$$

- Determine the percentage of rejects from each of categories. For example. 3 films fell into category labelled " over exposure". The percentage of rejected films falling into this categories is:

$$\frac{3}{7} \times 100\% = 43\%$$

Results:

- Should be ≤ 10 %.
- Cannot increase by more than 2 % from its previous rate.

B10.1 Individual Equipment Record (IER)

The DRC requires that the licensee compiles and maintains an IER which contains the following information:

- Equipment particulars e.g. make, model, serial number e.t.c.
- Operators manual.
- Details of the following:
    - Person responsible for the overall QA program.
    - Person or organization responsible for maintenance tests.
    - Records of the acceptance tests.
    - Maintenance tests to be conducted and their frequency.

The above information is to be entered into the designated input cells of the equipment IER worksheet.

APPENDIX C

X-RAY ROOM DATA COLLECTION FORM

Table B2: X-ray room data collection form.

X-ray generator	
X-ray generator model	
Generator waveform	
X-ray tube	
Filtration	
Bucky	
Grid ratio	
Grid strip frequency	
Interspace and cover material	
Image receptor	
Type of screen	
Speed	
Type of film	

APPENDIX D

PATIENT DATA COLLECTION FORM

ROOM NUMBER: _____

TYPE OF EXAMINATION: _____

Table B3: Patient data collection form.

Patient No.	Mass (kg)	Height (m)	Age	Gender	Tube Voltage (kVp)	Tube Loading (mAs)	Patient thickness (cm)	FFD (cm)	Cassette size (cm*cm)	Grid Used (Yes/No)	Film Density OK (Yes/No)

APPENDIX E

PARTICIPANT QUESTIONNAIRE FORM

Research Project: ***Dose Optimization in Diagnostic Radiology***

A Doctoral Research Study Being Undertaken Through the University of the Witwatersrand, Johannesburg

Principal Investigator: Thulani Nyathi
Division of Medical Physics
Area 348: Johannesburg Hospital
Private X39
Johannesburg 2000
South Africa
Tel: (011) 481 -2148
Fax: (011) 484 -9202

We are conducting a study to assess radiographic practice with the advent of digital radiography. For the purposes of this study the term digital radiography means both computed radiography (CR) and direct digital radiography (DDR). We would like to invite you to participate in this study.

Please complete the following questionnaire.

Name of Hospital	
Name and Surname of Respondent	
Status of qualification	Student ☐ Qualified ☐
Type of employment	Part-time ☐ Full-time ☐
If working as a qualified radiographer, how many years post qualification have you worked	<1 ☐ 2 -5 ☐ 6 - 10 ☐ 10 + ☐
Which type of digital radiography are you using	CR ☐ DDR ☐ Both ☐
Manufacturers of machines you are using	Philips ☐ Siemens ☐ Toshiba ☐ Agfa ☐ Fuji ☐ Kodak ☐ Konica Minolta ☐ Other ☐
If you answered Other, please specify the manufacturer	
How many years of experience do you have with digital X-ray units	<1 ☐ 2 -3 ☐ 4 - 5 ☐ 5 + ☐
How many years of experience do you have with conventional X-ray units	<1 ☐ 2 -3 ☐ 4 - 5 ☐ 5 + ☐
How many months did it take you to be confident with using a digital X-ray unit	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 5 +☐
Have you read the manual of the digital-ray unit you are operating	Yes ☐ No ☐
How do you rate the effectiveness of the X-ray examination type specific image processing algorithms?	Very Poor Very Good 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐
Do you think the digital X-ray units downtime (service, repairs, and breakdown) is longer than for conventional screen- film units?	More ☐ Less ☐ No difference ☐
Did you study digital radiography at university, college or technikon	Yes ☐ No ☐
How many radiography conferences or workshops have you attended in the past one year	1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 5 + ☐
Have you undergone any formal quality control training for digital X-ray units or for the unit you are using	Yes ☐ No ☐
If you answered Yes above, who conducted the training	
Do you do quality control on the workstation monitors	Yes ☐ No ☐

Who is in-charge of quality control in your department	Radiographer ☐ Medical Physicist ☐ Manufacturer representative ☐ Administrative person/ manager ☐ Do not know ☐
Does your department have a written quality - control or –assurance protocol.	Yes ☐ No ☐
How does the radiation dose from a chest X-ray compare to the annual dose a person receives from background radiation	1/100 ☐ 1/10 ☐ equal ☐ 10 times ☐ 100 times ☐
How much radiation dose does a patient absorb during a chest X-ray?	0.02mSv ☐ 0.2mSv ☐ 2mSv ☐ 20 mSv ☐ 200 mSv ☐
In your own opinion, which modality results in higher radiation dose between conventional general radiography and general digital radiography?	Conventional ☐ Digital ☐
Do you have a technique chart posted in the imaging room	Screen-Film Yes ☐ No ☐ Digital Yes ☐ No ☐
Digital radiography has a wider linear dynamic range in the dose response curve than conventional radiography	True ☐ False ☐

Based on your workplace technique chart enter the exposure settings you use for a **chest** X-ray examination for an medium sized patient using the listed modalities.		
	kV	mAs
Screen –film		
Computed radiography		
Direct Digital Radiography		

How many patients would you X-ray per day (shift) using screen –film radiography or digital radiography?	Screen-Film _____ Digital _____
Do you use grids for your digital imaging?	Yes ☐ No ☐
When comparing digital radiography with conventional screen film radiography which modality has better spatial resolution?	digital radiography ☐ screen- film ☐
When comparing digital radiography with conventional screen film radiography which modality has better image quality?	digital radiography ☐ screen- film ☐
With digital radiography I decide more easily to do a repeat exposure than with conventional radiography	Agree ☐ Disagree ☐
Are you performing reject analysis with digital radiography?	Yes ☐ No ☐
How are patient images at your workplace archived?	film ☐ paper ☐ compact disk ☐ network ☐
Are you linked to a PACS?	Yes ☐ No ☐
In digital radiography, do you prefer to collimate before you take an image or crop after you have taken the image?	Before ☐ After ☐

In your own view what are the advantages of digital radiography over conventional screen –film radiography

In your own view what are the disadvantages of digital radiography over conventional screen – film radiography

Any other comments

Thank you for your time and effort in assisting with this research.