Assessment of quality control in medical diagnostic x-ray facilities in the western region of Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as University Supervisors.

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DEDICATION

This work is dedicated to my beloved parents, my brothers and sisters, brethren in the Apostles' Church of Christ Jesus, my dear wife Jacky, son Moses and daughter Ellah.

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ABBREVIATIONS AND ACRONYMS

AEC	Automatic Exposure Control
AED	Automatic Exposure Devices
AERB	Atomic Energy Regulatory Board
AP	Antero-posterior
ASRT	American Society of Radiation Technologists
BIR	British Institute of Radiology
CRCPD	Conference of Radiation Control Programme Directors
DAP	Dose Area Product
DRL	Diagnostic Reference Level
DQE	Detective Quantum Efficiency
ESD	Entrance Surface Dose
EC	European Commission
ICRP	International Commission on Radiological Protection
IPEM	Institute of Physics and Engineering in Medicine
MTF	Modulation Transfer Function
NEXT	National Evaluation of X-ray Trends
NRPB	National Radiological Protection Board
PA	Posteroanterior
QA	Quality Assurance
QC	Quality Control
RMI	Radiological Medical Imaging
RPB	Radiation Protection Board

ABSTRACT

Amongst the man made ionizing radiations, X - ray diagnostic procedures contribute the highest per capita radiation dose to population over and above the natural background radiation. Although the X-ray diagnostic procedures have revolutionized medical diagnosis and treatment of many diseases, their extensive use has raised concern on possible over exposure. The patient may receive radiation dose in excess due to bad practice and bad equipment and hence every X-ray machine should be subjected to periodic quality assurance (QA) tests. Poor functioning of any parameter may lead to retake of X-ray, which in turn increases cost and radiation to patient and staff. Moreover the knowledge of radiation doses received by the patients during radiological procedure is necessary and all efforts must be made to keep the radiation dose to minimum level. The aim of this work was to determine the current status of diagnostic X-ray machines used in medical facilities in the western region of Kenya. In this study, we present the findings from quality control of general radiographic X-ray equipment in 31 medical facilities in western Kenya during 2009 and early 2010, including mobile X-ray units and film/screen fixed systems. The facilities were assessed by means of a visual checklist thereafter one functional X-ray machine per facility was subjected to QC tests since 90% of the facilities visited had only one X-ray machine being used. Four QC tests were performed on 15 X-ray machines. These were beam alignment and perpendicularity tests, kVp accuracy and reproducibility tests, exposure time accuracy and reproducibility tests and filtration tests. Beam alignment and perpendicularity tests showed unacceptable variation in 40% and 47% respectively while kVp accuracy test showed unacceptable variation in 27%. The study also showed

clearly the high rate of increase of the number of X-ray machines in the region. The facilities had a total of 52 X-ray machines of which 38.5% were functional, 42.3% were working with defects and 19.2% were out of order.

CHAPTER ONE

1.0 INTRODUCTION

1.1 General background

Radiography using film has been the primary tool in radiology for over a century. The radiation dose to the patient was given only minor consideration during the early days. As the number of examinations performed has increased and data on the long term risks of cancer arising from ionizing radiation exposure has emerged, more attention has been focused on keeping the doses received to a minimum. National programmes were set up to assess doses from radiological examinations in developed countries. A survey carried out in the UK in the early 1980s showed that mean doses from similar radiographic examinations varied by a factor of seven between different hospitals [Shrimpton, *et al*., 1986] and a factor of a hundred was present between doses for individual patients. The National Evaluation of X-ray Trends (NEXT) program has painted a similar picture in the United States [CRCPD, 2003]. It was apparent that in many hospitals the dose levels were much higher than required to provide a sufficiently high-quality image for the radiologist to make a diagnosis. Since that time more emphasis has been placed on the need to optimize imaging conditions to minimize the risk to patients from radiation exposure [NRPB, 1990].

The quality of an image and the anatomical detail seen within it depend on the properties of the imaging system and the radiation used. In general, use of more radiation will improve the quality of the image within certain limits, but will give the patient a higher radiation dose, although other factors also need to be considered. The important aspects of optimization are to first recognize the level of radiographic image quality that is required to make a diagnosis then determine the technique that provides that level of image quality with the minimum dose to the patient. The image quality should be sufficient to ensure that any clinical diagnostic information that could be obtained is imaged. However, the radiation dose to the patient should not be significantly higher than necessary. Finally the procedures should be reviewed from time to time to ensure that any dose reduction that has been achieved does not jeopardize the clinical diagnosis.

The thesis begins by giving an overview of radiography and the association of ionizing radiation with cancer. Chapter one examines the general introduction to radiography, QA and QC. Chapter two details with a review of optimization in radiography. In chapter three the theory of X-rays used in radiography has been detailed. Chapter four describes the equipment used and the methods followed in carrying out the quality control tests and general facility observations. The results and analysis of this research are discussed in chapter five and lastly in chapter six, the summary and suggestions for this work are given.

1.2 Objectives

1.2.1 General objective

To determine the current status of medical diagnostic X-ray machines in western Kenya in order to produce the data required to formulate and implement QC policies and strategies. These policies and strategies are needed to ensure that patients receive the lowest possible radiation risk and maximum health benefits from X-ray examinations

1.2.2 Specific objectives

a) To determine coincidence of the radiation field with the light field.

b) To assess the perpendicularity of the primary beam with the image receptor.

c) To determine how the measured kVp compares with the generator setting.

d) To determine the variation in average kVp over a number of exposures at the same generator setting.

e) To determine how the exposure time compares with the selected time.

f) To determine the variation in exposure time over a number of exposures at the same generator setting.

g) To assess the quality of X-ray beam.

1.3 Hypothesis

The medical X-ray installations in western Kenya are not working optimally due to increased demand for modern medical equipment with no commensurate increase in qualified personnel to provide the needed services. This may lead to unnecessary patient exposure resulting from use of bad equipment and bad practices.

1.4 Justification

The benefits of using high quality X-ray images in diagnosing disease and in the guidance of therapeutic procedures are well known. X-rays are used in the diagnosis of many diseases and disorders, and they help clinicians make a diagnosis. The risk to individuals from the radiation used in diagnostic X-rays is small compared to the benefits that accurate diagnosis and treatment can provide. Unfortunately, due to the rapid increase in the number of X-ray units in western Kenya, many users of X-ray equipment do not understand the basic principles of radiation protection, thus increasing the associated radiation risk to patients. The benefits of diagnostic Xrays are drastically reduced when the equipment is operated without adequate QC and maintenance. In most cases, such equipment has higher radiation risks, because of an increased dose in a single exposure and repeated exposure attributed to low image quality.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 X-ray quality control (QC)

Today, every field of medicine is required to develop and conduct a program that ensures the quality of patients care and management [Outif, 2004]. In diagnostic imaging, there are two areas of activity designed to make certain that the patient receives the benefit of the best possible diagnosis at an acceptable level of radiation dose with a minimum cost. These areas are called quality assurance (QA) and quality control (QC). Quality assurance deals with people and will monitor proper patient scheduling, reception, and preparation. On the other hand, QC deals with instrumentation and equipments. A QC program covers the entire X-ray system from machine to processor to viewing box. This program will enable the facility to recognize when parameters are out of limits, which will result in poor quality images and can increase the patients' exposure to radiation [Outif, 2004]. When designing a QC program for an X-ray department, one must guarantee that the following important objectives are met:

a) Continuous production of diagnostic images with optimum quality, using the minimum necessary patient radiation dose.

b) The image quality is stable with respect to information content and optical density and consistent with that obtained by other centers.

c) Optimizing of radiation dose to patient and minimizing of radiation dose to patient, staff and members of public.

To realize these objectives, a number of physical and technical parameters that affect the performance of the X-ray imaging system need to be measured. The characteristics of these parameters can vary with time; hence the tests need to be made at regular intervals. Each measurement should follow a written QC protocol that is adopted to a specific requirement of a local or a national QA program. Organizations such as ASRT [ASRT, 1994], ACR [ACR, 1997], NCRP [NCRP, 1998], IPEM [IPEM, 1996; IPEM, 1997] and WHO [WHO, 1982] have developed guidelines for QC tests in radiography. These guidelines have been used by various governmental organizations to develop their own directives and protocols. The current work is based on ICRP – 2007 guidelines.

2.1.1 The QC process

Essentially four steps are involved in any QC program: equipment specification and selection, acceptance testing, routine performance evaluation and error correction (calibration and repair). Under extensive use, all equipments deteriorate and this necessitates a periodic evaluation of equipments performances. Equipment must be monitored regularly to ensure a continuous reliable performance. The purpose of the QC tests is to detect any change in the equipment performance. Any change in the performance of the equipment should be rectified as soon as possible. Once the defect is rectified (or repaired), QC tests should be repeated to make sure that the defect has been accurately rectified and that the rectification action did not affect the overall performance of the system. The frequency of any routine performance QC test depends on many variations including the criticality of the characteristic performance being tested and its stability and the age of the machine. Obviously, a critical characteristic and older equipments require more frequent monitoring [Outif, 2004].

2.2 Assessment of radiation dose and image quality

Before discussing optimization in radiography in more depth, it is worth considering briefly the ways in which dose and image quality can be measured. There are several different quantities that are used for evaluating doses to patients. The dose quantities that can be measured for radiographic exposures are the entrance surface dose (ESD) and the dose-area product (DAP). The ESD is the dose to the skin at the point where an X-ray beam enters the body and includes both the incident air kerma and radiation backscattered from the tissue. It can be measured with small dosimeters placed on the skin, or calculated from radiographic exposure factors coupled with measurements of X-ray tube output [IPSM, 1992; Martin *et al*., 1993; George *et al*., 2004]. The DAP is the product of the dose in air (air kerma) within the X-ray beam and the beam area, and is therefore a measure of all the radiation that enters a patient. It can be measured using an ionization chamber fitted to the X-ray tube. DAP and ESD can be used to monitor, audit and compare radiation doses from a wide variety of radiological examinations. To provide a comparator that could be used to achieve more uniformity in patient doses for similar examinations in different hospitals, diagnostic reference levels (DRLs) or guidance levels for particular examinations have been established in terms of the ESD or DAP. National DRLs have been set up or proposed by various organizations based on surveys of doses in a large number of hospitals [Shrimpton *et al*., 1989; European Commission, 1996; Johnstone *et al*., 2000]. Conventionally, the third quartile of the distribution of mean doses from each of the hospitals in a survey for the particular examination is used as a guide in setting the DRLs, so that mean doses for three quarters of the hospitals are below the DRL and one quarter of them are above [Shrimpton *et al*., 1989; Wall, 2005]. DRLs proposed for a selection of radiographic examinations are given in Table 2-1 for adults and Table 2-2 for children [Hart *et al*., 2000; Hart *et al*., 2002]. The mean dose in a hospital for a selection of patients of average weight should be less than the relevant DRL. If the DRL is exceeded, this should trigger an investigation into whether further optimization is needed. Adoption of an optimization strategy with national and local DRLs in the UK has lowered patient doses, as demonstrated by the gradual reduction in third quartile values derived from UK-wide surveys of mean doses for large numbers of hospitals by the National Radiological Protection Board (NRPB) (Table 2-3) [Johnstone *et al*., 2000; Hart *et al*., 2002].

A radiographic image provides a representation of the spatial distribution of tissue components as variations in the optical density of film. Image quality can be quantified in terms of the characteristics; *contrast*, *sharpness* (or resolution), and *noise*. Contrast is a result of the different attenuations of X-ray radiation in tissue; sharpness is the capability to display small details; and noise refers to the random fluctuations across the image that tends to obscure the detail. Evaluation and diagnosis from the image requires structures of interest to be distinguished against the background. The difference between the film optical density of a structure of interest and that of the background can be thought of as the signal. Random fluctuations across the film can occur, which are superimposed on the image. These are referred to as noise, and result from a number of causes; quantum mottle due to statistical variations because of the finite number of photons; the granularity or finite grain size of the film; and anatomic

Radiograph	**ESD per radiograph (mGy)**	**DAP per radiograph (Gycm^2)**
Skull AP/PA	3	0.7
Skull LAT	1.5	0.5
Chest PA	0.2	0.12
Chest LAT	0.7	0.5
Thoracic spine AP	3.5	1.5
Thoracic spine LAT	10	2.0
Lumbar spine AP	6	1.6
Lumbar spine LAT	14	3
Lumbar spine LSJ	26	3
Abdomen AP	6	3
Pelvis AP	4	3

Table 2-1: Suggested DRLs for radiographs for adult patients [Hart *et al*., 2002]

Radiograph	**1 yr**	**5 yr**	**10 yr**	**15 yr**
Skull AP/PA	0.8	1.1	1.1	1.1
Skull LAT	0.5	0.8	0.8	0.8
Chest AP/PA	0.05	0.07	0.12	
Abdomen AP/PA	0.4	0.5	0.8	1.2
Pelvis AP	0.5	0.6	0.7	2.0

Table 2-2: Suggested DRLs for individual radiographs on paediatric patients in terms of ESD [European Commission, 1996; Hart *et al*., 2000]

Radiograph	ESD (mGy) Mid-1980s survey	ESD (mGy) 1995 review	ESD (mGy) 2000 review
Skull AP/PA	5	4	3
Skull LAT	3	2	1.6
Chest PA	0.3	0.2	0.2
Chest LAT	1.5	0.7	1
Thoracic spine AP	7	5	3.5
Thoracic spine LAT	20	16	10
Lumbar spine AP	10	7	6
Lumbar spine LAT	30	20	14
Lumbar spine LSJ	40	35	26
Abdomen AP	10	7	6
Pelvis AP	10	5	4

Table 2-3: Third quartile values for ESDs (mGy) from NRPB reviews of UK national patient data [Wall *et al*., 2005]

variations in structure density through the tissue. The fluctuations affect the detection of low contrast structures. Medical image quality is related to the subjective interpretation of visual data. It represents the clinical information contained in the image. It is more important that the observer interprets the image appropriately than whether the appearance of the image is pleasing to the eye. The ideal set of parameters to describe image quality should measure the effectiveness with which an image can be used for its intended purpose. However, since the interpretation and diagnosis made from an X-ray involve subjective opinions from the radiologist, results are likely to vary at different centres. Guidelines have been set up by the European Commission (EC) for assessing the basic aspects of quality for clinical radiographic images dependent on technique and imaging performance [European Commission, 1996; Maccia *et al*., 1995].

2.3 Radiation Intensity

2.3.1 Screen / film combinations

The most important factor in the optimization of conventional radiography is the choice of screen / film combination. The X-ray film is sandwiched between two screens inside a light-tight cassette. Each screen has a layer of a fluorescent phosphor, such as calcium tungstate or gadolinium oxysulphide, which converts X-ray photons into visible light photons .The sensitivity of screen / film combinations is quantified in terms of a speed index, which relates to the reciprocal of the dose to the cassette (in mGy) required to produce an optical density of 1.0 above the base plus fog level. It is analogous to the film speed employed in conventional photography. A higher speed index corresponds to a faster film and less radiation will be required to produce an image, although the radiograph will be noisier (more grainy). A speed index of 400 has been the standard for general radiography in Europe since the late 1980s [European Commission, 1996; Saure *et al*., 1995]. However, before that time, speed index combinations of 200 were widely used and may still be the combinations employed in many countries. In the UK, 200 speed index film cassettes are used for imaging fine detail, for example to visualize fractures in the extremities. 600 or 800 speed indices are very high speed systems, but may be satisfactory for some applications such as lumbar spine and lumbar sacral joint imaging [Almen *et al*., 2000; McVey *et al*., 2003]. Knowledge of the speed index of a film/screen combination plays an important role in optimization, and a combination used with a low speed index is the most probable reason for exposures being high.

2.3.2 Exposure control

To produce an image on film with an acceptable level of contrast, the exposure must be within a relatively narrow range of doses. The exposure factors used will be optimized through the experience of the radiographers, and exposure charts employed for each X-ray unit. The charts provide a guide to the best factors for different examinations for a patient of standard build. However, adjustments will need to be made for patients of different sizes. To achieve a consistent exposure level, an automatic exposure control (AEC) device is usually employed in fixed radiographic imaging facilities. This comprises a set of X-ray detectors behind the patient that measure the radiation incident on the cassette. The detectors are usually thin ionization chambers. Exposures are terminated when a pre-determined dose level is reached, thereby ensuring that similar exposures are given to the image receptor for imaging patients of different sizes. The important parameter involved in radiographic image formation is optical density and so the film is used in setting up the AEC to give a constant optical density.

2.4 X-Ray Beam Quality

Radiation quality refers to the proportions of photons with different energies within an X-ray beam. The contrast between different structures in an X-ray image results from removal of photons from the primary beam. The radiation quality influences the image quality and radiation dose through the mechanisms by which the X-ray photons of different energy interact with the tissue [Saure *et al*., 1995; Martin, 2002]. So metal filters are placed in the X-ray beam which remove more of the low energy photons. X-ray beams which contain more photons with energies between 30 keV and 50 keV give better image contrast, but a greater proportion of the photons are absorbed in the body, so larger radiation intensity must be used to obtain sufficient photons to form an image. The radiation quality of the X-ray beam chosen for each radiological examination should be selected to achieve the best compromise for the clinical task. The factors that determine the radiation quality are the tube potential and the beam filtration.

2.4.1 Tube potential

The potential applied to the X-ray tube determines both the maximum photon energy and the proportion of high energy photons. The optimum potential will depend on the part of the body being imaged, the size of the patient, the type of information required and the response of the image receptor. Tube potentials used for radiographic examinations have been established through experience. 80 kV to 85 kV are typical values used for radiographs of the abdomen, pelvis and lumbar spine antero-posterior (AP) views for an average patient. X-ray beams with tube potentials of 50 kV to 60 kV will give better contrast, but fewer photons will be transmitted. These are used for thinner regions of the body, such as the arms, hands and feet. 85 kV to 90 kV X-rays will provide better beam penetration and a lower radiation dose, but poorer contrast. They are employed for thicker, more attenuating parts of the body, such as the lumbar spine lateral projection. Patient doses will be significantly greater if lower tube potentials than those recommended are used [Martin *et al*., 1993; Martin *et al*., 1999].

As the thickness of the part of the body to be imaged or of the patient increases, the exposure will need to be increased. If the tube potential remains the same, the ESD is about doubled for each additional 50 mm of tissue in the range 80 kVp to 100 kVp, and will increase by 2.5 to 3 times at 60 kVp. Therefore the tube potential will normally be increased for larger patients to keep the dose at a reasonable level. Using a higher tube potential results in poorer contrast and tends to produce more scatter, further reducing the image quality. The reduction in effective dose when tube potential is increased is less than that in ESD or DAP, because the surface dose is proportionately higher with lower tube potentials. This type of investigation may be undertaken for assessment and evaluation of possible alternative techniques and therefore contribute to optimization.

2.4.2 Filtration

Thin sheets of metal such as aluminium or copper are incorporated into diagnostic X-ray tubes to reduce the proportion of low energy photons, as few are transmitted through the patient and contribute to the image. A filter equivalent to at least 2.5 mm of aluminium is incorporated as standard into medical X-ray tubes and is required by national guidance [IPEM, 2002]. Copper will absorb a higher proportion of the lower energy photons than aluminium. The disadvantage of using copper filters is that an increased tube output is required to compensate for the additional attenuation. With tube potentials of 70-80 kV, reductions of over 50% in ESD and 40% in effective dose can be achieved by using a 0.2 mm thick copper filter, but the tube output would need to be increased by about 50% to provide the necessary air kerma level [Martin, 2007]. Rare earth filters such as erbium have been investigated as possible alternatives to copper for imaging thinner tissue structures in paediatric and dental radiography. The advantage was their perceived ability to attenuate higher energy photons (>60 keV), and lower energy ones, therefore providing a narrower energy spectrum. However, apart from dental radiography, they have not provided significant advantages over copper filters.

2.5 Beam collimation and X-ray projection

Collimation of the X-ray beam is an important factor in optimization. Good collimation will both minimize the dose to the patient and improve image quality, because the amount of scattered radiation will increase if a larger volume of tissue is irradiated. Collimation is particularly important in paediatric radiography since the patient's organs are closer together and larger fields are more likely to include additional radiosensitive organs. Collimation in most cases depends on the technique of the radiographer, but regular quality assurance by checking that the X-ray beam and the field from the light beam diaphragm are accurately aligned is important, particularly for mobile equipment. Beam collimation in dental radiography is achieved through use of a fixed cone and the traditional aperture size is 60 mm diameter [IPEM, 2002; IPEM, 2005]. In older units which used a focus to film distance of 100 mm, a substantial proportion of the face was exposed. Optimization involved two stages, an increase in the focus to skin distance to 200 mm, and incorporation of a smaller rectangular aperture similar in size to the film. Both these have contributed to a reduction in the volume of tissue irradiated. However, the use of a smaller beam size means that alignment of the film is crucial. Therefore film holders placed in the mouth, with which the X-ray tube collimator can be aligned, should be used. Another aspect that influences the effective dose, is the projection chosen for a radiograph. The organs and tissues lying closer to the surface on which radiation is incident will receive higher radiation doses. If organs that are more sensitive to radiation are further from the surface on which the X-rays are incident, the X-ray beam will be attenuated by overlying tissues, and the doses to the organs will be lower. Chest examinations will normally be taken using a posteroanterior (PA) projection, to minimize the dose to the breast tissue and oesophagus. Many of the abdominal organs are closer to the anterior surface, so a PA radiograph of the abdomen is also likely to have a lower effective dose. Effective doses for the antero-posterior (AP) view can be 50% higher for chest and abdomen radiographs, and even higher for low tube potentials. The risks from exposure to an embryo or foetus are greater than those to children or adults [ICRP, 1991], so decisions involving investigations of pregnant women should be made carefully. The examination should only be performed if the risk of not making a diagnosis at that stage is greater than that of irradiating the foetus. Where the examination can be delayed without undue risk to the patient, this may be the better option, or if an acceptable technique using non-ionizing radiation is available, this may be employed. If it is necessary to carry out a radiograph of the abdomen for a woman who is pregnant, the PA projection would reduce the dose to the foetus as much as possible.

2.6 Film processing

The final stage in the production of a radiograph is processing the film. If processing conditions are not optimal, the film will require a higher radiation dose in order to provide an acceptable film density. Chemicals should be changed regularly, and the processing conditions, such as temperature and development time should be carefully optimized. These checks should be carried out daily to monitor performance in terms of film density, contrast and background fog level. The performance levels of processors that have a relatively low workload need to be monitored carefully. If a film is taken with optimized processing, it can be considered the reference standard. Checks can then be made by comparing future results with the reference standard to identify any deterioration.

CHAPTER 3

3.0 THEORY OF X-RAYS USED IN RADIOGRAPHY

3.1 X-ray production

X-ray composes of high energy photons. X-ray photons may be produced when an electron interacts with matter. When high-energy electron strikes a heavy metal target, the kinetic energy of the electron is converted into an electromagnetic radiation. The electron may interact with the matter via any of the following three types of interactions [Cameron and Skofronick, 1978; Stewart Bushong, 1993]:

a) Excitation.

b) Ionization.

c) Bremsstrahlung (braking radiation).

Each of these interaction processes is discussed independently in the following sections

3.1.1 The Excitation

In this interaction, the incident electron interacts with an outer-shell electron then gives it small amount of its kinetic energy and continues with most of its kinetic energy (figure 3- 1). The outer-shell electron in turn jumps up (excite) to a higher energy level. As this new energy level is not a stable state for the outer-shell electron, it immediately drops back to its previous energy level with an emission of energy equal to the energy it had gained. The energy is usually emitted in the form of infrared (or heat) [Stewart Bushong, 1993]. This kind of interaction is responsible for most of the heat generated in the anodes of X-ray tube (see section 3.3). Approximately 99% of the kinetic energy of the incident electrons is converted into heat [Jouns and Cunningham, 1983].

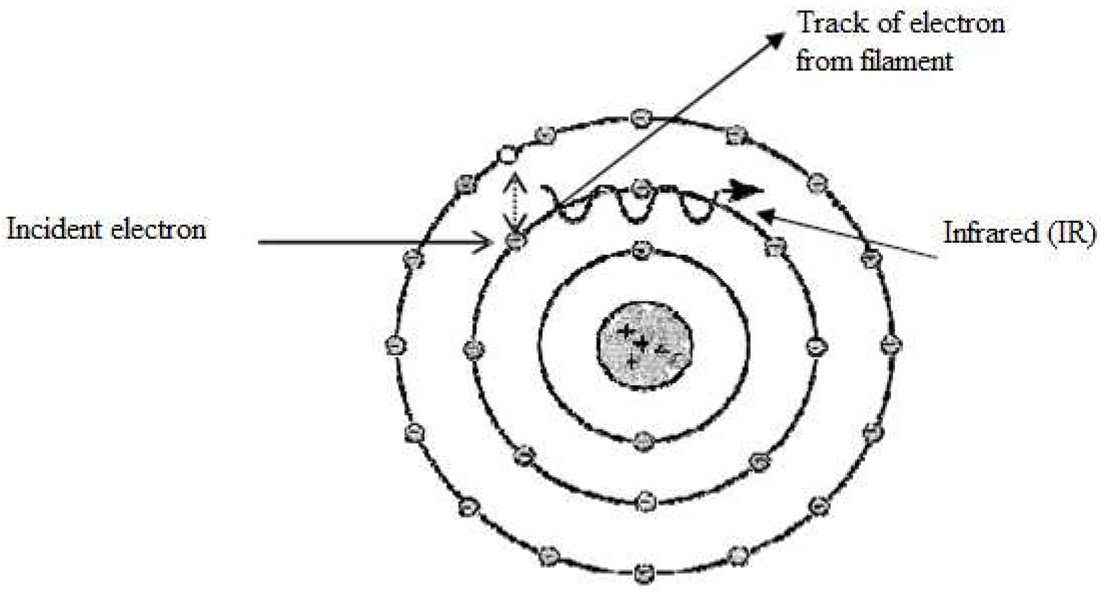

Figure 3-1: Schematic diagram of the excitation process [Stewart Bushong, 1993]

3.1.2 The ionization

In this interaction, the electron interacts with an atomic electron in the inner-shell (e.g. K-shell) of the target atom, transferring enough of its kinetic energy to the inner-shell electron causing it to be ejected outside its atom (figure 3-2) [Ball and Moore, 1997]. A temporary electron vacancy is produced in the K-shell. The vacancy is quickly filled by an electron dropping down from a higher energy level (outer-shell). This transition is accompanied by the emission of an X-ray called characteristic radiation. For ionization to take place, the incident electron must have kinetic energy that is at least equal to the ionization energy of the target electron. This type of X-ray production is termed characteristic X-ray because the emitted photon has an energy that is characteristic of the element of which the target is made of. Characteristic X-rays contribute less than 10% of an X-ray beam [William and Ritenour, 1992; Stewart Bushong, 1993].

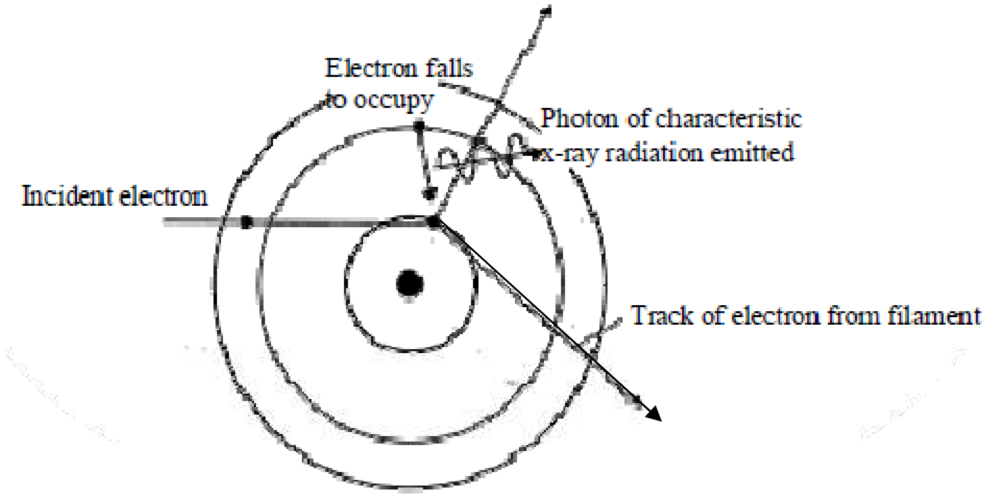

Figure 3-2: Schematic diagram of ionization process and production of characteristic X-ray [Ball and Moore, 1997].

3.1.3 Bremsstrahlung (braking radiation)

In this interaction, the electron interacts with the electric field of the nucleus. The electron has a negative charge and the nucleus has a positive charge. The electron as a result spins around the nucleus and loses much of its kinetic energy producing an X-ray photon. The energy of the emitted X-ray photon depends on the distance between the interacting electron and the nucleus of the target atom. The smaller the distance the higher the energy of the emitted photon [William and Ritenour, 1992; Ball and Moore, 1997]. This interaction is sometimes called Bremsstrahlung interaction, and the emitted radiation (photon) is called Bremsstrahlung radiation. Bremsstrahlung is the German description of this kind of interaction. The word Bremsstrahlung consists of two parts. The first part: "Brems" means braking and the second part “strahlung" means radiation [Cameron and Skofronick, 1978]. The principle of conservation of energy tells us that in producing an X-ray photon via Bremsstrahlung interaction, the electron has lost some of its kinetic energy, given by:

$$(KE)_{f(e)} = (KE)_{i(e)} - E_{ph} \quad 3.1$$

Where $(KE)_{f(e)}$ is the final kinetic energy of the incident electron, $(KE)_{i(e)}$ is the initial kinetic energy of the incident electron, E_{ph} is the photon energy. The energy of photons of Bremsstrahlung radiation may be of any value between zero and a maximum equal to the initial kinetic energy of the incident electron. This is different from the production of characteristic x-rays that have specific energies. Bremsstrahlung radiation has a maximum energy E_{max} corresponding to the maximum energy of the bombarding electrons:

$$E_{\max} = eV_p \quad 3.2$$

Where V_p is the maximum voltage across the X-ray tube, this maximum photon energy is produced when the incident electron interacts directly with the nucleus and loses all its kinetic energy in the form of photons but the probability of emitting such photons is rather minimum.

3.2 X-ray tube

The X-ray tube is an evacuated tube that contains two main components; the cathode and the anode (figure 3-3) [Cameron and Skofronick, 1978., Stewart Bushong, 1993]. The cathode is the negative side of the X-ray tube and the anode represents the positive side. The cathode contains a filament which is responsible for the production of electrons. The electrons are released when the filament is heated with an electric current. This phenomenon is known as thermionic emission. The filament is powered by an electric current that is supplied to it by a separate transformer. The released electrons are then accelerated toward the anode (positive side) by the application of high voltage to the tube.

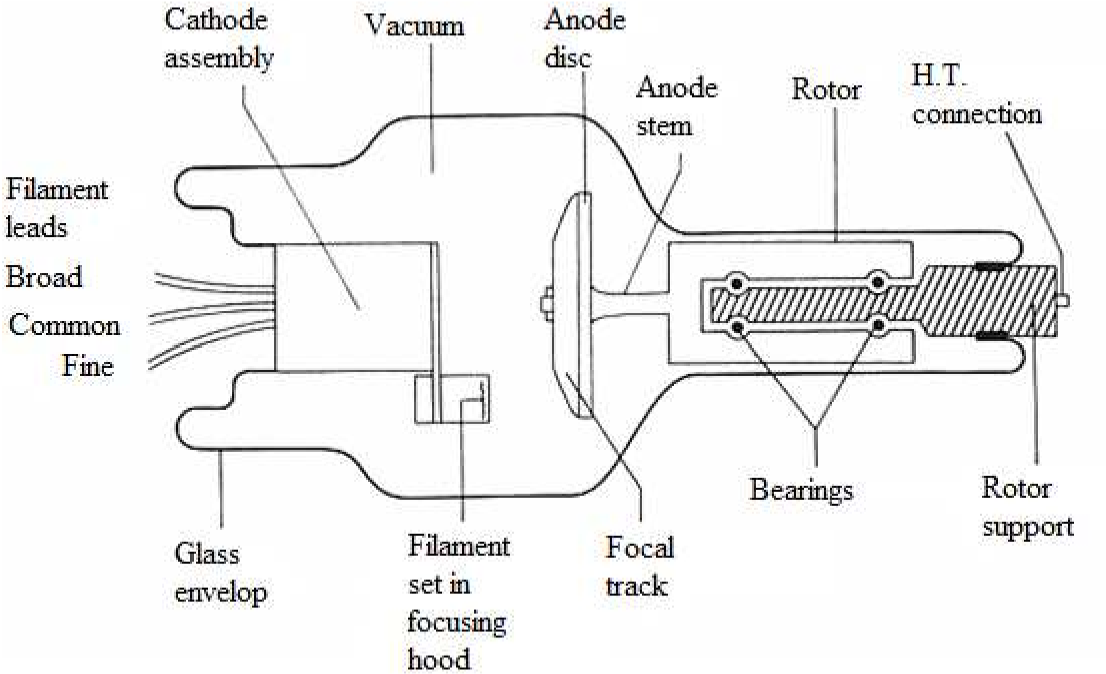

Figure 3-3: X-ray tube [Ball and Moore, 1997].

The number of electrons accelerated from the cathode to the anode represents the tube current and is measured in milliampere (mA). The accelerated electrons interact with the atoms of the anode producing X-rays. Under electron bombardment, the target of the X-ray tube may become hot enough to emit electrons in the same way as does the filament [Jouns and Cunningham, 1983; Ball and Moore, 1997]. In this case the negative part of an alternating voltage waveform will reverse the electron flow toward the filament; therefore the X-ray generator must first convert the alternating current into a direct current. Such a function is performed by an electronic piece called rectifier (diode). The rectifier is a device that allows a current to flow in only one direction. This function can be performed by any of the following four methods [Cameron and Skofronick, 1978; Stewart Bushong, 1997]:

a) Half-wave rectification: In this form of rectification (figure 3-4 a) the negative part of the voltage waveform is chopped off via a diode. A generator that produces this type of waveform is called single phase, half wave rectified generator. This type of generator produces 60 pulses of X-rays per second. In this case, an X-ray will be produced every half cycle of the voltage waveform.

b) Full-wave rectification: In this form of rectification (figure 3-4 b), the negative half wave of the voltage waveform is inverted via an electronic circuit that includes four diodes. A generator that produces this type of waveform is called a single phase, full wave rectified generator. Such a generator produces 120 pulses of X-rays per second. An X-ray in this case will be produced during the whole cycle of the voltage waveform.

c) Three-phase (six-pulse power and twelve-pulse power): In spite of the previous rectifications, X-rays are still produced with no constant level. In order to achieve this, an X-ray generator takes three separate lines of currents that have different phases and performs a full wave rectification (see figure 3-4 c and d). A generator that produces this type of waveform is called three-phases, full wave rectified generator. With a three-phases generator , the voltage waveform will multiply to become six pulses per 1/60 second and twelve pulses per 1/60 second, compared to the two pulses characteristic of a single phase generator [Jouns and Cunningham, 1983., Stewart C. Bushong, 1993].

d) High frequency: in this case, the three-phases generator is increased from 60 Hz to between 400 and 2000 Hz (see figure 3-4 e) [Stewart C. Bushong, 1993].

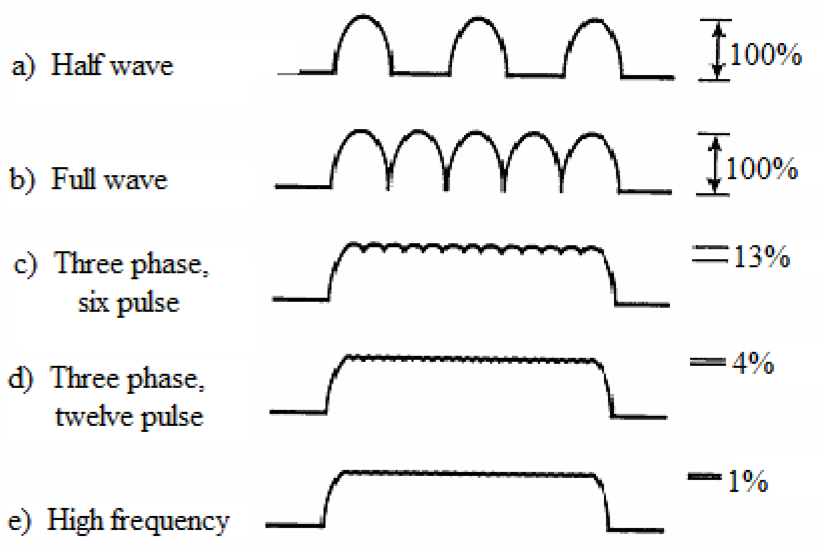

Figure 3-4: Schematic diagram of different voltage waveform rectification [Stewart Bushong, 1993].

3.3 X-ray beam characteristics

The X-ray beam produced by an X-ray tube can be described in term of its quantity (beam quantity) or its quality (beam quality). Each of these is described in the following sections.

3.3.1 X-ray beam quantity

The X-ray beam quantity or intensity is the number of X-ray photons in the useful beam. This is principally controlled by the applied tube current (mA). Beam quantity is also affected by the applied voltage, target material, filtration, distance from the source and voltage waveform [Cameron and Skofronick, 1978; Stewart Bushong, 1993; Ball and Moore, 1997]. The effect of each of these factors is discussed in the following sections.

3.3.1.1 Milliampere-second (mAs)

The accelerated electrons in an X-ray tube are generated via heating of the filament. Increasing the rate of thermionic emission of the cathode will increase the tube current, and hence the X-ray quantity. This is expressed mathematically as follow [Stewart Bushong, 1993]:

$$\frac{I_1}{I_2} = \frac{mAs_1}{mAs_2} \qquad 3.3$$

Where I_1 and I_2 is the X-ray intensities at mAs_1 and mAs_2 respectively. The X-ray quantity is directly proportional to the mAs, therefore if mAs is increased by 50% the X-ray quantity is also increased by 50% (equation 3.3), in other words, the X-ray spectrum will be changed in amplitude but not in shape and maximum energy *E* max (figure 3-5).

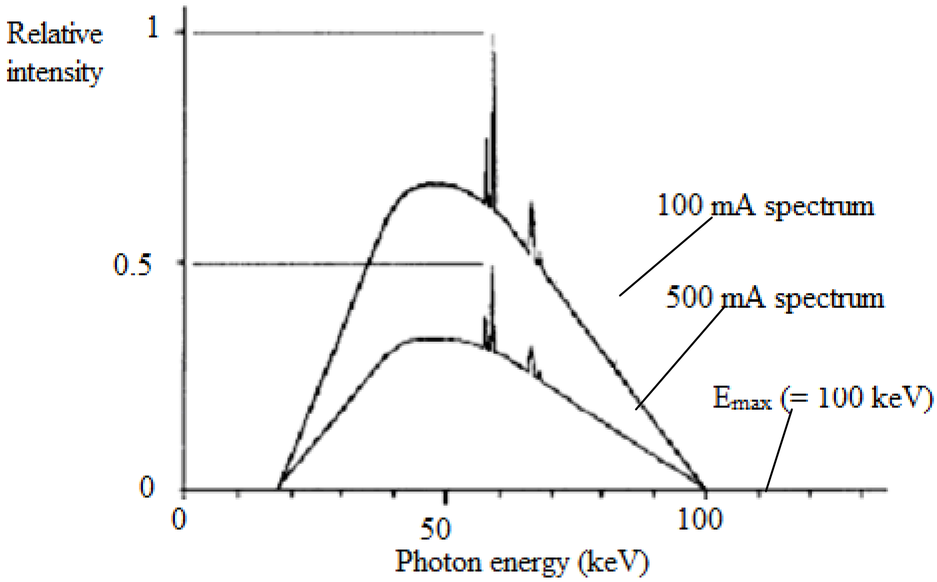

Figure 3-5: Schematic diagram showing the effect of mAs on spectrum intensity (Stewart Bushong, 1993]

3.3.1.2 Kilovoltage peak (kVp)

The peak kilovoltage (kVp) determines the kinetic energy of the accelerated electrons in the X-ray tube and the peak energy of the X-ray spectrum. When tube voltage (kVp) is increased, the X-ray quantity increases with the square of the applied voltage. This effect is represented mathematically as follow [Stewart Bushong, 1993]:

$$\frac{I_1}{I_2} = \left(\frac{kVp_1}{kVp_2}\right)^2 \qquad 3.4$$

Where I_1 and I_2 is the X-ray intensities at kVp_1 and kVp_2 respectively. If the kVp is doubled, the X-ray quantity will increase by a factor of four. In addition, with the increase of kVp, the peak of the continuous spectrum moves towards higher energies as illustrated in figure (3-6).

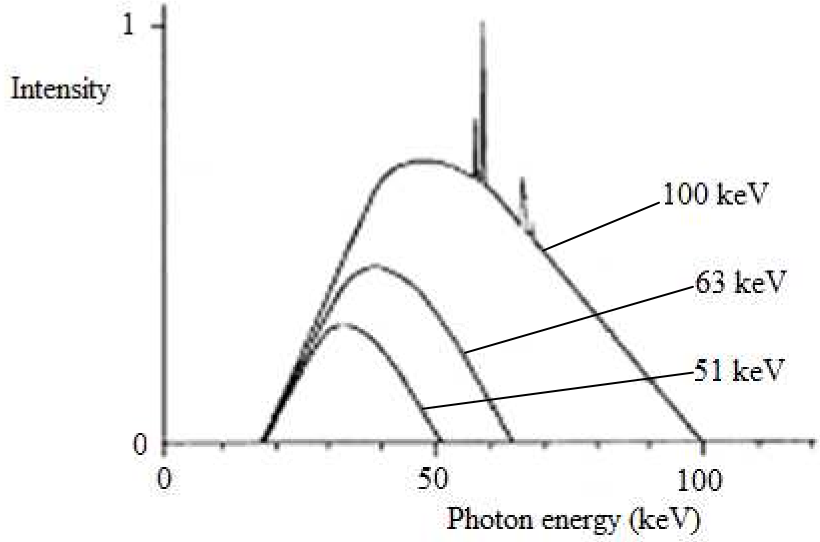

Figure 3-6: Schematic diagram showing the effect of tube voltage (kVp) on X-ray spectrum [Stewart Bushong, 1993]

3.3.1.3 Target material

The target material represents the anode side of the X-ray tube (see section 3.3) and has an important effect on the X-ray beam quantity. When the atomic number of the target material (*Z*) is high, the efficiency of Bremsstrahlung production increases, and as such, the number of the produced high-energy X-rays photon also increases as shown in figure (3-7). Furthermore, with the increase of the atomic number (*Z)* of the target material the characteristic x-rays shift towards higher photon energies, since more energy is needed to expel *K* and *L* electrons from higher *Z* atom [William and Ritenour, 1992., Ball and Moore, 1997].

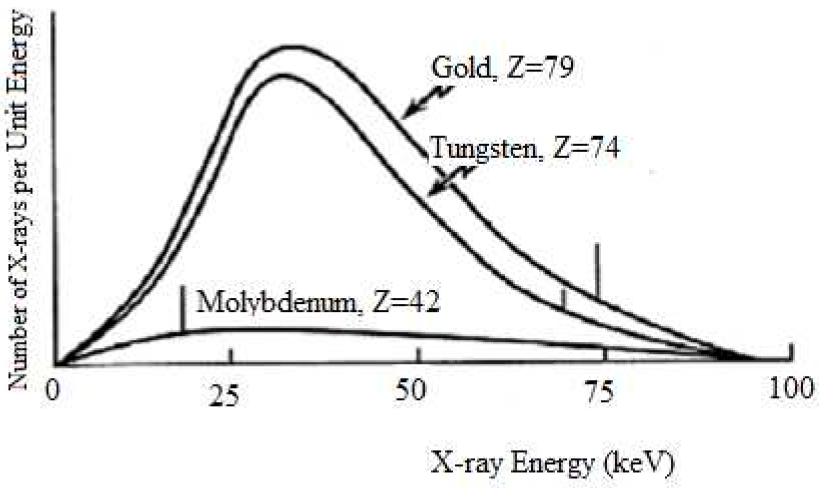

Figure 3-7: Schematic diagram showing the effect of target material on X-ray spectrum [Ball and Moore, 1997]

3.3.1.4 Filtration

Filtration takes place in any material which happens to be in the way of the X-ray beam. Materials like glass of the X-ray tube, coolant oil are called inherent filtration. Any material added to the beam is called added filtration. The total filtration of the beam includes the inherent and the added filtration. The filtration reduces the X-ray quantity by removing (absorbing) low energy photons. Although, this process leads to a reduction in the X-ray beam quantity, it improves the beam quality by absorbing the low energy photons [Ball and Moore, 1997; William and Ritenour, 1992]. The total effects of filtration on the X-ray beam can be summarized (figure 3-8) as follow:

1. A change in the X-ray spectrum shape with the preferential removal of lower energies.
2. The peak of the spectrum shifts toward higher energies

3. The maximum energy (E_{max}) remains unchanged.

4. The minimum energy (E_{min}) shifts toward higher energy.

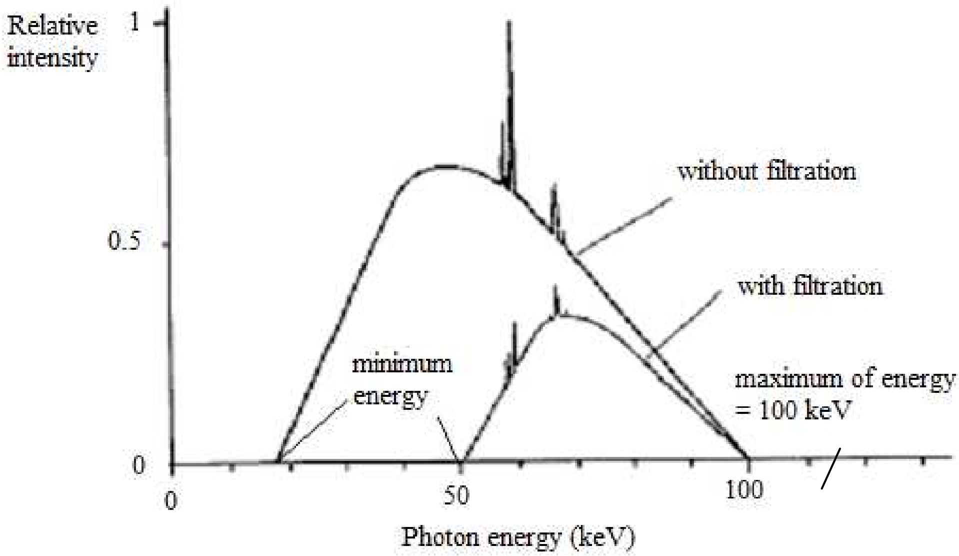

Figure 3-8: Schematic diagram showing the effect of filtration on X-ray spectrum.

[Ball and Moore, 1997]

3.3.1.5 Distance from the source

The X-ray beam quantity emitted from any X-ray source varies inversely with the square of the distance from the source. This relationship is called the ***inverse square law***. This law is represented mathematically as follow [Stewart Bushong, 1993]:

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2 \qquad 3.5$$

Where $I1$ is the intensity of the beam at distance $d\,1$ and $I2$ is the intensity of the beam at distance $d2$. The X-ray quantity of the beam therefore falls off rapidly with the distance. This reduction in X-ray quantity is due to the divergence of the beam rather than to any interaction between the beam and the atoms of the atmospheric gases [Ball and Moore, 1997].

3.3.1.6 Voltage waveform

For the same applied tube voltage, the effects of various types of voltage waveform on the X-ray emission are summarized in figure (3-9).

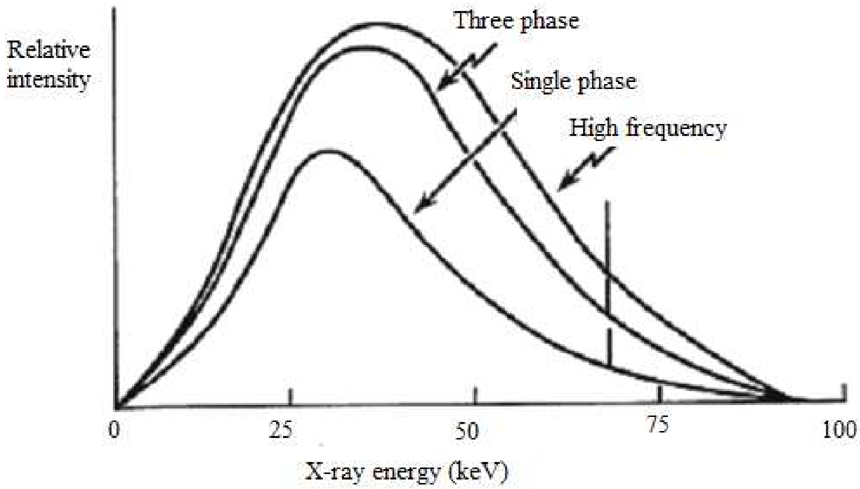

Figure 3-9: Schematic diagram showing the effect of voltage waveform on the X-ray spectrum [Stewart Bushong, 1993]

The X-ray quantity is larger for high frequency and three phases than that for a single phase. The X-ray output for the three-phase is equivalent to a 12% increase over a single-phase generator. The peak of the X-ray spectrum shifts toward higher energies with the maximum energy (*E* max *)* remaining unchanged. Characteristic X-ray lines energies remain fixed but increase slightly in magnitude because of the increase in the number of the projectile electrons available for K-shell electron interaction [Ball and Moore, 1997., Stewart Bushong, 1993].

3.3.2 X-ray beam quality

The X-ray beam quality is the ability of the beam to penetrate an object, therefore called penetrating power. An X-ray beam with high penetrability is termed hard beam and soft beam is the X-ray beam with low penetrating ability. The quality of an X-ray beam is expressed in terms of the half value layer (HVL). The half value layer is the thickness of the material required to reduce the beam intensity (quantity) to half of its original value. The quality of beam is controlled by the applied Kilovoltage (kVp), and filtration [Ball and Moore, 1997]. The effect of each of these factors is discussed in the following sections.

3.3.2.1 Kilovoltage *(*kVp)

As the applied kVp is increased, the maximum photon energy shifts to higher energy (see figure 3-6). The shift in maximum photon energy, increases the penetration quality of the X-ray beam .The maximum energy of the emission (*E* max) is numerically equal to the applied kVp. Furthermore, with the increase in kVp more characteristic X-ray may appear on the spectrum.

3.3.2.2 Filtration

As mentioned above, the increase of total filtration improves beam quality by absorbing low energy photons (see figure 3-8).

3.4 Interactions of photons (X-ray) with matter

When X-ray photons enter a medium such as soft tissue, these photons may lose their energies in the medium via any of the following interaction processes [James and Connolly, 2005]:

i) Simple scattering.

ii) Photoelectric absorption.

iii) Compton scattering.

iv) Pair production.

v) Photodisintegration.

Each of these processes of interaction is discussed in the following sections:

3.4.1 Simple scattering

In this interaction, the incident photon has an energy ($E\ ph$) less than the ionization energy of the atoms of the medium.

$$(E_{ph})_{incident} < E_b \qquad 3.6$$

Where E_b is the binding energy of the atomic electron. The incident photon does not have enough energy to remove an electron from the outer shell of the atom. The photon interacts with the whole atom and deflects without change in its energy (see figure 3-10). Because of its low energy, this kind of interaction has no important role to play in diagnostic radiology.

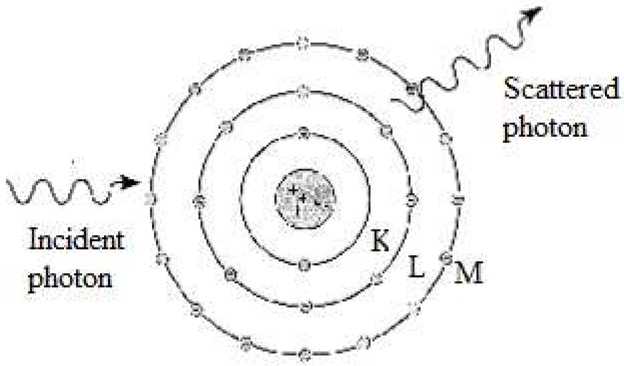

Figure 3-10: Schematic diagram of simple scattering [Ball and Moore, 1997]

3.4.2 Photoelectric absorption

In this interaction, the energy of the incident photon E_{ph} is greater than the binding energy of an atomic electron (E_b). The photon transfers all its energy to an inner orbital electron. The electron as a result is then ejected from its atom with a kinetic energy E_e given by:

$$E_e = E_{ph} - E_b \quad 3.7$$

Where E_{ph} is the energy of the incident photon. A photoelectric absorption process leaves the ionized atom with an electron vacancy that is filled immediately by an electron from a higher energy level, accompanied by an emission of characteristic radiation. The energy of the characteristic radiation is very low and is rapidly absorbed, increasing slightly the internal energy of the medium such as soft tissue and producing very small rise in temperature. The probability of a photoelectric absorption decreases rapidly as the incident photon energy is increased. This probability increases rapidly as the atomic number of an absorbing material is increased.

3.4.3 Compton scattering

In this interaction, figure (3-11) the energy of an incident photon *E ph* is much greater than the binding energy of the electron *E b* . Only part of the photon energy is given up during the interaction with an outer electron, which is effectively free. The photon suffers a change of direction as a result of the collision with the electron. The scattered X-ray photon has less energy and therefore a greater wavelength than the incident photon. The ejected electron (known as Compton recoil electron) dissipates its energy through ionization or excitation process (see section 3.2.1 and 3.2.2) [Ball and Moore, 1997].

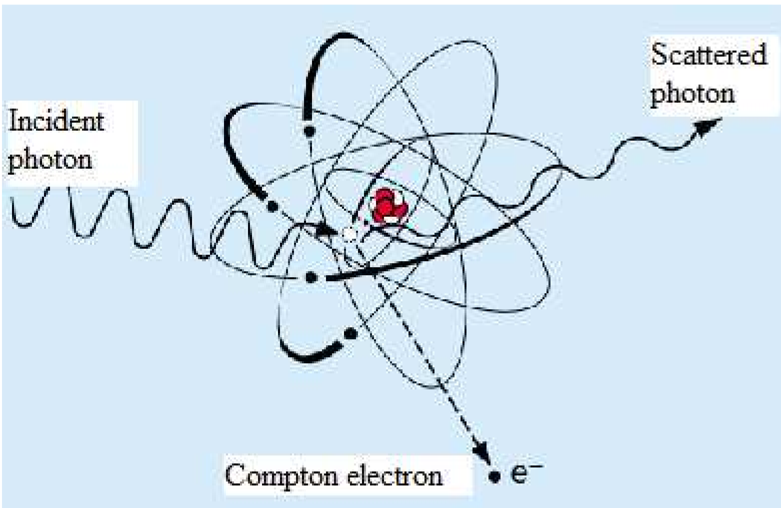

Figure 3-11: Schematic diagram of Compton effect [Eric *et al*., 2006]

The energy of Compton electron is given by:

$$E_e = hv - hv' \qquad 3.8$$

Where E_e is the kinetic energy of the electron, hv is the energy of the incident X-ray photon, and hv' is the energy of the scattered X-ray photon. Compton effect occurs with very low atomic weight targets even at relatively low X-ray energies.

3.4.4 Pair production

In this interaction, (figure 3-12) the incident photon approaches and interacts with the atomic nucleus and its energy is transformed into the creation of two particles (an electron and positron). The two particles move in opposite directions with a total kinetic energy given by the equation:

$$K_{(e^- + e^+)} = (E_{ph} - 1.02)MeV \qquad 3.9$$

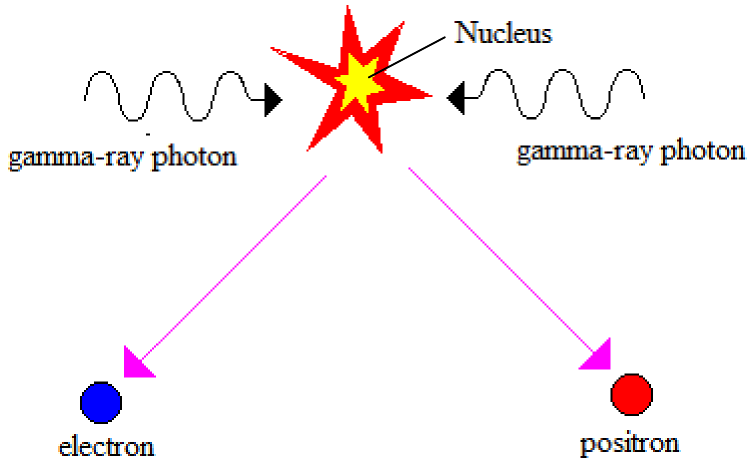

Figure 3-12: Schematic diagram of pair production [Eric *et al.*, 2006]

The positron lives for a very short period and disappears on meeting another electron with the formation of two photons with 0.51 *MeV* each. The minimum photon energy E_{min} required for pair production to occur is 1.02 MeV as shown below.

$$E_{min} = 2m_e C^2 \qquad 3.10$$

$$= 2 \times 9.11 \times 10^{-31} \times (3 \times 10^8)^2 \text{ J}$$

$$= 1.46 \times 10^{13} \text{ J}$$

$$= 1.02 \text{ MeV}$$

Thus, for a photon to interact with matter via pair production, the incident photon must have energy greater than 1.02 MeV. For this reason, such an interaction is not important in diagnostic radiology, where maximum kVp is not more than 140 kVp.

3.4.5 Photodisintegration

In this interaction, the incident photon is of high energy (greater than 10 MeV). The photon interacts with the nucleus of the material, and splits (disintegrate) the nucleus into fragments with the emission of neutrons. Because of the high threshold energy, this interaction is not important in diagnostic radiology.

3.5 Biological effects of X-ray

The mechanism by which radiation causes damage to human tissue, or any other material, is the ionization of the medium atoms [Cember *et al*., 1985]. When a living cell absorbs ionizing radiation, there are four possible effects on the living cell (figure 3-13) and are as follow.

1) The living cell may suffer enough damage to cause loss of proper function, and will eventually die.
2) The living cell may lose its ability to reproduce.
3) The genetic code of the living cell (DNA) may be damaged such that future copies of

   the living cell are altered. Such an effect may result in cancerous growth or may lead to other deformity.
4) The living cell may be undamaged by the ionizing radiation.

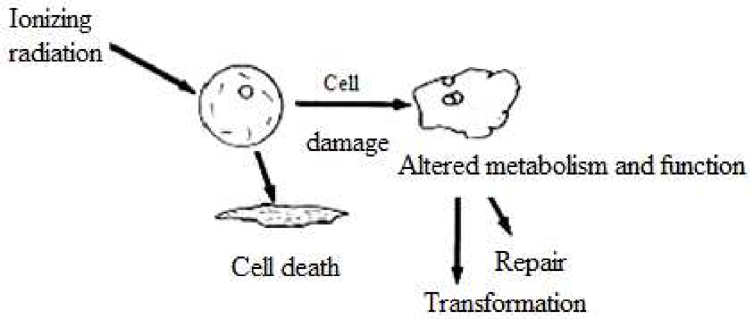

Figure 3-13: Schematic diagram for possible radiation effects [Cember *et al*., 1985].

The body has repair mechanisms against damage induced by radiation as well as by chemical carcinogens. A living cell can often repair radiation damage, but if the living cell multiplies, (splits into two identical living cells) before it has time to repair the most recent radiation damage, then the new living cells might not be accurate copies of the old ones. Some examples of a rapidly multiplying living cell are those in a foetus and cancer living cells. Cell damage may occur as a result of direct or indirect effects of radiation.

3.5.1 Direct effect

When the radiation energy is absorbed in the cell, it is possible for the radiation to interact directly with critical elements within the cell (DNA). The atoms in the target's molecule may be ionized or excited, initiating a chain of events, which could lead to biological change or damage

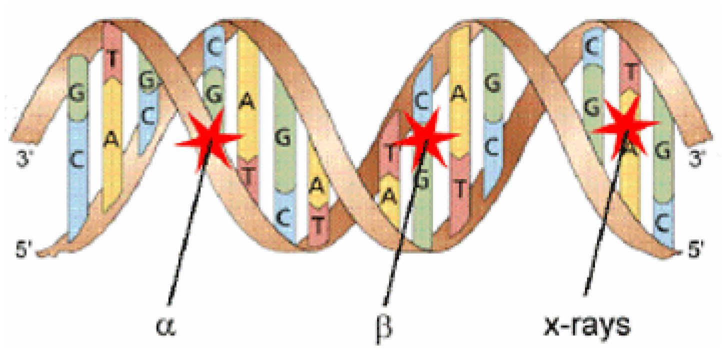

Figure 3-14: Schematic diagram of the direct effects of radiation [Eric *et al*., 2006]

3.5.2 Indirect effect

Absorption of radiation energy may result in a chemical species called *free-radical*. A *free radical* is a free atom or molecule carrying an unpaired orbital electron in the outer shell. An atom with an unpaired electron in the outer shell usually exhibits high degree of chemical reactivity. The two substances in a cell likely to be involved in a free radical formation due to ionization are oxygen and water. Although free radicals are extremely reactive, most of the free-radicals recombine to form oxygen and water in about 10^{-5} seconds without causing any biological effects. However, biological effects may occur if these free radicals interact with other nearby chemical compounds then they may diffuse far enough to damage critical cell components (DNA) (see figure 3-15) [Cember *et al*., 1985].

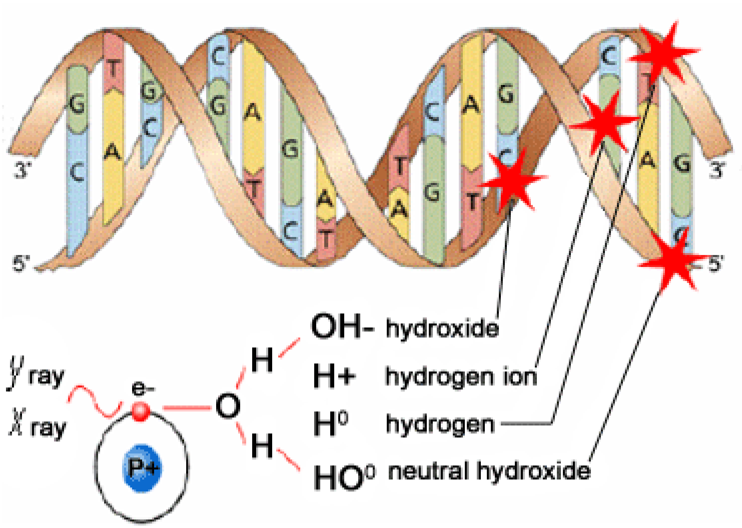

Figure 3-15: Schematic diagram of the indirect effects of radiation [Eric *et al*., 2006]

3.5.3 Classification of biological effects

The biological effects of radiation may be categorized either into somatic and genetic effects, or into stochastic and non- stochastic effects [Ball and Moore, 1997].

3.5.3.1 Somatic effects

Somatic effects are those effects, which appear on the individuals who suffered exposure to radiation [Ball and Moore, 1997; Cember *et al*., 1985] and can be classified into two basic categories:

1) Acute effects
2) Late effects

3.5.3.1.1 Acute effects

These effects are caused by relatively high doses of radiation delivered over a short period [Ball and Moore, 1997]. These effects are dependent on the quantity of the radiation exposure, the exposed area of the body and exposure rate, e.g. the skin reddening (radiation erythema) (see figure 3-16). These acute effects include nausea and vomiting, malaise and fatigue and blood changes [Ball and Moore, 1997., Cember *et al*., 1985].

Figure 3-16: Example of skin damage as a result of exposure to a high X-ray dose during an angiographic procedure [Ball and Moore, 1997]

3.5.3.1.2 Late effects

Late effects of radiation are those that appear within years after the exposure [Cember *et al*., 1985]. Late radiation effects may result from previous acute, high-dose exposure or from chronic low-level exposures over a period of years. It should be emphasized that there is no unique disease associated with the long-term effects of radiation. Late effects may include:

1) Different kinds of cancers (e.g. Leukemia, Bone cancer, Lung cancer)).

2) The clouding of the eye lens, known as **cataract** (figure 3-17).

Figure 3-17: The cataract

3.5.3.2 Genetic effects

Genetic effects of radiation are those effects that appear in descendants **(**new generations**)**. Such genetic effects are the consequence of irradiation of the male or female gonads. Genetic effects may include conditions such as congenital blindness, deafness, foetal death, [James and Connolly, 2005].

3.5.3.3 Stochastic effects

Stochastic effects can either be somatic or genetic. Stochastic effects are those effects in which the probability of an effect occurring increases with radiation dose (see figure 3-18). This means that there is no threshold dose for stochastic effects. Due to the statistical nature of these effects it is difficult to prove conclusively, that exposure to radiation is the cause of such effects [Ball and Moore, 1997].

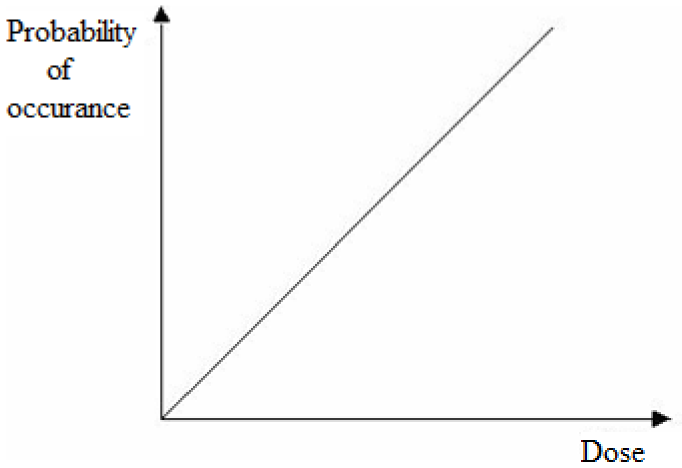

Figure 3-18: Schematic diagram of the stochastic dose response curve [Ball and Moore, 1997]

3.5.3.4 Non-stochastic effects

Non-stochastic effects are always somatic; these effects have a threshold dose for each effect, below which the somatic effect is not produced. The threshold dose is different from an individual to another. The severity of the effect increases with the increase of radiation dose (see Figure 3-19). The cataract (see figure 3-17) is an example for non-stochastic effects [Ball and Moore, 1997., Cember *et al*., 1985].

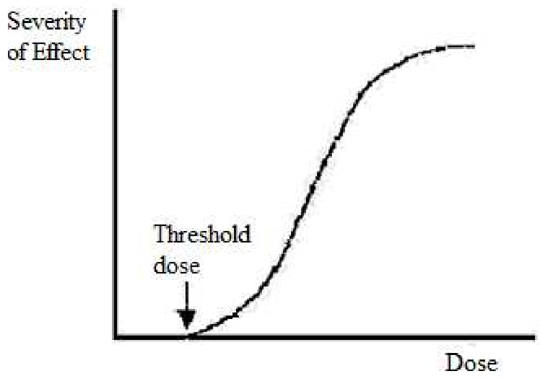

Figure 3-19: Schematic diagram of the non-stochastic dose response curve [Cember *et al*., 1985]

3.6 Radiation quantities

Any radiation beam such as an X-ray beam may be described by two main quantities, namely quantities that describe the radiation beam itself (the number of particles or photons of the beam and the amount of energy it caries) and quantities that describe the amount of the energy it may deposit in some medium [Podfarask, 2005]. Each of these quantities is described in the following sections:

3.6.1 Quantities that describe number of photons

The photon fluence Φ is defined as the number of X-ray photon (N) that crosses an area (A) [William and Ritenour, 1992]:

$$\Phi = \frac{N}{A} \qquad 3.11$$

The unit of the fluence in the international system of units (SI) is m^{-2} . If the X-ray photons beam are uniform, then the location or size of the area A is unrelated so long as it is perpendicular to the direction of the beam. But if the X-ray beam was not uniform over its entire area, the fluence must be averaged over a number of small areas [William and Ritenour, 1992]. In this case, the photon fluence can be written as:

$$\Phi = \frac{dN}{dA} \qquad 3.12$$

The time rate of change of photon fluence is called fluence rate or flux and is given by:

$$\phi = \frac{\Phi}{t} = \frac{N}{A.t} \qquad 3.13$$

If the fluence varies with time, the flux must be averaged over time, which can be given by:

$$\phi = \frac{d\Phi}{dt} = \frac{dN}{dA.dt} \qquad 3.14$$

The unit of fluence rate is $m^{-2} \cdot s^{-1}$.

3.6.1.1 Quantity that describes beam energy (Energy fluence)

The energy fluence Ψ describes the energy flow of the beam and is the product of the photons fluence Φ and the energy E per an X-ray photon [William and Ritenour, 1992., Jouns and Cunningham, 1983].

$$\Psi = \Phi E = \frac{NE}{A} \qquad 3.15$$

Equation 3.15 is true in case that all the X-ray photons possess the same energy. But in case the photons have different energies, the energy fluence can be given by:

$$\Psi = \int_{0}^{E_{\max}} \Phi.dE \qquad 3.16$$

The energy fluence unit is $MeV \cdot m^{-2}$.

In the same way, the photon flux may be converted to the energy flux ψ by multiplying it by the energy photon.

$$\psi = \Phi E = \frac{NE}{At} \qquad 3.17$$

Energy flux Ψ is also called Intensity, and its unit is $MeV \cdot m^{-2} \cdot s^{-1}$. In case that the radiation beam consists of photons having different energies, the energy flux or intensity can be given by:

$$\psi = \int_{0}^{E_{\max}} \phi . dE \qquad 3.18$$

3.6.2 Quantities to describe the amount of energy deposited in a medium

The preceding quantities describe the quality and quantity of radiation beam. These quantities do not present any information when the radiation beam interacts with the matter. Therefore, other quantities that describe the actual amount of energy deposited within the medium [William and Ritenour, 1992., Jouns and Cunningham, 1983] are discussed in the following sections.

3.6.2.1 Radiation exposure (*X*)

The concept of radiation exposure is based on the assumption that the absorbing medium is air. The Radiation exposure is the total charge (negative or positive) liberated as X-ray or γ-ray interacts in a small volume of air of mass m [William and Ritenour, 1992]. Exposure is thus a measure of the ability of radiation to ionize air

[Jouns and Cunningham, 1983] and is measured in coulombs per kg (C/kg) and is given by:

$$X = \frac{Q}{m} \qquad 3.19$$

The old unit of exposure is called roentgen (R), where:

$$1R = 2.58 \times 10^{-4} C.kg^{-1} \ \ of\ air \qquad 3.20$$

3.6.2.1.1 Relationship between exposure, energy and photon fluence

To produce one coulomb charge by ionization of air it requires energy absorption of 33.85 joules [William and Ritenour, 1992., Jouns and Cunningham, 1983]. Thus, an exposure of 1 R is equivalent to an energy absorption in air of:

$$Energy\ absorbed\ in\ air = \text{X.}(33.85) \qquad 3.21$$

Also the absorbed energy in air can be given by [William and Ritenour, 1992]:

$$Energy\ absorbed\ in\ air = \Psi \times \left(\frac{\mu_{en}}{\rho}\right)_{air} \qquad 3.22$$

Where **Ψ** is energy fluence and $(\mu_{en}/\rho)_{air}$ is the total mass energy absorption coefficient of air [Podfarask, 2005].

From equations 3.21 and 3.22:

$$\text{X. } (33.85) = \Psi.\left(\frac{\mu_{en}}{\rho}\right)_{air} \qquad 3.23$$

Substituting **Ψ** from the equation 3.15

$$\text{X. } (33.85) = \Phi.E.\left(\frac{\mu_{en}}{\rho}\right)_{air}$$

or $$X = \Phi.E(33.85)^{-1}.\left(\frac{\mu_{en}}{\rho}\right)_{air} \qquad 3.24$$

3.6.2.2 Kerma

The kerma stands for **k**inetic **e**nergy **r**eleased per unit **m**ass [Jouns and Cunningham, 1983., Ball and Moore, 1997]. The unit of kerma is J/kg or Gray (Gy). If the kerma measurements are derived from the deposition of energy in air, then the measured kerma is known as air kerma ($K\ air$) [Ball and Moore, 1997]. Kerma is defined as the sum of initial kinetic energies of all charged particles produced by the radiation per unit mass of irradiated material. The kerma can be given by:

$$K = \left(\frac{dE_{tr}}{dm}\right) \qquad 3.25$$

here the dE_{tr} is the kinetic energy transferred from photons to electrons in a volume element whose mass is dm .

3.6.2.2.1 Relationship between air kerma, energy and photon fluence

For a monoenergetic photon beam in air, the air kerma ($K\ air$) at a given point away from the source is proportional to the energy fluence Ψ or photon fluence Φ as follows:

$$K_{air} = \Psi\left(\frac{\mu_{tr}}{\rho}\right)_{air} = \Phi.E\left(\frac{\mu_{tr}}{\rho}\right)_{air} \qquad 3.26$$

Where $(\mu_{\mathrm{tr}}/\rho)_{\mathrm{air}}$ is the mass–energy transfer coefficient for air at photon energy E [Jouns and Cunningham,1983., Podfarask, 2005].

3.6.2.3 Air kerma and exposure

Equation 3.26 can be rewritten as follow:

$$\Psi = \left[\frac{\rho k_{air}}{\mu_{tr}}\right] \qquad 3.27$$

Substituting equation (3.27) in equation (3.23) results in

$$X = K_{air}\left[\left(\frac{\mu_{en}}{\rho}\right) \div \left(\frac{\mu_{tr}}{\rho}\right)\right] \div 33.85 \qquad 3.28$$

The mass–energy transfer coefficient $\left(\frac{\mu_{tr}}{\rho}\right)$ and mass–energy absorption coefficient $\left(\frac{\mu_{en}}{\rho}\right)$ are related through the following relationship [Jouns and Cunningham, 1983., Podfarask, 2005]:

$$\left(\frac{\mu_{en}}{\rho}\right) = \left(\frac{\mu_{tr}}{\rho}\right) \times (1-g) \qquad 3.29$$

Where g is the fraction of the energy of secondary charged electrons that is lost to bremsstrahlung rather than being deposited in the medium. Substituting equation (3.29) in equation (3.28) results in,

$$X = K_{air} \cdot \frac{1-g}{33.85} \qquad 3.30$$

or

$$K_{air} = X \cdot \frac{1-g}{33.85} \qquad 3.31$$

3.6.2.4 Absorbed dose

The biological changes in tissue exposed to ionizing radiation (e.g. X-ray) depend on the energy absorbed in this tissue from the radiation rather than on the amount of ionization that the radiation produces in air. The quantity which describes the energy absorbed in a medium from any type of ionizing radiation (e.g. X-ray) is called absorbed dose [Podfarask, 2005; Geijer, 2001]. The absorbed dose can be given by:

$$D = \frac{dE_{ab}}{dm} \qquad 3.32$$

Where dE_{ab} is the mean energy imparted by the ionizing radiation to a mass dm of a medium. The unit of absorbed dose is called gray (Gy). From equation 3.32, the absorbed dose depends on both the photon energy of the beam and on the type of absorbing medium.

3.6.2.5 Entrance skin dose (ESD)

The measured dose to the skin of a patient is called entrance skin dose (ESD), and is considered the best indicator of deterministic effects such as skin burns . For the diagnostic X-ray the ESD is defined as the air kerma multiplied by backscatter factor (BSF) [Oresegun *et al.*, 1999]. The BSF is the ratio of exposure due to primary and scattered photons to exposure due to primary photons

CHAPTER FOUR

4.0 EXPERIMENTAL METHODS

4.1 Equipment

The Kenya Radiation Protection Board under the Ministry of Health provided the Non-invasive X-Ray Test Device , Collimator and Beam Alignment Test Tools and a set of aluminium sheets of various thickness for the study. The radiation facilities studied allowed access to their X-ray machines for QC tests. Fifty two X-ray machines were assessed.

4.1.1 Digital Multimeter

The multimeter X-ray test device is a noninvasive X-ray test device which simultaneously measures kVp, exposure time and exposure rate (or air kerma) in a single exposure. The multimeter used in the current work (figure 4-1) was Victoreen model 4000M+ manufactured by Fluke Biomedical Corporation in the United States of America.

Figure 4-1: The Multimeter used in the current work (The Model 4000M+).

This multimeter features a dual sensitive preamplifier and can be used with radiographic, fluoroscopic and dental X-ray machines. In addition, it is factory calibrated for both tungsten anode (W/Al) and molybdenum (Mo/Mo) anode X-ray tubes, making it suitable for general X-ray tubes as well as for mammography applications. It measures kVp via a pair of CsI photodiode detectors (figure 4-2) partially shielded by copper filters of different thickness. The differential filtering provides a ratio that can be used to calculate kVp. X-rays striking the diode assembly produce currents that are amplified, resulting in a voltage output applied to an analog to digital converter.

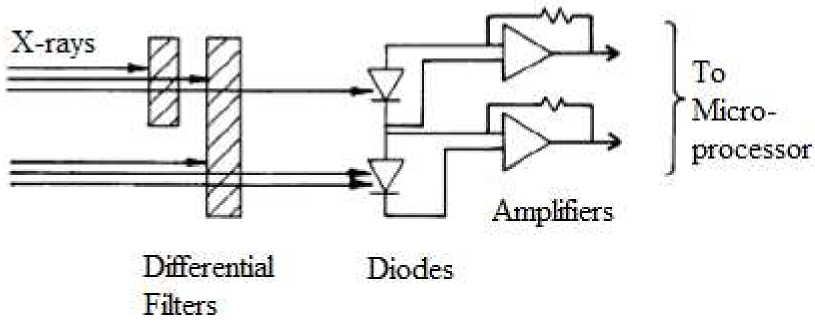

Figure 4-2: Schematic diagram of electric circuit used for kVp measure in the 4000M+ multimeter.

From this data, the microprocessor of this unit can calculate tube voltage and obtain the waveform. This model has five separate, selectable filters to ensure an optimum accuracy over the entire diagnostic range with the minimum filtration dependence [Fluke Corporation, 2005; William *et al*., 1987]. Exposure measurements are made with a 36 cm^3 parallel plate ionization chamber located above the filter wheel. This multimeter can also accept an external chamber and provide it with the necessary power and hence acts as a multimeter. The exposure time is measured in this model

(4000M+) by determining the time between the first and the last passages through 75% of kVp average using a quartz crystal.

4.1.2 Collimator and beam alignment test tools

The collimator and beam alignment test tools (figure 4-3) are used to assess the alignment of the X-ray field with the light field and the perpendicularity of the X-ray beam to the image receptor. The collimator test tool consists of a sheet of copper with a scale to identify the actual X-ray field size.

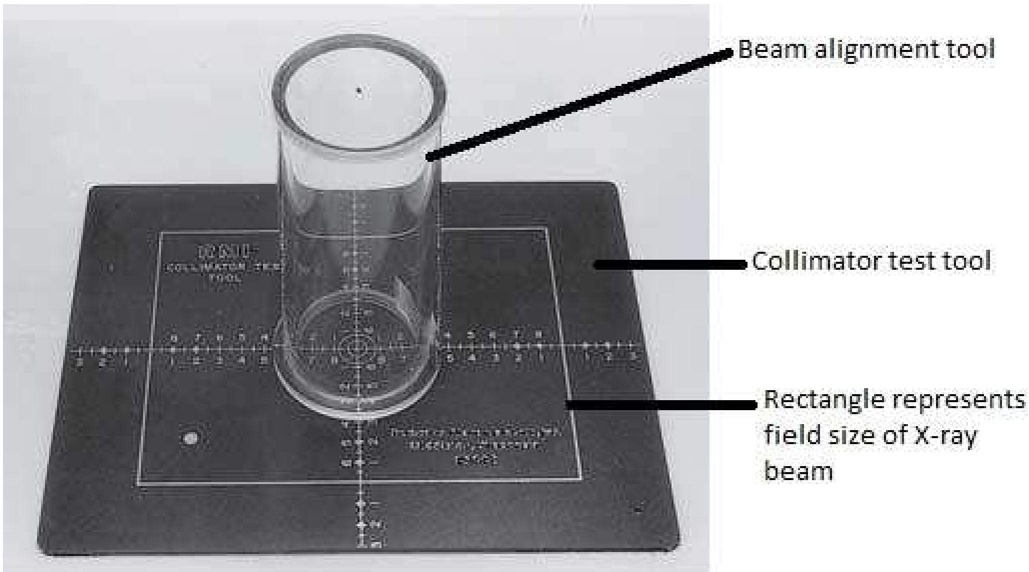

Figure 4-3: The collimator and alignment test tools manufactured by Fluke Biomedical Corporation in the USA which was used in the current work.

When this test tool is placed on the X-ray table (perpendicular to it), an image of the plate is produced and is used to assess the misalignment distance, if any, between the rectangular outline of the collimator test tool and the edge of the X-ray field of view. The beam alignment test tool consists of a plastic cylinder with two balls mounted at the center of the two disc ends of the plastic cylinder. When this test tool is placed in the centre of the collimator tool on the X-ray table centered to the X-ray field, and its image is generated, the image of the two steel balls overlaps only when the beam is accurately perpendicular to the image receptor.

4.2 The study area

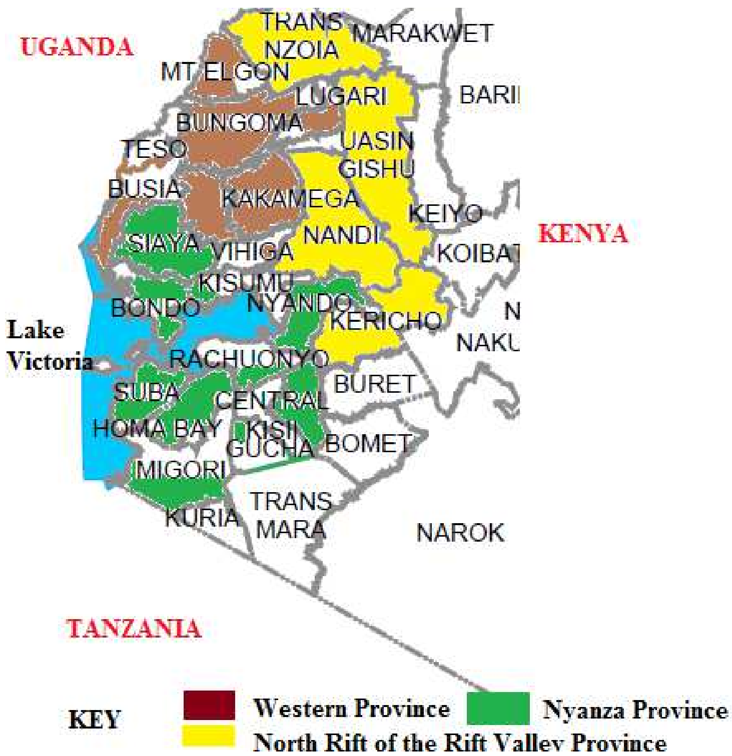

Figure 4-4: A map showing the study area

Medical X-ray facilities in the western region of Kenya were studied both public and private facilities. In Nyanza Province, 11 facilities were visited, 13 facilities were visited in the Western Province and 7 facilities in the north rift of the Rift Valley Province. The medical X-ray facilities in these provinces were chosen at random but all areas of the region were represented in the study.

4.3 Facilities QC Tests

4.3.1 Facilities with medical diagnostic X-ray units

First the facilities were assessed by means of a visual checklist to assure that all components of the radiographic X-ray system indicator lights, displays, mechanical locks and detents are working properly and that the mechanical rigidity and stability of the equipment is optimum. This was done by ensuring that each of the items listed in the QC visual checklist passed or received a check mark. Items not passing the visual check test were to be replaced or corrected as soon as possible.

QC Visual Checklist [CRCPD, 2003]

1. Collimator light brightness and cleanliness.
    - Determine if light is functioning and is clearly defined under normal operating conditions, without visible dust or foreign matter shadows.
2. Collimator beam limiting devices (BLDs) available and used.
    - If unit provides variable collimation, determine that they are functioning correctly and smoothly. If manual beam limiting devices are being used, assure they are sufficient for confining the x-ray beam to the area of clinical interest. Assure that both types are being used correctly.
3. Locks and detents operable.
    - Check to make sure all locks and detents are functioning as intended. Assure that the x-ray tube maintains its position at the clinically used angles
4. Hazard warning light provided.

- Inspect for the provision of hazard warning signs or lights provided at the entrance to the X-ray room and in the case of light, determine its functionality.

5. Tube or generator oil leakage.
    - Visually inspect areas around x-ray tube and generator for oil or abnormal collection of dust attaching to oil leaks.
6. Cassettes and screens condition.
    - Cassettes and screens should be cleaned regularly. Check screen condition for dust particles, scratches, and areas of discoloration. Assure screens are properly fitted and attached to cassettes. Check cassette latches to make sure they are functioning properly and are not broken. Cassettes and screens should be replaced if necessary.
7. Control panel indicators.
    - Assure all control panel switches, lights, and meters are functioning correctly.
8. Technique chart.
    - Make sure a technique chart is available, current, and appropriate for all procedures normally performed.
9. Lead aprons, gloves and collars.
    - Assure proper items are available and stored correctly without bends or folds.
10. Functional air-conditioning provided.
    - Make sure the X-ray room has fresh circulating air and that its not stuffy.

The X-ray machines that passed the QC visual check test, referred to us functional, were then subjected to more QC tests but only one machine per facility since 90% of the facilities visited had one X-ray machine being used. Four QC tests were performed on 15 X-ray machines. The machines were tested for Beam alignment and perpendicularity, kVp accuracy and reproducibility, exposure time accuracy and reproducibility and filtration tests. The devices used for the test of the X-ray machines was a calibrated non-invasive X-ray test device, Victoreen model 4000M+ used to determine the accuracy and timer setting as well as X-ray machine output and Collimator / Beam Alignment Test Tools used to evaluate beam alignment and congruence of light fields and X-ray fields. Detailed descriptions of the tests done are given separately below.

4.3.2 Performance assessment of X-ray machine and beam characteristics

The current work was performed in selected medical facilities in the western region of Kenya and the following QC tests were performed on each X-ray unit according to ICRP Recommendations of 2007.

4.3.2.1 X-ray beam alignment and perpendicularity

X-ray machines are usually provided with a beam restriction system (or collimator) to regulate the size of the X-ray field. This restriction system plays a significant role in patient's dose as it is used to identify and restrict the X-ray field to the desired scan area. To collimate X-ray field to the correct size and position, a light beam is projected through the X-ray collimator to coincide with the X-ray field. Thus, the X-ray beam is simulated by the light beam and allows the technologist to identify and collimate the X-ray beam to the desired scan area. Misalignment between the light field and the X-ray field may result in exposing a larger or smaller area than that required and this may result in an unnecessary exposure or repeat exposure. It is very important to ensure that the X-ray field is perpendicular to the plane of the image receptor and that the image receptor is centered to the X-ray field. Improper perpendicularity between the X-ray beam and the image receptor may result in an image distortion and loss of resolution. In this work the beam alignment and perpendicularity were assessed simultaneously using the beam alignment test tool (Victoreen model 07-662) and the collimator test tool (Victoreen model 07-661) (see figure 4-3). The beam alignment test tool was placed on top of the collimator test tool. The beam alignment test tool was centered to the collimator test tool and both the alignment and collimator test tools were placed on the X-ray table centered to the image receptor. The X-ray film (with cassette) was placed in the X-ray bucky, and the X-ray field was centered to the film and the test tools using the light field (see figure 4-5).

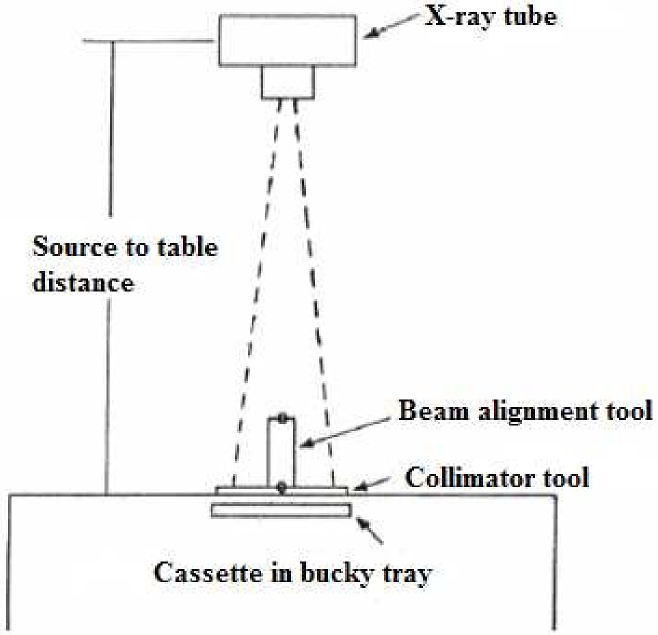

Figure 4-5: Determining beam alignment and its perpendicularity.

The light field was open to the field size of 9 x 7 cm^2, and a radiograph of the test tools was acquired using appropriate kVp and mAs at the clinically used source-to-image distance (SID) for each room. These exposure factors were established prior to the test as optimum exposure factors for the test tools. The produced image was used to measure the misalignment distance between the rectangular outline of the collimator test tool and the edge of the X-ray field of view. The produced image of steel balls was used to measure misalignment angle between X-ray beam and the image receptor. For any machine to pass this test, the difference between the light field and X-ray field must be within ± 1% of the used source to image distance (SID) on each side. In addition, the error between the centre of the image receptor (X-ray film) and the centre of the X-ray field (X-ray image) must be within ±1 % of the used SID and the misalignment angle must be within 1.5 degree of perpendicularity [ICRP, 2007].

4.3.2.2 X-ray tube kVp accuracy and reproducibility

The applied potential across an X-ray tube has a significant effect on the penetration ability (beam quality) of the generated X-ray beam and hence on the film contrast of the produced X-ray image, the optical density and the patient's dose. Therefore, accuracy and reproducibility of the control panel indicating tube potential is very important for a proper exposure technique selection. The voltage shown on the X-ray control console normally indicates the peak value of the potential applied across the tube, and is normally represented by kVp or kilovolt peak. In this test Victoreen multimeter (Model 4000M+) was used to assess kVp accuracy and reproducibility. This device was placed under the X-ray tube and centered to the X-ray field as shown in figure 4-6.

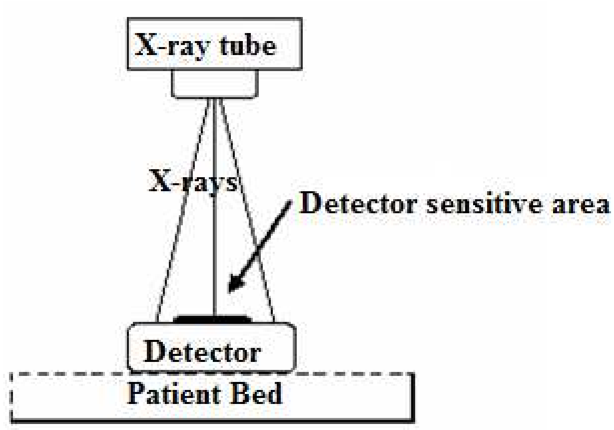

Figure 4-6: Schematic diagram for performing different QC tests.

To assess kVp accuracy, the test was first performed with constant mAs and variable kVp. Both the dialled kVp (DkVp) and the measured kVp (MkVp) were noted and the percentage difference between the DkVp and the MkVp, were then calculated for each DkVp using the following equation:

$$\%dif\,(kVp) = \frac{DkVp - MkVp}{MkVp} \times 100 \qquad 4.1$$

The results for different X-ray rooms were tabulated. For any machine to pass this test, the percentage difference between the DkVp and MkVp should be within $\pm$ 5% [ICRP, 2007].

To assess kVp reproducibility, the test was performed with constant kVp and variable mAs. The DkVp and MkVp were noted and the MkVp coefficient of variance (CV) was then calculated using the following equation:

$$CV = \frac{S}{m} \qquad 4.2$$

Where S is the estimated standard deviation of the different MkVp and m is the mean of the MkVp. The results of different X-ray machines in the facilities were tabulated. For any machine to pass this test, the coefficient of variance (CV) of the MkVp should be less than 10% [ICRP, 2007]

4.3.2.3 Exposure time accuracy and reproducibility

The X-ray generator should be capable of terminating exposure after a pre-selected time interval. Exposure time directly affects the total quantity of radiation emitted from an X-ray tube, therefore, an accurate exposure timer is critical for properly exposed radiographs and a reasonable patient dose. Any appreciable variation from the desired exposure time may lead to poor image quality and/or an increased patient and staff radiation dose.

To assess exposure time accuracy: The multimeter was placed under the X-ray tube in the same arrangement as that used for kVp accuracy and reproducibility . Several exposures with constant kVp and mA and with variable exposure time that cover the whole possible exposure time range were then performed. The dialled exposure time (DEXT) and the measured exposure time (MEXT) were noted and the percentage difference between DEXT and MEXT was then calculated using the following equation:

$$\%dif\,(EXT) = \frac{DEXT - MEXT}{MEXT} \times 100 \qquad 4.3$$

The results of different X-ray facilities were tabulated. It was not possible to conduct this test for some facilities due to the fact the X-ray machine in those facilities were old X-ray unit which did not have an indicator for the dialed exposure time. For any machine to pass this test, the percentage difference between DEXT and MEXT should be within ± 5% (for exposure times greater than 10 ms) and ± 10% (for exposure times less than 10 ms) [ICRP, 2007].

To assess exposure time reproducibility: the multimeter was placed under the X-ray tube in the same arrangement as that used in section (4.3.2.2). Several exposures with constant exposure time and appropriate kVp and mAs were then performed. The coefficient of variance (CV) of the exposure time was then calculated using the following equation:

$$CV = \frac{S}{m} \quad 4.4$$

Where S is the estimated standard deviation of the different measured MEXT and m is the mean of MEXT. The results of different X-ray facilities were tabulated. It was not possible to conduct this test for some facilities due to the fact that the X-ray machines in these facilities were old X-ray unit which did not have an indicator for the dialed exposure time. For any machine to pass this test, the MEXT *CV* of the exposure time must be less than 5% [ICRP, 2007].

4.3.2.4 Filtration (HVL) check

The thickness of any given material where 50% of the incident energy has been attenuated is known as the half-value layer (HVL). The HVL is expressed in units of distance (mm or cm). Like the attenuation coefficient, it is photon energy dependant. Increasing the penetrating energy of a stream of photons will result in an increase in a material's HVL. The effects of filtration on the X-ray beam have been discussed in chapter three. A proper filtration is necessary to remove low-energy photons from an X-ray beam. Patient's skin dose can increase as much as 90% if the low energy photons are not removed [Outif, 2004]. Half Value Layer will change as the X-ray tube ages due to deposition of the target material on the inside of the tube window and roughening of the target. This test was performed using the same device and arrangement as that used in section 4.3.2.2. Several exposures with constant kVp, mAs and variable aluminum (Al) filter thickness (figure 4-7) were taken. The Al sheets were attached to the tube collimator. The output of the X-ray tube was noted for each thickness of filter. The results of different facilities were tabulated. The relationship between total Al thickness, and the measured output was plotted and from this figure, the thickness required to reduce the exposure to half of its original value (without filter) was determined.

Figure 4-7: An image of the aluminum sheets used in the current work.

For any X-ray machine to pass this test, it should have a minimum HVL as in table 4-1.

kVp	Minimum HVL in mm of Aluminium
30	0.3
40	0.4
50	0.5
51	1.2
60	1.3
70	1.5
71	2.1
80	2.3
90	2.5
100	2.7
110	3.0
120	3.2
130	3.5
140	3.8
150	4.1

Table 4-1: The minimum recommended HVL for an X-ray machine [ICRP, 2007]

CHAPTER FIVE

5.0 RESULTS AND ANALYSIS

5.1 Personnel and general observations

Table 5-1 shows the visual checklist observations about the facilities provided for the patients and personnel safety, it is evident from the table that there was no hazard warning light, dose reference chart or technique chart and functional air-conditioning in most of the facilities that were studied. Collimator light of most of X-ray machines was functional however other machines had beam limiting devices that were not functioning correctly and smoothly. Technique chart was only available where there were registered radiographers but facilities without the technique chart had either unregistered radiographers or on lockum basis. This was so especially in the private facilities. Cassettes and screen conditions was good in facilities with registered radiographers but in most of the private facilities they were full of dust particles, scratches and even others were broken. More than half of the X-ray machines observed had loose panel switches, dead panel indicators and irregular functioning meters. Some facilities had very old aprons full of bends, folds and so stuffy. We recommended for closing down of X-ray departments for two facilities that had terrible X-ray tube oil leakage. The visual checklist observations reveals that X-ray machines in the majority of the facilities in western Kenya are being used with major defects that can be detrimental to the health of patients and staff. *Figure 5-1* shows the year of manufacture of various radiological units surveyed that clearly shows the high rate of increase of the number of X-ray machines in the region.

NO.	OBSERVATION	PASS (%)	FAIL (%)
1	Collimator light brightness and cleanliness	68	32
2	Collimator (BLD) available and used	61	39
3	Locks and detents operable	52	48
4	Hazard warning light provided	23	77
5	Tube or generator oil leakage	75	25
6	Cassettes and screens condition	58	42
7	Control panel indicators	41	59
8	Technique chart	06	94
9	Provisions of lead aprons, gloves and collars	68	32
10	Functional air-conditioning provided	23	77
TEST RESULTS		**60%**	**40 %**

Table 5-1: Visual checklist observations

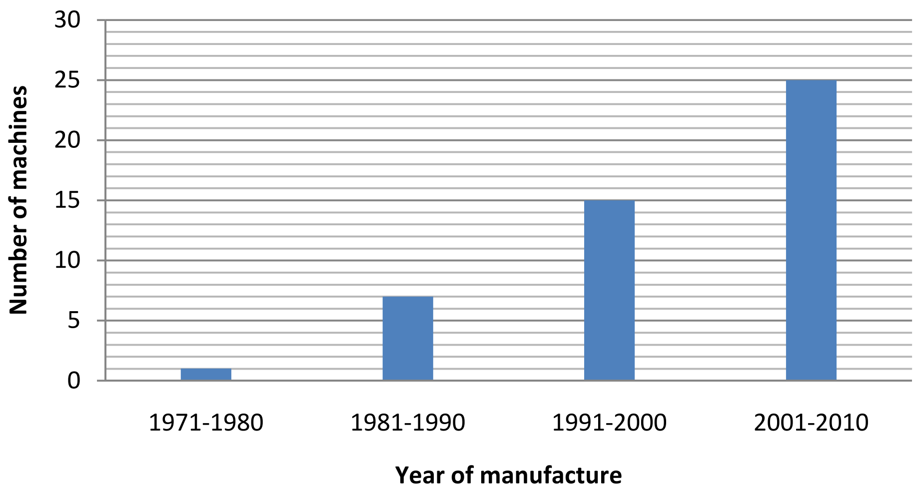

Figure 5-1: Year of manufacture of radiological units surveyed

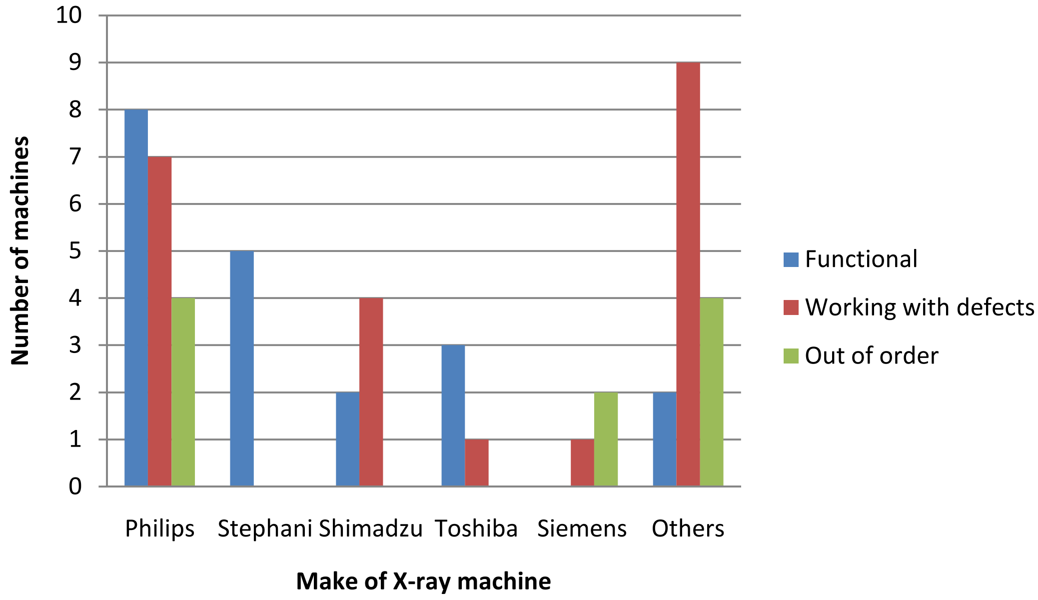

Figure 5-2: Brands of radiological installations in the region

5.2 Results of the Performance Assessment

The results of each facility are discussed separately in the following sections:

5.2.1 RESULTS AND DISCUSSIONS FOR FACILITY P1 [ICRP, 2007]

5.2.1.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-2 summarizes the result of this test. The maximum outside and inside misalignment ratios were 0.0 % and 0.9 % of the SID, respectively. The displacement error between the X-ray field and the image receptor was 1 cm, which is equivalent to 0.9% of the SID.

Shift between X-ray and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	1	0.9%	0	0%
Left	0	0.0%	0	0%
Up	0	0.0%	0	0%
Down	1	0.9%	0	0%

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to Image receptor
Displacement error = 1 cm ≈ 0.9% of SID	Angle ≈ 2.6 º

Table 5-2: Results of the X-ray beam alignment and perpendicularity for facility P1

The X-ray beam was found to be perpendicular to the image receptor to about 2.6º. It is clear from the above mentioned results that this machine has failed the perpendicularity test.

5.2.1.2 X-ray tube potential accuracy

This test was conducted at 109 cm source to detector distance (SDD), 10 mAs, 19 x 18 cm^2 field size and large focal spot. The kVp accuracy was performed between 40 and 125 kVp.

DKVp	40	45	50	70	81	90	109	102	125
MKVp	36.20	38.81	43.95	60.47	67.73	74.78	105.00	90.32	123.60
% Dif	10.5	16	13.8	15.8	19.6	20.4	3.8	12.9	1.1

Table 5-3: Results of the X-ray tube potential accuracy for facility P1

Table 5-3 summarizes the result of this test. The calculated minimum percentage difference was 1.1 at 125 kVp and the maximum percentage difference was 20.4 at 90 kVp. It is clear from these results that this machine has failed the test.

5.2.1.3 X-ray tube potential reproducibility

This test was conducted at 109 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-4 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2.5 mAs to 250 mAs.

DmAs	2.5	10	20	50	80	100	140	200	250
$MKVp_{max}$	55.47	60.52	60.8	64.24	64.87	65.49	64.81	64.99	65.29
Mean = 63, Standard Deviation = 3.4, Coefficient of Variance = 0.05									

Table 5-4: Results of the X-ray tube potential reproducibility for facility P1

The calculated coefficient of variance (CV) of the kVp reproducibility was equal to 0.05, and this value was within the acceptable limit (<0.1).

5.2.1.4 Exposure time

It was not possible to conduct this test due to the fact that this machine was an old X-ray unit which did not indicate the dialed exposure time.

5.2.1.5 Filtration (HVL) check

This test was conducted at 109 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-5 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	91.35	80.47	66.88	61.66	49.70	38.09	34.12	33.10	27.43

Table 5-5: Results of the filtration (HVL) check for facility P1

The determined HVL was 2.6 mm Al , and this value was within the acceptable range for 90 kVp.

5.2.2 RESULTS AND DISCUSSIONS FOR FACILITY P2 [ICRP, 2007]

5.2.2.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-6 summarizes the result of this test.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0.50	0.40%	0	0%
Left	0.25	0.20%	0	0%
Up	0.00	0.00%	0	0%
Down	0.25	0.20%	0	0%

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to Image receptor
Displacement error = 0.7 cm ≈ 0.6% of SID	Angle ≈ 1.73º

Table 5-6: Results of the X-ray beam alignment and perpendicularity for facility P2

The maximum outside and inside misalignment ratios were 0.0 % and 0.004 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.7 cm, which is equivalent to 0.6% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 1.73º. It is clear from the above mentioned result that this machine has failed the perpendicularity test.

5.2.2.2 X-ray tube potential accuracy

This test was conducted at 110.5 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot and variable kVp (40-125 kVp). Table 5-7 summarizes the result of this test.

DKVp	40	46	50	70	81	90	102	109	125
MKVp	43.98	50.04	56.9	78.68	82.10	96.72	112.5	123.9	132.7
% Dif	-9.1	-8.1	-12.1	-11.0	-1.3	-7	-9.3	-12.0	-5.8

Table 5-7: Results of the X-ray tube potential accuracy for facility P2

The calculated minimum percentage difference was -12.13 at 50 kVp and the calculated maximum percentage difference was -1.34 at 81 kVp. It is clear from these results that this machine has failed this test.

5.2.2.3 X-ray tube potential reproducibility

This test was conducted at 110.5 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-8 summarizes the result of this test.

DmAs	2	10	20	50	80	100	160	200	250
$MKVp_{max}$	75.90	73.87	79.75	79.78	78.57	75.70	78.19	75.14	74.75
Mean = 76.9, Standard Deviation = 2.2, Coefficient of Variance = 0.03									

Table 5-8: Results of the X-ray tube potential reproducibility for facility P2

The test was performed at different mAs setting covering the range from 2 to 250 mAs. The calculated coefficient of variance of the kVp reproducibility was equal to 0.03, and this value was within the acceptable limit (<0.1).

5.2.2.4 Exposure time

It was not possible to conduct this test due to the fact that this machine was an old X-ray unit which did not indicate the dialed exposure time.

5.2.2.5 Filtration (HVL) check

This test was conducted at 110.5 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-9 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	176.4	155.3	133.9	122.1	96.08	77.05	69.81	66.36	55.38

Table 5-9: Results of the filtration (HVL) check for facility P2

The determined HVL is 2.8 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.3 RESULTS AND DISCUSSIONS FOR FACILITY P3 [ICRP, 2007]

5.2.3.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 50 kVp, 5 mAs and large focal spot. Table 5-10 summarizes the result of this test.

Shift between X-ray and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0.2	0.2%	0	0%
Left	1.0	0.9%	0	0%
Up	0.2	0.2%	0	0%
Down	0.5	0.5%	0	0%

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 1.1 cm ≈ 0.96% of SID	Angle ≈ 0.58º

Table 5-10: Results of the X-ray beam alignment and perpendicularity for facility P3.

The maximum outside and inside misalignment ratios were 0.0 % and 0.01 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.1 cm, which is equivalent to 0.96% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 0.58º. It is clear from the above mentioned result that this machine has passed this test.

5.2.3.2 X-ray tube potential accuracy

This test was conducted at 109 cm SDD, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 125 kVp. Table 5-11 summarizes the result of this test. The calculated minimum percentage difference was -19.6 at 40 kVp and the calculated maximum percentage difference was 9.1 at 125 kVp. It is clear from these results that this machine has failed this test.

DKVp	40	46	50	70	81	90	109	102	125
$MKVp_{max}$	49.74	54.52	59.38	74.68	82.91	86.93	100.7	95.82	114.6
% Dif	-19.6	-15.6	-15.8	-6.3	-2.3	3.5	8.2	6.5	9.1

Table 5-11: Results of the X-ray tube potential accuracy for facility P3

5.2.3.3 X-ray tube potential reproducibility

This test was conducted at 109 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-12 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 mAs to 250 mAs.

DmAs	2	10	20	50	80	100	160	200	250
$MKVp_{max}$	73.15	74.09	82.38	83.04	82.89	81.86	81.86	81.39	81.26
Mean = 80.1, Standard Deviation = 3.7, Coefficient of Variance = 0.07									

Table5-12: Results of the X-ray tube potential reproducibility for facility P3

The calculated coefficient of variance of the kVp reproducibility was equal to 0.05, and this value is within the acceptable limit (<0.1).

5.2.3.4 Exposure time

It was not possible to conduct this test due to the fact that this machine was an old X-ray unit which did not indicate the dialed exposure time.

5.2.3.5 Filtration (HVL) check

This test was conducted at 109 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size and large focal spot. The test was performed at variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-13 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	127.9	114.7	110.6	93.22	81.56	59.96	55.26	51.41	48.19

Table 5-13: Results of the Filtration (HVL) check for facility P3

The determined HVL was 3.48 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.4 RESULTS AND DISCUSSIONS FOR FACILITY P4 [ICRP, 2007]

5.2.4.1 X-ray beam alignment and perpendicularity

The test was conducted at 166 cm SID, 113 kVp, 13 mAs and large focal spot. Table 5-14 summarizes the result of this test.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	1	0.6 %	0	0%
Left	1.5	0.9 %	0	0%
Up	1.5	0.9 %	0	0%
Down	3	2 %	0	0%

Alignment of X-ray field with Image	**Perpendicularity of X-ray beam to image**

receptor	receptor
Displacement error = 1.5 cm ≈ 0.9% of SID	Angle ≈ 2.5º

Table 5-14: Results of the X-ray beam alignment and perpendicularity for facility P4

The maximum outside and inside misalignment ratios were 0.0 % and 2 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.5 cm, which is equivalent to 0.9% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 2.5º. It is clear from the above mentioned results that this machine has failed the perpendicularity and alignment of the X-ray beam with light beam tests.

5.2.4.2 X-ray tube potential accuracy

This test was conducted at 107 cm SDD, 50 ms, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-15 summarizes the result of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	39.13	43.19	48.17	74.36	80.01	88.74	97.75	108	118
% Dif	2.2	4.2	3.8	0.9	1.2	1.4	1.3	0.9	2.5

Table 5-15: Results of the X-ray tube potential accuracy for facility P4

The calculated minimum percentage difference was 0.9 at 75 kVp and the calculated maximum percentage difference was 4.2 at 45 kVp. It is clear from these results that this machine has passed this test.

5.2.4.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-16 summarizes the result of this test. The test was performed at different values of mAs setting covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	69.58	70.6	70.69	70.67	70.73	70.64	70.35	70.71	69.66
Mean = 70.4, Standard Deviation = 0.46, Coefficient of Variance = 0.007									

Table 5-16: Results of the X-ray tube potential reproducibility for facility P4

The calculated coefficient of variance of the kVp reproducibility was equal to 0.007. This calculated value was within the acceptable limit (<0.1).

5.2.4.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-18 summarizes the result of this test.

DEXT (ms)	3.18	16	32.5	84.5	138	176	255	384	578
MEXT (ms)	2.8	15.6	32.7	86.4	140.6	180.8	261.1	388.3	395.4
% Dif	13.6	2.6	-0.6	-2.2	-1.9	-2.7	-2.3	-1.1	46.2

Table5-17: Results of the exposure time accuracy for facility P4

The calculated percentage differences ranged from -2.7 at 176 ms dialed time to 46.2 at 578 ms dialed time. It is clear from table 5-17 that the exposure timer of this machine performed well within the region below 384 ms.

5.2.4.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-18 summarizes the result of this test. The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.0008 and this value was within the acceptable limit (< 0.05).

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	63.3	63.4	63.3	63.4	63.3	63.4	63.3	63.4	63.4	63.3
Mean = 63.4, Standard Deviation = 0.05, Coefficient of Variance = 0.0008										

Table 5-18: Results of the exposure time reproducibility for facility P4

5.2.4.6 Filtration (HVL) check

This test was conducted at 107 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-19 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	189.1	173.7	149.1	138.9	114	91.37	82.38	78.53	67.96

Table 5-19: Results of the filtration (HVL) check for facility P4

The determined HVL was 3.33 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.5 RESULTS AND DISCUSSIONS FOR FACILITY P5 [ICRP, 2007]

5.2.5.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-20 summarizes the results of this test. The maximum outside and inside misalignment ratios were 0.43 % and 1.3 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.8 cm, which is equivalent to 0.7% of the SID.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0	0 %	0.5	0.43 %
Left	1.5	1.3 %	0	0 %
Up	0.5	0.43 %	0	0 %
Down	0.5	0.43 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 0.8 cm ≈ 0.7 % of SID	Angle ≈ 1.7º

Table 5-20: Results of the X-ray beam alignment and perpendicularity for facility P5

The X-ray beam was found to be perpendicular to the image receptor to about 1.7º. It is clear from the above mentioned results that this machine has failed the X-ray beam alignment and perpendicularity tests.

5.2.5.2 X-ray tube potential accuracy

This test was conducted at 107 cm SDD, 10 mAs, 19 x 18 cm^2 field size and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-21 summarizes the results of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	39.53	44.16	48.85	76.15	80.57	89.93	98.43	107.5	118.4
% Dif	1.2	1.9	2.4	-1.5	0.5	0.1	0.6	1.4	2.2

Table 5-21: Results of the X-ray tube potential accuracy for facility P5

The calculated minimum percentage difference was -1.5 at 75 kVp and the calculated maximum percentage difference was 2.4 at 50 kVp. It is clear from these results that this machine has passed this test.

5.2.5.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-22 summarizes the results of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	74.55	70.64	73.82	72.02	74.68	73.82	72.11	73.63	72.32
Mean = 73, Standard Deviation = 1.4, Coefficient of Variance = 0.02									

Table 5-22: Results of the X-ray tube potential reproducibility for facility P5

The calculated coefficient of variance of the kVp reproducibility was equal to 0.02, and this value was within the acceptable limit (<0.1).

5.2.5.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 70 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-23 summarizes the results of this test.

DEXT (ms)	2.5	50	140	220	280	450	710	1100
MEXT (ms)	2.5	50.8	145	225.7	290.2	466.9	444.3	25.4
% Dif	0	-1.6	-3.4	-2.5	-3.5	-3.6	59.8	4230.7

Table 5-23: Results of the exposure time accuracy for facility P5

The calculated percentage differences ranged from 0 at 2.5 ms dialed time to 4230.7 at 1100 ms dialed time. It is clear from table 5-24 that the exposure timer of this machine performed well within the region below 450 ms. As the exposure time increased above 450 ms, the measured exposure time decreased dramatically (see figure 5-8).

5.2.5.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-24 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	64.1	64.2	63.9	64.2	64.1	64.1	64.1	63.9	63.9	63.9
Mean = 64, Standard Deviation = 0.1, Coefficient of Variation = 0.002										

Table 5-24: Results of the exposure time reproducibility for facility P5

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.002 and this value was within the acceptable limit (< 0.05).

5.2.5.6 Filtration (HVL) check

This test was conducted at 107 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at variable thickness of aluminum filters from 0 to 5.6 mm Al. Table 5-25 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	159.9	147.9	126.9	118.7	98.3	78.57	71.72	68.22	59.62

Table 5-25: Results of the filtration (HVL) check for facility P5

The determined HVL was 3.5 mm AL at 90 kVp which is within the acceptable range.

5.2.6 RESULTS AND DISCUSSIONS FOR FACILITY P6 [ICRP, 2007]

5.2.6.1 X-ray beam alignment and perpendicularity

This test was performed at 90 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-26 summarizes the results of this test.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0.25	0.3 %	0	0 %
Left	0.25	0.3 %	0	0 %
Up	0.25	0.3 %	0	0 %
Down	0.25	0. 3 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 1 cm ≈ 1 % of SID	Angle ≈ 1.35º

Table 5-26: Results of the X-ray beam alignment and perpendicularity for facility P6

The maximum outside and inside misalignment ratios were 0 % and 0.003% of the SID respectively. The displacement error between the X-ray field and the image receptor was 1 cm, which is equivalent to 1% of SID. The X-ray beam was found to be perpendicular to the image receptor to about 1.35º. All these measured values are within the acceptable limit.

5.2.6.2 X-ray tube potential accuracy

This test was conducted at 110 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-27 summarizes the result of this test. The calculated maximum percentage difference was 3.5 at 45 and 50 kVp and the calculated minimum percentage different was 0.2 at 75 kVp.

DKVp	40	45	50	75	81	90	109	121
$MKVp_{max}$	38.69	43.48	48.33	74.84	80.01	88.28	107.7	117.7
% Dif	3.4	3.5	3.5	0.2	1.2	1.9	1.1	2.8

Table 5-27: Results of the X-ray tube potential accuracy for facility P6

It is clear from these results that this machine has passed this test.

5.2.6.3 X-ray tube potential reproducibility

This test was conducted at 110 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-28 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 mAs to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	68.85	69.41	69.16	69.16	69.72	69.28	69.57	69.4	69.75
Mean = 69.4, Standard Deviation = 0.3, Coefficient of Variance = 0.004									

Table 5-28: Results of the X-ray tube potential reproducibility for facility P6

The calculated coefficient of variance of the kVp reproducibility was equal to 0.004, and this value was within the acceptable limit (<0.1).

5.2.6.4 Exposure time accuracy

This test was conducted at 110 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-29 summarizes the result of this test.

DEXT (ms)	12	23.5	60.5	100	127	184	277	412
MEXT (ms)	10.7	23.1	61	100.8	129.2	184.8	271.6	352.2
% Dif	12.1	1.7	-0.8	-0.8	-1.7	0.4	2	17

Table 5-29: Results of the exposure time accuracy for facility P6

The calculated percentage differences ranged from -1.7 at 127 ms dialed time to 17 at 412 ms dialed time. It is clear from table 5-30 that the exposure timer of this machine performed well with the region below 277 ms.

5.2.6.5 Exposure time reproducibility

This test was conducted at 110 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-30 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	61.4	61.5	61.8	61.1	61.2	61.1	61.6	61.5	61.4	61.4
Mean = 61.4, Standard Deviation = 0.22, Coefficient of Variance = 0.004										

Table 5-30: Results of the exposure time reproducibility for facility P6

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.004, and this value was within the acceptable limit (< 0.05).

5.2.6.6 Filtration (HVL) check

This test was conducted at 110 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2, field size, 63 ms, and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-31 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	129.60	120.10	103.80	97.71	80.80	64.97	67.40	64.40	56.31

Table 5-31: Results of the filtration (HVL) check for facility P6

The determined HVL was 4.3 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.7 RESULTS AND DISCUSSIONS FOR FACILITY P7 [ICRP, 2007]

5.2.7.1 X-ray beam alignment and perpendicularity

The test was conducted at 110 cm SID, 60 kVp, 10 mAs and large focal spot.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0.25	0.22 %	0	0 %
Left	1.5	1.4 %	0	0 %
Up	0.5	0.45 %	0	0 %
Down	0.5	0. 45 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 1.2 cm ≈ 1 % of SID	Angle ≈ 0.55º

Table 5-32: Results of the X-ray beam alignment and perpendicularity for facility P7

Table 5-32 summarizes the results of this test. The maximum outside and inside misalignment ratios were 0.0 % and 1.4 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.2 cm, which is equivalent to 1 % of the SID. The X-ray beam was found to be perpendicularity to the image receptor to about 0.55º. All these measured values were within the acceptable limit. It is clear form above mentioned results that this machine has failed the X-ray beam alignment with light field.

5.2.7.2 X-ray tube potential accuracy

This test was conducted at 107.5 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-33 summarizes the result of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	40.34	44.25	49.40	75.37	80.43	89.97	99.0	109.0	119.20
% Dif	-0.8	1.7	1.2	-0.5	0.7	0.03	0.0	0.0	1.5

Table 5-33: Results of the X-ray tube potential accuracy for facility P7

The calculated minimum percentage difference was -0.8 at 40 kVp and the calculated maximum percentage difference was 1.7 at 45 kVp. It is clear from these results that this machine has passed the test.

5.2.7.3 X-ray tube potential reproducibility

This test was conducted at 107.5 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-34 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	70.77	70.74	71.11	71.15	70.51	70.34	70.82	70.21	70.42
Mean = 70.7, Standard Deviation = 0.33, Coefficient of Variance = 0.005									

Table 5-34: Results of the X-ray tube potential reproducibility for facility P7

The calculated coefficient of variance (CV) of the kVp reproducibility was equal to 0.005, and this value was within the acceptable limit (<0.1).

5.2.7.4 Exposure time accuracy

This test was conducted at 107.5 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-35 summarizes the result of this test.

DEXT (ms)	4	20.5	40.5	101	161	202	286	450	693
MEXT (ms)	3.8	20.5	40.5	103.0	163.6	205.5	247.7	271.7	243.5
% Dif	5.3	2.5	0	-1.9	-1.6	-1.7	15.5	65.6	184.6

Table 5-35: Results of the exposure time accuracy for facility P7

The calculated percentage differences ranged from -1.9 at 101 ms dialed time to 184.6 at 693 ms dialed time. It is clear from table 5-35 that the exposure timer of this machine performed well within the region below 202 ms. As the exposure time increased above 202 ms, the measured exposure time fell of gradually.

5.2.7.5 Exposure time reproducibility

This test was conducted at 107.5 cm SDD, 81 kVp, 20 mAs, 40 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-36 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	63.1	63.1	63.1	63	63	63.1	63.1	63	63	63
Mean = 63.1, Standard Deviation = 0.05, Coefficient of Variance = 0.0008										

Table 5-36: Results of the exposure time reproducibility for facility P7

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.0008, and this value was within the acceptable limit (< 0.05).

5.2.7.6 Filtration (HVL) check

This test was conducted at 107.5 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2, field size, 63 ms and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-37 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	125.8	117.6	102.7	96.55	80.05	65.74	68.34	65.46	57.15

Table 5-37: Results of the filtration (HVL) check for facility P7

The determined HVL was 4.69 mm Al (figure 5-13), and this value was within the acceptable range for 90 kVp.

5.2.8 RESULTS AND DISCUSSIONS FOR FACILITY P8 [ICRP, 2007]

5.2.8.1 X-ray beam alignment and perpendicularity

The test was conducted at 100 cm SID, 60 kVp, 5 mAs and large focal spot. The different measured misalignments were summarized in table 5-38. The maximum outside and inside misalignment ratios were 0.0 % and 1.5 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.55°, which is equivalent to 1.55% of the SID.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	1	1 %	0	0 %
Left	1.5	1.5 %	0	0 %
Up	1.5	1.5 %	0	0 %
Down	1	1 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 0.5 cm ≈ 0.5 % of SID	Angle ≈ 0.5º

Table 5-38: Results of the X-ray beam alignment and perpendicularity for facility P8.

The X-ray beam was found to be perpendicular to the image receptor to about 1.70º. It is clear from the above mentioned results that this machine has failed the alignment of the X-ray beam with light beam.

5.2.8.2 X-ray tube potential accuracy

The test was conducted at 107 cm SDD, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-39 summarizes the result of this test. The calculated minimum percentage difference was -3.7 at 81 and 109 kVp and the calculated maximum percentage difference was 4.4 at 45 kVp.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	39.32	43.09	48.49	74.67	84.12	88.79	98.05	107.2	118.9
% Dif	1.7	4.4	3.1	0.4	-3.7	1.4	1	1.7	1.8

Table 5-39: Results of the X-ray tube potential accuracy for facility P8

It is clear from these results that this machine has passed this test.

5.2.8.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-40 summarizes the results of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	70.66	76.12	75.7	72.23	75.47	69.81	70.24	70.69	73.5
Mean = 72.7, Standard Deviation = 2.55, Coefficient of Variance = 0.04									

Table 5-40: Results of the X-ray tube potential reproducibility for facility P8

The calculated coefficient of variance of the kVp reproducibility was equal to 0.04, and this value was within the acceptable limit (<0.1).

5.2.8.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-41 summarizes the result of this test. The calculated percentage differences ranged from -0.8 at 255 ms dialed time to 68.9 at 578 ms dialed time.

DEXT (ms)	16	32.5	84.5	138	176	255	384	578
MEXT (ms)	15	31.5	83.5	136.3	176.2	257.1	380.7	342.2
% Dif	6.7	3.2	1.2	1.2	-0.1	-0.8	0.9	68.9

Table 5-41: Results of the exposure time accuracy for facility P8

It is clear from table 5-41 that the exposure timer of this machine performed well with the region below 384 ms. As the exposure time increased above 384 ms, the measured exposure time fell off slowly.

5.2.8.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 40 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-42 summarizes the result of this test.

DEXT (ms)	40	40	40	40	40	40	40	40	40	40
MEXT (ms)	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7	38.7
Mean = 38.68, Standard Deviation = 0.063, Coefficient of Variation = 0.002										

Table 5-42: Results of the exposure time reproducibility for facility P8

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.002, and this value was within the acceptable limit (< 0.05).

5.2.8.6 Filtration (HVL) check

This test was conducted at 107 SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-43 summarizes the result of this test. The determined HVL was 3.13 mm AL at 90 kVp and this value was within the acceptable range for 90 kVp.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	147	135.5	100.6	108.3	88.42	70.61	63.6	60.54	56.31

Table 5-43: Results of the filtration (HVL) check for facility P8

5.2.9 RESULTS AND DISCUSSIONS FOR FACILITY P9 [ICRP, 2007]

5.2.9.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-44 summarizes the result of this test.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	0.50	0.40%	0	0%
Left	0.25	0.20%	0	0%
Up	0.00	0.00%	0	0%
Down	0.25	0.20%	0	0%

Alignment of X-ray field with Image receptor	**Perpendicularity of X-ray beam to Image receptor**
Displacement error = 0.7 cm ≈ 0.6% of SID	Angle ≈ 1.73º

Table 5-44: Results of the X-ray beam alignment and perpendicularity for facility P9.

The maximum outside and inside misalignment ratios were 0.0 % and 0.004 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.7 cm, which is equivalent to 0.6% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 1.73º. It is clear from the above mentioned result that this machine has failed the perpendicularity test.

5.2.9.2 X-ray tube potential accuracy

This test was conducted at 110.5 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot and variable kVp (40-125 kVp). Table 5-45 summarizes the result of this test.

DKVp	40	46	50	70	81	90	102	109	125
$MKVp_{max}$	39.23	45.02	49.10	69.34	80.48	89.41	101.7	108.1	123.4
% Dif	1.96	2.18	1.83	0.95	0.65	0.66	0.29	0.83	1.30

Table 5-45: Results of the X-ray tube potential accuracy for facility P9

The calculated minimum percentage difference was 0.29 at 102 kVp and the calculated maximum percentage difference was 2.18 at 46 kVp. It is clear from these results that this machine has passed this test.

5.2.9.3 X-ray tube potential reproducibility

This test was conducted at 110.5 cm SDD, 70 kVp, 19 x 18 cm2 field size and large focal spot. Table 5-46 summarizes the result of this test. The test was performed at different mAs setting covering the range from 2 to 250 mAs.

DmAs	2	10	20	50	80	100	160	200	250
$MKVp_{max}$	76.90	74.37	80.65	80.78	79.67	76.70	78.19	74.24	75.75
Mean = 77.5, Standard Deviation = 2.4, Coefficient of Variance = 0.03									

Table 5-46: Results of the X-ray tube potential reproducibility for facility P9

The calculated coefficient of variance of the kVp reproducibility was equal to 0.03, and this value was within the acceptable limit (<0.1).

5.2.9.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-47 summarizes the result of this test.

DEXT (ms)	3.18	16	32.5	84.5	138	176	255	384	578
MEXT (ms)	2.8	15.1	32.6	86.4	140	180.8	260.1	388	395.4
% Dif	13.6	6.0	-0.31	-2.2	-1.43	-2.7	-1.96	-1.0	46.2

Table 5-47: Results of the exposure time accuracy for facility P9

The calculated percentage differences ranged from -2.7 at 176 ms dialed time to 46.2 at 578 ms dialed time. It is clear from table 5-47 that the exposure timer of this machine performed well within the region below 384 ms.

5.2.9.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-48 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	63.3	63.3	63.3	63.4	63.4	63.4	63.3	63.4	63.4	63.3
Mean = 63.4, Standard Deviation = 0.05, Coefficient of Variance = 0.0008										

Table 5-48: Results of the exposure time reproducibility for facility P9

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.0008 and this value was within the acceptable limit (< 0.05).

5.2.9.6 Filtration (HVL) check

This test was conducted at 107 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-49 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	186.1	175.7	150.1	138.9	114.6	95.37	83.38	80.53	66.96

Table 5-49: Results of the filtration (HVL) check for facility P9

The determined HVL was 3.45 mm Al (figure 5-17), and this value was within the acceptable range for 90 kVp.

5.2.10 RESULTS AND DISCUSSIONS FOR FACILITY P10 [ICRP, 2007]

5.2.10.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 50 kVp, 5 mAs and large focal spot. Table 5-50 summarizes the result of this test.

Shift between X-ray and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	0.2	0.2%	0	0%
Left	1.0	0.9%	0	0%
Up	0.2	0.2%	0	0%
Down	0.5	0.5%	0	0%

Alignment of X-ray field with Image receptor	**Perpendicularity of X-ray beam to image receptor**
Displacement error = 1.1 cm ≈ 0.96% of SID	Angle ≈ 0.58º

Table 5-50: Results of the X-ray beam alignment and perpendicularity for facility P10.

The maximum outside and inside misalignment ratios were 0.0 % and 0.01 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.1 cm, which is equivalent to 0.96% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 0.58º. It is clear from the above mentioned result that this machine has passed this test.

5.2.10.2 X-ray tube potential accuracy

This test was conducted at 109 cm SDD, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 125 kVp. Table 5-51 summarizes the result of this test.

DKVp	40	46	50	70	81	90	109	102	125
$MKVp_{max}$	48.74	53.52	58.40	73.69	83.30	85.91	101.8	96.85	115.5
% Dif	-17.9	-14.1	-14.4	-5.0	-2.8	4.8	7.1	5.3	8.2

Table 5-51: Results of the X-ray tube potential accuracy for facility P10

The calculated minimum percentage difference was -17.9 at 40 kVp and the calculated maximum percentage difference was 8.2 at 125 kVp. It is clear from these results that this machine has failed this test.

5.2.10.3 X-ray tube potential reproducibility

This test was conducted at 109 cm SDD, 70 kVp, 19 x 18 cm2 field size and large focal spot. Table 5-52 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 mAs to 250 mAs.

DmAs	2	10	20	50	80	100	160	200	250
$MKVp_{max}$	74.25	75.19	83.48	84.14	83.39	82.86	82.86	82.49	82.36
Mean = 81.2, Standard Deviation = 3.5, Coefficient of Variance = 0.04									

Table5-52: Results of the X-ray tube potential reproducibility for facility P10

The calculated coefficient of variance of the kVp reproducibility was equal to 0.04, and this value is within the acceptable limit (<0.1).

5.2.10.4 Exposure time

It was not possible to conduct this test due to the fact that this machine was an old X-ray unit which did not indicate the dialed exposure time.

5.2.10.5 Filtration (HVL) check

This test was conducted at 109 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size and large focal spot. The test was performed at variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-53 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	130.9	117.7	113.6	96.22	84.56	62.96	58.26	54.41	52.19

Table 5-53: Results of the Filtration (HVL) check for facility P10

The determined HVL was 3.48 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.11 RESULTS AND DISCUSSIONS FOR FACILITY P11 [ICRP, 2007]

5.2.11.1 X-ray beam alignment and perpendicularity

The test was conducted at 166 cm SID, 113 kVp, 13 mAs and large focal spot. Table 5-54 summarizes the result of this test.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	1	0.6 %	0	0%
Left	1.3	0.8 %	0	0%
Up	1.3	0.8 %	0	0%
Down	3	2 %	0	0%

Alignment of X-ray field with Image receptor	**Perpendicularity of X-ray beam to image receptor**
Displacement error = 1.5 cm ≈ 0.9% of SID	Angle ≈ 2.5º

Table 5-54: Results of the X-ray beam alignment and perpendicularity for facility P11.

The maximum outside and inside misalignment ratios were 0.0 % and 2 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.5 cm, which is equivalent to 0.9% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 2.5º. It is clear from the above mentioned results that this machine has failed the perpendicularity and the alignment of the X-ray beam with light beam tests.

5.2.11.2 X-ray tube potential accuracy

This test was conducted at 107 cm SDD, 50 ms, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-55 summarizes the result of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	40.13	44.19	49.17	75.38	81.05	89.50	98.70	107	119
% Dif	-0.3	1.8	1.7	-0.5	-0.1	0.6	0.3	1.9	1.7

Table 5-55: Results of the X-ray tube potential accuracy for facility P11

The calculated minimum percentage difference was – 0.5 at 75 kVp and the calculated maximum percentage difference was 1.9 at 109 kVp. It is clear from these results that this machine has passed this test.

5.2.11.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-56 summarizes the result of this test. The test was performed at different values of mAs setting covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	69.38	70.5	70.29	70.77	70.03	70.54	70.38	70.81	69.67
Mean = 70.3, Standard Deviation = 0.46, Coefficient of Variance = 0.007									

Table 5-56: Results of the X-ray tube potential reproducibility for facility P11

The calculated coefficient of variance of the kVp reproducibility was equal to 0.007. This calculated value was within the acceptable limit (<0.1).

5.2.11.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-57 summarizes the result of this test.

DEXT (ms)	3.18	16	32.5	84.5	138	176	255	384	578
MEXT (ms)	2.9	15.6	32.7	86.4	140.6	180.8	261.1	388.3	398.4
% Dif	9.7	2.6	-0.6	-2.2	-1.9	-2.7	-2.3	-1.1	45

Table5-57: Results of the exposure time accuracy for facility P11

The calculated percentage differences ranged from -2.7 at 176 ms dialed time to 46.2 at 578 ms dialed time. It is clear from table 5-57 that the exposure timer of this machine performed well with the region below 384 ms.

5.2.11.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-58 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	63.4	63.5	63.4	63.5	63.4	63.5	63.4	63.5	63.5	63.4
Mean = 63.5, Standard Deviation = 0.05, Coefficient of Variance = 0.0008										

Table 5-58: Results of the exposure time reproducibility for facility P11

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.0008 and this value was within the acceptable limit (< 0.05).

5.2.11.6 Filtration (HVL) check

This test was conducted at 107 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-59 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	189.2	173.8	149.2	138.9	114.1	91.38	82.39	78.54	67.97

Table 5-59: Results of the filtration (HVL) check for facility P11.

The determined HVL was 3.3 mm Al (figure 5-20), and this value was within the acceptable range for 90 kVp.

5.2.12 RESULTS AND DISCUSSIONS FOR FACILITY P12 [ICRP, 2007]

5.2.12.1 X-ray beam alignment and perpendicularity

This test was conducted at 115 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-60 summarizes the results of this test.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	0	0 %	0.5	0.43 %
Left	1.6	1.4 %	0	0 %
Up	0.5	0.43 %	0	0 %
Down	0.5	0.43 %	0	0 %

Alignment of X-ray field with Image receptor	**Perpendicularity of X-ray beam to image receptor**
Displacement error = 0.8 cm ≈ 0.7 % of SID	Angle ≈ 1.7º

Table 5-60: Results of the X-ray beam alignment and perpendicularity for facility P12.

The maximum outside and inside misalignment ratios were 0.43 % and 1.4 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.8 cm, which is equivalent to 0.7% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 1.7º. It is clear from the above mentioned results that this machine has failed the X-ray beam alignment and perpendicularity tests.

5.2.12.2 X-ray tube potential accuracy

This test was conducted at 107 cm SDD, 10 mAs, 19 x 18 cm^2 field size and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-61 summarizes the results of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	38.53	43.16	47.85	75.15	80.47	88.93	97.43	106.5	117.4
% Dif	3.8	4.3	4.5	-0.2	0.7	1.2	1.6	2.3	3.1

Table 5-61: Results of the X-ray tube potential accuracy for facility P12

The calculated minimum percentage difference was -0.2 at 75 kVp and the calculated maximum percentage difference was 4.5 at 50 kVp. It is clear from these results that this machine has passed this test.

5.2.12.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-62 summarizes the results of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	75.50	71.60	74.81	73.10	75.68	74.80	73.10	74.64	73.30
Mean = 74.1, Standard Deviation = 1.27, Coefficient of Variance = 0.02									

Table 5-62: Results of the X-ray tube potential reproducibility for facility P12

The calculated coefficient of variance of the kVp reproducibility was equal to 0.02, and this value was within the acceptable limit (<0.1).

5.2.12.4 Exposure time accuracy:

This test was conducted at 107 cm SDD, 70 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-63 summarizes the results of this test.

DEXT (ms)	2.5	50	140	220	280	450	710	1100
MEXT (ms)	2.5	50.8	145	225.7	290.2	466.9	440.3	37.6
% Dif	0	-1.6	-3.4	-2.5	-3.5	-3.6	61.3	2825.5

Table 5-63: Results of the exposure time accuracy for facility P12

The calculated percentage differences ranged from 0 at 2.5 ms dialed time to 2825.5 at 1100 ms dialed time. It is clear from table 5-64 that the exposure timer of this machine performed well within the region below 450 ms. As the exposure time increased above 450 ms, the measured exposure time decreased dramatically.

5.2.12.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-64 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	64.0	64.1	63.8	64.1	64.0	64.0	64.0	63.8	63.8	63.8
Mean = 63.9, Standard Deviation = 0.12, Coefficient of Variance = 0.002										

Table 5-64: Results of the exposure time reproducibility for facility P12.

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.002 and this value was within the acceptable limit (< 0.05).

5.2.12.6 Filtration (HVL) check

This test was conducted at 107 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at variable thickness of aluminum filters from 0 to 5.6 mm Al. Table 5-65 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	159.8	147.8	126.8	118.6	98.2	78.56	71.70	68.21	59.60

Table 5-65: Results of the filtration (HVL) check for facility P12

The determined HVL was 3.2 mm Al (figure 5-22), and this value was within the acceptable range for 90 kVp.

5.2.13 RESULTS AND DISCUSSIONS FOR FACILITY P13 [ICRP, 2007]

5.2.13.1 X-ray beam alignment and perpendicularity

This test was performed at 90 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-66 summarizes the results of this test.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	0.20	0.22 %	0	0 %
Left	0.20	0.22 %	0	0 %
Up	0.20	0.22 %	0	0 %
Down	0.20	0. 22 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 1 cm ≈ 1 % of SID	Angle ≈ 1.35º

Table 5-66: Results of the X-ray beam alignment and perpendicularity for facility P13.

The maximum outside and inside misalignment ratios were 0 % and 0.22% of the SID respectively. The displacement error between the X-ray field and the image receptor was 1 cm, which is equivalent to 1% of SID. The X-ray beam was found to be perpendicular to the image receptor to about 1.35º. All these measured values are within the acceptable limit.

5.2.13.2 X-ray tube potential accuracy

This test was conducted at 110 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-67 summarizes the result of this test.

DKVp	40	45	50	75	81	90	109	121
$MKVp_{max}$	38.69	43.48	48.33	74.84	80.11	88.38	107.9	117.8
% Dif	3.4	3.5	3.5	0.2	1.1	1.8	1.0	2.7

Table 5-67: Results of the X-ray tube potential accuracy for facility P13

The calculated maximum percentage difference was 3.5 at 45 and 50 kVp and the calculated minimum percentage different was 0.2 at 75 kVp. It is clear from these results that this machine has passed this test.

5.2.13.3 X-ray tube potential reproducibility

This test was conducted at 110 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-68 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 mAs to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	68.86	69.42	69.18	69.12	69.74	69.27	69.55	69.7	69.72
Mean = 69.4, Standard Deviation = 0.3, Coefficient of Variance = 0.004									

Table 5-68: Results of the X-ray tube potential reproducibility for facility P13

The calculated coefficient of variance of the kVp reproducibility was equal to 0.004, and this value was within the acceptable limit (<0.1).

5.2.13.4 Exposure time accuracy

This test was conducted at 110 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-69 summarizes the result of this test.

DEXT (ms)	12	23.5	60.5	100	127	184	277	412
MEXT (ms)	10.6	23.0	61.4	100.7	129.1	184.7	272.5	352.1
% Dif	13.2	2.2	-1.5	-0.7	-1.6	-0.4	1.7	17

Table 5-69: Results of the exposure time accuracy for facility P13

The calculated percentage differences ranged from -1.6 at 127 ms dialed time to 17 at 412 ms dialed time. It is clear from table 5-69 that the exposure timer of this machine performed well with the region below 277 ms.

5.2.13.5 Exposure time reproducibility

This test was conducted at 110 cm SDD, 81 kVp, 20 mAs, 63 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-70 summarizes the result of this test.

DEXT (ms)	63	63	63	63	63	63	63	63	63	63
MEXT (ms)	62.4	62.5	62.8	62.1	62.2	62.1	62.6	62.5	62.4	62.4
Mean = 62.4, Standard Deviation = 0.21, Coefficient of Variance = 0.003										

Table 5-70: Results of the exposure time reproducibility for facility P13

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.003, and this value was within the acceptable limit (< 0.05).

5.2.13.6 Filtration (HVL) check

This test was conducted at 110 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2, field size, 63 ms, and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-71 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	127.60	119.10	103.80	98.70	81.80	65.97	68.40	65.40	57.30

Table 5-71: Results of the filtration (HVL) check for facility P13

The determined HVL was 4.0 mm Al (figure 5-24), and this value was within the acceptable range for 90 kVp.

5.2.14 RESULTS AND DISCUSSION FOR FACILITY P14 [ICRP, 2007]

5.2.14.1 X-ray beam alignment and perpendicularity

The test was conducted at 110 cm SID, 60 kVp, 10 mAs and large focal spot. Table 5-72 summarizes the results of this test.

Shift between X-rays and light fields	**Inside (cm)**	**Inside % of SID**	**Outside (cm)**	**Outside % of SID**
Right	0.2	0.18 %	0	0 %
Left	1.5	1.4 %	0	0 %
Up	0.6	0.5 %	0	0 %
Down	0.6	0. 5 %	0	0 %

Alignment of X-ray field with Image receptor	**Perpendicularity of X-ray beam to image receptor**
Displacement error = 1.3 cm ≈ 1.2 % of SID	Angle ≈ 0.6º

Table 5-72: Results of the X-ray beam alignment and perpendicularity for facility P14

The maximum outside and inside misalignment ratios were 0.0 % and 1.4 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 1.2 cm, which is equivalent to 1.2 % of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 0.6º. It is clear form above mentioned results that this machine has failed the X-ray beam alignment with light field.

5.2.14.2 X-ray tube potential accuracy

This test was conducted at 107.5 cm SDD, 10 mAs, 19 x 18 cm^2 field size, large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-73 summarizes the result of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	40.30	44.20	49.40	75.30	80.40	89.90	99.0	109.0	119.20
% Dif	-0.7	1.8	1.2	-0.4	0.7	0.1	0.0	0.0	1.5

Table 5-73: Results of the X-ray tube potential accuracy for facility P14

The calculated minimum percentage difference was -0.7 at 40 kVp and the calculated maximum percentage difference was 1.8 at 45 kVp. It is clear from these results that this machine has passed the test.

5.2.14.3 X-ray tube potential reproducibility

This test was conducted at 107.5 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-74 summarizes the result of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	70.71	70.75	71.10	71.12	70.56	70.35	70.88	70.23	70.49
Mean = 70.7, Standard Deviation = 0.29, Coefficient of Variance = 0.004									

Table 5-74: Results of the X-ray tube potential reproducibility for facility P14

The calculated coefficient of variance (CV) of the kVp reproducibility was equal to 0.004, and this value was within the acceptable limit (<0.1).

5.2.14.4 Exposure time

It was not possible to conduct this test due to the fact that this machine was an old X-ray unit which did not indicate the dialed exposure time.

5.2.14.5 Filtration (HVL) check

This test was conducted at 107.5 cm SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2, field size, 63 ms and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-75 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	128.8	120.6	105.7	99.55	83.05	68.74	71.34	68.46	60.15

Table 5-75: Results of the filtration (HVL) check for facility P14

The determined HVL was 4.4 mm Al, and this value was within the acceptable range for 90 kVp.

5.2.15 RESULTS AND DISCUSSIONS FOR FACILITY P15 [ICRP, 2007]

5.2.15.1 X-ray beam alignment and perpendicularity

The test was conducted at 100 cm SID, 60 kVp, 5 mAs and large focal spot. The different measured misalignments were summarized in table 5-76.

Shift between X-rays and light fields	Inside (cm)	Inside % of SID	Outside (cm)	Outside % of SID
Right	1.2	1.2 %	0	0 %
Left	1.5	1.5 %	0	0 %
Up	1.5	1.5 %	0	0 %
Down	1.2	1.2 %	0	0 %

Alignment of X-ray field with Image receptor	Perpendicularity of X-ray beam to image receptor
Displacement error = 0.5 cm ≈ 0.5 % of SID	Angle ≈ 0.5º

Table 5-76: Results of the X-ray beam alignment and perpendicularity for facility P15

The maximum outside and inside misalignment ratios were 0.0 % and 1.5 % of the SID respectively. The displacement error between the X-ray field and the image receptor was 0.5 cm, which is equivalent to 0.5% of the SID. The X-ray beam was found to be perpendicular to the image receptor to about 0.5º. It is clear from the above mentioned results that this machine has failed the alignment of the X-ray beam with light beam.

5.2.15.2 X-ray tube potential accuracy

The test was conducted at 107 cm SDD, 10 mAs, 19 x 18 cm^2 field size, and large focal spot. The kVp accuracy was performed between 40 and 121 kVp. Table 5-77 summarizes the result of this test.

DKVp	40	45	50	75	81	90	99	109	121
$MKVp_{max}$	39.35	43.19	48.50	74.66	84.15	88.19	98.35	107.3	118.8
% Dif	1.7	4.2	3.1	0.5	-3.7	2.1	0.7	1.6	1.9

Table 5-77: Results of the X-ray tube potential accuracy for facility P15

The calculated minimum percentage difference was -3.7 at 81 kVp and the calculated maximum percentage difference was 4.2 at 45 kVp. It is clear from these results that this machine has passed this test.

5.2.15.3 X-ray tube potential reproducibility

This test was conducted at 107 cm SDD, 70 kVp, 19 x 18 cm^2 field size and large focal spot. Table 5-78 summarizes the results of this test. The test was performed at different mAs settings covering the range from 2 to 280 mAs.

DmAs	2	10	20	50	80	100	140	200	280
$MKVp_{max}$	78.66	79.12	80.7	79.23	75.47	78.81	77.24	75.69	76.5
Mean = 77.9, Standard Deviation = 1.69, Coefficient of Variance = 0.02									

Table 5-78: Results of the X-ray tube potential reproducibility for facility P15

The calculated coefficient of variance of the kVp reproducibility was equal to 0.02, and this value was within the acceptable limit (<0.1).

5.2.15.4 Exposure time accuracy

This test was conducted at 107 cm SDD, 75 kVp, 10 mAs, 19 x 18 cm^2 field size and large focal spot. Table 5-79 summarizes the result of this test.

DEXT (ms)	16	32.5	84.5	138	176	255	384	578
MEXT (ms)	15	31.4	83.4	136.2	176.2	257.1	380.8	342.2
% Dif	6.7	3.5	1.3	1.3	-0.1	-0.8	0.8	68.9

Table 5-79: Results of the exposure time accuracy for facility P15

The calculated percentage differences ranged from -0.8 at 255 ms dialed time to 68.9 at 578 ms dialed time. It is clear from table 5-80 that the exposure timer of this machine performed well with the region below 384 ms. As the exposure time increased above 384 ms, the measured exposure time fell of slowly.

5.2.15.5 Exposure time reproducibility

This test was conducted at 107 cm SDD, 81 kVp, 20 mAs, 40 ms, 19 x 18 cm^2 field size and large focal spot. Table 5-80 summarizes the result of this test.

DEXT (ms)	40	40	40	40	40	40	40	40	40	40
MEXT (ms)	39.7	39.7	39.7	39.7	39.7	39.7	39.7	38.4	38.2	39.7
Mean = 39.42, Standard Deviation = 0.56, Coefficient of Variance = 0.014										

Table 5-80: Results of the exposure time reproducibility for facility P15

The calculated reproducibility coefficient of variance (CV) of the exposure time was equal to 0.014, and this value was within the acceptable limit (< 0.05).

5.2.15.6 Filtration (HVL) check

This test was conducted at 107 SDD, 90 kVp, 20 mAs, 11 x 11.5 cm^2 field size, 63 ms, and large focal spot. The test was performed at a variable thickness of aluminum filter from 0 to 5.6 mm Al. Table 5-81 summarizes the result of this test.

Thickness (mm)	0	0.3	1	1.3	2.3	3.6	4.3	4.6	5.6
Output (mR)	147	135.5	100.6	108.3	88.42	70.61	63.6	60.54	56.31

Table 5-81: Results of the filtration (HVL) check for facility P15

The determined HVL was 3.6 mm Al (figure 5-27), and this value was within the acceptable range for 90 kVp.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Twenty three private facilities and twenty nine public facilities were visited. Sixty percent of the facilities passed the general facilities observations test that was carried out by means of a visual checklist. 77% of the facilities had no hazard warning light provided at the entrance to the X-ray room. 94% of the facilities had no reference chart for various radiographic exposures and so the radiographer chose the exposure parameters at will. 77% of the facilities had no functional air-conditioning provided in the X-ray room. All the public facilities visited had qualified radiographer(s). The private facilities relied so much on radiographers in public facilities to carry out X-ray examination and quality control tests on X-ray machines in their facilities. 38.5% of all the X-ray machines in the facilities were functional while 42.3% had one or more failures identified. The majority of these failures were minor ones even though other faults were major. The region had 52 X-ray machines in the facilities visited of which 48% of the machines were manufactured between 2001 to 2010. There was only one old X-ray machine that was manufactured in 1983 and was not functional. Philips machines were more popular in the region with 42% of the Philips being functional, 37% working with defects and 21% out of order. 33% of Shimadzu X-ray machines were functional and 67% were working with defects. 75% of Toshiba X-ray machine were functional and 25% working with defects. 33.3% of Siemens X-ray machines were working with defects. All the Stephani X-ray machines were new and functional and were installed in Public facilities. Out of the 52 X-ray machines in the facilities visited 38.5% were functional, 42.3% were working with defects and 19.2% were completely out of order. Most of the X-ray machines subjected to QC tests failed one or more tests and yet these were the functional machines in the region. Beam alignment and perpendicularity tests showed unacceptable variation in 40% and 47% respectively while kVp accuracy test showed unacceptable variation in 27%. All the X-ray machines tested for timer accuracy and reproducibility passed the test although some machines did not indicate the dialed exposure time hence making it difficult to conduct this test. Since these machines are used in busy medical facilities within the region, this calls for the need to formulate X-ray QC program in our medical facilities to ensure that patients receive the lowest possible radiation risk and maximum health benefits from X-ray examinations. The study also showed clearly the high rate of increase of the X-ray machines in the region.

From the findings of this research, medical facilities in the western region of Kenya falls below average as far as quality control in diagnostic X-ray department is concerned. The facilities were characterized by inadequate staff. The region requires more radiographers and quality control technologists like medical physicists. The Government should therefore introduce Medical Physics and Health Physics in our university curriculum. The findings also call for frequent monitoring of these facilities by the Radiation Protection Board (RPB) or decentralizing the services of RPB by setting up county offices. Therefore a comprehensive quality assurance programme needs to be carried out in the region to monitor imaging process, form a learning process of those taking part and improve overall cost-effectiveness of the department.

6.2 Recommendations

As a result of the foregoing findings from the visual checklist and QC tests, the following recommendations were made;

a) Responsibility

(i) Responsibility and authority for the overall quality assurance program as well as for monitoring, evaluation, and corrective measures should be specified and recorded in a quality assurance manual.

(ii) The owner or practitioner in charge of the facility has primary responsibility for implementing and maintaining the quality assurance program.

(iii) Staff technologists should be delegated a basic quality assurance role by the practitioner in charge. Responsibility for specific quality control monitoring and maintenance techniques or quality administration procedures should be assigned, if the staff technologists are qualified by training or experience for these duties. The staff technologists should also be responsible for identifying problems or potential problems requiring actions beyond the level of their training. They should bring these problems to the attention of the practitioner in charge, or his or her representative, so that assistance in solving the problems may be obtained from inside or outside of the facility.

(iv) In most facilities there were no physicists, supervisory technologists, or quality control technologists. These specialized personnel should be assigned responsibility for day-to-day administration of the program and they should carry out monitoring duties beyond the level of training of the staff technologist. If desired by the facility, they should relieve the staff technologists of some or all of their basic monitoring duties. Staff service engineers should also be assigned responsibility for certain preventive or corrective maintenance actions.

(v) Responsibility for certain quality control techniques and corrective measures may be assigned to personnel qualified by training or experience, such as consultants, institutions or industrial representatives, from outside of the facility to carry out the procedures on behalf of the Kenya Radiation Protection Board, provided there is a written agreement clearly specifying these services.

b) Purchase specifications.

(i) Before purchasing new equipment, the staff of the diagnostic radiology facility should determine the desired performance specifications for the equipment. The final purchase specifications should be in writing and should include performance specifications. The availability of experienced service personnel should also be taken into consideration in making the final purchase decisions. Any understandings with respect to service personnel should be incorporated into the purchase specifications.

(ii) At the time of installation, the vendor should conduct equipment performance evaluations to ensure that the purchase specifications for the equipment meet State regulatory requirements. The equipment should not be formally accepted until the vendor has made any necessary corrections. The purchase specifications and the records of the acceptance testing should be retained through out the life of the equipment for comparison with monitoring results in order to assess continued acceptability of performance.

c) Monitoring and maintenance.

A routine quality control monitoring and maintenance system incorporating state-of-the-art procedures should be established and conducted on a regular schedule. The purpose of monitoring is to permit evaluation of the performance of the facility's X-ray system(s) in terms of the standards for image quality established by the facility and compliance with applicable state regulatory requirements. The maintenance program should include corrective maintenance to eliminate problems revealed by monitoring or other means before they have a serious deleterious impact on patient care. To the extent permitted by the training of the facility staff, the maintenance program should also include preventive maintenance, which could prevent unexpected breakdowns of equipment and disruption of departmental routine.

d) A quality management program for our medical facilities should be urgently put in place and must have radiation safety policies and procedures.

e) Medical facilities with X-ray procedures should engage Radiation safety officer (at least) and perhaps medical physicist.

f) To enhance adequate documentation of all activities, log book should be provided for recording and references. A record keeping system is to be handled by record officer, to document quality control procedures and compliance with the accepted norms. The items to be included are room log books, incident reports, control chart, equipment checklist, and examination requisition, film badge report of every personnel and image interpretation reports. All inadequacy of equipment and personnel and corrective measures should be documented in the log book.

g) Warning lights and signs at the entrance to the X-ray rooms to indicate a “controlled area” due to X-ray should be provided and put in place.

h) Finally, QC tests should be carried out on mammographic units which are on the rise in the western region of Kenya.

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APPENDICES

Appendix I: Data for the various medical facilities

NO	NAME OF X-RAY MACHINE	MODEL	YEAR OF MANUFACTURE	TYPE (D: M)	LOCATION (N:R:W)	FACILITY (P : PR)	STATUS (F:WD: O)
1.	Stephani	A23SX	2008	D	1N	P	F
2.	Philips Bucky Diagnost	98002369	2005	D	1N	P	F
3.	Toshiba	T2606543	1992	M	1N	P	F
4.	Siemens Mobile	Simox D	--	D	2N	PR	WD
5.	Toshiba	QR	1996	M	2N	PR	F
6.	Allengers Mob.	100	2004	D	3N	PR	F
7.	Stephani	N40HF	2008	D	4N	P	F
8.	Dean	MHF	--	M	5N	PR	WD
9.	Stephani	P177XT	2007	D	6N	P	F
10.	Philips Bucky Diagnost	003696	2001	D	7W	P	F
11.	Philips	17082	1990	D	7W	P	F
12.	Stephani	N66HG	2006	D	8W	P	F
13.	Techniqu Mob.	Chinese	--	M	8W	PR	WD
14.	Technix Mob.	03001675	2003	D	9W	P	WD
15.	Philips	--	2001	D	10W	P	WD
16.	Stephani	HP18876	2007	D	11W	P	F
17.	Shimadzu	8876544	1983	M	12R	P	WD
18.	Toshiba	HG123P	2006	M	12R	PR	F
19.	Philips	Rotalix	1997	M	13R	PR	F

20.	Philips	Bucky D	1993	M	14R	PR	WD
21.	Collimax	FD12/77	1993	M	14R	P	WD
22.	Acoma	D14432P	1993	M	15W	P	O
23.	Stephani	170/141	2007	D	15W	P	F
24.	Philips D	A133-24	1991	D	16W	P	O
25.	Shimadzu Mob.	89111882	1989	M	16W	PR	WD
26.	Dynamax	C542	1975	M	17W	PR	O
27.	Shimadzu	62771	2006	D	17W	P	F
28.	Chinese	F100DC	2007	D	18W	PR	WD
29.	Philips	Rotalix	1982	M	19W	PR	WD
30.	Siemens Mobilett	536884	1985	M	20W	PR	O
31.	Philips Mobile	910762R	2001	D	20W	PR	O
32.	Siemens Mob.	02563S11	1985	M	20W	PR	O
33.	Philips Mobile	Super Practix	1994	M	20W	PR	WD
34.	Shimadzu	1/2P13DK	2005	D	21W	P	WD
35.	Chinese	XD51/100	1995	M	22W	PR	O
36.	MRS Rayonex	Emarald 125	1996	M	23N	PR	WD
37.	General Electric Mobile	13G394	2007	D	24N	P	WD
38.	Chinese	FB-GT22	--	M	25R	PR	WD
39.	Shimadzu	6717-8	1998	M	26R	PR	WD
40.	Toshiba	41014	2004	M	27R	PR	WD
41.	Philips	2949250	1995	D	28R	P	F

42.	Philips Mobile	Practix 33	2006	D	28R	P	WD
43.	Philips	910750	1995	D	28R	P	F
44.	Philips	21632A	2008	D	28R	P	WD
45.	Philips	2G8823A	2007	D	28R	P	F
46.	Philips	2A/78128	2008	D	28R	P	WD
47.	Philips	964271	2001	D	29N	P	F
48.	Philips	847197	--	M	29N	P	O
49.	Philips Mobile	Practix 30	2005	D	29N	P	O
50.	Technix Mobile	10478	--	D	29N	P	O
51.	Rotanode	DR-160	1995	M	30N	PR	WD
52.	Shimadzu	4760-3	1996	D	31N	PR	F

[***KEY***: D=Digital, M=Manual, N=Nyanza, R=North Rift, W=Western, P=Public, PR=Private, F=Functional, WD=Working with defects and O=Out of order]

Appendix II: Radiographic Visual Checklist (CRCPD, 2003) used in this work

YEAR:__________ FACILITY: ____________________________________

NO.	**ASPECT**	**YES**	**NO**
1.	Collimator light brightness and cleanliness		
2.	Collimator beam limiting devices (BLDs) available and used		
3.	Locks and detents operable		
4.	Hazard warning light provided		
5.	Tube or generator oil leakage		
6.	Cassettes and screens conditions		
7.	Technique chart		
8.	Control panel indicators		
9.	Provision of lead aprons, gloves, collars		
10	Functional air-conditioning provided		

Appendix III: General facility observations

FACILITY	X-RAY MACHINES	TYPE	GENERAL FACILITY OBSERVATIONS (As per Table : A-2 above) Y=YES, N=NO									
			1	2	3	4	5	6	7	8	9	10
1N	3	P	Y	Y	N	N	Y	Y	Y	Y	Y	N
2N	2	PR	Y	Y	N	N	N	N	N	N	Y	Y
3N	1	PR	N	N	N	N	N	N	N	N	Y	Y
4N	1	PR	Y	Y	N	N	N	N	N	N	Y	Y
5N	1	P	N	Y	N	N	N	Y	Y	Y	N	Y
6N	1	PR	Y	Y	Y	N	Y	N	Y	Y	N	Y
7W	2	P	Y	N	Y	N	Y	Y	Y	Y	Y	Y
8W	2	P	Y	N	N	N	Y	N	Y	Y	N	Y
9W	1	PR	Y	Y	N	N	N	N	N	N	Y	Y
10W	1	P	Y	Y	N	N	N	Y	N	N	N	Y
11W	1	P	Y	Y	N	N	Y	Y	N	N	Y	N
12R	2	P	Y	N	N	N	N	Y	Y	Y	N	N
13R	1	PR	Y	Y	N	N	N	N	Y	N	Y	Y
14R	2	PR	Y	N	N	N	N	Y	N	N	Y	Y
15W	2	P	Y	Y	N	N	N	Y	Y	Y	N	N
16W	2	P	Y	Y	Y	N	N	N	Y	Y	N	N
17W	2	PR	N	N	N	N	N	N	N	N	Y	N
18W	1	P	Y	Y	Y	N	N	N	Y	Y	N	Y
19W	1	PR	N	Y	N	N	N	N	N	N	N	Y
20W	4	PR	Y	N	N	N	N	N	Y	Y	Y	N
21W	1	PR	Y	Y	N	N	N	N	N	N	Y	Y
22W	1	P	Y	Y	N	Y	N	Y	Y	Y	N	Y
23N	1	PR	Y	Y	N	N	N	N	N	N	Y	Y
24N	1	P	Y	Y	N	N	N	Y	Y	Y	N	Y
25R	1	PR	Y	Y	Y	N	Y	N	Y	Y	N	Y
26R	1	PR	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
27R	1	PR	Y	Y	Y	N	N	N	N	N	Y	Y
28R	6	P	Y	N	Y	Y	N	Y	Y	Y	Y	N
29N	4	P	Y	N	N	N	N	Y	Y	Y	Y	N
30N	1	PR	Y	Y	N	N	N	N	Y	Y	N	Y
31N	1	PR	Y	Y	N	N	N	Y	Y	Y	N	Y

[***KEY***: N=Nyanza, W=Western, R=North Rift, P=Public, PR=Private]

Appendix IV: Forms and Checklists

The following forms and checklists may be reproduced as necessary to aid in maintaining quality control program in X-ray department:

- *Quality Control Program Contact Sheet*
  - A form designed to be completed, posted in the QC work area, and used as a quick reference.
- *Daily Quality Control Checklist (Form 1)*
  - Is a daily checklist to ensure that Processor QC (Sensitometry), Daily and Weekly Darkroom QC Procedures are completed.
- *Quarterly Radiographic Visual Checklist (Form 2)*
  - This is the Radiographic System Visual Checklist that should be completed every calendar quarter.
- *Monthly, Quarterly, and Semiannually Quality Control Checklist (Form 3)*
  - Is a checklist for System Constancy Test, View boxes Test, Repeat Analysis Check, Film and Chemical Storage Check, Artifact Evaluation Check, Intensifying Screen Cleaning Procedure and Darkroom Integrity or Fog Test Procedures.
- *Annual and Biennial Radiographic Quality Control Checklist (Form 4)*
  - Is a checklist for Screen-Film Contact Test, Collimation Tests, Source-to-Image Distance Indication, Automatic Collimation (PBL) Accuracy, Lead Apron, Glove, Gonadal and Thyroid Shield Integrity check Procedures and the routine survey by the qualified expert.
- *Repeat Analysis Form (Form 5)*
  - Is used for the ongoing tracking of repeat films and to calculate the repeat rate, following Repeat Analysis Procedure.

QUALITY CONTROL PROGRAM CONTACT SHEET

	NAME AND ADDRESS	PHONE
Doctor Responsible for QA	____________________________	__________
QA Coordinator	____________________________	__________
State Radiation Control Program	____________________________ ____________________________ ____________________________ ____________________________	__________
Medical Physicist or Qualified Expert	____________________________ ____________________________ ____________________________ ____________________________	__________
X-ray Machine(s) Technical Representative	____________________________ ____________________________ ____________________________ ____________________________	__________
Film Processor Technical Representative	____________________________ ____________________________ ____________________________ ____________________________	__________
X-ray Film and Intensifying Screens Technical Representative	____________________________ ____________________________ ____________________________ ____________________________	__________
Service Engineer	____________________________ ____________________________ ____________________________ ____________________________	__________
Radiation Safety Officer	____________________________ ____________________________ ____________________________	__________

Current as of: ___

DAILY

QUALITY CONTROL CHECKLIST

(Form 1)

Facility: _________________ Month: ______________ Year: ___________

DAY	INITIALS	PROCESSOR QC	DARKROOM CLEANLINESS
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			
17			
18			
19			
20			
21			
22			
23			
24			
25			
26			
27			
28			
29			
30			
31			

Comments (Date problems noted and identified, corrective action taken):

____

____

____

____

Pass = P Fail = F Does Not Apply = NA

QUARTERLY

RADIOGRAPHIC VISUAL CHECKLIST

(Form 2)

Year: ___________ Facility: ______________________

Calender quarter (1st , 2nd, 3rd and 4th).	**FIRST**	**SECOND**	**THIRD**	**FOURTH**
Date				
Initials				
1. Collimator light brightness and cleanliness				
2. Collimator filters in place				
3. Locks and detents operable				
4. Table, Tube and Bucky smoothness of Motion				
5. Grid condition and Operation				
6. Condition of Cables				
7. Tube or Generator Oil Leakage				
8.Cassettes and Screens condition				
9. Loaded Cassette Storage				
10. Control Panel Indicators				
11. Technique Chart				
12.Patient Viewability				
13. Exposure Switch Placement				
14. Lead Aprons, Gloves, Collars				

Each radiographic unit should be evaluated and any failures noted above should be described in detail in the Remarks section.

Remarks (Date problems noted and identified, corrective action taken):

____

____

____

____

Pass = P Fail = F Does Not Apply = NA

MONTHLY, QUARTERLY, AND SEMIANNUALLY

QUALITY CONTROL CHECKLIST

(Form 3)

Year: __________ Facility: ________________________

Date												
Initials												
System Constancy												
Viewboxes												
Repeat Analysis												
Artifact Evaluation												
Film and Chemistry storage												
Screen and Cassette Cleanliness												
Darkroom Fog												

Remarks (Explain problems identified and corrective action taken):

____

____

____

____

____

____

____

____

Pass = P Fail = F Does Not Apply = NA

ANNUAL AND BIENNIAL

RADIOGRAPHIC QUALITY CONTROL CHECKLIST

(Form 4)

Date			*Qualified Expert Survey Date*	
			Half Value Layer	
Light and X-ray Field Alignment			Focal Spot and Resolution	
Field Size Indicator Accuracy			Timer Accuracy and Reproducibility	
PBL Accuracy			KVp Accuracy and Reproducibility	
SID Indication			MA Linearity and Reproducibility	
Lead Aprons, Gloves, Collars			Exposure Reproducibility	
Screen-film Contact			AEC Operation	
			ESE Evaluation	
			Operator and Personnel Safety	
			Compliance with Regulations	
			Technique Chart Evaluation	

Remarks (Explain problems identified and corrective action taken):

The qualified expert report for each unit, as well as documentation on the corrective action taken on identified problems should be maintained along with this checklist.

Pass = P Fail = F Does Not Apply = NA

REPEAT ANALYSIS FORM
(Form 5)

From: ____________ To: ____________

Facility: _________________________

CAUSE	**Number of Films**	**Percentage of Repeats**
1. Positioning		
2. Patient Motion		
3. Light Films		
4. Dark Films		
5. Black Films		
6. Static		
7. Fog		
8. Incorrect Patient ID		
9. Double Exposure		
10. Miscellaneous		
11. Good Films (No Apparent Problem)		
12. Clear Films		

TOTAL

Repeats (1-12)		**%**

Total Film Used _____________

EXAMPLE REPEAT ANALYSIS FORM

From: __1/1/11__ To: __3/31/11__

Facility: __Hometown Medical

CAUSE		**Number of Films**	**Percentage of Repeats**
1. Positioning	*III III I*	*7*	*19%*
2. Patient Motion	*III III III*	*9*	*24%*
3. Light Films	*III*	*3*	*8%*
4. Dark Films	*III III III III I*	*13*	*35%*
5. Black Films		-	-
6. Static	*I*	*1*	*2.7%*
7. Fog	*II*	*2*	*5.4%*
8. Incorrect Patient ID	*II*	*2*	*5.4%*
9. Double Exposure		-	-
10. Miscellaneous		-	-
11. Good Films (No Apparent Problem)		-	-
12. Clear Films		-	-

	TOTAL	
Repeats (1-12)	***37***	***5.3 %***

Total Film Used ___**694**______

37 total repeats / 694 total film used = 0.053 or 5.3%

7 total positioning problems / 37 total repeats = 0.19 or 19%.

ANNUAL QUALITY CONTROL REVIEW FORM

(Form 6)

Facility Name:______________________ QC Coordinator:______________________

Date of Review:____________________ Year Reviewed:____________

Attendees:____

____

____

____

____

____

< Is image quality being maintained at the desired level?

< What is the facility repeat rate? Are changes addressed when necessary?

< Is the x-ray technique chart up-to-date?

< Is the screen-film combination still the best for the facility? Are the screens over 15years old? If so, consider replacing them.

< Do all personnel meet required or established qualifications?

< Based on QC trends (variations or inconsistencies on QC charts), do any procedures, practices, or equipment need to be modified?

< Do any QC procedures need to be changed or updated?

< Are personnel adequately performing assigned tasks?

< Are patient and personnel radiation exposures as low as reasonably achievable compared to national data?

Appendix V: Definition of terms

As used in this thesis, the following definitions apply:

"A functional X-ray machine" is an X-ray machine that has received a check mark on each of the items listed in the QC Visual Checklist according to CRCPD, 2003 Recommendations.

"An X-ray machine working with defects" refers to an X-ray machine that has failed to receive a check mark on one or more of the items listed in the QC Visual Checklist according to CRCPD, 2003 Recommendations.

"An X-ray machine that is out of order" refers to an X-ray machine that has broken down and is completely not being used although it's firmly mounted in the X-ray room.

"Diagnostic radiology facility" means any facility in which an x-ray system(s) is used in any procedure that involves irradiation of any part of the human or animal body for the purpose of diagnosis or visualization. Offices of individual physicians, dentists, podiatrists, chiropractors, and veterinarians as well as mobile laboratories, clinics, and hospitals are examples of diagnostic radiology facilities.

"Quality assurance" means the planned and systematic actions that provide adequate confidence that a diagnostic x-ray facility will produce consistently high quality images with minimum exposure of the patients and healing arts personnel. The determination of what constitutes high quality will be made by the facility producing the images. Quality assurance actions include both "quality control" techniques and "quality administration" procedures.

"Quality assurance program" means an organized entity designed to provide "quality assurance" for a diagnostic radiology facility. The nature and extent of this program will vary with the size and type of the facility, the type of examinations conducted, and other factors.

"Quality control techniques" are those techniques used in the monitoring (or testing) and maintenance of the components of an x-ray system. The quality control techniques thus are concerned directly with the equipment.

"Quality administration procedures" are those management actions intended to guarantee that monitoring techniques are properly performed and evaluated and that necessary corrective measures are taken in response to monitoring results. These procedures provide the organizational framework for the quality assurance program.

"X-ray system" means an assemblage of components for the controlled production of diagnostic images with X- rays. It includes minimally an X-ray high voltage generator, an X-ray control, a tube-housing assembly, a beam-limiting device, and the necessary supporting structures. Other components that function with the system, such as image receptors, image processors, view boxes, and darkrooms, are also parts of the system.