

**EXPERIMENTAL DETERMINATION OF BEAM QUALITY CORRECTION FACTORS  
IN CLINICAL HIGH-ENERGY PHOTON AND ELECTRON BEAMS**



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A research report submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science.

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## DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the degree of Master of Science in the University of the Witwatersrand, Johannesburg. It has never been produced before for any degree or examination in any other University.



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13 October 2010

## ABSTRACT

**Background:** Recent protocols for the determination of absorbed dose to water in high-energy photon and electron beams are based on air ionisation chambers calibrated in terms of absorbed dose to water in a  $^{60}\text{Co}$  gamma ray beam ( $N_{D,w}^{60\text{Co}}$ ). To determine the absorbed dose to water in any other high-energy beam (excluding neutrons), the protocols use chamber dependent beam quality conversion factors. Such factors are published in different protocols but only for a selected number of ionisation chambers used clinically. These beam quality correction factors can alternatively be determined experimentally in the user's beam qualities for each ionisation chamber. The measurement of beam quality correction factors ( $k_Q$  for photons and  $k_{q,E}$  for electrons) accounts for the actual design of different ionisation chambers. Direct measurement in the user's beams also helps to minimise the uncertainties inherent in the theoretical determination of beam quality correction factors based on a unified design.

**Purpose:** The purpose of this work was to determine values of the beam quality correction factors in clinical high-energy photon and electron beams for PTW 30013 and PTW 23333 0.6 cm<sup>3</sup> ionisation chambers, a PTW 31006 'Pinpoint' ionisation chamber, a PTW 31010 0.125 cm<sup>3</sup> ionisation chamber, a PTW 23343 Markus and a PTW 34045 Advanced Markus ionisation chamber.

**Methods and materials:** Siemens Primus linear accelerators were used to generate 6 and 18 MV photon beams and 5, 6, 7, 9, 12, 14, 15, 18 and 21 MeV electron beams. An Equinox Theratron External Beam Therapy System was used to generate the  $^{60}\text{Co}$  beam used in this study. The ionisation chambers were all cross-calibrated for  $N_{D,w}^{60\text{Co}}$  against the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber at 5 cm water-equivalent depth in the  $^{60}\text{Co}$  beam. The field size at the reference depth was 10 cm x 10 cm. For the same set-up, the absorbed dose to water using the IAEA TRS-398 (IAEA, 2000) was determined using the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber. The exposure calibration factor ( $N_x$ ) for the PTW 23333 0.6 cm<sup>3</sup> reference chamber was then derived by equating the absorbed dose to water calculated from the IAEA TRS-398 protocol to the absorbed dose to water calculated from the AAPM TG-21 (AAPM, 1983) protocol. The cavity-gas calibration factor ( $N_{gas}$ ) was then determined for the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber. The cross-calibrated  $N_{D,w}^{60\text{Co}}$  for each cylindrical chamber and the absorbed dose to water due to the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber in the 6 MV and 18 MV photon beams were used to determine  $k_Q$  for each

ionisation chamber at the respective photon energies. The plane-parallel and the cylindrical ionisation chambers were then cross-calibrated for  $N_{gas}$  in the 21 MeV electron beam. The absorbed dose to water in the electron beams was then calculated from first principles using the AAPM TG-21 worksheets for all of the chambers. The  $k_{q,E}$  were then derived for each of the ionisation chambers at each of the electron energies.

**Results:** The measured  $k_Q$  values as a function of  $TPR_{20,10}$  (the tissue-phantom ratio in water at depths of 20 cm and 10 cm, for a field size of 10 cm x 10 cm and a constant source-chamber distance of 100 cm) for the different ionisation chambers and the published IAEA TRS-398  $k_Q$  values for the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber are tabulated below:

Nominal energy/MV	$TPR_{20,10}$	PTW 23333	PTW 31006	PTW 31010	PTW 30013	PTW 30013 (IAEA TRS-398)
6	0.674	0.991	0.998	0.997	0.993	0.991
18	0.770	0.973	0.973	0.985	0.973	0.972

The measured  $k_{q,E}$  values as a function of  $R_{50}$  for the electron beam qualities for the different ionisation chambers and the published IAEA TRS-398  $k_{q,E}$  values for the PTW 23343 Advanced Markus ionisation chamber are tabulated below:

Nominal Energy (MeV)	$R_{50}/$ cm	PTW 23333	PTW 30013	PTW 31006	PTW 31010	PTW 34045	PTW 23343	PTW 23343 (IAEA TRS-398)
5	2.05	0.890	0.899	1.035	0.877	0.950	0.917	0.925
6	2.40	0.884	0.890	1.023	0.872	0.946	0.915	0.921
7	2.75	0.878	0.884	1.022	0.870	0.946	0.917	0.918
9	3.51	0.868	0.873	1.002	0.862	0.926	0.900	0.913
12	4.68	0.858	0.859	0.988	0.864	0.912	0.891	0.906
14	5.28	0.851	0.854	0.978	0.859	0.904	0.885	0.902
15	5.93	0.851	0.852	0.978	0.851	0.895	0.893	0.899
18	7.30	0.859	0.861	0.986	0.861	0.893	0.899	0.893
21	8.23	0.820	0.824	0.932	0.822	0.847	0.850	0.888

The average observed difference between the measured values and those published in the IAEA TRS-398 protocol was 0.2% for the PTW 30013 0.6 cm<sup>3</sup> in the photon beams and 1.2% for the PTW 23343 Markus ionisation chamber in the electron beams.

**Conclusion:** Beam quality correction factors for ionisation chambers can be determined experimentally or confirmed in an end-user's beam quality.

## **DEDICATION**

To JJaaja Elios Nakisozi  
(1926-2006)

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## DEFINITION OF TECHNICAL TERMS, ACRONYMS AND SYMBOLS.

AAPM	American Association of Physicists in Medicine.
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency.
TG	Task Group.
AAPM TG-21	A protocol of the AAPM TG-21 for the determination of absorbed dose from high-energy photon and electron beams.
IAEA	International Atomic Energy Agency.
TRS	Technical Report Series.
IAEA TRS-398	An international code of practice for the absorbed dose determination in external beam radiotherapy, published by the IAEA on its own behalf, and on behalf of the World Health Organisation (WHO), the Pan American Health Organisation (PAHO) and the European Society of Therapeutic Radiology and Oncology (ESTRO).
$E_o$	The mean electron energy of the incident spectrum striking the phantom surface.
$E$	The mean energy of an electron beam at any depth.
MV	Megavoltage.
Q	The beam quality in the user's photon or electron beam for which clinical reference dosimetry is performed. For photon beams it is in terms $TPR_{20,10}$ and for electron beams, in terms of $R_{50}$ . However, in this report Q is used exclusively for photon beams and $q,E$ is for electron beams.
<i>SAD</i>	Source-axis distance.
<i>SSD</i>	Source-surface distance.
<i>TPR</i>	Tissue phantom ratio.

NAP	Nominal accelerating potential.
$q_{ecal}$	An arbitrary electron beam quality taken as $R_{50}= 7.5$ cm. It is introduced to simplify the factors needed in electron beam dosimetry in IAEA TRS-398.
$TPR_{20,10}$	The ratio of doses on the beam central axis at depths of 20 cm and 10 cm in a water phantom, obtained with a constant source-chamber distance of 100 cm and a field size of 10 cm x 10 cm at the plane of the chamber.
$N_{D,w}^{60Co}$	The absorbed dose to water calibration factor (in Gy/C) for the ionisation chamber in the reference $^{60}Co$ beam.
$N_{D,w}^{q,E}$	The absorbed dose to water calibration factor (in Gy/C) for the ionisation chamber in an electron beam of quality $q,E$ .
$k_Q$	A chamber specific factor which corrects the absorbed dose to water calibration factor in a $^{60}Co$ beam to another photon beam of quality $Q$ .
$k_{q,E}$	$k_{q,E}$ is a beam quality conversion factor for electrons to convert $N_{D,w}^{60Co}$ to $N_{D,w}^{q,E}$ for an electron beam of quality $q,E$ . In this report, the notation $k_{q,E}$ is adopted for electron beam qualities to distinguish it from $k_Q$ for photon beam qualities.
$k_{ecal}$	The photon to electron conversion factor defined for a given chamber model that converts the absorbed dose to water calibration factor at $^{60}Co$ to the absorbed dose to water calibration factor in the electron beam of quality $q_{ecal}$ .
$k'_{R_{50}}$	The electron quality conversion factor used to convert $N_{D,w}^{q_{ecal}}$ into the absorbed dose to water calibration factor $N_{D,w}^{q,E}$ for any electron beam of quality $q,E$ .
$D_w$	The absorbed dose to water for a particular set up and monitor units.

MU	The number of monitor units or time for which a given irradiation is performed.
$P_{cav}$	Factor that corrects the response of an ionisation chamber for effects related to the air cavity ; predominately the in-scattering of electrons that makes the electron fluence inside a cavity different from that in the absence of the cavity.
$P_{gr}$	Corrects for the gradient effects at the reference depth when a cylindrical chamber is used in an electron beam, and depends on the ionisation gradient at the point of measurement.
SSDL	Secondary Standards Dosimetry Laboratory.
BIPM	Bureau International de Poids et Mesure, Paris.
PTB	Physikalisch-Technische Bundesanstalt.
PTW	Physikalisch Technische Werkstätten.

## CHAPTER ONE: INTRODUCTION

### 1.1 Introduction

The International Atomic Energy Agency and the American Association of Physicists in Medicine are among the various organisations that have published dosimetry protocols and Codes of Practice for the calibration of radiotherapy beams (Pedro & Saiful, 2001). Currently an ionisation chamber, calibrated in terms of the absorbed dose to water in a  $^{60}\text{Co}$  gamma ray beam, is used to determine the dose in a medium. The rationale of this trend is to deal directly with absorbed dose to water, a quantity which relates closely to radiobiological effects in humans and is therefore of interest in the clinic (IAEA, 2000). This approach offers the possibility of reducing the uncertainty in dosimetry compared to air kerma based formalisms, provides a robust system of primary standards with dissemination and allows the use of a simple formalism (IAEA, 2000; Pedro & Saiful, 2004; Saiful, 2001). The formalism and dosimetry procedures use the absorbed dose to water calibration factor of an ionisation chamber at  $^{60}\text{Co}$   $\left(N_{D,w}^{60\text{Co}}\right)$  together with a theoretical beam quality conversion factor ( $k_Q$  for photons or  $k_{q,E}$  electrons) for the determination of absorbed dose to water in other high-energy beams excluding neutrons (IAEA, 2000; Saiful, 2001). The absorbed dose to water in a  $^{60}\text{Co}$  gamma ray beam is therefore an international reference standard, which provides global uniformity in radiotherapy dosimetry. This study aimed at determining the beam quality correction factors for several different ionisation chambers, which could be used in the measurement of absorbed dose to water in high-energy photon and electron beams at the Charlotte Maxeke Johannesburg Academic Hospital.

### 1.2 Background to the problem

Measurements in radiotherapy dosimetry are either relative or absolute. In absolute dosimetry, the physical quantity is measured at the reference point under reference conditions to yield the absorbed dose to water at the reference point (European Medical Radiation Learning Development, 2001).

It is imperative to determine dose as accurately and precisely as possible in order to deliver the prescribed dose to a point or a given volume of interest (AAPM, 1983). There are

different parameters that enter into the formalisms for determination of absorbed dose to water. These physical quantities need to be studied carefully and accurately in order to determine the absorbed dose to water within uncertainties of  $\pm 3.5\%$  or better (IAEA, 2000). It is known for example, that the relative uncertainty of ionometric determinations of absorbed dose to water in reference dosimetry of high-energy photon beams is dominated by the uncertainty of the calculated chamber- and energy-dependent correction factors,  $k_Q$  (Achim & Ralf-Peter, 2007).

Many reviewers (Hugo et al., 2002; Podgorsak, 2005; Rogers, 1990) recommend that the beam quality correction factors for megavoltage radiotherapy beams are measured directly in the user's beam for each ionisation chamber. Often these factors are calculated theoretically from data available in different protocols. It is known that  $k_Q$  can be measured with a standard uncertainty of less than 0.3% (Achim & Ralf-Peter, 2007; IAEA, 2000; Saiful, 2001).

The experimental determination of  $k_Q$  and  $k_{q,E}$  at various beam qualities intrinsically takes into account the response of different ionisation chambers. In contrast, the calculated values of  $k_Q$  ignore chamber-to-chamber variations in response to energy within a given chamber type, and its uncertainty is therefore larger than for experimentally determined  $k_Q$  values (Saiful, 2001). Direct calibration, in terms of absorbed dose to water at each beam quality, reduces the total uncertainty of absorbed dose determination in the user's beam by 1–1.5% (Hugo, Wim & Hubert, 1999). This study aimed at determining the beam quality correction factors for several different ionisation chambers used for the dosimetry of high-energy photon and electron beams at the Charlotte Maxeke Johannesburg Academic hospital.

### **1.3 Statement of the problem**

Many reviewers recommend that the beam quality correction factors for radiotherapy megavoltage beams are measured directly in the user's beam for each ionisation chamber. Can the beam quality correction factors of different ionisation chambers at different high-energy photon and electron beams be determined accurately in a clinical set up?

## 1.4 Objectives of the study

The primary aim of this study is to experimentally determine the  $k_Q$  and  $k_{q,E}$  factors for different ionisation chambers in a range of high-energy photon and electron beams used at the Charlotte Maxeke Johannesburg Academic hospital. The specific aims of the study were fourfold;

- Cross-calibrate the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber, a PTW 31006 ‘Pinpoint’ ionisation chamber, a PTW 31010 0.125 cm<sup>3</sup> ionisation chamber, a PTW 23343 Markus and a PTW 34045 Advanced Markus ionisation chamber against a PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber which has a traceable calibration.
- Determine the absorbed dose-to-water in a range of photon and electron beams using IAEA TRS-398 with the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber with  $N_{D,w}^{60Co}$  and  $N_k^{60Co}$  calibration factors of proven stability and traceability and IAEA TRS-398 published  $k_Q$  and  $k_{q,E}$  values.
- Measure the response of the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber, the PTW 31006 ‘Pinpoint’ ionisation chamber, and the PTW 31010 0.125 cm<sup>3</sup> ionisation chamber in the photon beams.
- Measure the response of the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber, the PTW 31006 ‘Pinpoint’ ionisation chamber, the PTW 31010 0.125 cm<sup>3</sup> ionisation chamber, the PTW 23343 Markus and the PTW 34045 Advanced Markus ionisation chamber in the electron beams.
- Compare the experimentally determined values of  $k_Q$  and  $k_{q,E}$  with published ones for the PTW 30013 0.6 cm<sup>3</sup> and PTW 23343 Markus ionisation chambers, respectively.
- Derive  $k_Q$  and  $k_{q,E}$  for the PTW 31010 0.125 cm<sup>3</sup>, PTW 31006 ‘Pinpoint’ and PTW 34045 Advanced Markus models of ionisation chambers for which published data do not exist.

## CHAPTER TWO: LITERATURE REVIEW

### 2.1 Photon beam dosimetry

The absorbed dose to water  $D_w$ , at a reference depth in a photon beam of quality  $Q$ , and in the absence of an ionisation chamber is determined from:

$$D_w = M \cdot N_{D,w}^{60Co} \cdot k_Q \cdot \prod k_i, \dots\dots\dots (1)$$

where

- $M$  is the charge measured under standard conditions of temperature, pressure and humidity.
- $N_{D,w}^{60Co}$  is the absorbed dose to water calibration factor (in Gy/C) for the ionisation chamber in the  $^{60}Co$  reference beam.
- $k_Q$  is a chamber specific factor which corrects  $N_{D,w}^{60Co}$  to the user's beam quality  $Q$  (different from the  $^{60}Co$  beam).
- $\prod k_i$  is the product of the factors to correct for non-reference conditions in the setup and incomplete ion collection efficiency of the ionisation chamber (Rogers, 1990). Factors  $k_i$  represent a correction for the effect of  $i$ -th influence quantity. Such correction factors may have to be applied as the calibration coefficient refers, strictly speaking, only to reference conditions. By definition, the value of  $k_i$  is unity when influence quantity  $i$ , assumes its reference value (Rogers, 1990).

The product  $N_{D,w}^{60Co} \cdot k_Q (= N_{D,w}^Q)$  is of special interest and is the absorbed dose to water calibration factor (in Gy/C) of the ionisation chamber in the beam quality  $Q$ . The current accepted relative uncertainty of  $D_w$  in equation (1) is of the order of 1.5% as determined by ionometric methods and the uncertainty in  $k_Q$  is 1% (Achim & Ralf-Peter, 2007).

## 2.2 Electron beam dosimetry

According to AAPM TG-51(Almond et al., 1999), the absorbed dose to water in an electron beam of quality  $q,E$  is given by;

$$D_w^{q,E} = M \cdot N_{D,w}^{60Co} \cdot k_{q,E} \dots\dots\dots (2)$$

where

- $M$  is the reading of the dosimeter with the *point of measurement* of the chamber positioned at the reference depth under reference conditions and corrected for ion recombination, polarity effect, electrometer correction factor and the standard environmental conditions of temperature, pressure and relative humidity of the air in the ion chamber.
- $N_{D,w}^{60Co}$  is the absorbed dose to water calibration factor (in Gy/C) of the ionisation chamber in the reference  $^{60}Co$  beam.
- $k_{q,E}$  is a beam quality conversion factor for electrons to convert  $N_{D,w}^{60Co}$  to  $N_{D,w}^{q,E}$  for an electron beam of quality  $q,E$ .

## 2.3 Beam quality specification

Among the difficulties of the  $k_Q$  and  $k_{q,E}$  concept is the need for a unique beam quality specification and the possible variation in the  $k_Q$  and  $k_{q,E}$  values for different chambers of the same type (Hugo, Wim & Hubert, 1999). The AAPM TG-21 (AAPM, 1983) protocol specifies photon beam energy in terms of the energy of the electron beam as it strikes the target (the nominal accelerating potential) which is related to the “ionisation ratio”. The ionisation ratio is defined as the ratio of the ionisation charge or dose measured at 20 cm depth in water to that measured at 10 cm depth for a constant source to detector distance in a 10 cm x 10 cm field at the plane of the chamber. The ionisation ratio is the same as the  $TPR_{20,10}$  expression used by the IAEA TRS-398 (IAEA, 2000)dosimetry protocol. The ionization ratio or  $TPR_{20,10}$  is a measure of the effective beam attenuation coefficient through 10 cm of water.  $TPR_{20,10}$  is empirically related to the percentage depth dose, through

$$TPR_{20,10} = 1.2661PDD_{20,10} - 0.0595 \dots\dots\dots (5)$$

where  $PDD_{20,10}$  is the ratio of percentage depth doses at 20 cm and 10 cm depths for a field size of 10 cm x 10 cm field size defined at the water phantom surface with a source to surface distance of 100 cm ( IAEA, 2000; Podgorsak, 2005).

When linear accelerator electron beams strike a phantom or a patient surface at the nominal SSD, a spectrum results from the energy spread. This is caused by interactions within the air and with the linear accelerator components like the collimators, scattering foil, monitor chamber and applicator. The electron beam is therefore degraded and contaminated. The quality of clinical electron beams has been specified as  $E_o$ , the mean electron energy of the incident spectrum striking the phantom surface (Podgorsak, 2005).  $E_o$  is empirically derived from  $R_{50}$ , the depth at which the electron beam depth dose decreases to 50% of its maximum value (IAEA, 2000). The reference depth  $d_{ref}$ , for electron beam calibrations in water is expressed as

$$d_{ref}(\text{cm}) = 0.6R_{50}(\text{cm}) - 0.1(\text{cm}) \dots\dots\dots (6)$$

The reference depth  $d_{ref}$  is used clinically because it is known to significantly reduce machine to machine deviations in chamber calibration coefficients (Hugo et al., 2002).

**2.3.1 Photon beam quality specification**

The use of ionisation ratios for the determination of photon beam quality indices provides an acceptable accuracy owing to the slow variation with depth of water/air stopping power ratios (Podgorsak, 2005) and the assumed constancy of ionisation chamber perturbation factors beyond the depth of maximum dose.

For high-energy beams,  $TPR_{20,10}$  is an insensitive quality specifier. For example a 1% change in  $TPR_{20,10}$  for values near 0.8 leads to a 3 MV change in the nominal accelerating potential (near 20 MV) and a 0.4% change in the water to air stopping-power ratio. In contrast, for values of  $TPR_{20,10}$  near 0.7 a 1% change corresponds to a 0.1% change in stopping-power ratio and only 0.5 MV change in the nominal accelerating potential (Rogers, 1990).

### 2.3.2 Electron beam quality specification

The beam quality index for electron beams is the half-value depth ( $R_{50}$ ) in water. This is the depth in water at which the electron beam depth dose decreases to 50% of its maximum value, measured with a constant SSD of 100 cm and a reference field size at the phantom surface. Different protocols recommend different field sizes for different mean incident electron energies. According to IAEA TRS 398, the field sizes should be at least 10 cm x 10 cm for  $R_{50} \leq 7 \text{ g/cm}^2$  ( $E_0 \leq 16 \text{ MeV}$ ) and at least 20 cm x 20 cm for  $R_{50} > 7 \text{ g/cm}^2$  ( $E_0 \geq 16 \text{ MeV}$ ). The AAPM TG-51 recommends the field size to be greater than 20 cm x 20 cm for  $R_{50} > 8.5 \text{ cm}$ , i.e.,  $E > 20 \text{ MeV}$ , where  $E_0$  and  $E$  is the mean energy of an electron beam at the phantom surface and at any depth, respectively. Nitschke (1998) recommends a field size of at least 12 cm x 12 cm for  $E_0 < 15 \text{ MeV}$  or 20 cm x 20 cm for  $E_0 \geq 15 \text{ MeV}$ . A plane parallel chamber is recommended for  $E_0 \leq 10 \text{ MeV}$  (AAPM, 1983; IAEA, 1987; AAPM, 1991, IAEA, 2000) and for all relative dose measurements.

The use of  $R_{50}$  as the beam quality index is a simplification and a change from specifying beam quality in terms of mean electron energy ( $E_0$ ) of the incident spectrum striking the phantom surface.

One way of determining  $R_{50}$  is to determine the 50% ionization,  $I_{50}$  in a water phantom at an SSD of 100 cm from the relative depth-ionization curve. For cylindrical chambers, there is a need to correct for gradient effects by shifting the relative depth-ionization curve upstream by  $0.5 r_{\text{cav}}$ , the radius of the air cavity in a chamber in question. For plane-parallel chambers no shift is needed, as the effective point of measurement is at the inside surface of the front electrode which is at the point of interest. All the readings must be corrected for ion recombination and polarity (IAEA, 2000; Khan, 2003).

As an alternative the percentage depth dose curve can be determined directly using a good quality diode detector. This requires test comparisons with an ionisation chamber in order to establish whether the diode is suitable for depth dose measurements or not (Almond et al., 1999).

If a plastic phantom is used for measuring dose, the values of the depths are scaled to water equivalent depths (IAEA, 1987; Nitschke, 1998)  $d_w$  according to

$$d_w = d_{pl} C_{pl} \dots\dots\dots (7)$$

$C_{pl}$  is the plastic to water depth scaling factor and the reading in plastic is scaled to the equivalent reading in water according to

$$M = M_{pl} h_{pl} \dots\dots\dots (8)$$

where  $M$  is the reading when the chamber is used with plastic and  $h_{pl}$  is a material dependent fluence scaling factor to correct for the differences in electron fluence in plastic compared with that in water at the equivalent depth.

The plastic material should be conductive. However, insulating materials can be used provided the problems resulting from charge storage are considered. The effect of charge storage can be minimized by using sheets not exceeding 2 cm in thickness (IAEA, 2000).

**2.4 Theoretical expressions for the beam quality correction factors in high energy photon and electron beams.**

**2.4.1 Theoretical expression for  $k_Q$  (photon beams).**

The  $k_Q$  factor can be calculated using two different methods. The first method applies the AAPM TG-51 formalism (Almond et al., 1999).

$$k_Q = \frac{\left[ P_{wall} P_{repl} \left( \frac{\bar{L}}{\rho} \right)_{air}^w \right]_Q}{\left[ P_{wall} P_{repl} \left( \frac{\bar{L}}{\rho} \right)_{air}^w \right]_{Q_0}} \dots\dots\dots (9)$$

where

- $p_{repl} = p_{gr} \cdot p_{fl} \dots\dots\dots (10)$

$p_{gr}$  accounts for the fact that the cavity introduced by a cylindrical chamber with its centre at the reference depth, samples the electron fluence at a point which is closer to the radiation source than the reference depth.  $p_{gr}$  depends on the inner radius of the cavity of the ionisation chamber (Ma & Nahum, 1995). The cavity correction  $p_{fl}$  corrects for the perturbation of the electron fluence due to scattering differences between the air cavity and the medium (Pedro & Saiful, 2001).

- $p_{wall}$  accounts for the differences in the photon mass energy-absorption coefficients and the electron stopping powers of the chamber wall material and the medium. If the central electrode of a cylindrical ionisation chamber is not air equivalent, a correction  $P_{cell}$ , would also need to be made for this lack of equivalence.

- $\left(\frac{\bar{L}}{\rho}\right)_{air}^w$  is the mean restricted collision mass stopping power of water to air (AAPM, 1983).

The second method uses the IAEA TRS-398 formalism (IAEA, 2000; ARPANSA, 2001; Achim & Ralf-Peter, 2007):

$$k_Q = \frac{(S_{w,air})_Q \cdot (W_{air})_Q \cdot p_Q}{(S_{w,air})_{60Co} \cdot (W_{air})_{60Co} \cdot P_{60Co}} \dots\dots\dots(11)$$

where,

- $(S_{w,air})_x$  is the Spencer-Attix water to air stopping-power ratio for beam quality  $x$ , which is the ratio of the mean restricted mass stopping powers of water to air, averaged over a complete spectra.
- $W_{air}$  is 33.7 J/C, the mean energy expended in air per ion pair formed.
- $p_x$  is the perturbation factor (includes the displacement effect) taking into account the deviations from the ideal Bragg-Gray conditions when real ionisation chambers are used.

#### 2.4.2 Theoretical expression for $k_{q,E}$ (electron beams).

According to Khan (Khan, 2003) the electron beam quality conversion factor  $k_{q,E}$  is given as

$$k_{q,E} = P_{gr}^{q,E} \cdot k_{R_{50}}' \cdot k_{ecal} \dots\dots\dots(12)$$

where

- $P_{gr}^{q,E}$  corrects for the gradient effects at the reference depth when a cylindrical chamber is used in an electron beam, and depends on the ionisation gradient at the point of measurement (Kubo, Kent & Krithivas, 1986).
- $k_{ecal}$  is the photon to electron conversion factor (Almond et.al., 1999) defined for a given chamber model and is used to convert the absorbed dose to water calibration

factor at  $^{60}\text{Co}$ ,  $N_{D,w}^{60\text{Co}}$  into  $N_{D,w}^{q_{ecal}}$ , the absorbed dose to water calibration factor in the electron beam of quality  $q_{ecal}$ , i.e.

$$k_{ecal} N_{D,w}^{60\text{Co}} = N_{D,w}^{q_{ecal}} \dots\dots\dots (13)$$

- $k'_{R_{50}}$  is the electron quality conversion factor used to convert  $N_{D,w}^{q_{ecal}}$  into  $N_{D,w}^{q,E}$  for any beam quality  $q,E$ , i.e.

$$k'_{R_{50}} N_{D,w}^{q_{ecal}} = N_{D,w}^{q,E} \dots\dots\dots (14)$$

where  $R_{50}$  is usually fixed at  $7.5 \text{ g cm}^{-2}$  for nominal energies of 3 MeV to 50 MeV and with field sizes  $\geq 10 \text{ cm} \times 10 \text{ cm}$  (Almond et.al., 1999).

### 2.5 Reference conditions of the irradiation geometry for absorbed dose measurements using an ionisation chamber in a phantom.

A water phantom is the reference medium for the absorbed dose measurements. For absolute dose measurements in electron beams with  $E_0 < 10 \text{ MeV}$  and for relative dose measurements, a plastic phantom may be used but depths and ranges must be converted to the water equivalent. There should be a margin of at least 5 cm on all sides of the largest field size used at measurement depth, and beyond the maximum depth of measurement. The chamber is always used with its effective point of measurement at the reference depth. The effective point of measurement for a plane parallel chamber is the inside surface of the front electrode (IAEA, 2000).

## CHAPTER THREE: MATERIALS AND METHODS

### 3.1 The Charlotte Maxeke Academic Hospital Johannesburg linear accelerator.

Two Siemens PRIMUS™ linear accelerators (LINACS) were used for the measurements. Figure 3.1 shows one of the accelerators used. These linear accelerators can generate collimated photon beams with nominal accelerating voltages of 6 and 18 MV and electron energies of 5, 6, 7, 9, 12, 14, 15, 18 and 21 MeV. The output rate of the linear accelerator is 200 MU/min for 6 MV and 300 MU/min for 18 MV and the electron modes. The machine delivers 1 Gy/ 100 MU in a 10 cm x 10 cm field size at a point in a 4.4 cm build up of perspex phantom, 100 cm from the source focus in the photon beams referenced to the PTW 23333 ionisation chamber. For electrons, the machine likewise delivers 1 Gy/ 100 MU at the central axis depth of maximum dose at 100 cm SSD in a field size defined by a 10 cm x 10 cm applicator. The applicator is such that there is an air gap of 5 cm between the end face and the phantom surface.



**Figure 3.1:** A Siemens PRIMUS linear accelerator used in this study.

### 3.2 The Theratron Equinox External Beam Therapy System.

The  $^{60}\text{Co}$  beam used in this study is produced by a Theratron Equinox<sup>TM</sup> External Beam Therapy System (Figure 3.2). This model is an 80 cm SAD unit. The therapy source used is a sealed capsule. The head of the machine is shielded with lead. A pneumatic air system controls the source drawer, which drives the source from the fully shielded position to the fully exposed position. The source drawer is a cavity of approximately 2.8 cm diameter by 12 cm long, held in place with an end plug and securing clip. The machine is equipped with a display monitor, to display beam parameters, primary and secondary timers and system messages. The control panel allows for treatment control and monitoring. The source is a metallic isotope of  $^{60}\text{Co}$ , sealed in two stainless steel capsules of approximately 1.5 cm in diameter and 3 cm long. The  $^{60}\text{Co}$  nuclei decay to  $^{60}\text{Ni}$  with emission of gamma rays of energies of 1.17 MeV and 1.33 MeV. The half-life of  $^{60}\text{Co}$  is 5.26 years.



**Figure 3.2:** The Theratron Equinox<sup>TM</sup> External Beam Therapy System used in this study.

### 3.3 Ionisation chambers

Four cylindrical and two parallel plate ionisation chambers were used in this study. The PTW cylindrical chambers were of the type PTW 23333 0.6 cm<sup>3</sup>, 30013 0.6 cm<sup>3</sup>, 31006 ‘Pinpoint’ and PTW 31010 0.125 cm<sup>3</sup>, and the PTW plane-parallel chambers were of the type PTW 23343 Markus and 34045 Advanced Markus. The PTW 23333 0.6 cm<sup>3</sup> is the reference ionisation chamber of Charlotte Maxeke Johannesburg Hospital. The PTW 23333 0.6 cm<sup>3</sup> is of proven stability with a drift of only 0.3% between 1997 and 2005. A track record of its absorbed dose to water calibration factors over the years is presented in Table 3.1. The uncertainty budget for its  $N_x$  and  $N_{gas}$  is shown in Table 3.2.

**Table 3.1:** The calibration factor history of the PTW 23333 reference ionisation chamber.

Calibration Date	$N_{D,w}^{60Co}$	Stated uncertainty
Feb –1992	0.516 Gy/V, 10.122 nF (= 5.098 E+07 Gy/C)	5.0%
Oct-1997	5.182 E+07 Gy/C	2.2%
Oct-2005	5.198 E+07 Gy/C	2.2%

**Table 3.2:** The uncertainty budget of  $N_x$  and  $N_{gas}$  of the ionisation chambers used in this study.

UNCERTAINTY BUDGET FOR $N_x$	
Contributing components	Uncertainty
$D_w$ from IAEA/RS-398	-1.1%
Backscatter	+1.5%
$F_{med}$	-1.5 %
In-air measurement	+1.5%
<b>Uncertainty</b>	$\sqrt{(1.1^2 + 1.5^2 + 1.5^2 + 1.5^2)} = 2.8\%$
UNCERTAINTY BUDGET FOR $N_{gas}$	
Contributing components	Uncertainty
$N_x$	2.8%
$W/e$	0.2%
<b>Uncertainty</b>	$\sqrt{(2.8^2 + 0.2^2)} = 2.8\%$

The PTW 30013 0.6 cm<sup>3</sup> model was selected for this work because of its geometric equivalence to the PTW 23333 0.6 cm<sup>3</sup>, its proven stability, and because it was representative of a series of over seven ionisation chambers used for the daily calibration of the teletherapy machines at the facility. The PTW 31006 ‘Pinpoint’ and PTW 31010 0.125 cm<sup>3</sup> ionisation chambers are often employed in relative dosimetry measurements in high dose gradient regions of clinical beams, e.g. the penumbra and small field beam dosimetry. The PTW 31006 is recommended for stereotactic field measurements in radiation therapy.

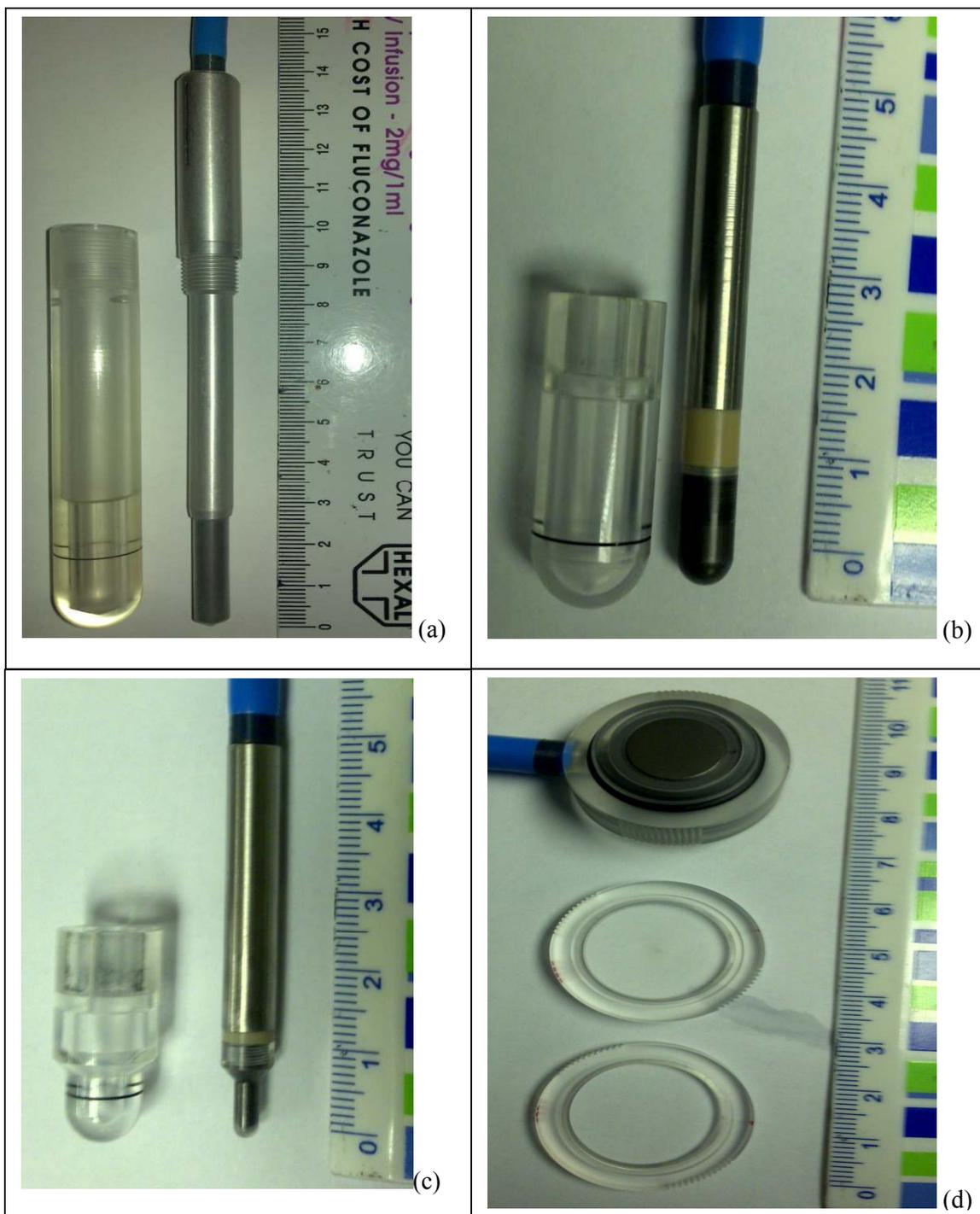
The PTW 23343 Markus and PTW 34045 Advanced Markus plane- parallel ionisation chambers are used for absolute and relative dosimetry in high-energy electron beams. The Markus chamber has a volume of 0.055 cm<sup>3</sup> and the Advanced Markus has a volume of 0.02 cm<sup>3</sup>. The Advanced Markus is marketed as a perturbation-free version of the Markus chamber.

The plane-parallel chambers have nominal useful ranges of energies of 2 MeV to 45 MeV. The nominal useful range for the cylindrical chambers is from <sup>60</sup>Co to 50 MV for photons and from 10 to 45 MeV for electrons. The 31010 0.125 cm<sup>3</sup> exceptionally covers a useful range of 66 keV to 50 MeV for electron beams. The description of the wall, build up caps and the various dimensions for the six ionisation chambers are shown in Table 3.3. Figure 3.3 shows the apparatus used for this study. The measurement volumes of all the above chambers are vented, fully guarded and suitable for use in solid state phantoms.

**Table 3.3:** The characteristics of the different ionisation chambers types used in this study.

Ionisation chamber type	Cavity volume (cm <sup>3</sup> )	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness (g cm <sup>-2</sup> )	Central electrode material	Water proof
PTW 23333 (4.6 mm cap)	0.6	21.9	3.0505	PMMA	0.053	Aluminium	No
PTW 30013 Farmer	0.6	23	3.0505	PMMA	0.057	Aluminium	Yes
PTW 31010	About 0.125	0.325	0.36	PMMA +Graphite	0.055 +0.015	Aluminium 99.98 R	Yes
PTW 31006 Pin point	0.015	5	1.00	PMMA +Graphite	0.056 +0.015	Steel	Yes
PTW 34045 Advanced Markus	0.02		2.50	CH <sub>2</sub> Polyethylene	0.003	-	Yes
PTW 23343 Markus	0.055		2.65	CH <sub>2</sub> Polyethylene	0.003	Acrylic + graphite coated	Yes

The electrode separation and the guard ring width for the PTW 23343 Markus are 2.00 mm and 0.2 mm respectively. The electrode separation and the guard ring width for the PTW 34045 Advanced Markus are 1.00 mm and 2.0 mm respectively.



**Figure 3.3:** Photographs of the ionisation chambers used in this study. (a) The PTW 23333 0.6 cm<sup>3</sup> chamber/ PTW 30013 0.6 cm<sup>3</sup> chamber, (b) The PTW 31010 0.125 cm<sup>3</sup> chamber (c) The PTW 31006 ‘Pinpoint’ 0.015 cm<sup>3</sup> chamber (d) The PTW 34045 0.02 cm<sup>3</sup> Advanced Markus chamber/ PTW 23343 0.055 cm<sup>3</sup> Markus chamber.

### 3.4 Perspex phantom

The exposure readings in all the photon and electron measurements were taken in solid perspex sheet phantoms. The perspex media was preferred to water because set-ups are more reproducible especially with respect to depth and the reference chamber used in this study was not waterproof. The perspex phantoms were of dimensions 30 cm x 30 cm x 30 cm and in thermodynamic equilibrium with the treatment rooms.

### 3.5 Other materials used

The electrometer used was a PTW Unidos E T10008 (see Figure 3.4) capable of positive and negative polarity settings over a range of 0 to 400 V in intervals of 50 V. For in air dosimetric methods, a retort stand was used to hold the chamber firmly at the measurement point.



**Figure 3.4:** The PTW T10008 Unidose E Electrometer

### 3.6 The cross-calibration of ionisation chamber in photon and electron beams.

Except for the PTW 23343 Markus ionisation chamber, the absorbed dose to water  $N_{D,w}^{60Co}$  calibration factors for all the other ionisation chambers were available from the PTW standards dosimetry laboratory in Germany. All the  $N_{D,w}^{60Co}$ ,  $N_x$  and  $N_k$  calibration factors for the different ionization chambers were independently cross-calibrated in the  $^{60}Co$  beam against the calibrated PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber.  $N_{gas}$  for the plane parallel chambers was derived from the cross-calibration at 21 MeV against the reference

ionisation chamber. The recommendations of the AAPM TG-21 and IAEA TRS-398 protocols were followed for the cross-calibration procedures.

### 3.6.1 Cross-calibration of the $N_{D,w}^{60Co}$ for ionisation chambers in $^{60}Co$ beam.

The absorbed dose to water calibration factors for any ionisation chamber Y, under test against a reference ionisation chamber ref, is given by

$$(N_{D,w}^{60Co})_Y = \frac{(M)_{ref}}{(M)_Y} \cdot (N_{D,w}^{60Co})_{ref} \dots\dots\dots (15)$$

Where  $(M)_{ref}$  and  $(M)_Y$  are the electrometer readings for an ionisation chamber in the  $^{60}Co$  beam for the reference and the chamber under test, respectively.

### 3.6.2 Cross-calibration of the $^{60}Co$ exposure calibration factor $N_x$ 's.

The  $^{60}Co$  exposure calibration factor  $N_x$  for the PTW 23333 0.6 cm<sup>3</sup> was calculated using

$$(N_x)_{AAPMTG-21} = \frac{(D_w)_{IAEATRS-398}}{(MfA_{eq}BSF)_{AAPMTG-21}} \dots\dots\dots (16)$$

Where  $D_w$  is as given in equation (1); f is 0.967 cGy/R, the dose to water per roentgen of exposure;  $A_{eq}$  is 0.989, a factor that accounts for attenuation and scattering in a small mass of water of 0.5 cm radius at the reference depth;  $BSF$  is the 0.5 cm depth tissue air ratio; and M (nC) is the electrometer reading for 10 cm x 10 cm field size, normalized to 20°C temperature and a pressure of one standard atmosphere and corrected for timer errors in accordance with the IAEA TRS-398 formalism i.e.

$$M = \frac{M_{raw}}{t + \tau} \cdot k_{TP} \cdot k_{pol} \cdot k_{elec} \cdot k_s \dots\dots\dots (17)$$

where  $M_{raw}$  the uncorrected reading,  $\tau$  is the timer error,  $k_{TP}$  is temperature pressure correction factor,  $k_{elec}$  is the electrometer calibration correction factor and  $k_s$  is the recombination correction factor.

### 3.6.3 Cross-calibration of the $N_{gas}$ for plane-parallel chambers in electron beams.

The plane-parallel chambers were cross-calibrated against the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber whose replacement correction ( $P_{rep}$ ) was 0.994 at 21 MeV, the highest electron energy available at the department. The AAPM TG-21 formalism was used i.e.

$$(N_{gas})^{p-p} = \frac{(MN_{gas} P_{ion} P_{repl})^{cylin}}{(MP_{ion})^{p-p}} \dots\dots\dots (18)$$

where  $M$  is the response of the chamber in question at  $d_{max}$ ,  $p-p$  and  $cylin$  refer to the plane-parallel and cylindrical chambers respectively.

### 3.7 The absorbed dose measurement in megavoltage photon beams.

The charge readings at a point in the perspex phantom were measured with ionization chambers with the center of the sensitive volume placed at 4.4 cm depth, the water equivalent reference depth as used for calibration of the ionisation chambers in the <sup>60</sup>Co beams i.e. 5 cm of water. The centers of the chambers were aligned with the isocentre of the treatment machine. The dose was referenced to the PTW 23333 0.6 cm<sup>3</sup> ionisation chamber using its <sup>60</sup>Co absorbed dose to water calibration factor  $N_{D,w}^{60Co}$ . The dose to water at the reference depth with the chamber removed was calculated using equation (1).

The chambers and the perspex phantom were allowed to equilibrate with the ambient air temperature. With the PTW 23333 0.6 cm<sup>3</sup> reference chamber connected to the electrometer and the machine in the beam off mode, the leakage at the positive polarity of the electrometer was -0.023 nC (with medium range settings, 12.0 nA) for 732.0 seconds.

Charge readings were taken for 100 monitor units. The measurements were repeated three times at each polarity of each ionization chamber. The mean value of the readings was then calculated. Throughout the study, the absolute value of the polarising voltages was maintained at either +400V, -400V or +200 V. The readings were corrected for the standard environmental conditions of temperature and pressure, ion recombination and polarity effects but the humidity corrections were not considered. The resultant corrected charge reading and the known absorbed dose rate to the water under reference conditions were used to derive the calibration factor for each cylindrical ionization chamber  $N_{D,w}^Q$ . The measurement of absorbed dose to water requires a beam quality specifier  $TPR_{20,10}$ . The

beam quality specifier  $TPR_{20,10}$  for the two photon energies (6 MV and 18 MV) was 0.674 and 0.770, respectively.

### 3.8 The absorbed dose measurement in electron beams.

The charge readings for 100 monitor units in a perspex phantom were measured with the centre of the sensitive volume of the ionization chambers placed at the depth of maximum dose, at a constant source to surface distance of 100 cm, in a 10 cm x 10 cm field size. The chambers and the perspex phantom were allowed to equilibrate with the ambient air temperature. The chambers were first cross-calibrated for  $N_{gas}$  against the cylindrical reference ionisation chamber at 21 MeV using equation (18).

The measurements were repeated three times at each polarity of the ionization chamber. The mean value of the readings was then calculated. Throughout the study, the absolute value of the polarising voltages was maintained at either +400V, -400V or +200 V. The readings were corrected for the standard environmental conditions of temperature and pressure, ion recombination and polarity effects. Humidity corrections were not considered. Equation (2) was used for the determination of absorbed dose to water. Table 3.4 shows the beam characteristics used for the measurement and calculation process.

**Table 3.4:** The beam characteristics for the clinical electron beams and the mean restricted collision mass stopping power of perspex to air used in this study.

Energy (MeV)	$R_{50}$ /(cm)	$E_o$ /(MeV)	$d_{max}$ /(cm)	$R_p$ / cm	$E_{dmax}$	$\left(\frac{\bar{L}}{\rho}\right)_{air}^{perspex}$
5	2.05	4.77	1.17	2.5	2.60	1.038
6	2.40	5.58	1.38	3.0	3.04	1.028
7	2.75	6.41	1.59	3.5	3.50	1.020
9	3.51	8.18	2.03	4.5	4.46	1.006
12	4.68	10.90	2.66	6.0	6.15	0.988
14	5.28	12.31	2.89	7.0	7.31	0.977
15	5.93	13.83	2.64	7.5	9.77	0.968
18	7.30	17.01	2.03	9.0	13.91	0.947
21	8.23	19.19	1.40	11.5	18.51	0.939

$R_{50}$  is extracted from the commissioning data at Charlotte Maxeke Johannesburg Academic Hospital for the Siemens Primus linear accelerators.

### 3.9 Determination of beam quality correction factors

The photon beam quality correction factors were determined according to equation (1) in which the dose measured by PTW 23333 ionisation chamber was used as the reference dose. The corrected average measured charge readings and the absorbed dose to water calibration factor from the cross-calibration process in the  $^{60}\text{Co}$  were used for calculation i.e.

$$(k_Q)_Y = \frac{(D_w^Q)_{ref}}{M_Y^Q (N_{D,w}^{60Co})_Y} \dots\dots\dots(19)$$

Where Q denotes the quality of the beam in which the chambers ref and Y were used for beam quality correction measurements.

The electron beam quality correction factors ( $k_{q,E}$ ) were determined as the ratio of the absorbed dose to water calibration factors in the electron beam and the reference  $^{60}\text{Co}$  beam for that particular chamber Y (Hubert, Hugo & Wim, 1999, Achim & Ralf-Peter, 2007, González-Castaño et.al.,2009).

$$k_{q,E} = \frac{(N_{D,w}^{q,E})_Y}{(N_{D,w}^{60Co})_Y} \dots\dots\dots(20)$$

The absorbed dose to water calibration factors in the electron beam  $(N_{D,w}^{q,E})_Y$  is determined as the ratio of the absorbed dose to water measured by the PTW 23333 reference ionisation chamber to the absorbed dose to water measured by the chamber Y under test.

$$(N_{D,w}^{q,E})_Y = \frac{(D_{water} (at d_{max}))_{ref}^{q,E}}{(D_{water} (at d_{max}))_Y^{q,E}} \dots\dots\dots(21)$$

where  $(N_{D,w}^{60Co})_Y$  in equation (20) is obtained from the result of the cross-calibration in equation (15).

## CHAPTER FOUR: RESULTS AND DISCUSSIONS

### 4.1 The results of the cross-calibration of the ionisation chambers.

Measurements in all the photon beams were performed with the ionisation chambers using the PTW 23333 first, followed by the PTW 30013 0.6 cm<sup>3</sup>, the PTW 31006 ‘Pinpoint’, the PTW 31010 0.125 cm<sup>3</sup>, and then the PTW 23333 0.6 cm<sup>3</sup> again. The experiment with each ionisation chamber was repeated on three occasions and a mean value then calculated. The maximum deviation observed between any three measurements taken with all ionisation chambers was ± 0.01 nC. The experiment was carried out in May 2009 and July 2009 and no significant difference between the measurements was observed. As expected the <sup>60</sup>Co energy does not change and so any deviations would thus be attributed to the dosimetric apparatus’ drift. It was observed that the dosimetric apparatus showed no significant drift during the time of the study.

Table 4.1 shows the results of the measured  $N_{D,w}^{60Co}$  from the cross-calibration against the PTW 23333 0.6 cm<sup>3</sup> reference chamber. Also shown are the  $N_{D,w}^{60Co}$  values obtained from the PTW standards laboratory for each chamber.

**Table 4.1:** The absorbed dose to water calibration factors for the ionization chambers used in this study.

Chamber Model	Measured $N_{D,w}^{60Co}$ Gy/C (cross-calibration)	$N_{D,w}^{60Co}$ Gy/C (PTW Certificate) (±2.2%)	Deviation (%)
PTW 23333 0.6 cm <sup>3</sup>	Reference	5.198E+09 (Oct.2005)	-
PTW 30013 0.6 cm <sup>3</sup>	5.311E+07 ± 2.3%	5.315E+07 (Aug.2005)	0.1
PTW 31006 ‘Pinpoint’	2.528E+09 ± 2.7%	2.500E+09 (Jan.2000)	1.1
PTW 31010 0.125 cm <sup>3</sup>	3.034E+08 ± 3.3%	3.040E+08 (Jun.2006)	0.2
PTW 23343 Markus	5.385E+08 ± 2.8%	Not available	-
PTW 34045 Advanced Markus	1.293E+09 ± 3.3%	1.360E+09 (Aug.2005)	5.2

The <sup>60</sup>Co exposure calibration factor,  $N_x$  for the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber was 5.408E+09 R/C. This value compares well with 5.353 E+09 R/C, the value

calculated in 1998 at the same facility. The air-kerma calibration factor  $N_k$  for PTW 23333 0.6 cm<sup>3</sup> was 4.754E+07 Gy/C. This calibration factor was then used in the cross-calibration of other ionisation chambers in air and is shown in Table 4.2.

**Table 4.2:** The results of  $N_x$  and  $N_{gas}$  calibration factors for the ionization chambers used.

Chamber	$N_x / R/C$	$N_{gas} / Gy/C$
PTW 23333 0.6 cm <sup>3</sup>	5.408E +09	4.513 E +07
PTW 30013 0.6 cm <sup>3</sup>	5.473E+09	4.614 E +07
PTW 31006 ‘Pinpoint’	2.636E+11	2.256 E +09
PTW 31010 0.125 cm <sup>3</sup>	3.124E+10	2.625 E +08

The in-air measurements were taken for 0.5 minute irradiations in a <sup>60</sup>Co beam, at 80 cm source to chamber distance in a 10 cm x 10 cm field size, with the <sup>60</sup>Co build-up cap and using the T10008 electrometer. The polarity correction factor and recombination correction factor for the reference ionisation chamber was 0.999 and 1.002, respectively.

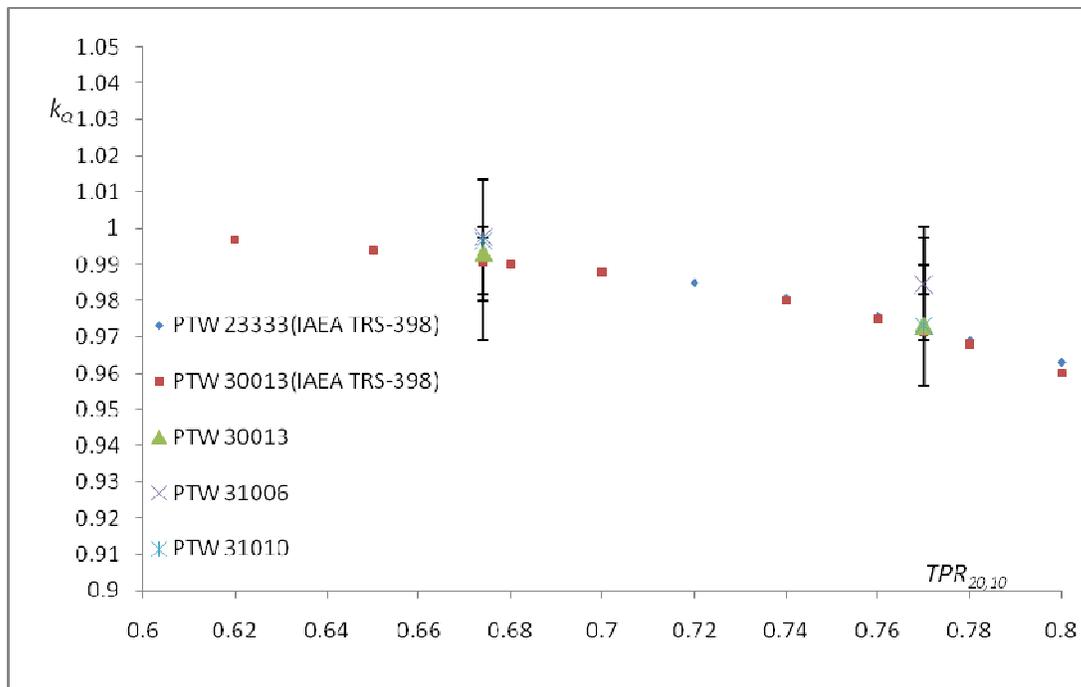
The cross-calibration to determine  $N_{gas}$  of the plane-parallel chambers from  $N_{gas}$  of the PTW 23333 0.6 cm<sup>3</sup> ionisation chamber was done at 21 MeV, the highest electron energy available in phantom. The replacement correction factor for PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber is 0.994 at 21 MeV. The results of the  $N_{gas}$  cross-calibration process were 4.97E+08 Gy/C, and 1.19E+09 Gy/C for PTW 23343 Markus and PTW 34045 Advanced Markus ionisation chamber, respectively.

#### 4.2 Measurement results in 6 MV and 18 MV photon beams

The dose to water to within 2.2% at the point of measurement was 0.9289 Gy per 100 monitor units and 0.9864 Gy per monitor units at 6 MV and 18 MV respectively as measured with the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber according to the IAEA TRS-398 (IAEA, 2000) protocol. The  $k_Q$  derived as a function of  $TPR_{20,10}$  for the various ionisation chambers are shown in Table 4.3. A plot of the measured and published values of  $k_Q$  as a function of  $TPR_{20,10}$  for the various ionisation chambers is shown in Figure 4.1. The  $k_Q$  results obtained for the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber compare well with the IAEA TRS-398 data.

**Table 4.3:** The measured  $k_Q$  as a function of  $TPR_{20,10}$  of the various ionisation chambers used in this study.

Chamber	First experiment (May 2009)		Second experiment (July 2009)	
	<b>0.674</b>	<b>0.770</b>	<b>0.674</b>	<b>0.770</b>
<b>PTW 23333</b> ( $\pm 0.0090$ )	0.9893	0.9714	0.9908	0.9725
<b>PTW 30013</b> ( $\pm 0.0100$ )	0.9918	0.9721	0.9933	0.9732
<b>PTW 31006</b> ( $\pm 0.0070$ )	0.9961	0.9835	0.9976	0.9846
<b>PTW 31010</b> ( $\pm 0.0120$ )	0.9951	0.9720	0.9966	0.9731



**Figure 4.1:** A plot of  $k_Q$  values from this work for PTW 23333  $0.6 \text{ cm}^3$ , PTW 30013  $0.6 \text{ cm}^3$ , PTW 31006 ‘Pinpoint’ and PTW 31010  $0.125 \text{ cm}^3$  and those published in the IAEA TRS-398 for PTW 23333  $0.6 \text{ cm}^3$  and PTW 30013  $0.6 \text{ cm}^3$  as a function of  $TPR_{20,10}$ .

### 4.3 Measurement results in the electron beam qualities.

For the electron beams, the doses were measured with the reference point of each of the chambers at the reference depth in a perspex phantom using a 10 cm x 10 cm applicator and an SSD of 100 cm. The measured electron doses are as summarized in Table 4.4.

**Table 4.4.** Summary of the doses in Gy per 100 monitor units at  $d_{max}$  using each of the ionization chambers.

<b>Nominal Energy (MeV)</b>	<b><math>R_{50}</math>/cm</b>	<b>PTW 23333 0.6 cm<sup>3</sup></b>	<b>PTW 30013 0.6 cm<sup>3</sup></b>	<b>PTW 31006 Pinpoint</b>	<b>PTW 31010 0.125 cm<sup>3</sup></b>	<b>PTW 23343 Markus</b>	<b>PTW 34045 Advanced Markus</b>
5	2.05	0.980	0.970	0.999	0.996	1.030	0.985
6	2.40	0.983	0.976	1.005	0.996	1.030	0.983
7	2.75	0.971	0.965	0.988	0.981	1.010	0.963
9	3.51	0.973	0.968	0.996	0.980	1.010	0.971
12	4.68	0.965	0.965	0.987	0.958	0.996	0.962
14	5.28	0.954	0.952	0.977	0.945	0.981	0.949
15	5.93	0.955	0.954	0.973	0.948	0.962	0.950
18	7.30	0.934	0.931	0.944	0.928	0.936	0.932
21	8.23	0.975	0.971	0.992	0.970	0.981	0.974

The unrestricted stopping power ratio of water to air is 1.033 and the replacement correction factors used for the determination of dose for the various ionisation chambers are shown in Table 4.5. The values of the replacement correction factors for the PTW 23333 0.6 cm<sup>3</sup> and PTW 30013 0.6 cm<sup>3</sup> as reported by Khan (2003) are also included.

**Table 4.5:** The replacement correction factors for the cylindrical ionisation chambers at each electron beam quality and the replacement correction factors published by Khan (2003) for the PTW 23333 0.6 cm<sup>3</sup>, as used for the absorbed dose determination in the electron beams.

<i>R</i> <sub>50</sub> / cm	PTW 30013 0.6 cm <sup>3</sup>	PTW 23333 (Khan) 0.6 cm <sup>3</sup>	PTW 31006 'Pinpoint'	PTW 31010 0.125 cm <sup>3</sup>
2.05	0.957	0.958	0.984	0.961
2.40	0.959	0.960	0.984	0.962
2.75	0.960	0.962	0.985	0.964
3.51	0.963	0.965	0.987	0.967
4.68	0.969	0.974	0.989	0.972
5.28	0.972	0.979	0.991	0.975
5.93	0.981	0.982	0.995	0.977
7.30	0.989	0.991	0.996	0.990
8.23	0.994	0.993	0.997	0.994

Overall, the average deviation of the measured doses with all the chambers from the dose measured with the PTW 23333 0.6 cm<sup>3</sup> was 0.8%. The maximum deviation from the PTW 23333 0.6 cm<sup>3</sup> dose was 5% as measured with the PTW 23343 Markus electron chamber at the electron energies of 5 MeV and 6 MeV.

On the other hand, the PTW 34045 Advanced Markus dose measurements agree with the PTW 23333 0.6 cm<sup>3</sup> dose measurements to within 0.8-1.0%. The PTW 34045 Advanced Markus has a smaller volume compared to either the PTW 23333 0.6 cm<sup>3</sup> or the PTW 23343 Markus. The PTW 34045 Advanced Markus therefore perturbs the water medium less and the electron fluence may be taken to be closer to unity. Furthermore the PTW 34045 Advanced Markus has a better spatial resolution than the PTW 23333 0.6 cm<sup>3</sup>. Since the results of the PTW 23343 Markus and the PTW 34045 Advanced Markus do not compare well with the results of the PTW 23333 0.6 cm<sup>3</sup>, it could be confirmed that cylindrical chambers should not be used to measure the dose to water in electron beams of  $E_0 \leq 10$  MeV (AAPM, 1983; IAEA, 1987; AAPM, 1991; IAEA, 2000).

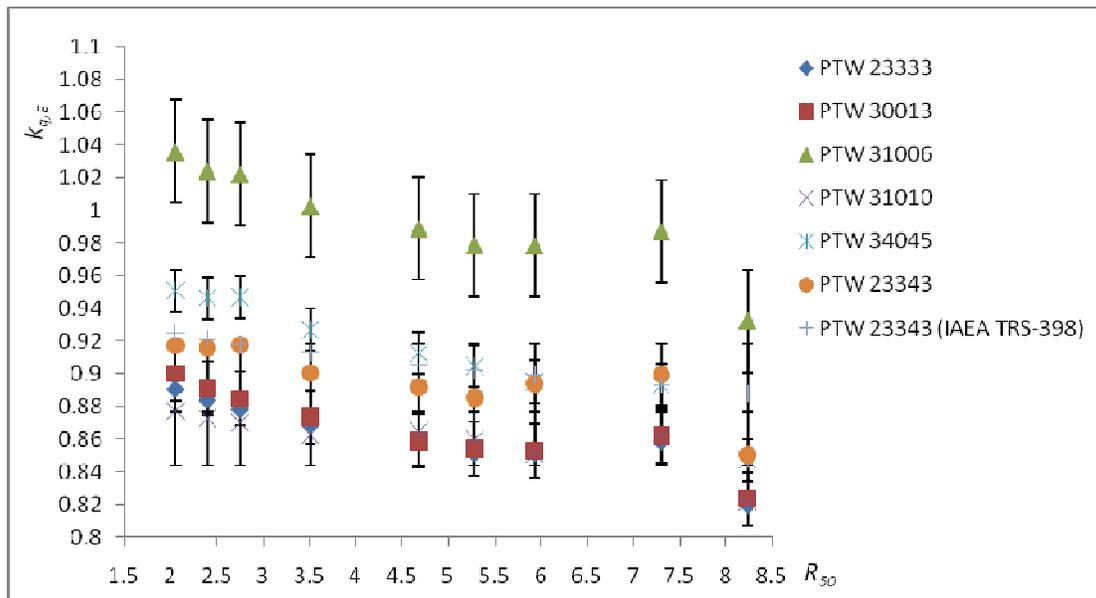
The measured doses were used to derive the absorbed dose to water calibration factors for the electron beams. These absorbed dose to water calibration factors  $N_{D,w}^{q,E}$  (shown in Table 4.6) were in turn used to determine the  $k_{q,E}$  for each of the ionisation chambers at each electron energy. The  $k_{q,E}$  obtained as a function of  $R_{50}$  for the cylindrical chambers and for the parallel plate chambers are shown in Table 4.7 and Figure 4.2. It can be noted that the  $k_{q,E}$  value for PTW 31006 ‘Pinpoint’ whose replacement correction factor is small, is very close to unity.

**Table 4.6:** The calculated  $N_{D,w}^{q,E} \times 10^7$  Gy/C at each electron energy for the various ionisation chambers.

$R_{50}$ / cm	PTW 23333 0.6 cm <sup>3</sup>	PTW 30013 0.6 cm <sup>3</sup>	PTW 31006 Pinpoint	PTW 31010 0.125 cm <sup>3</sup>	PTW 23343 Markus	PTW 34045 Advanced Markus
<b>2.05</b>	4.63	4.78	233	26.6	49.4	123
<b>2.40</b>	4.60	4.73	231	26.5	49.3	122
<b>2.75</b>	4.56	4.70	230	26.4	49.4	122
<b>3.51</b>	4.52	4.64	226	26.2	48.5	120
<b>4.68</b>	4.46	4.56	223	26.2	48.0	118
<b>5.28</b>	4.43	4.54	220	26.1	47.7	117
<b>5.93</b>	4.43	4.53	220	25.8	48.1	116
<b>7.30</b>	4.46	4.58	222	26.1	48.4	115
<b>8.23</b>	4.26	4.37	210	24.9	45.8	110

**Table 4.7:** The results of the  $k_{q,E}$  values determined as a function of  $R_{50}$  for the various ionisation chambers.

$R_{50}$ (cm)	PTW 23333	PTW 30013	PTW 31006	PTW 31010	PTW 23343	PTW 34045
	$\pm 0.007$	$\pm 0.008$	$\pm 0.010$	$\pm 0.005$	$\pm 0.011$	$\pm 0.007$
<b>2.05</b>	0.891	0.900	1.036	0.877	0.917	0.951
<b>2.40</b>	0.884	0.891	1.024	0.873	0.916	0.946
<b>2.75</b>	0.878	0.884	1.022	0.870	0.918	0.947
<b>3.51</b>	0.869	0.873	1.003	0.862	0.901	0.927
<b>4.68</b>	0.859	0.859	0.989	0.865	0.892	0.913
<b>5.28</b>	0.852	0.854	0.978	0.860	0.885	0.905
<b>5.93</b>	0.852	0.853	0.978	0.851	0.894	0.895
<b>7.30</b>	0.859	0.862	0.987	0.862	0.899	0.893
<b>8.23</b>	0.820	0.824	0.932	0.822	0.850	0.847



**Figure 4.2:** A plot of  $k_{q,E}$  as a function of  $R_{50}$  for the plane-parallel and the cylindrical ionisation chambers.

## CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

Cross-calibrations of  $N_{D,w}^{60Co}$  and  $N_x$  for the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber, the PTW 31006 ‘Pinpoint’ ionisation chamber, the PTW 31010 0.125 cm<sup>3</sup> ionisation chamber, the PTW 23343 Markus and the PTW 34045 Advanced Markus ionisation chamber against the PTW 23333 0.6 cm<sup>3</sup> reference ionisation chamber were performed. The cross-calibration factors compare well with those on their respective chamber certificates. These cross-calibration factors have been obtained using the existing international dosimetry protocols, they are therefore traceable to standard dosimetry laboratories and they can be applied in the routine and periodical quality assurance programmes of Charlotte Maxeke Johannesburg Academic Hospital radiation clinics, with confidence.

The beam quality correction factors for the PTW 30013 0.6 cm<sup>3</sup> ionisation chamber in photon beams with TPR<sub>20,10</sub> of 0.674 and 0.770 were determined with an accuracy of 0.2%, compared to the IAEA TRS-398 published values.

The beam quality correction factors for the PTW 23343 Markus ionisation chamber in a range of electron beam qualities of R<sub>50</sub> of 2.05 cm to 8.23 cm (4.77 MeV ≤ E<sub>0</sub> ≤ 19.19 MeV) were determined with an accuracy of 1.2%, compared to the IAEA TRS-398 published values. Since the uncertainties are systematically low and not significant, this study establishes that any of the ionization chamber types used in this study could be used as reference chambers for clinical dosimetry. Although different centers may have different beam designs and measuring methods, the  $k_Q$  values for the chambers used in this study can be applied to other beams of the same beam quality.

The overall deviation of 5% in the results of the PTW 23343 Markus and the PTW 34045 Advanced Markus from the results of the PTW 23333 0.6 cm<sup>3</sup> confirms that cylindrical chambers should not be used to measure the dose to water in electron beams of  $E_0 \leq 9$  MeV. Cylindrical chambers, however, can be used for less precise daily quality control checks of electron beams of  $E_0 \leq 9$  MeV where compliance to a range of dose or dose rates only is to be confirmed.

The beam quality correction factors  $k_Q$  and  $k_{q,E}$  for the PTW 31010 0.125 cm<sup>3</sup>, 31006 ‘Pinpoint’ and 34045 Advanced Markus models of ionisation chambers for which no published data exist, were determined with reasonable accuracy. The electron beam quality correction factors were determined at a dose-rate of 300 MU/ min. They could also be

tested at higher-energy electron dose rates, i.e. 900 MU/min for the Siemens PRIMUS™ LINACS.

This work is one of the few studies which demonstrates clearly the ability to determine beam quality correction factors in a clinical setting. Cross-calibrations were performed of the absorbed dose to water calibration factors of the Markus, the ‘PinPoint’ and the Advanced Markus ionisation chambers (M’ule, 2008). The  $k_{q,E}$  values determined for the Advanced Markus ionisation chamber will provide improved accuracy in dosimetry with this chamber since the error previously introduced by using published or extrapolated  $k_{q,E}$  values for the Markus ionisation chamber is now eliminated. The ‘PinPoint’ ionisation chamber can also be used for absolute dosimetry since the beam quality correction factors are now determined for the beam qualities available at the Charlotte Maxeke Johannesburg Academic Hospital.

Although the results of this study are clinically accurate, a Monte Carlo Simulation Code could be resourced to test the validity of their statistical uncertainties.

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