Calibration of Working Standard Ionization Chambers and Dose Standardization

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DEDICATION

To my parents especially my mother
    Wife
    Sisters
    Brothers
And all those whom I love
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ABSTRACT

Measurements were performed for the calibration of two working standard ionization chambers in the secondary standard dosimetry laboratory of Sudan. 600 cc cylindrical former type and 1800 cc cylindrical radcal radiation protection level ionization chambers were calibrated against the 1000 cc spherical reference standard ionization chamber. The chambers were calibrated at X-ray narrow spectrum series with beam energies ranged from (33-116 KeV) in addition to $^{137}$Cs beam with 662 keV energy. The chambers 0.6 cc and 0.3 cc therapy level ionization were used for dose standardization and beam output calibrations of cobalt-60 radiotherapy machine located at the National Cancer Institute, University of Gazira. Concerning beam output measurements for $^{60}$Co radiotherapy machine, dosimetric measurements were performed in accordance with the relevant IAEA dosimetry protocols TRS-277 and TRS-398. The kinetic energy released per unit mass in air (air kerma) were obtained by multiplying the corrected electrometer reading (nC/min) by the calibration factors (Gy/n C) of the chambers from given in the calibration certificate. The uncertainty of measurements of air kerma were calculated for the all ionization chambers (combined uncertainty) the calibration factors of these ionization chambers then were calculated by comparing the reading of air kerma of secondary standard ionization chambers to that from radcal and farmer chambers. The result of calibration working standard ionization chambers showed different calibration factors ranged from 0.99 to 1.52 for different radiation energies and these differences were due to chambers response and specification. The absorbed dose to water calculated for therapy ionization chamber using two code of practice TRS-277 and TRS-398 as beam output for $^{60}$Co radiotherapy machine and it can be used as a reference for future beam output calibrations in radiotherapy dosimetry. The measurements of absorbed dose to water showed that the new code of practice TRS398 is easier and has fewer components than TRS-277 therefore it has some advantage over the previous protocols which were based on air kerma standards.
الخلاصة

اجريت هذه القياسات لمعايرة غرفة تأين عياريتين بعمل المعادن الشاذ تأين لتصبحا اساس لقياس الجرعة الإشعاعية بالسودان وهي 600cc و 1800cc من نوع farmer و 137Cs النوع. قياسات الجرعة الإشعاعية الأساسية للمعمل 1000cc التي عُبرت بمعامل الوكالة الدولية لطاقة الذرية (IAEA) وقد تم معايرة الغرفيتين في حزم الإشعاع السينية الصعبة ذات الطاقة 662 (بالإضافة إلى حزمة إشعاع فاما من مصدر 137Cs) (33,48,65,83,100 and 116 KeV). اجريت قياسات لغرفة التأين 0.6cc و 0.3cc في مستوى العلاج بالأشعة لمعايرة وتبسيط مرجعية الجرعة بالنسبة للجهاز الالكتروني للسرطان جامعتي الجزيرة كل قياسات المعايير ومرجعية الجرعة الإشعاعية اجريت وفقاً للطرق المتاحة في الوكالة الدولية لطاقة الذرية (IAEA) (TRS-277 TRS-398). قيست كبرى الهواء من حصول ضرب قراءة الجهاز الناتجة من معامل معايرة غرفة التأين نفسها (Gy/n C) من شهادة المعايرة. اجريت قياسات عدم التاكد بالنسبة لقياس كبرى الهواء بالنسبة لجميع غرف التأين. تم إيجاد معامل المعايرة (Uncertainty) بالمقارنة مع الغرفة الإحساسية المرجعية (TRS-277 TRS-398) للغرف الثانية في المدى من (1.52-0.99) لطاقات مختلفة وعجز هذا الاختلاف إلى استجابة الرغبة للأشعة. وخصصفارغرة التأين. اجريت قياسات الجرعة المخصصة للماء بالنسبة لغرفة التأين نوع 60Co باستخدام TRS-277 TRS-398 وسوف تستخدم في المستقبل لقياس الجرعة المخصصة للماء بالنسبة لغرفة التأين نوع 60Co. لمعايرة خارج الإشعاع من مصدر الالكتروني. سيوضح القياسات ان 398 TRS-277 TRS-398 هو المستخدم في هذه الاورة في قياس الجرعة الإشعاعية في العلاج بالأشعة.
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CHAPTER ONE

INTRODUCTION

1.1 General review:-

Radiation doses from applications in medical field must be accurately determined in order to maintain a reasonable balance between the purpose of application and the exposure. There is, thus, a need to establish quality assurance for this application (measurements). In order to achieve this, dose measurements must be reproducible and the uncertainties associated with that measurements should be known. The need for accurate measurement has been appreciated from the early days of the use of ionizing radiation in the early 20th century, particularly in the fields of diagnostic and therapeutic medicine. Over the years, the range of applications for ionizing radiation has expanded both in scope and in the types and energies of radiation employed. This has led to the need to develop a wide variety of measurement techniques and standards covering fields ranging from the low doses experienced in environmental and protection applications to the extremely high doses used in industrial processing. The different types of radiation employed give rise to the need for dose measurements in radiation beams whose effective penetration through a material such as water ranges from a few micrometers to several meters.

Secondary Standard Dosimetry Laboratory (SSDL) situated at Sudan Atomic Energy Commission (SAEC), currently calibrates most of the national measuring equipment used in radiation protection and radiotherapy. Standard for radiation measuring instruments used in diagnostic radiology are still under developments. The objective of the SSDL is to calibration field radiation measuring instruments, provide traceability from Primary Standard Dosimetry Laboratories (PSDLs) and advise on all aspects of ionizing radiation metrology.
The calibration procedures of field radiation measuring instruments used in radiotherapy are based on well-known and widely accepted dosimetry protocols. Most clinical dosimetry protocols in the past were based on air kerma standards to establish the absorbed dose to water in clinical radiotherapy beams. However, this approach has several problems. From the perspective of the clinical user, the dosimetry protocols are excessively complex and may reduce the accuracy of clinical dosimetry as a result of mistakes. From the perspective of a standards laboratory, the air kerma standards themselves have problems because of changes in the theory of cavity ion chambers and uncertainties in some of the physical data required. The basic problem is that all the standards are based on the same measurement technique and are thus potentially subject to common errors.

In contrast, many primary standards laboratories are developing standards of absorbed dose to water. These are based on different approaches and thus a much more robust system is being put in place. Once a high energy absorbed dose calibration service is established, the question is how to use it most effectively. Since it is much more expensive to calibrate chambers in accelerator beams than in $^{60}$Co beams, and because the vast majority of dosimetry standards laboratories do not have linear accelerators, any dosimetry protocol based on absorbed dose calibration factor should be based on calibrations in a $^{60}$Co beam. Clinical dosimetry based on such a system is much simpler than that based on air kerma calibrations.

1.2 Calibration and traceability:

The traceability of dose measurements to the international measurement system in a few developed countries is ensured through national hierarchies of primary and secondary standards dosimetry laboratories, and in the rest of the world through the network of SSDLs maintained by the International Atomic Energy Agency (IAEA) and the World Health Organisation (WHO). The role of SSDLs is crucial in providing traceable calibration with goal of achieving an uncertainty of the therapy level calibration factors
of the order of about 1%. The SSDLs should also play an important role in the global effort to provide quality audits to radiotherapy centers. Besides the obvious needs of accurate dose measurement in radiotherapy, accurate calibrations are needed for reliable measurements in diagnostic radiology and radiation protection. The requirements for traceable and reliable calibrations are also becoming more important for international trade where radiation products are manufactured within strict quality control system in order to conform to given safety and performance criteria (IAEA, 1999).

1.3 The aim of this study:

The objectives of this study were quality control for protection and therapy level ionization chambers based on air kerma and absorbed dose measurements in addition to that beam output as standard measurements which are:

1. Beam output calibration for the radiation protection calibration sources for the available radiation energies using different protection level ionization chambers; Calibration of two working standard ionization chambers against the national Secondary Standard Ionization Chamber;

2. Beam output calibration of $^{60}$Co radiotherapy unit in National Institute for cancer based on absorbed dose to water (TRS-398) and air kerma (TRS-277) based protocols

3. Analysis of uncertainties in the measurements air kerma for beam output calibrations; and estimation of uncertainty in the calibration factor for the two working standards. Measurements

1.4 Thesis outlines:

This thesis comprise six chapters: in chapter one general introduction is given, literature review is given chapter two, in chapter three introduction on radiation physics and
dosimetry is given including the standard dose measurements. In chapter four, materials and methods used in the study are presented. In chapter five results of the study are presented and discussion is given on the results. Conclusions are given in chapter six.
CHAPTER TWO
LITERATURE REVIEW

2.1 General background

P Munck af Rosenschöld et al (2008) performed study on calibration of a kilovoltage X-ray unit in terms of absorbed dose to water at the surface of a full-scatter phantom using the guidelines of several different dosimetry protocols which are presently in use. The authors used and compared the results of both $N_K$- and $N_{D,w}$-based protocols. Therefore, not only the methodology and dosimetric data provided in each specific protocol, but also the inherent differences in the air kerma and absorbed dose to water standards were compared. The dosimetric differences found in their study were generally rather small and inside the estimated experimental uncertainty pertaining to the reproducibility of measurements, except for the in-air methods using the AAPM TG-61 and IPEMB protocols in the 120 kV beam. In that case, results were obtained that were outside the estimated uncertainty budget as compared to the NCS-10, the DIN and IAEA TRS-277 and TRS-398 protocols. Similarly, the in-air method for the AAPM TG-61 protocol yielded results that were outside the estimated uncertainty budget as compared to results obtained using the IAEA TRS-398 and ($N_{D,w}$-based) DIN protocols for the 200 kV beam. It should be noted that the magnitude of the deviation correlated with the magnitude of the backscatter factor ($B_W$) as a function of HVL is given by the AAPM TG-61 protocol. This fact suggests that the deviations found in this study can be related to uncertainties in the backscatter factor, whether it was intrinsically included in the measurement made or taken from the protocol. The authors derived backscatter factors for the 120 and 200 kV beams using a Monte Carlo model for the actual x-ray machine studied. When using the Monte Carlo calculated backscatter factors the convergence between the protocols improved, which indicates that applying generic backscatter factors tends to increased dosimetric uncertainties. It is possible that the problem of using the HVL as the sole
beam quality specifier might be the cause for the observed deviations. The measured central percentage depth dose data using plane-parallel and cylindrical ionization chambers were shown to be in reasonably in good agreement with the data from the literature, for the same beam qualities, as specified in first half-value layers of aluminum and copper. Measured PDDs for both the 120 and 200 kV beams were in fair agreement (within 2%) at 2 cm depth, using plane-parallel and cylindrical ionization chambers as well as a diamond detector. Taken together, the present study leans in favor of calibrating medium-range kilovoltage x-ray beams at 2 cm depth and using measured PDDs rather than using the in-air method with generic backscatter factors. In the specification/ordering of kilovoltage x-ray units, it is advantageous if the beam qualities of the machine are matched to those available for the calibration of dosimeters at the standards laboratory. By doing so, the dosimetric uncertainties in the commissioning phase can be reduced. In addition, the authors concluded that medical physicist needs to consider the limitations of the dosimetry protocol of choice in order to avoid the need to deviate from the methods stipulated therein.

Jurado et al (2005) studied the performance and dose characterization of the Therapax SXT 150. The dose characterization in that study was performed by applying the IAEA TRS-398 protocol to the indicated beam qualities, which provides a solid, consistent and reliable way of measuring the dosimetric parameters. Mechanical movements, interlocks and applicator characteristics agreed with specifications. The tube head leakage was two orders of magnitude less than the limits established in the ICRP 33. Timer accuracy was better than 0.2% and linearity with dose was good. The output was stable, with repeatability better than 0.3%, long term reproducibility better than 1.5% and no dependence with tube head orientation. Measured first HVLs agreed with those of the BJR Supplement 25 when comparison was possible, value so as to obtain absorbed doses at the surface from absorbed dose measurements performed at 2 cm depth. This PDD value involves the use of measurements at the surface, which are difficult to perform for these qualities. To avoid this, the output factors used in our centre for these beam
qualities were re-defined to take into account only measurements performed at 2 cm depth. Beam optical density profiles had small penumbras and field sizes agreed with the applicator specifications. These profiles had good symmetry and flatness except for the lowest energy beam, for which a heel effect was observed. Measurements of all the parameters of the unit are strongly recommended. The data presented may provide a base for comparison and a reference for other or potential new users of the unit.

Vargas and Francisco (2008) compared IPSM 1990 photon dosimetry code of practice with AAPM TG-51 and IAEA TRS-398, and the similarities and differences between IPSM 1990 and AAPM TG-51/IAEA TRS-398 have been discussed. Uncertainties have been computed for all experimental results according to the ISO Guide for the Expression of Uncertainty in measurement recommendations. Absorbed dose to water determinations according to the three protocols agree within experimental uncertainty, and this Uncertainty is similar to the one reported in IAEA TRS-398. The maximum difference in absorbed dose to water determination is obtained for 18 MV: IPSM 1990 result is 0.7% lower than the IAEA TRS-398 one using its theoretical beam quality conversion factors. This maximum difference is mainly related to the use of experimental beam quality conversion factors for IPSM 1990 and theoretical ones for IAEA TRS-398. It must be stressed that this comparison has been performed with a single calibration from NPL and that the use of different protocols and calibrations traceable to different standards laboratories will add further differences increasing or lowering results.

Jan Seuntjens, et al (2005) presented a framework within which ionization chambers, calibrated in terms of absorbed dose to water, can be used to determine absorbed dose to water under reference conditions from a measurement in a solid phantom of known density and composition. Such a procedure has the distinct advantage that measurements in plastics can be done under conditions that simplify the interpretation of the chamber signal and make the conversion to absorbed dose to water under reference conditions direct and straightforward. We define a phantom dose conversion factor that relates an absorbed dose-to-water calibration coefficient to an in-solid phantom absorbed dose-to-
water calibration coefficient valid at a depth scaled by electron density. For an Exradin A12 C552 ionization chamber, we calculated and measured the phantom dose conversion factor for a set of Solid Water phantoms and found that measured and calculated factors differed by between 0.0% and 0.7% and the average measured dose conversion factor was low by 0.4% compared to the calculated factor. For the one Lucite phantom tested the difference was 0.2% or less for all energies. The magnitude of a difference between measurement and calculation depends on the consistency of phantom composition with the composition assumed in the calculations and on the phantom homogeneity and construction in the experiments. When these are independently verified by the user in accurate experiments for each phantom used, dose measurements using ionization chambers calibrated in terms of absorbed dose to water lead to reference dose determinations that are consistent with in-water measurements and absorbed dose-based protocols to within a few tenths of a percent. As the calculation of phantom dose conversion factors for different chamber types in combination with different phantom materials is straightforward, a more general availability of these factors for different chamber types and phantom materials could be useful.

M. Saiful Huq and Pedro Andreo (2000) compared the result of measurements from AAPM TG-51 and TG-21 made with PTW and NE farmer chamber in water phantom and exposed to 6, 18 and 25 photon beams. Depending upon the choice of ionization chamber and beam quality, the discrepancy in absorbed dose to water between the two protocols is found to range between 0.7% and 1.3% the AAPM TG-51 dose to water are found to be higher than the AAMP TG-21 doses by up to 0.9% at 6 MV and up to 1.0% at 18 MV. The large discrepancy of 1.3% is observed when NE chamber is used at 25 MV. The reason of the discrepancies has been analyzed, with the finding that the data and procedures recommended in the AAPM TG 51 protocol are responsible for a maximum contribution of about 0.5%; the rest of difference is presumably caused by the change in the primary standard used for chamber calibrations.
The recommendation of AAPM TG 51 protocol are followed the ratio of NE ti PTW chamber doses are found to be 0.999, 1.009 and 1.005 at 6.18 and 25 MV respectively. The corresponding result for the AAPM TG protocol are 0.999, 1.006 and 1.002 this apparent inconsistency is presumably attributed to deficiencies in our present knowledge to perturbation tractors and quantities used to calculate $K_Q$ values which are expected to be reduced when direct calibration in terms of absorbed dose to water become feasible at high energy photon qualities. The most important differences between this two protocol are the formalism in the AAPM TG-51 is based on the calibration of ionization chamber in term of absorbed dose to water on the other hand TG-21 based on exposure calibration factor the lead to differences of up to 1, 4% between the measured $N_{D,W}$ and value to $N_{D,W}$ calculated from $N_X$.

Fujio Araki and H.Dal kubo,(2002). calculated the ratio of absorbed dose to water between the existing JARP, TRS -277 and the new TRS-398 protocols and the new TG-51 protocol for various farmer type chamber in photon and the electron beams, they found in photon beams, the absorbed doses determined with TG-51 increases by 0.6% to 2.1 % ,0.7% to 1.7 % in comparison to those with JARP and TRS-277, respectively ,and agree with TRS-398 within 0.4% for electron beams ,TG-51 shows slightly higher increases i.e,1.5-3.8% and 0.2-1.9% in comparison to JARP and TRS-277, respectively, and agrees with TRS 398 within 0.6% reasons for the observed discrepancies are discussed by comparing $N_{gas}$ or $N_D$ and a dose conversion factors $F_w$. it is found that the $N_{gas}$ values calculated from the value of $M^{co}_{D,W}$ and $F_w$ define with TG-51 become higher by 1.8-2.9% and 0.5 – 1.5%with JARP and TRS -277,respectively.also, the ratio of the cavity-gas calibration factor evaluated from this discrepancy, The ratio of TG-51 and TRS-381 protocols is1.008. This ratio corresponds to discrepancy of 1.1%in the ratio of the absorbed –dose to discrepancy of 1.1%in the ratio of the absorbed-dose to water between MISI and MRC. However, the estimated uncertainty of the ratio between the two cavities –gas calibration factors is 0.9 %( 1 s.d) and consequently, the observed difference of 0.8%is not significant. In photon beams, $F_w$ values for TG-51 deaorease by
up to 1.8.1. Compared to JARP and agree with TRs-277 and TRs-398 within 0.7-1 for the Fw values in electron beams, TG-51 agrees with the existing JARP and TRs-277 protocols within 1.1 and with TRs-398 within 0.3%.

(GX Ding and J.E.and/ C.B.Kwok 2000) determined absorbed dose to water at the reference point which within 1% for C\textsuperscript{60}, 0.5% for photon beam with energies of 6 and 18 MV and compared the result with that at electron beam and the result from ionization chamber calibration factors (N\textsubscript{D,w}, N\textsubscript{s}). The implementation of new protocol will not change the results of clinical reference dosimetry in photon beams by more than roughly 1% compared to those obtained by TG21. It can be seen that there may be no significant clinical consequences as a result to the implantation of the TG51. The estimated dose changes in reference dosimetry are within 2% for Co\textsuperscript{60} beam, 1.5% for photon beam with energies of 6 and 18\mu v, and 3%-4% for electron beam with the same energies.
CHAPTER THREE
RADIATION PHYSICS AND DOSIMETRY

3.1 Ionizing Radiation

Radiation is classified into two categories: non ionizing and ionizing radiation depending on the ability to ionize matter. Non ionizing radiation can not ionize matter because its energy is lower than ionization potential of matter (the minimum energy required for ionization). Ionizing radiation can ionize matter either directly or indirectly because its energy exceeds the ionization potential of matter, it contains two major categories:

1. Directly ionizing radiation (charged particles): electrons, protons, alpha particles, heavy ions

2. Indirectly ionizing radiation (neutral particles): photon (X-ray, gamma rays), neutrons

Ionizing radiation is generally characterized by their ability to excite and ionize atoms of matter with which they interact. The important types of ionizing radiation are as follow:

3.1.1 Gamma ray:

It is electromagnetic radiation emitted from a nucleus or annihilation reaction between matter and anti matter, the quantum energy of any electromagnetic photon given in KeV by

\[ E = h \nu = \frac{hc}{\lambda} \]  

(3.1)

Where, \( h \) is blank constant
\( \nu \) is the frequency
\( \lambda \) is the wave length
3.1.2 X-ray:

Electromagnetic radiation emitted by charged particles (usually electrons) in changing atomic energy level (characteristic X-ray) or in slowing down coulomb force field (continuous or bremsstrahlung) the energy of X-ray ranging from low energy (soft X-ray) to megavoltage X-ray.

3.1.3 Heavy charged particle

Usually obtained from acceleration by Coulomb force field in cyclotron or heavy particle linear accelerator, alpha particle also emitted from radioactive nuclei and these types include proton, deuteron, triton and an alpha particle which is known as helium nucleus (two protons and two neutrons).

3.1.4 Fast electron:

If positive in charge they are called positrons. If they are emitted from a nucleus they are usually referred to as beta ray (positive, negative) and if they are result from a charged particle collision they referred to as delta ray.

3.1.5 Neutrons:

Neutral particles obtained from nuclear reaction or fission since they can not themselves be accelerated electrostatically.

All this type of ionizing radiation can interact with matter by tow way directly and indirectly, the fast charged particles which deliver their energy to matter directly through coulomb interaction along the particles track. Uncharged particles (photons, neutrons) at first transfer their energy to charged particles in the matter through which they pass, the resulting fast charged particles then in turn deliver the energy to the matter. That means the deposition of energy in matter by (photon and neutrons) is tow step process. (F. Attix, 1986).
3.2 Interaction of radiation with matter:

The interaction of radiation with matter depend on several factors such as types of radiation, the energy of radiation and the material it self. Thus the photon interaction with matter differs significantly from that with beta and alpha.
Heavy charged particles and fast electrons interact with matter through the Coulomb force with the electrons present in any medium through which they pass. Neutrons and photons because they have no charge therefore are not subject to the Coulomb force, these radiations first undergo a catastrophic interaction (often involving the nucleus of constituent atoms).
X-ray and gamma ray transfer all or a part of its energy to electrons bears a close similarity to the fast electron radiation (beta particles)

3.2.1 Charged particle interactions:

Electron as energetic traverse matter, it interact with matter through coulomb interaction with atomic orbital electrons and atomic nuclei through this collisions the electron may lose their kinetic energy or change their direction of travel. energy losses are describe by stopping power.
When the incident electron interact with orbital electron (elastic collision) the electron is deflected from its original path but no energy loss occurs, while in an inelastic collision the electron is deflected from its original path and some of its energy transferred to an orbital electron or emitted in the form of bremsstrahlung, the interaction between the incident electron and orbital electron result in ionization (ejection of an orbital electron from the absorber atom), and excitation (transfer of an orbital electron of the absorber atom from an allowed orbit to a higher allowed orbit), atomic excitation and ionization are characterized by collision stopping power.
The coulomb interaction between incident electron and nuclei of the absorber atom result in electron scattering and energy loss of the electron through production of X-ray photon and these types of energy loss is characterized by radiative stopping power.

### 3.2.2 Stopping power:

The inelastic energy losses by an electron moving through a medium with density $\rho$ are describe by the total mass energy stopping power ($S/ \rho$), represents the kinetic energy $E$ loss by the electron per unit path length ($X$) or:

$$
\frac{S}{\rho} = \frac{1}{\rho} \frac{dE}{dx} \text{ (MeV cm}^2 \text{g}^{-1})
$$

(3.2)

The mass energy stopping power consist of tow components, the mass collision stopping power $\left( \frac{S}{\rho} \right)_{col}$ resulting from electron –orbit electron interaction, and the mass radiative stopping power $\left( \frac{S}{\rho} \right)_{rad}$ resulting from electron- nucleus interaction.

$$
\left( \frac{S}{\rho} \right)_{tot} = \left( \frac{S}{\rho} \right)_{col} + \left( \frac{S}{\rho} \right)_{rad}
$$

(3.3)

$\left( \frac{S}{\rho} \right)_{col}$ Has an important role in radiation dosimetry and for expressing the absorbed dose in a medium (E.D Podgorsak.E 2003)

### 3.2.3 Linear energy transfer:

The linear energy transfer or linear collision stopping power, $L$, of a material, for a charged particle, is the quotient of $dE$ and $dl$, where $dE$ is the mean energy lost by the particle, due to collisions with electrons, in traversing a distance $dl$; thus

$$
L = \frac{dE}{dl}
$$

(3.4)
Unit: J·m⁻¹

$E$ may be expressed in eV, and hence $L$ may be expressed in eV·m⁻¹ or some convenient submultiple or multiple, such as keV·μm⁻¹. (IAEA.2000)

**3.2.4 Photons interactions:**

Depending on their origin, photon radiation falls in to one of the following four categories:

1. Bremsstrahlung (continuous X-ray) emitted through electron-nucleus interaction

2. Characteristic X-ray (discrete) emitted in transition of orbital electrons from one allowed orbit to a vacancy in another allowed orbit.

3. Gamma ray (discrete) emitted through nuclear transition in gamma decay.

4. Annihilation radiation (discrete, typically 0.511 MeV)

**3.2.5 Photon beam attenuation:**

The intensity $I(x)$ of a narrow photon beam attenuated by attenuator of thickness $x$ given by

$$I(x) = I(0)e^{-\mu x}$$

Where $I(0)$ is the original intensity of un attenuated beam

$\mu$ is the linear attenuation coefficient.

**3.3 Types of photon beam interaction:**

Photons interact with the atom of an attenuator in various ways depending on the energy ($h\nu$) of the photon and on the atomic number ($Z$) of the attenuator.
It can also interact with bound electron with an atom as whole (photo electric effect), with the field of the nucleus (pair production), or with free orbital electron (Compton Effect)

### 3.3.1 Photo electric effect:

In the photo electric effect the photon interact with bound orbital electron of an attenuator and disappear, while the orbital electron is ejected from the atom as a photo electron with kinetic energy \( E_K \) given as :( padgorsak E.B, 2003)

\[
E_K = h\nu - E_B \quad (3.6)
\]

Where \( h\nu \) is the incident photon energy and \( E_B \) is the binding energy of the electron

### 3.3.2 Compton Effect:

The Compton Effect represents a photon interaction with orbital electron. The incident photon energy is much larger than the binding energy of the orbital electron, the loses part of its energy to recoil electron and is scattered as photon through a scattering angle \( \theta \), angle \( \varphi \) represents the angle between the incident photon direction and the direction of the recoil electron. The change in photon wave length \( \Delta\lambda \) is given by the well known Compton relationship :( padgorsak E.B 2003)

\[
\Delta\lambda = \lambda (1 \cos \theta) \quad (3.7)
\]

### 3.3.3 Pair production:

In pair production the photon disappear and an electron-positron pair is a combined kinetic energy is produced in the nuclear coulomb field.

### 3.4 Radiometric quantities

The radiation field can be defined by radiometric quantities such as :

#### 3.4.1 Particle Fluence (\( \varphi \)):

Is the number of particles incident on sphere of cross sectional area
\[ \Phi = \frac{dN}{dA} \]  
Unit = m²

**3.4.2 Energy fluence (Ψ):**

The energy fluence is the quotient \( dR \) by \( dA \) where \( dR \) is the radiant energy incident on sphere of cross sectional area \( dA \):

\[ \Psi = \frac{dR}{dA} \]  
(3.9)

Energy fluence can be calculated from particle fluence by

\[ \Psi = \left( \frac{dN}{dA} \right) E = \Phi E \]  
(3.10)

Where \( E \) is the energy of the particle and \( dN \) represents the number of particles with energy \( E \).

The particle fluence and energy fluence may change with time result in particle fluence rate and energy fluence rate with units \( (\text{m}^2 \text{s}^{-1}\text{and Jm}^{-2}\text{s}^{-1}) \) respectively.

Radiation dosimetry It is now a pure physical science and has its origin in the medical applications of ionizing radiation and we a protection against it, these applications required quantitative method to determine a dose of radiation.

The radiation quantities are deal with energy deposited in a given medium by directly and indirectly ionizing radiation. Number of physical quantities and units has been defined for describing a beam of radiation and the dose of radiation.

**3.5 Charged particles equilibrium:**

If there is volume \( V \) containing a distributed radioactive source and there is also small volume \( v \) inside \( V \) and there are four conditions for radiation equilibrium

1. The atomic composition of the medium is homogeneous
2. The density of the medium is homogeneous
3. The radioactive source is uniformly distributed
4. There are no electric or magnetic fields present to perturb the charged particle path, except the fields associated with atoms.

Charged particle equilibrium (CPE) exists for a given volume when for each charged particle that exits the volume, there is a charged particle entering the volume. When (CPE) exists, the dose is equal to the collision kerma (frank Herbert Attix 1986).

### 3.6 Dosimetric quantities

#### 3.6.1 Exposure (X):

Is defined as the quotient of $dQ$ by $dm$ where the value $dQ$ is the absolute of the total charge of the ions of one sign produced in air when all the electrons and positrons liberated or created by photon in mass $dm$ of air are completely stopped in air

$$X = \frac{dQ}{dm} \quad (3.11)$$

With unit C/Kg and the unit used is (R) roentgen

$$1R = 2.58 \times 10^{-4} \text{ C/Kg}$$

The average energy expended in air per ion pair formed $W_{air}$ is the quotient of $E_K$ by $N$ where $N$ is the mean number of ion pair formed when the initial kinetic energy $E_K$ of charged particles is dissipated in air

$$W_{air} = \frac{E_K}{N} \quad (3.12)$$

The current best estimated for the average value of $W_{air}$ is 33.97 $eV/ionpair$

#### 3.6.2 Energy imparted:

Energy imparted, $\epsilon$, by ionizing radiation to matter in a volume, is defined by the relation

$$\epsilon = R_{in} - R_{out} + \sum Q \quad (3.13)$$
where $R_{\text{in}}$ is the sum of the energies (excluding rest energies) of all charged and uncharged ionizing particles that enter the volume, $R_{\text{out}}$ is the sum of the energies (excluding rest energies) of all charged and uncharged ionizing particles that leave the volume, and $\sum Q$ is the sum of all changes of the rest mass energy of nuclei and elementary particles in any interactions that occur in the volume. The unit of energy imparted is joule.

### 3.6.3 Kerma:

Kerma is an acronym for kinetic energy released per unit mass. It has applicable to indirectly ionizing radiation such as photons and neutrons; it quantifies the average amount of energy transferred from indirectly to directly ionizing radiation. For example, the energy of photons is imparted to matter in two stage process, in the first stage the photon radiation transfers energy to the secondary charged particles (electrons) through various photon interactions. In the second stage the charged particles transfers’ energy to the medium through atomic excitation and ionization. Through this the kerma is defined as the mean energy transferred from the indirectly ionizing radiation to charged particles in the medium $\text{d}E$ per unit mass $\text{d}M$:

$$K = \frac{dE_{x}}{dm}$$

(3.14)

With unit J/Kg

Component of kerma:

The kerma for X or gamma rays consist of the energy transferred to electrons and positrons per unit mass of medium. The kinetic energy of fast electron may be spent in two ways:
• Coulomb force interaction with atomic electrons of the absorbing material resulting in the local dissipation of the energy as ionization and excitation in or near the electron track. These are called collision kerma

• Radiative interaction with the Coulomb force field at atomic nuclei in which Xray photons are emitted as the electron decelerates. These Xray photons are relatively penetrating compared to electrons and carry their quantum energy far away from the charged particle track. Thus kerma include collision and radiative and:

\[ K = K_c + K_r \]  \hspace{1cm} (3.15)

K_c Is collision kerma

K_r Is radiative kerma

3.6.4 Absorbed dose:

It’s the energy imparted by the ionizing radiation to matter of mass m in a finite volume V.

And it is a quantity applicable to both indirectly and directly ionizing radiations.

Indirectly ionizing radiation means: the energy is imparted to matter in a two step process.

• In the first step (resulting in kerma), the indirectly ionizing radiation transfers energy as kinetic energy to secondary charged particles.

• In the second step, these charged particles transfer a major part of their kinetic energy to the medium (finally resulting in absorbed dose).

For directly ionizing radiation means: charged particles transfer a major part of their kinetic energy directly to the medium (resulting in absorbed dose).

(Padgorsak E.B 2005)
Thus the absorbed dose $D$ is the expectation value of the energy imparted to matter per unit mass.

### 3.7 Bragg cavity theory:

The Bragg–Gray cavity theory was the first cavity theory developed to provide a relation between the absorbed dose in a dosimeter and the absorbed dose in the medium containing the dosimeter. The conditions for application of the Bragg–Gray cavity theory are:

1. The cavity must be small when compared with the range of charged particles incident on it, so that its presence does not perturb the fluence of charged particles in the medium;

2. The absorbed dose in the cavity is deposited solely by charged particles crossing it (i.e. photon interactions in the cavity are assumed negligible and thus ignored).

Under these two conditions, according to the Bragg–Gray cavity theory, the dose to the medium $D_{med}$ is related to the dose in the cavity $D_{cav}$ as follows:

$$ D_{med} = D_{cav} \left( \frac{S}{\rho} \right)_{med,cav} $$

(3.16)

$$ \left( \frac{S}{\rho} \right)_{med,cav} $$

It’s the ratio of the average unrestricted mass collision stopping powers of the medium and the cavity. The use of unrestricted stopping powers rules out the production of secondary charged particles (or delta Electrons) in the cavity and the medium.
3.8 Relation between dosimetric quantities:

The absorbed dose (D) defined for all types of radiation, and for mono-energetic photon radiation valid:

\[
D = cpe \frac{\phi E \mu_{en}}{\rho} \quad (3.17)
\]

Where D is the absorbed dose in (Gy)
\(\phi\) is particle fluence (m\(^{-2}\))
\(E\) is photon energy (J)
\(\mu_{en}/\rho\) is mass energy cross section (m\(^2\)Kg\(^{-1}\))

And for charged particle valid:

\[
D = \phi \left(\frac{S}{\rho}\right)_{el} \quad (3.18)
\]

Where \(\left(\frac{S}{\rho}\right)_{el}\) is the mass electron energy loss cross section (Jm\(^2\)Kg\(^{-1}\))

Kerma defined for indirectly ionizing and for mono-energetic photon and neutron radiation valid

\[
K = \phi E \frac{\mu_{tr}}{\rho} \quad (3.19)
\]

Where \(\phi\) is particle fluence (m\(^{-2}\))
\(E\) is the energy (exclusive rest energy) (J)
\(\mu_{tr}/\rho\) is the mass energy transferred cross section (m\(^2\)Kg\(^{-1}\))

For mono-energetic photons of energy E the exposure is given by

\[
X = \phi E \left(\frac{\mu_{tr}}{\rho}\right)_{air} \left(\frac{e/\mu}{W_{air}}\right) \quad (3.20)
\]
Thus

\[ X = K_{C_{\text{AIR}}} \left( \frac{e}{W} \right) \]  \hfill (3.21)

In charged particle equilibrium

\[ D = K_e \]  \hfill (3.22)

So

\[ D_{\text{air}} = \left( \frac{W_{\text{air}}}{e} \right) X \]  \hfill (3.23)

And

\[ D^{\text{cpe}} = \phi E \left( \frac{\mu_{en}}{\rho} \right)_{\text{air}} \]  \hfill (3.24)

Then

\[ X = \phi E \left( \frac{\mu_{en}}{\rho} \right)_{\text{air}} \frac{e}{W_{\text{air}}} \]  \hfill (3.25)

### 3.9 Radiation protection quantities:

#### 3.9.1 Organ dose:

The organ dose is defined as the mean dose \( dT \) in a specified tissue or organ \( T \) of human body, given by : (Padgorsak E.B 2005)

\[ D_T = \frac{1}{m_T} \int_{m_T} D \, dm = \frac{\varepsilon_T}{m_T} \]  \hfill (3.26)

Where

- \( m_T \) is the mass of the organ or tissue under consideration
- \( \varepsilon_T \) is the total energy imparted by radiation to that tissue or organ

#### 3.9.2 Equivalent dose:

The absorbed dose in an organ or tissue, \( D_T \) is the absorbed dose averaged over the volume of a tissue or organ \( T \) (rather than at a point). While the absorbed dose at a point
generally is the fundamental dose quantity, in radiation protection, the mean dose in an organ becomes the basic protection quantity correlated with the exposure risk. This concept, therefore, is obviously based on the linear dose-effect relationship and the additively of doses for risk assessment as an appropriate approximation in the low dose region. Otherwise, averaging of doses and adding of doses over long periods would not be an acceptable procedure.

The equivalent dose in an organ or tissue is defined by (ICRP 1991)

\[ H_T = \sum W_R D_{T,R} \]

(3.27)

Where \( D_{T,R} \) is the mean organ dose in the organ or tissue \( T \) from radiation of type \( R \) incident on the Human body and \( W_R \) are radiation weighting factors characterizing the biological Effectiveness of the specific radiation \( R \) relative to photons. The sum is taken over all types of radiation involved.

Radiation weighting factors:

For external irradiation, the values of the radiation weighting factors are given by the parameters of the external radiation field only (by the type and spectral distribution of the radiation incident on the body). This means that \( w_R \) is a body-averaged value representing a mean value for the relative biological effectiveness of all tissues of the body. Because the \( W_R \) value is the same for all organs in a body, this procedure obviously ignores any local variation of the radiation quality in the human body which may result from the generation of secondary radiation of different types in the human body. This effect is important mainly in the case of incident neutrons where secondary photons strongly contribute to the absorbed doses of various organs. The \( w_R \) values for various types of radiation are specified in table (3.1)
Table (3.1) radiation weighting factor

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>Radiation weighting factor, $w_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photon</td>
<td>1</td>
</tr>
<tr>
<td>Electrons and mouns</td>
<td>1</td>
</tr>
<tr>
<td>Proton and charged pions</td>
<td>2</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, heavy ions</td>
<td>20</td>
</tr>
<tr>
<td>neutrons</td>
<td>A continuous function of neutron energy</td>
</tr>
</tbody>
</table>

3.9.3 Effective dose:

The effective dose is the mean absorbed dose from a uniform whole-body irradiation that results in the same total radiation detriment as from the non-uniform, partial-body irradiation in question. The effective dose is the weighted average of the mean absorbed dose to the various body organs and tissues, where the weighting factor is the radiation detriment for a given organ from a whole-body irradiation. (ICRP 2007)

$$E = \sum w_T H_T$$  \hspace{1cm} (3.28)

Where

- $w_T$: weighting factor for organ or tissue.
- $H_T$: equivalent dose for organ or tissue.

Recommended tissue weighting factor:
Table (3.2) tissue weighting factor

<table>
<thead>
<tr>
<th>tissue</th>
<th>$W_T$</th>
<th>$\sum W_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone marrow (red), colon, lung, stomach, breast, remainder tissues</td>
<td>0.12</td>
<td>0.72</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Bladder, esophagus, liver, thyroid</td>
<td>0.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Bone surface, brain, salivary glands, skin</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Remainder tissues: adrenals, extrathoracic (ET) region, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix.

3.10 Operational radiation protection quantities:

3.10.1 Ambient dose equivalent: $H^*(d)$

At a point in radiation field, is the dose equivalent that would be produced by the corresponding aligned and expanded radiation field, in the ICRU sphere at a depth $d$, on the radius vector opposing the direction of radiation incidence. For penetrating radiation it is $d = 10$ mm.

3.10.2 Directional dose equivalent: $H'(d, \Omega)$

The directional dose equivalent $H'(d, \Omega)$ at a point of interest in the actual radiation field, is the dose equivalent that would be produced by the corresponding expanded radiation field, in the ICRU sphere at a depth $d$, on a radius in a specified direction $\Omega$. For low-penetrating radiation $d$ is equal to 0.07 mm.
3.10.3 Personal dose equivalent: $H_p(d)$,

The personal dose equivalent, $H_p(d)$, is the dose equivalent in ICRU tissue at a depth $d$ in a human body below the position where an individual dosimeter is worn. For monitoring of the skin dose $d = 0.07$ mm is recommended and for monitoring effective dose $d = 10$ mm. In rare cases of monitoring the dose to the lens of the eye a depth $d = 3$ mm may be appropriate.

3.11 Measurements of absorbed dose:

The basic output calibration of a clinical radiation beam by virtue of direct measurement of dose or dose rate in water under specific reference conditions is referred to as reference dosimetry. Three types of reference dosimetry technique are currently known:

1. Calorimetry
2. Fricke dosimetry
3. Ionization chamber dosimetry

These dosimeters can be used as absolute dosimeters but seldom used as such in clinics, because their use in absolute dosimetry is cumbersome and more over, calibration in a known radiation field offers certain advantage. When an absolute dosimeter is used independently, it relies on its own accuracy instead of referring to a standard in common with other radiation users.

3.11.1 Calorimetry:

It’s the most fundamental dosimetry technique since it relies on basic definitions of either electrical energy or temperature. In principle calorimetry is simple, in practical however the need for measuring extremely small temperature differences makes the technique very complex and relegates it to sophisticated standards laboratories.

Two main types of absorbed dose calorimeter are currently used in standards laboratories:
1. Graphite calorimeters;

2. Sealed water calorimeters.

In graphite calorimeters the average temperature rise is measured in a body that is thermally insulated from surrounding bodies (‘jackets’) by evacuated vacuum gaps. Gap corrections and dose transfer procedures are used in conjunction with graphite calorimeters to allow for the transfer of absorbed dose from graphite to water. In stagnant sealed water calorimeters use is made of the low thermal diffusivity of water, which enables the temperature rise to be measured directly at a point in (continuous) water. Dose transfer procedures are not needed, but the measurement and analysis are complicated by the presence of conductive heat loss (or gain) and by the heat defect induced by radiolysis.

![Diagram of a standard water calorimeter](image)

Figure 1: standard water calorimeter.

Water calorimetry in stagnant water is fundamentally possible due to the fact that the thermal diffusivity of water is so low that the temperature distribution remains in place to enable accurate measurements at a point. Hence, in stagnant water calorimeters a
measured temperature rise $T_W$ is measured at a point and multiplication with the specific heat capacity of water $C_W$ leads immediately to absorbed dose to water at that point. However, practical determination of absorbed dose to water is complicated by effects that can be categorized as either fundamental or technical. Fundamental effects are those that potentially disturb the energy balance between absorbed energy and energy appearing as a temperature rise. Technical issues are those that complicate a correct measurement of the water temperature rise. Both these effects are usually treated as correction factors in the dose equation. A water calorimeter determination of absorbed dose to water can be thus based on the following generic equation:

$$D_W = C_{W,P}TK_h K_{hd} K_p K_{dd} K_\rho$$  \hspace{1cm} (3.29)

Where $C_{W,P}$ is the specific heat capacity of water at constant pressure; $T$ is the measured thermistor temperature rise; $K_{hd}$ is the correction for the heat defect $h$ (i.e. equal to $1/(1 - h)$, where $h$ represents the heat defect ); $K_h$ is a general heat transfer correction factor, which can result from conductive or convective modes of heat transfer; $K_p$ is a perturbation correction factor to account for the absorption and scattering of radiation due to the presence of non-water materials; $K_{dd}$ is a dose profile correction factor that corrects the measured dose to the dose at the reference point and $K_\rho$ is a density correction factor to account for the difference in density between the calorimeter operation temperature and the temperature at which another detector (such as an ionization chamber) is calibrated (Jan seuntjens and Simon Duane 2009).

3.11.2 Fricke dosimetry:

The energy of ionizing radiation absorbed in certain media produces chemical change in the absorbing medium, the amount of this change used as a measure of absorbed dose. Fricke dosimetry which relies on oxidation of ferrous ions ferric ions produced in the solution is measured by absorption spectrometry which ultraviolet light at 304 nm which is strongly absorbed by the ferric ions.
Fricke dosimetry (sometimes referred to as chemical dosimetry or ferrous sulphate dosimetry) depends on an accurate knowledge of the radiation chemical yield of ferric ions, measured in moles produced per 1 J of energy absorbed in the solution. The chemical yield is related to an older parameter, the G value, defined as the number of ferric molecules produced in the ferrous sulphate solution by 100 eV of absorbed energy. An accurate value of the chemical yield is difficult to ascertain because the chemical yield is affected to a certain degree by the energy of the radiation, dose rate and temperature of the solution during irradiation and readout. The best G value for $^{60}$Co g rays is 15.6 molecules per 100 eV, corresponding to a chemical yield of $1.607 \times 10^{-6}$ mol/J. The typical dynamic range for ferrous sulphate Fricke dosimeters is from a few grays to about 400 Gy, making Fricke dosimetry impractical for routine use in a clinic.

### 3.11.3 Ionization chamber dosimetry:

The ionization chamber is the most practical and most widely used type of dosimeter for accurate measurement of machine output in radiotherapy. It may be used as an absolute or relative dosimetry. It is sensitive volume is usually filled with ambient air. And the dose or dose rate related measured quantities are the ionization charge $Q$ or ionization current $I$ respectively produced by radiation in the chamber sensitive air mass $m_{air}$. Charge $Q$ and air mass $m_{air}$ are related to absorbed dose in air $D$ by:

$$D = \frac{Q}{m_{air}} \left( \frac{W_{air}}{e} \right)$$

(3.30)

Where $\left( \frac{W_{air}}{e} \right)$ is the mean energy required to produce an ion pair in air per unit charge (the current value for dry air is 33.97 eV/ion pair or 33.97 J/C). The subsequent
conversion of the air cavity dose \(D_{air}\) to dose to medium (usually water) \(D_{W}\) is based on the Bragg–Gray or Spencer–Attix cavity Theories

The sensitive air volume or mass in an ionization chamber is determined:

- Directly by measurement (the chamber becomes an absolute dosimeter under special circumstances);

- Indirectly through calibration of the chamber response in a known radiation field (the chamber is used as a relative dosimeter).

### 3.12 Reference dosimetry with ionization chamber:

Three types of ionization chamber are used in reference dosimetry as absolute dosimetry

- Standard free air ionization chamber
- Cavity ionization chamber
- Phantom embedded extrapolation chamber

#### 3.12.1 Standard free air ionization chamber:

This chamber measure the air kerma in air according to its definition by collecting all ions produced by the radiation beam that result from the direct transfer of energy from photons to primary electrons in a defined volume in air, the determination of air kerma

\[
\frac{W_{air}}{e}
\]

required accurate knowledge about \(\frac{W_{air}}{e}\), the use of the standard free air ionization chamber is limited to photons below 0.3 MeV
Figure 3.2: a Schematic diagram of a free-air chamber. Photons enter through an aperture of radius $r_{ap}$ and interact with the air of the chamber to produce secondary electrons ($e_1$, $e_2$, $e_3$). If the electrode separation $d$ is sufficiently large, the secondary electrons come to rest within the chamber. In the course of slowing down, charge is liberated and is swept in the electric field between the electrodes. An isolated section of electrode creates a region of air of length $l$ (shaded) from which charge is collected and measured as ionization current (D T Burn and L Buermann. 2009).

3.12.2 Cavity ionization chamber:

This chamber measures the air kerma for energies in the range from 0.6 to 1.5 MeV by making use of the Bragg gray cavity relationship to standard free air ionization chambers. The measurements required accurate knowledge of the sensitive air volume.

3.12.3 Phantom embedded extrapolation chambers:

This chamber is an uncalibrated variable air volume extrapolation chamber built as an integral part of a water equivalent phantom. And it serves as radiation dosimeters in the measurement of absorbed dose for megavoltage photon and electron beam.

Ionization chamber based dosimetry system:
Ionization chamber based dosimetry systems are in principle quite simple and consist of three main components:

1. a suitable ionization chamber;

2. An electrometer

3. a power supply.

The circuitry of a simple ionization chamber based dosimetry system resembles a capacitor (ionization chamber) connected to a battery (power supply), with the electrometer measuring the ‘capacitor’ charging or discharging current.

Two types of ionization chamber are used in routine beam calibration:

1. Cylindrical (often referred to as thimble) chambers;

2. Parallel-plate (sometimes called end window or plane-parallel) chambers

For each ionization chamber, reference conditions are described by a set of influence quantities for which a chamber calibration coefficient is valid without any further corrections. Influence quantities are defined as quantities that are not the subject of a measurement but yet influence the quantity being measured. Examples of influence quantities in ionization chamber dosimetry are:

1. Ambient temperature and pressure

2. Ion recombination

3. Polarity effect
Outputs of clinical photon and beams are usually measured with ionization chambers that have calibration coefficients traceable to a standards laboratory and are thus used as relative dosimeters.

Before such a chamber is used in radiotherapy machine output calibration, the user must identify a dosimetry protocol (code of practice) appropriate for the given radiation beam. A dosimetry protocol provides the formalism and the data to relate a calibration of a chamber at a standards laboratory to the measurement of absorbed dose to water under reference conditions in the Clinical beam. Two types of dosimetry protocol are available:

- Protocols based on air kerma in air calibration coefficients;
- Protocols based on absorbed dose to water calibration coefficients

Most current megavoltage dosimetry protocols rely on chamber calibration coefficients determined in Co-60 beams at standards laboratories. It is expected that the use of megavoltage beam calibration qualities (X rays and electrons), today available only in a few PSDLs, will become more widespread in the future.

It should be noted that the formalisms presented here, based on a Co-60 calibration coefficient, work well for megavoltage photon and electron beams. The calibration of superficial and orthovoltage X ray beams, on the other hand, relies on different principles and the chamber calibration coefficient should be obtained for the particular X ray beam quality that is being calibrated (IAEA2003) E. D. podgorsk.E).

3.13 **Air kerma based protocol:**

Air kerma based protocols use the air kerma in air calibration coefficient $N_K$, Co-60 obtained for a local reference ionization chamber in a Co-60 beam at a standards laboratory. Routine ionization chambers are then cross-calibrated with the reference ionization chamber in a local Co-60 beam. Two steps are involved in an air kerma based protocol for the calibration of megavoltage photon beam.
A formalism based on an air kerma calibration of the user, ionization chamber is recommended. It is recommended that the transfer be carried out according to the procedure of calibration

The cavity air calibration coefficient $N_{D,\text{air}}$ is defined as:

$$N_{D,\text{air}} = \frac{D_{\text{air},Co}}{M_{Co}} \quad (3.31)$$

Where

- $D_{\text{air},Co}$ is the absorbed dose to air in the chamber cavity.
- $M_{Co}$ is the chamber signal corrected for influence quantities.

The absorbed dose to air in the cavity $D_{\text{air},Co}$ is determined from the total air kerma in air ($K_{\text{air}}$) as follows:

$$D_{\text{air},Co} = \left( K_{\text{air}} \right)_{\text{air}} (1 - g) K_m \cdot K_{\text{att}} \quad (3.32)$$

Where

- $g$ is the radiative fraction, i.e., the fraction of the total transferred energy expended in radiative interactions on the slowing down of the secondary electrons in air.
- $K_m$ corrects for the non-air equivalence of the chamber wall and Buildup cap needed for an air kerma in air measurement.
- $K_{\text{att}}$ corrects for attenuation and scatter in the chamber wall.

The air kerma in air calibration coefficient $N_{K,Co}$ is:

$$N_{K,Co} = \frac{\left( K_{\text{air}} \right)_{\text{air}}}{M_{Co}} \quad (3.33)$$

$$D_{\text{air},CO} = \left( K_{\text{air}} \right)_{\text{air}} (1 - g) K_m K_{\text{att}} \quad (3.34)$$

The cavity air calibration coefficient $N_{D,\text{air}}$ is now:
\[ N_{D,\text{air}} = N_{K,\text{Co}} \left( 1 - g \right) K_m K_{att} \]  

The absorbed dose to water at the point of interest can be calculated using:

\[ D_W \left( P_{eff} \right) = D_{air,u} \left( S_{W,\text{air}} \right)_u P_u \]  

Where \( (S_{W,\text{air}})_u \) is the stopping power ratio water to air

And the absorbed dose to water is:

\[ D_W = M_u N_D \left( S_{W,\text{air}} \right)_u \]  

The above calculations is for Co-60 and for X-ray the absorbed dose can be calculated from

\[ D_W = M_u N_K K_u \left( \frac{\mu_{en}}{\rho} \right)_{W,\text{air}} \]  

For medium energy and

\[ D_W = M_u N_K BK_u \left( \frac{\mu_{en}}{\rho} \right)_{W,\text{air}} \]  

For low energy (IAEA 1987)

### 3.14 Absorbed dose to water based protocol:

All dosimetry protocols aim at determination of the quantity absorbed dose to water. It is therefore logical to provide ionization chambers directly with a calibration coefficient in terms of this quantity, rather than in terms of the air kerma in air, if at all possible. Recent developments have provided support for a change in the quantity used at present to calibrate ionization chambers and provide calibration coefficients in terms of absorbed dose to water \( N_{D,W} \) for use in radiotherapy beams. Many PSDLs now provide \( N_{D,W} \)
calibrations in $^{60}$Co gamma ray beams and some laboratories have already extended these calibration procedures to high energy photon and electron beams. Cobalt-60 calibration coefficients for megavoltage photon and electron beam. And Calibration coefficients obtained for the particular beam quality used for superficial and orthovoltage x-ray beams.

Calibration in a quality $Q_0$ beam (usually cobalt-60) at the standards laboratory:

$$D_{W,Q_0} = M_{Q_0} N_{W,Q_0}$$  \hspace{1cm} (3.40)

Where $M_{Q_0}$ is the chamber reading under the reference conditions used in the standards laboratory and corrected for influence quantities and $N_{W,Q_0}$ is the water dose calibration coefficient for the chamber at beam quality $Q_0$ (usually cobalt-60).

3.15 Estimating the uncertainty:

The uncertainty associated with a measurement is a parameter that characterizes the dispersion of the values ‘that could reasonably be attributed to the measurand’ this parameter is normally an estimated standard deviation. An uncertainty, therefore, has no known sign and is usually assumed to be symmetrical. It is a measure of our lack of exact knowledge after all recognized

An uncertainty may be estimated by some known statistical method (Type A) or otherwise (Type B). This distinction is mainly of pedagogical relevance and can be dropped once the numerical values for the uncertainties have been chosen. The Type A standard uncertainty is obtained by the usual statistical analysis of repeated measurements. It is not expected that a Type A standard uncertainty will be determined individually for each instrument calibrated, but rather that representative values will be obtained from a number of typical calibrations. It is normally found that the reproducibility of each dosimeter model is essentially the same from one instrument to the next. Thus, if the Type A standard uncertainty of an air kerma rate measurement is
determined for one kind of dosimeter, the same value can generally be used for other instruments of that same model, measured under the same conditions.

There are many sources of measurement uncertainty that cannot be estimated by repeated measurements. These are called Type B uncertainties. These include not only unknown, although suspected, influences on the measurement process, but also little known effects of influence quantities (pressure, temperature, etc.), application of correction factors or physical data taken from literature. The Type B standard uncertainty can be derived by first estimating some limits ±\( L \) and then dividing that limit by a suitable number. Some times Type B uncertainties can be described by a rectangular probability density, i.e. that they have equal probability anywhere within the given maximum limits −\( M \) and +\( M \). It can be shown that with this assumption the Type B standard uncertainty \( u_B \) is given by:

\[
\frac{u_B}{M} = \frac{1}{\sqrt{3}}
\]

And if the assumed distribution is triangular (with the same limits), the above relation becomes:

\[
\frac{u_B}{M} = \frac{1}{\sqrt{6}}
\]

Thus there are no rigid rules for estimating type B uncertainty and we should use our best knowledge and experiences, and whatever method applied, provide estimates that can be used as if they were standard deviations (IAEA 2000).

Type A and Type B uncertainties are both estimated standard deviations, they are combined by using the statistical rules for combining variances (which are squares of standard deviations).
CHAPTER FOUR
MATERIALS AND METHODS

In this study measurements were carried out in two irradiation facilities: the part on ionization chamber calibration was carried out at the Secondary Standard Dosimetry Laboratory of Sudan Atomic Energy Commission whereas beam output calibrations for a cobalt-60 radiotherapy unit were performed at the National Cancer Institute, University of Gazira.

4.1 Secondary Standard Dosimetry Laboratory:

The Secondary Standard Dosimetry Laboratory (SSDL) of Sudan atomic energy commission was installed on 1995 under supervision of the International Atomic Energy Agency. The laboratory is located in Suba, 15 Km distant from Khartoum in the premises of Sudan Atomic Energy Commission. It was designated by the competent national authorities to undertake the duties of ionizing radiation calibrations and standardization of dose measurements within the country. The laboratory is equipped with devices for improving accuracy and precision in applied radiation dosimetry used throughout the country. SSDL consist of gamma calibrators OB-85 and X-ray unit producing ISO 4037 radiation energies of the narrow beam series (N-40, N-60, N80, N100, N120, N150) Two moving trays were positioned in fixed metal tracks to allow the irradiation from the three sources at different distances in a reproducible way. A laser system was positioned on the right hand side of the calibration tray allowing for the accurate positioning of the reference point of the instrument at a specified distance, and a second laser system, was used for the alignment of the instrument according to the beam axis. The dosimeters readings were viewed via a camera, which was coupled to a parallel display in the control area. Two other cameras were positioned in the calibration room to provide for area surveillance monitoring. Ionization chambers, electrometers, a gamma-calibrator unit, and x-ray generator are used for different calibration purposes. During the calibration, the
reference gamma radiation was provided by a Cs-137 and Co-60 sources irradiator (OB-85, is circular, with a diameter 50 cm at a distance of 2 m from the source) OB-85 containing three sources Co-60, Cs-137 and external Am-241 with activity 37 GBq, 740 GBq, 7.4 GBq, respectively. Sources Irradiator is supplied with a set of lead attenuators with thickness of 2, 1.8 cm that are placed at the exit window of the irradiator to vary the air Kerma that is required to cover the instrument scales at a particular calibration distance. The arrangement for air kerma measurements using reference ionization chamber used from OB-85 gamma calibrator is shown in Figure 4.1.
Figure 4.1. Air kerma measurements using reference ionization chamber used from OB-85 gamma calibrator.
Measurements were also performed at University of Gezira, National Cancer Institute in a $^{60}$Co machine type cirus manufactured by Eric ROUCHON. This machine has the following specifications: Source model: CoT20; S/N: 4273; Radionuclide: Co-60

Contained activity: 254.9 TBq (6890 Ci).

4.1.2 Ionization chambers and dosimetry system:

Five ionization chambers were used in this study three were radiation protection level whereas two were therapy level ionization chambers.

1. Spherical 1 liter chamber LS-01 type 32002 with PTW electrometer. with polarizing voltage 400 V(max), wall material from POM (CH$_2$O)$_n$, electrode material graphite coated energy ranged from 45 keV to 50 MeV

2. 2575 600 cc Thin window ionization chamber with farmer electrometer manufactured by nuclear technology, England. Wall material SRBP, collecting electrode material is polypropylene, graphite coated. And the chamber has additional three windows A, B and C made of clear melinex that are used for different energies

3. Radcal 1800 cc cylindrical ionization chamber with Radcal electrometer intended for low dose radiation. This chamber can be used in the energy ranged from 33 keV to 1.33 Me. Bias (300 VDC-600 VDC), wall material is polycarbonate.

Characteristics of cylindrical ionization chamber types (as stated by manufacturers) are presented in Table 3.1.
Table 3.1. Characteristics of cylindrical ionization chamber types as stated by the manufacturers.

<table>
<thead>
<tr>
<th>Ionization chamber type</th>
<th>PTW 30010 Farmer</th>
<th>PTW 31003 flexible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity volume(cm$^3$)</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Cavity length(mm)</td>
<td>23</td>
<td>16.3</td>
</tr>
<tr>
<td>Cavity radius(mm)</td>
<td>3.1</td>
<td>2.8</td>
</tr>
<tr>
<td>Wall material</td>
<td>PMMA</td>
<td>PMMA</td>
</tr>
<tr>
<td>Wall thickness(g cm$^{-2}$)</td>
<td>0.045</td>
<td>0.078</td>
</tr>
<tr>
<td>Build-up cap material</td>
<td>PMMA</td>
<td>PMMA</td>
</tr>
<tr>
<td>Build-up cap thickness(g cm$^{-2}$)</td>
<td>0.541</td>
<td>0.357</td>
</tr>
<tr>
<td>Central electrode material</td>
<td>aluminum</td>
<td>aluminum</td>
</tr>
<tr>
<td>Waterproof</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

4.1.3 Phantoms and other devices:

In dosimetry system there were many devices to be used in additional to the ionization chambers such as thermometer and barometer for measuring the temperature and pressure used for the correction reading of electrometer. There are also phantom (PMMA)10X10X5 with hole for holing ionization chamber, radioactive check sources suitable for each chamber ($^{90}$Sr and $^{241}$Am).
4.2 Experimental setup:

The calibration of ionization chamber was performed at secondary standard dosimetry laboratory at Sudan Atomic Energy Commission in $^{137}$Cs gamma ray beam and narrow X-ray series (N40, N60, N80, N100, N120, and N150). The measurements of secondary standard ionization chamber type LS-01 were taken in charge mode and subsequently converted to air kerma using the appropriate calibration factor. All measurements were carried out at 2 m distance from the relevant sources ($^{137}$Cs source contained in a gamma calibrator OB-85 and X-ray beam series previously specified. Prior to any measurement, stability measurements were performed using radioactive check source ($^{241}$Am). Measurements of ambient conditions (temperature and pressure) were done during the experiment. Measurements of the ion recombination and polarity effect were made according to the formulae 4.1-4.3:

$$K_{ion} = \frac{\left(\frac{u_1}{u_2}\right)^2 - 1}{\left(\frac{u_1}{u_2}\right)^2 - \frac{M_1}{M_2}}$$

(4.1)

$$K_p = \frac{|M_{-}| + |M_{+}|}{2M}$$

(4.2)

$$K_{TP} = \left(\frac{T + 273.2}{T_0 + 273.2}\right) \left(\frac{P_0}{P}\right)$$

(4.3)

For farmer ionization chamber and radcal the measurements were performed similar to those with spherical ionization chamber at all qualities and conditions with all available corrections.

The calculations of air kerma to all ionization chambers were performed utilizing the formula:

$$K_{air} = MN_K K_{TP} K_{ion} K_p$$

(4.4)

Where M was the electrometer reading in (nC/min).
$N_K$ is the calibration factor of chamber from its certificate

$K_{TP}$ correction for temperature and pressure

$K_{ion}$ correction for ion recombination

$K_p$ correction for polarity effect.

The uncertainties of these measurements were estimated using:

$$U(K_{\text{corr}}) = \sqrt{\left(\frac{U(M)}{M}\right)^2 + \left(\frac{U(K_{pr})}{K_{pr}}\right)^2 + \left(\frac{U(K_T)}{K_T}\right)^2 + \left(\frac{U(K_{ion})}{K_{ion}}\right)^2 + \left(\frac{U(K_p)}{K_p}\right)^2 + \left(\frac{U(K_d)}{K_d}\right)^2 + (U(N_K))^2}$$  \(3.43\)

Where $U(M)/M$ is the uncertainty of the reading, $U(K_{pr})/K_{pr}$ for pressure, $U(K_T)/K_T$ for temperature ,$U(K_{ion})/K_{ion}$ for ion recombination, $U(K_p)/K_p$ for polarity effect, $U(K_d)/K_d$ for distance and the factor $U(N_K)$ is for calibration factors of the ionization chamber from its certificate.

The calibration factor of the ionization chamber at reference was calculated according to:

$$N_K = N_{ref} \frac{M_{ref} K_{ref}}{M_k K_K}$$  \(4.5\)

Where $N_{ref}$ is the calibration factor of the reference ionization chamber from the certificate

$M_{ref}$ and $K_{ref}$ are the reading and correction for the reference chamber

$M_K$ and $K_K$ are the reading and correction for the other chamber

Thus calibration factors of farmer and radcal ionization chambers were calculated for all qualities using:

$$C_f = \frac{M}{m}$$  \(4.6\)

Where $(M)$: is reading of secondary standard ionization chamber (spherical) and $(m)$ the reading of farmer or Radcal ionization chamber.

Concerning therapy level ionization chambers, and 0.6 cc ionization chamber was calibrated in term of air kerma and absorbed dose to water whereas 0.3 cc ionization
chamber was only calibrated in terms of air kerma. Measurements were carried out using 20x20x10 cm water phantom at a reference depth of 5 cm, field size 10x10, and source to surface distance (SSD) of 80 cm. The electrometer readings were corrected for ion recombination, temperature, and pressure and polarity effect. The calculations of absorbed dose to water according to TRS-277 and TRS-398 were performed using relevant IAEA dosimetry protocol: initially absorbed dose to water at reference point of 60Co beam were made according to IAEA TRS-277:

\[ D_w = M_a N_D S_{w,air} P_u \]  \hspace{1cm} (4.7)

\[ N_D = N_K (1 - g) K_{att} K_m \]  \hspace{1cm} (4.8)

Where

Next, the absorbed dose to water at reference point of 60Co beam was made IAEA according to protocol TRS-398:

\[ D_w(Z_{ref}) = MN_{D,w} \]  \hspace{1cm} (4.9)
CHAPTER FIVE
RESULTS AND DISCUSSION

5.1 Results

The results obtained are presented in this chapter. These include quality assurance measurements, beam output calibration measurements, measurements performed for ion chamber calibrations and uncertainty analysis.

5.1.1 Beam output measurements:

Results of measurements of air kerma rate at different distances from $^{137}$Cs source are presented graphically in the Figure 5.1. A linear relationship is observed between the air kerma rate and the reciprocal of distance square according to the inverse square law. The standard deviation of the measured mean air kerma rate is shown as error bars.

Results of measurements of air kerma rate at 2 m distance from three X-ray beam qualities are presented in Table 5.1. The measured output ranged from 69 µGy/min to 178 µGy/min at 60 and 80 tube voltages; respectively. Variation of tube output between different X-ray beam qualities is attributed to the different filtration used.
Figure 5.1 a graph show output measurements of $^{137}$Cs at different distances and the kerma rate range from few µGy to 550 µGy.

<table>
<thead>
<tr>
<th>Quality (kV/mA)</th>
<th>Effective Energy (keV)</th>
<th>Output (µGy/min) at 2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>40/10</td>
<td>33</td>
<td>68.7</td>
</tr>
<tr>
<td>60/6</td>
<td>48</td>
<td>176.86</td>
</tr>
<tr>
<td>80/19</td>
<td>65</td>
<td>178.49</td>
</tr>
<tr>
<td>100/19</td>
<td>83</td>
<td>106.5</td>
</tr>
<tr>
<td>120/19</td>
<td>100</td>
<td>135.25</td>
</tr>
<tr>
<td>150/3</td>
<td>116</td>
<td>118.51</td>
</tr>
</tbody>
</table>
5.1.2 Spherical reference standard chamber

For accurate measurements of air kerma rate using an ionisation chambers ion recombination and polarity effect should be measured and subsequently applied. Measurements of these correction factors for spherical 1000 cc reference standard ionization chamber are presented in Table 5.2.

The calculated air kerma and the related correction factors for spherical reference chamber are presented in Table 5.3.

The measurements were performed by multiplying the corrected electrometer reading in (nC) by the calibration factor $N_X$ (µGy/nC) of the chamber taken from the calibration certificate according to equation 4.4. These measurements consider as a reference reading at SSDL for routine calibration of the all instruments being calibrated in Sudan. The results of uncertainty of the measurement evaluated at 95% confidence level are presented in Table 5.4.

The calculated of air kerma ($k_{air} \pm U_{exp}$) for (33, 48, 65, 83,100,116 and 662 KeV) were (65.23±2.166), (186.77±6.065), (188.34±6.048), (111.02±3.567), (137.82±4.535), (126.41±4.037) and (148.69±4.742); respectively.

<table>
<thead>
<tr>
<th>Energy</th>
<th>V1</th>
<th>V2</th>
<th>M1</th>
<th>M2</th>
<th>M_</th>
<th>M+</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>400</td>
<td>100</td>
<td>2.4</td>
<td>2.3</td>
<td>2.5</td>
<td>2.4</td>
</tr>
<tr>
<td>48</td>
<td>400</td>
<td>100</td>
<td>7.4</td>
<td>7.4</td>
<td>7.35</td>
<td>7.4</td>
</tr>
<tr>
<td>65</td>
<td>400</td>
<td>100</td>
<td>7.3</td>
<td>7.3</td>
<td>7.2</td>
<td>7.2</td>
</tr>
<tr>
<td>83</td>
<td>400</td>
<td>100</td>
<td>4.4</td>
<td>4.41</td>
<td>3.89</td>
<td>4.1</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>100</td>
<td>5.5</td>
<td>5.7</td>
<td>5</td>
<td>5.5</td>
</tr>
<tr>
<td>100</td>
<td>400</td>
<td>100</td>
<td>4.8</td>
<td>4.8</td>
<td>4.75</td>
<td>4.78</td>
</tr>
<tr>
<td>116</td>
<td>400</td>
<td>100</td>
<td>5.35</td>
<td>5.33</td>
<td>5.36</td>
<td>5.35</td>
</tr>
<tr>
<td>662</td>
<td>400</td>
<td>100</td>
<td>5.35</td>
<td>5.33</td>
<td>5.36</td>
<td>5.35</td>
</tr>
</tbody>
</table>
V1 : normal operating voltage

V2 : reduced voltage value

M1 : electrometer reading at the normal operating voltage, V1

M2 : electrometer reading at the reduced operating voltage, V2

M- : electrometer reading at the reverse bias normal operating voltage, V1

M+ : electrometer reading at the normal operating voltage, V1

<table>
<thead>
<tr>
<th>Quality</th>
<th>Q 40/10</th>
<th>Q 60/6</th>
<th>Q 80/10</th>
<th>Q 100/19</th>
<th>Q 120/19</th>
<th>Q 150/13</th>
<th>¹³⁷Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (keV)</td>
<td>33</td>
<td>48</td>
<td>65</td>
<td>83</td>
<td>100</td>
<td>116</td>
<td>662</td>
</tr>
<tr>
<td>Readings</td>
<td>2.39</td>
<td>7.33</td>
<td>7.41</td>
<td>4.40</td>
<td>5.57</td>
<td>4.84</td>
<td>5.50</td>
</tr>
<tr>
<td>Nx</td>
<td>25.00</td>
<td>23.90</td>
<td>24.10</td>
<td>24.20</td>
<td>24.30</td>
<td>24.50</td>
<td>25.10</td>
</tr>
<tr>
<td>Ktp</td>
<td>1.07</td>
<td>1.07</td>
<td>1.07</td>
<td>1.07</td>
<td>1.07</td>
<td>1.07</td>
<td>1.08</td>
</tr>
<tr>
<td>Kp</td>
<td>1.02</td>
<td>0.99</td>
<td>0.99</td>
<td>0.97</td>
<td>0.95</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Kion</td>
<td>1.0002</td>
<td>0.995</td>
<td>1</td>
<td>0.999</td>
<td>0.997</td>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>μGy/min</td>
<td>65.23</td>
<td>186.77</td>
<td>188.34</td>
<td>111.02</td>
<td>137.82</td>
<td>126.41</td>
<td>148.69</td>
</tr>
</tbody>
</table>

Nx  calibration factors of spherical chamber from certificate

Ktp  correction for temperature and pressure

Kp  correction for polarity effect
Table 5.4: the uncertainty of calculation air kerma by spherical ionization chamber.

<table>
<thead>
<tr>
<th>quality</th>
<th>40/10</th>
<th>60/6</th>
<th>80/10</th>
<th>100/19</th>
<th>120/19</th>
<th>150/3</th>
<th>$^{137}$Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(M)/M</td>
<td>0.010</td>
<td>0.006</td>
<td>0.002</td>
<td>0.001</td>
<td>0.006</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>U(T)</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>U(P)</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>U(ION)</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>U(PO)</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.017</td>
<td>0.018</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>U(D)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>U(Nk)</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>U(k$_{air}$)</td>
<td>0.033</td>
<td>0.032</td>
<td>0.032</td>
<td>0.032</td>
<td>0.033</td>
<td>0.032</td>
<td>0.032</td>
</tr>
</tbody>
</table>
5.1.3 Working standard cylindrical chamber

Measurements for the determination of polarity effect of 600 cc cylindrical chamber with 2526 farmer electrometer are presented in Table 5.5 The results of air kerma rate calculated according to IAEA TRS 277 are presented in Table 5.6

Table 5.5, 5.6 and 5.7 show polarity effect measurements, air kerma rate calculations and the uncertainty a combined with these measurements by 600 cc farmer ionization chamber for different energies (33, 48, 65, 83, 100, 116 and 662 KeV). The air kerma rates were (43±2.122), (163.9±7.919), (153.5±7.412), (91±4.485), (125.7±6.071), (103.9±6.158), (126.2±6.116) respectively. The ratio of air kerma rate from farmer by that from spherical secondary standard ionization chamber were calculated for calculations the calibration factors of each beams. In these measurements the air kerma calculation were done also by multiplying the corrected electrometer reading (nC) by the chamber sensitivity (m Gy/nC)
### Table 5.5 Measurements for the determination of polarity effect of cylindrical chamber

<table>
<thead>
<tr>
<th>Quality</th>
<th>Q40/10</th>
<th>Q60/6</th>
<th>Q80/10</th>
<th>Q100/19</th>
<th>Q120/19</th>
<th>Q150/13</th>
<th>137Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Energy (keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>48</td>
<td>65</td>
<td>83</td>
<td>100</td>
<td>116</td>
<td>662</td>
<td></td>
</tr>
<tr>
<td>m-</td>
<td>0.93</td>
<td>3.47</td>
<td>3.25</td>
<td>1.9</td>
<td>2.66</td>
<td>2.69</td>
<td>2.67</td>
</tr>
<tr>
<td>m+</td>
<td>0.93</td>
<td>3.45</td>
<td>3.24</td>
<td>1.97</td>
<td>2.65</td>
<td>2.69</td>
<td>2.68</td>
</tr>
</tbody>
</table>

M- : electrometer reading at the reverse bias normal operating voltage
M+ : electrometer reading at the normal operating voltage

### Table 5.6 Calculation of air kerma and correction factors for of 600 cc cylindrical chamber

<table>
<thead>
<tr>
<th>Beam Quality</th>
<th>Q40/10</th>
<th>Q60/6</th>
<th>Q80/10</th>
<th>Q100/19</th>
<th>Q120/19</th>
<th>Q150/13</th>
<th>137Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Energy (keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>48</td>
<td>65</td>
<td>83</td>
<td>100</td>
<td>116</td>
<td>662</td>
<td></td>
</tr>
<tr>
<td>Reading (nC)</td>
<td>0.93</td>
<td>3.46</td>
<td>3.25</td>
<td>1.97</td>
<td>2.66</td>
<td>2.70</td>
<td>2.68</td>
</tr>
<tr>
<td>Nx (µGy/nC)</td>
<td>43.73</td>
<td>43.73</td>
<td>43.73</td>
<td>43.73</td>
<td>43.73</td>
<td>43.73</td>
<td>43.73</td>
</tr>
<tr>
<td>Ktp</td>
<td>1.08</td>
<td>1.08</td>
<td>1.08</td>
<td>1.08</td>
<td>1.08</td>
<td>1.08</td>
<td>1.08</td>
</tr>
<tr>
<td>Kp</td>
<td>1</td>
<td>1.003</td>
<td>1.002</td>
<td>0.982</td>
<td>1.002</td>
<td>1</td>
<td>0.998</td>
</tr>
<tr>
<td>K_{air} (µGy/min)</td>
<td>43.87</td>
<td>163.97</td>
<td>153.47</td>
<td>91.17</td>
<td>125.73</td>
<td>127.32</td>
<td>126.16</td>
</tr>
</tbody>
</table>

Nx :  calibration factors of farmer chamber from certificate.
Ktp : correction for temperature and pressure.
Kp  : correction for polarity effect

### Table 5.7 Calculated uncertainty in the air kerma measurements
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Q40</th>
<th>Q60</th>
<th>Q80</th>
<th>Q100</th>
<th>Q120</th>
<th>Q150</th>
<th>$^{137}$Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U(M)/M$</td>
<td>0.001</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>$U(T)/T$</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
<td>0.019</td>
</tr>
<tr>
<td>$U(P)/P$</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>$U(N_k)$</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>$U(d)$</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>$U(Po)$</td>
<td>0.044</td>
<td>0.044</td>
<td>0.044</td>
<td>0.045</td>
<td>0.044</td>
<td>0.044</td>
<td>0.044</td>
</tr>
<tr>
<td>$U(K_{air})$</td>
<td>0.048</td>
<td>0.048</td>
<td>0.048</td>
<td>0.049</td>
<td>0.048</td>
<td>0.048</td>
<td>0.048</td>
</tr>
</tbody>
</table>
5.1.4 Radcal working standard ionization chamber:

Table 5.8: Calculation of air kerma for 1800 cc Radcal ionization chamber

<table>
<thead>
<tr>
<th>Quality</th>
<th>Q 40/10</th>
<th>Q 60/6</th>
<th>Q80/10</th>
<th>Q100/19</th>
<th>Q120/19</th>
<th>Q150/13</th>
<th>$^{137}$Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>33</td>
<td>48</td>
<td>65</td>
<td>83</td>
<td>100</td>
<td>116</td>
<td>662</td>
</tr>
<tr>
<td>Reading(mGy/h)</td>
<td>2.498</td>
<td>9.906</td>
<td>9.324</td>
<td>5.452</td>
<td>7.86</td>
<td>7.162</td>
<td>7.9</td>
</tr>
<tr>
<td>Reading(µGy/min)</td>
<td>41.63333</td>
<td>165.1</td>
<td>155.4</td>
<td>90.86667</td>
<td>131</td>
<td>119.3667</td>
<td>131.6667</td>
</tr>
<tr>
<td>Ktp</td>
<td>1.062796</td>
<td>1.0627</td>
<td>1.0627</td>
<td>1.0627</td>
<td>1.0627</td>
<td>1.0627</td>
<td>1.0627</td>
</tr>
<tr>
<td>µ Gy/min</td>
<td>44.25</td>
<td>175.45</td>
<td>165.14</td>
<td>96.56</td>
<td>139.21</td>
<td>126.85</td>
<td>142.46</td>
</tr>
</tbody>
</table>

Table 5.9: calculations of uncertainty for air kerma by Radcal ionization chamber

<table>
<thead>
<tr>
<th>quality</th>
<th>Q40</th>
<th>Q60</th>
<th>Q80</th>
<th>Q100</th>
<th>Q120</th>
<th>Q150</th>
<th>$^{137}$Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>U(M)/M</td>
<td>0.012</td>
<td>0.002</td>
<td>0.002</td>
<td>0.002</td>
<td>0.001</td>
<td>0.003</td>
<td>0.002</td>
</tr>
<tr>
<td>U(T)/T</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
<tr>
<td>U(P)/P</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
<td>0.004</td>
</tr>
<tr>
<td>U(Nk)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>U(d)</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>U(Kair)</td>
<td>0.026</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
<td>0.023</td>
</tr>
<tr>
<td>U*Kair</td>
<td>1.148</td>
<td>4.075</td>
<td>3.829</td>
<td>2.236</td>
<td>3.222</td>
<td>2.951</td>
<td>3.304</td>
</tr>
</tbody>
</table>

Table 5.8 and 5.9 show air kerma calculations with their correction by Radcal ionization chamber for different energies (33, 48, 65, 83, 100, 116 and 662 KeV), and the air kerma rate were (44.25±1.148), (175±4.075), (165.14±3.829), (96.56±2.236), (139.21±3.222), (126.85±2.951) and (142.46±3.304) respectively. And the ratio of air kerma rate, arising
from radcal ionization chamber to that from spherical secondary standard ionization chamber, were calculated to evaluate the calibration factors.

### 5.1.5 Determination of the calibration coefficients

Calibration factors of cylindrical and Radcal ionization chamber obtained by dividing the air kerma rate of secondary standard ionization chamber by that from cylindrical and Radcal are presented in Table 5.10 with regard to the two working standard ionisation chambers and considering all energies, optimum factor was shown in 116 keV i.e. 150 tube voltage X-ray beam quality using Radcal ionization chamber. As can be seen from the Table 5.10, the calibration factor for the cylindrical ionization chamber in all energies were extremely high in some X-ray beam qualities and do not conform with the relevant international recommendations. Concurrently, appropriate calibration factor was evident in 120 X-ray tube voltage (100 keV).

Based on the results obtained, Radcal ionization chamber showed good performance for low energy beam qualities compared to the cylindrical ionization chamber.
Table 5.10. The calculated $N_k$ factor for two working standard ionization chambers

<table>
<thead>
<tr>
<th>Beam Quality (kV)</th>
<th>Effective Energy (KeV)</th>
<th>Air kerma (µ Gy/min)</th>
<th>$N_k$ for Cylindrical chamber</th>
<th>$N_k$ for Radcal chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Reference chamber</td>
<td>Cylindrical chamber</td>
<td>Radcal chamber</td>
</tr>
<tr>
<td>40</td>
<td>33</td>
<td>65.23</td>
<td>43</td>
<td>44.25</td>
</tr>
<tr>
<td>60</td>
<td>48</td>
<td>186.77</td>
<td>163.9</td>
<td>175.45</td>
</tr>
<tr>
<td>80</td>
<td>65</td>
<td>188.34</td>
<td>153.5</td>
<td>165.14</td>
</tr>
<tr>
<td>100</td>
<td>83</td>
<td>111.02</td>
<td>91</td>
<td>96.56</td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>137.82</td>
<td>125.7</td>
<td>139.21</td>
</tr>
<tr>
<td>150</td>
<td>116</td>
<td>126.41</td>
<td>103.9</td>
<td>126.85</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>662</td>
<td>148.69</td>
<td>126.2</td>
<td>142.46</td>
</tr>
</tbody>
</table>
5.1.6 Therapy level ionisation chambers

Table 5.11 presents the results of absorbed to water measurements using two therapy level type PTW ionization chambers for $^{60}$Co beam. Measurements were made according to international code of practice – IAEA TRS-277 based on air kerma calibration standards.

Beam output was measured in term of air kerma at 80 cm SSD, the field size 10x10 and 5 cm depth. According to air kerma based protocol (TRS-277), measurements were performed by calculating the absorbed dose to air ($D_{air}$) and then the absorbed dose to water ($D_{w}$) utilizing the formalism given in the protocol.

Table 5.12 presents the results of absorbed dose to water measurements using 0.3 cc therapy level type PTW ionization chambers for $^{60}$Co beam. Measurements were made according to international code of practice – IAEA TRS-398 based on absorbed dose to water standards. Beam output was measured in term of absorbed dose to water using the formalism of absorbed dose water based protocol.
Table 5.11 Results of absorbed dose to water measurements using TRS-277.

<table>
<thead>
<tr>
<th>chamber</th>
<th>0.3 cc Farmer type chamber</th>
<th>0.6 cc Farmer type chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>reading</td>
<td>13.23</td>
<td>7.12</td>
</tr>
<tr>
<td>Kion</td>
<td>0.99</td>
<td>1.0</td>
</tr>
<tr>
<td>Kp</td>
<td>1.01</td>
<td>1.02</td>
</tr>
<tr>
<td>NK(Gy/n C)</td>
<td>1.08</td>
<td>1.07</td>
</tr>
<tr>
<td>Km.Katt</td>
<td>0.048</td>
<td>0.09</td>
</tr>
<tr>
<td>g</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>ND(Gy/n C)</td>
<td>0.003</td>
<td>0.01</td>
</tr>
<tr>
<td>Sw,air</td>
<td>1.13</td>
<td>1.13</td>
</tr>
<tr>
<td>Pu</td>
<td>0.99</td>
<td>1.001</td>
</tr>
<tr>
<td>Dw(eff)</td>
<td>0.76</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Table 5.12 Results of absorbed dose to water measurements using TRS-398

<table>
<thead>
<tr>
<th>Reading (nC)</th>
<th>Kion</th>
<th>Kp</th>
<th>Ktp</th>
<th>ND(Gy/nc)</th>
<th>Dw(eff)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.234</td>
<td>0.998521</td>
<td>1.011364</td>
<td>1.077726</td>
<td>0.05</td>
<td>0.720169</td>
</tr>
</tbody>
</table>
5.2 Discussion:

5.2.1 Calibration of working standards:

In this study two working standard ionization chambers were calibrated using secondary standard ionization chamber. This was performed as a part of traceability of measurements. Based on current measurement results, the determined calibration coefficient ranged from 0.99-1.52 these chambers performed adequately and satisfy international recommendations for calibration procedures and radiation dosimetry.

Determination of any reference field used for the calibration of dosemeters under certain conditions can be achieved by selecting a suitable quantity of the operational radiation protection. This requires the use of suitable and traceably calibrated secondary standard dosemeters (Peter Ambroshi 2009). In this study a quantity being used in the calibration of the ionization chamber was the air kerma which related to the operational quantities by conversion coefficients. For low and medium energy dosimetry the calibration of dosimeters performed is based on air kerma standards. The uncertainty specified for the secondary standard dosemeter is sufficiently small for the purpose of calibrating the reference field. In calibration of ionization chamber, measurements performed are combined with relevant uncertainties. In this study, uncertainties were evaluated in the calculation of beam output in terms of the physical quantity air kerma rate and also uncertainties in the calibration factor determined. The uncertainty values in air kerma rate measurements ranged from 1.15 to 7.9 for all beam qualities. These are expanded uncertainty (over all uncertainty) evaluated at 95% confidence level (two standard deviations).
5.2.2 Radiotherapy beam output calibration:

Based on the internationally accepted protocols for radiation dose measurements in radiotherapy, radiation dose rely on many factors such as backscatter, the percentage dose depth distribution, the uncertainty components and the formalism of used to determine the absorbed dose to water as most recently developed procedures but also already existing air kerma based standards. The results obtained in the present study demonstrated that the the absorbed dose to water measured using IAEA air kerma based protocol was well within 5% deviation from the absorbed dose to water measured using IAEA absorbed dose to water based protocol measured using 0.3 cc therapy level ionisation chamber. The result clearly envisaged that both protocols can be used for teletherapy beam output calibration with accuracy recommended. However, measurements of absorbed dose to water more straightforward when using absorbed to water based protocols as demonstrated elsewhere. The two ionization chambers used were cylindrical type which is suitable for reference dosimetry in high energy photon beam. The preference of absorbed dose to water based protocols such as IAEA TRS 398 come from the fact that the formalism for absorbed dose to water calculation using TRS-277 has many parameters which makes the calculation somewhat complicated. These problems were clearly addressed in the new and recently developed absorbed dose to water protocols. Beam output measurements for Co-60 radiotherapy machine can be used as a reference for future beam output calibration at the specified radiotherapy centre.
CHAPTER SIX
CONCLUSION AND RECOMMENDATIONS

Calibration coefficients were determined for two working standard ionization chambers. This offered the possibility of using three ionization chambers for routine beam output measurements and calibration for all instruments being calibrated at SSDL in Sudan. Uncertainties of measuring air kerma were estimated for all photon beam qualities and for all ionization chambers. Measuring of beam output in term of air kerma rate using secondary standard ionization chamber and beam output for Co-60 radiotherapy beam in term of absorbed dose to water was performed as a part of dose standardization and beam output calibration. We proposed for any laboratories be continue in quality control and implementation of quality system according to ISO recommendations such as ISO 17025. As result of this study we recommend that:

- The authority has a rule to govern quality in radiation measurements
- In presence of all dosimetry tools researcher can expand their studies in ionization chamber dosimetry
- In our country we have two centres for radiotherapy till now so the need for quality is a priority
- Quality of measurements in radiation protection is required
- Available radiation sources (lineac, $^{60}$Co and other sources) and radiation equipments encourage and motivate the researchers to doing hard in their research.
- Use of different protocols in the measurements and the select suitable one for being the main procedures.
REFERENCES:


12- Jan Seuntjens, Jan Seuntjens, A Marina Olivares, Michael Evans, and Ervin Podgorsak , ( 2005). Absorbed dose to water reference dosimetry using solid phantoms in the context of absorbed-dose protocols Department of Medical Physics, McGill University Health Centre, 1650 Cedar , Montreal, H3G 1A4, Canada Med, Ph, Vol. 32, No. 9


