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Achievable accuracy of radiation dose measurement for linear accelerators using different protocols

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ACHIEVABLE ACCURACY OF RADIATION DOSE MEASUREMENT FOR LINEAR ACCELERATORS USING DIFFERENT PROTOCOLS

Mariam Hamad Al Darmaki

This thesis is submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics

Under the Supervision of Professor Bashar Issa

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Declaration of Original Work

I, Mariam Hamad Al Darmaki, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Achievable Accuracy of Radiation Dose Measurements for Linear Accelerators Using Different Protocols*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Bashar Issa, in the College of Science at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

The aim of radiotherapy treatment is to deliver a specified radiation dose throughout a definite target volume within predetermined levels of accuracy and homogeneity; at the same time ensuring adequate dose sparing of surrounding normal tissue. Radiotherapy is a complex process involving a number of steps and the accuracy of each stage has a direct impact on the treatment outcome. At each stage, comprehensive quality assurance procedures are required to ensure safe and accurate delivery of the prescribed dose.

This project will aim to determine the currently achievable accuracy and reproducibility of radiotherapy dosimetry and assess the current recommendations for quality assurance tolerances. Alongside, it will examine the traceability of different codes of practice in measuring absorbed dose results from high energy photon and electron beams.

The study will present a theoretical and a practical comparison between different codes of practice: International Atomic Energy Agency (IAEA TRS-398), American Association of Physics in Medicine, (AAPM TG-51), Institute of Physical Engineering in Medicine (IPEM-2003) for electron beams, and Institute of Physical Science in Medicine (IPSM-1990) for photon beams.

Our study confirms that our results are within the ± 5 % internationally suggested accuracy and provides detailed comparison between the mentioned protocols. We measured the data and analyzed them in detail and presented them with the reference conditions to determine the absorbed dose to water for high energy photon and electron beams with the chosen protocols. Our obtained results are consistent with the reference beam data from Varian Medical Systems. This enhances the confidence on Tawam hospital's Quality Assurance on the Linear Accelerators.

Keywords: IAEA TRS-398, AAPM TG-51, IPEM, IPSM, Radiotherapy, Linear Accelerator, Accuracy, Dosimetry, Quality Assurance, Tawam Hospital.

Title and Abstract (in Arabic)

الدقة المُتحقّقة في قياس جرعة الإشعاع الصادرة عن المسارعات الخطية باستخدام بتوصيات عالمية مختلفة

الملخص

الهدف من العلاج الإشعاعي هو تقديم جرعة محددة من الإشعاع إلى هدفٍ واضحٍ ضمن مستويات محددة سلفاً من الدقة، إلى جانب ضمان تجنيب الأنسجة السليمة المحيطة بالهدف من التعرض لجرعة غير ضرورية من الإشعاع. يتضمّن العلاج الإشعاعي عدّة خطوات مترابطة، دقة كل مرحلة لها تأثير مباشر على نتائج العلاج. كل مرحلة من مراحل العلاج تتطلب إجراءات تدقيقيّة شاملة لضمان الجودة في إيصال الجرعة الموصوفة من الإشعاع.

ستهدف هذه الأطروحة لتحديد الدقة المُتحقّقة حالياً لأجهزة المسارعات الخطّية وإمكانية الحصول على نتائج متطابقة عند تكرار القياس لضمان الجودة. سنقوم أيضاً بدراسة إمكانية تتبّع التوصيات العالمية المختلفة في قياس جرعات الإشعاع المُمتصّة الناتجة عن الفوتونات عالية الطاقة وحزم الإلكترونات.

هذه الدراسة ستطرح مقارنة نظرية وعملية بين التوصيات العالمية المختلفة : الوكالة الدولية للطاقة الذرية (IAEA TRS-398)، الجمعية الأمريكية للفيزياء في الطب (AAPM TG-51)، معهد الهندسة الفيزيائية في الطب (IPEM- 2003) للحزم الإلكترونية، ومعهد العلوم الفيزيائية في الطب (IPSM-1990) للأشعة الفوتون.

تؤكد الأطروحة أن نتائج قياس الجرعة المُمتصّة من الأشعّة كانت ضمن حدود الدقة المقترحة دولياً (± 5٪)، كما توفر الدراسة مقارنة تفصيلية بين االتوصيات العالمية المتبعة. تمّ قياس وجمع البيانات ثم تحليلها بالتفصيل وعُرضت النتائج مع شرح للشروط المرجعية لتحديد جرعة الأشعة الممتصة في الماء للفوتونات عالية الطاقة وحزم الالكترونات. في النهاية حصلنا على نتائج متوافقة مع النتائج المرجعية لشركة الأنظمة الطبية Varian، وهذا يعزز الثقة في جودة الإجراءات التدقيقية الشاملة للمسرعات الخطية في مستشفى توام .

مفاهيم البحث الرئيسية: الوكالة الدولية للطاقة الذرية IAEA TRS-398، الجمعية الأمريكية للفيزياء في الطب AAPM TG-51، IPEM-2003 معهد الهندسة الفيزيائية في الطب ، معهد العلوم الفيزيائية في الطب IPSM-1990، العلاج الإشعاعي، المسارع الخطي، الدقة، قياس الجرعات، التأكّد من الجودة، مستشفى توام.

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I owe my dearest thanks to the most precious people in my life, my husband, my sons and daughters and my parents who believed in me along the way. In addition, special thanks are extended to my family and friends for their assistance and friendship.

Dedication

To my home country the UAE, which I proud to belong to

To my beloved husband, Saif Al Jaberi, for his love, understanding and support throughout my journey

To my lovely sons and daughters, Ali, Hind, Aisha and, Hamad, whose presence fill my life with joy

To my parents and entire family and friends who have always been proud of me and whose love, kindness, help, and prayers have brought me this far

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List of Abbreviations

IAEA	International Atomic Energy Agency
AAPM	American Association of Physics in Medicine
IPEM	Institute of Physical Engineering in Medicine
IPSM	Institute of Physical Science in Medicine
TCP	Tumor control probability
NTCP	Normal tissue complication probability
z_{ref}	Reference depth
Z_{max}	Maximum depth
SSD	Fixed source to surface distance
SAD	Fixed source to axis distance
PSDL	Primary Standard Dosimetry Laboratory
SSDL	Secondary Standard Dosimetry Laboratory
D_w	Absorbed dose to water
TPR	Tissue phantom ratio
TMR	Tissue maximum ratio
%DD	Percentage depth dose
%DI	Percentage depth ionization
R_{50}	Beam quality index for electrons

Chapter 1: Introduction

1.1 Overview

The radiotherapy treatment is a nested process that involves many data transfers between different professional groups as shown in figure 1.

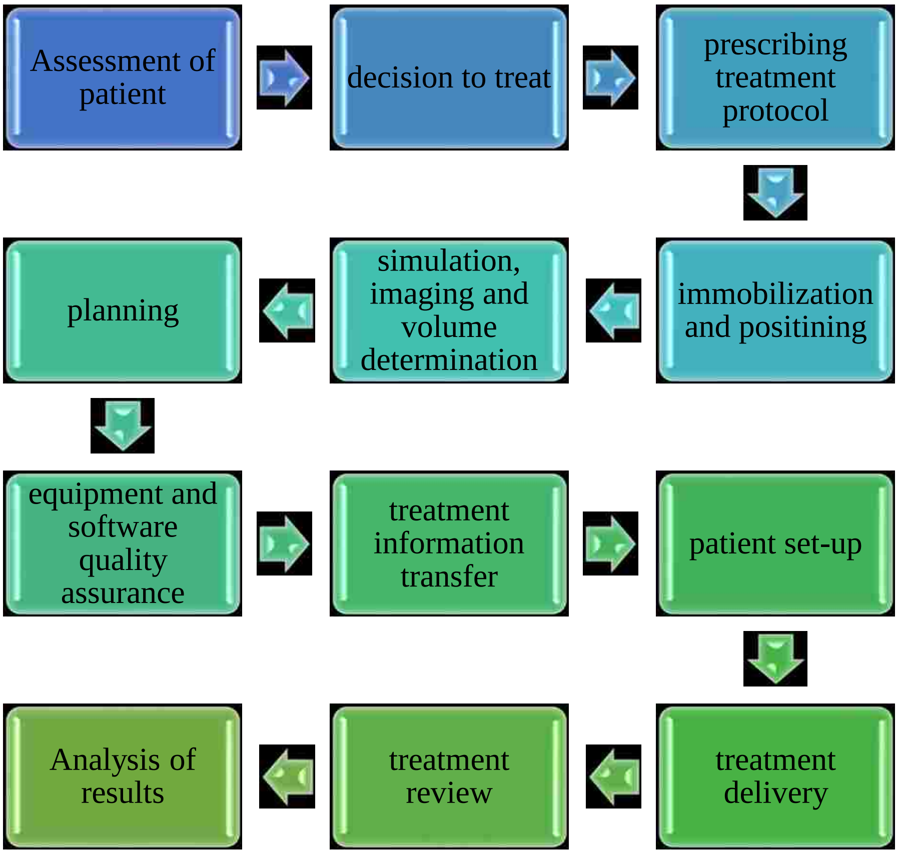

Figure 1: Schematic representation for radiotherapy processes

Decisions regarding treatment of a patient's cancer typically begins within the context of a tumour review board (organized by disease site) at which the patient's case is presented, reviewed, and choices of treatment (including not only radiation but other treatment options including surgery and chemotherapy) are discussed. This is followed by a detailed treatment prescription, including the volume that will be treated, the specification of dose and the number of fractions given to the patient.

Generally, the patient will be scheduled for “simulation” involving a series of steps including design of custom immobilization with the help of a mould room technician to ensure stable and reproducible positioning of the patient followed by acquisition of volumetric imaging studies that are used to precisely define the target volume, and critical neighbouring anatomy.

Next, the radiation oncologist will generate volumetric definitions of the target and surrounding anatomical features. A dosimetrist interactively chooses valid arrangements of directed external beams of high-energy x-rays or particles with computer assisted treatment planning system to achieve the optimal dose distributions and the relative shapes of dose volume curves. Once the planned dose distribution is approved by the physician, the chart of the patient is ready to be transferred to the treatment machine with all the required data for treatment delivery.

Prior to that, the medical physicist runs through a series of quality assurance steps where the treatment plan is delivered to a test phantom with dose measurement devices, the measured data then is analysed and compared to dose estimations from the treatment planning system and the comparison approved prior to treatment.

For the treatment, the patient is placed on the treatment table by the radiation therapist using the same immobilization device created during simulation and is moved to the approximate treatment position using laser guided adjustments. Typically orthogonal portal images or cone-beam CT volumes are taken to verify the patient position against a computer generated image (DRRs) using the planning CT volumes. Also, a review of the patient’s setup is repeated for each fraction, to reduce unavoidable geometrical errors (Lake, 1999).

1.2 The Need for Accuracy in Radiotherapy

The aim of radiotherapy is to concentrate the dose to the tumor to improve local control and minimize the radiation dose to normal tissues to ensure no serious complications occur to the normal, surrounding tissues. Therefore, high accuracy is an important requirement in the delivery of the radiation dose in radiotherapy.

The International Commission of Radiological Units and Measurements (ICRU) recommend that an accuracy requirement of ± 5% is desirable for the overall dose delivered to the patient (ICRU, 1976).

To achieve this accuracy, the balance between the probability of tumor control (TCP) and the risk of normal tissue complications (NTCP) is a measure of the therapeutic ratio of the treatment at a specified level of response for normal tissue considering early and late complications as shown in figure 2.

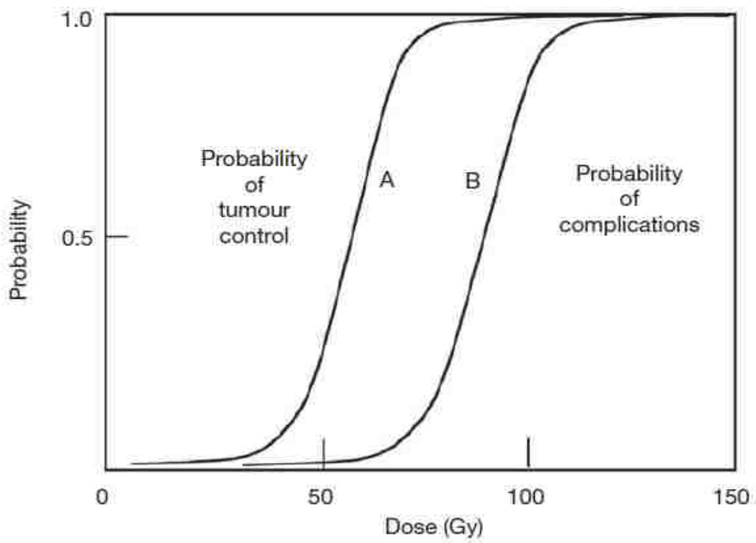

Figure 2: The principle of therapeutic ratio
Curve A represents the TCP and curve B represents NTCP. If the therapeutic ratio is large then the aim of radiotherapy is achieved

For radiotherapy treatment, ideally one requires TCP ≥ 0.5 and NTCP ≤ 0.05; if the NTCP curve is further along the x-axis, the radio-therapeutic goal is more effectively achieved, producing a larger therapeutic ratio with a lower probability of normal tissue complications (Podgorsak, 2005). If these curves are closer together, the need for accuracy becomes higher because a small change in dose will lead to a very big change in response.

1.3 Beam Calibration

The output of the photon and electron beams produced by external beam radiotherapy machines must be calibrated before clinical use and periodically thereafter in order to ensure accurate dose delivery to the patient. The medical physicist is responsible for the acceptance testing, commissioning, calibration, and periodic quality assurance (QA) of the therapy equipment, and new ancillary delivery technologies.

The basic output for a radiotherapy machine is stated as absorbed dose at a reference depth (Z_{ref}) in a water phantom by using either a fixed source to surface distance (SSD) or fixed source to axis distance (SAD), and a reference field size of 10×10 cm^2 at surface or isocentre; refer to figure 3. The output is in Gy/MU (absorbed dose unit/ monitor unit) (Podgorsak, 2005).

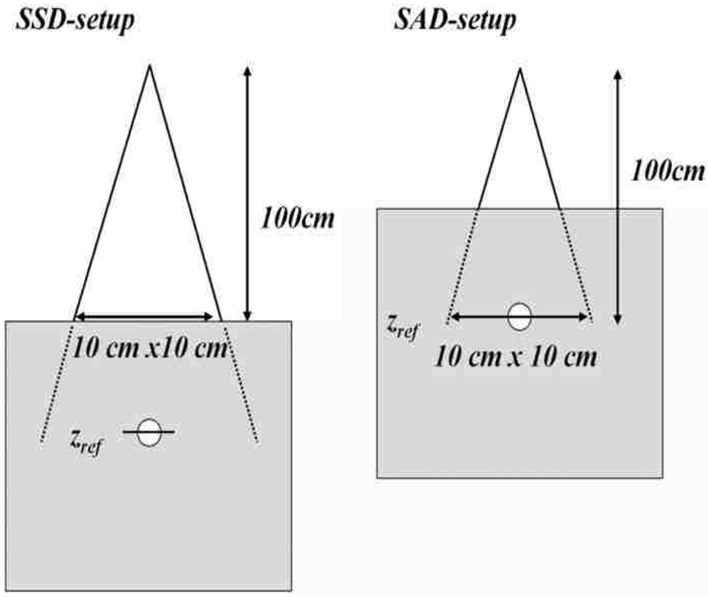

Figure 3: The geometry setup of SSD and SAD

A radiation dosimeter is a device used to measure exposure in the dosimeter's sensitive volume by ionizing radiation. Three types of dosimeters are currently used:

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

The most common form of dosimeters used in clinical photon and electron beam calibration nowadays are ionization chamber dosimeters (IAEA1, 2000).

1.3.1 Ionization Chamber Based Dosimetry Systems

This system is quite simple and consists of three main components as shown in figure 4. The components are as follows:

1. Electrometer: It is a very sensitive device that measures the very small current or charge that is induced in the ionization chamber.
2. Power supply: This is either a standalone unit or an integral part of the electrometer.

3. The ionization chamber: It is a gas filled cavity surrounded by three electrodes that determines the chamber sensitive air volume; typically in the order of 0.1 to 1.0 cm^3. The electrodes are:

   - Polarizing electrode: directly connected to the power supply.
   - Measuring electrode: connected to ground through the electrometer.
   - Guard electrode: directly grounded.

The ionization chamber is usually connected to the electrometer through a shielded low noise tri-axial cable. The central wire carries the signal from the measuring electrode to the electrometer. The other shield connects the guard electrode to ground and the outer shield connects the polarizing electrode to the power supply.

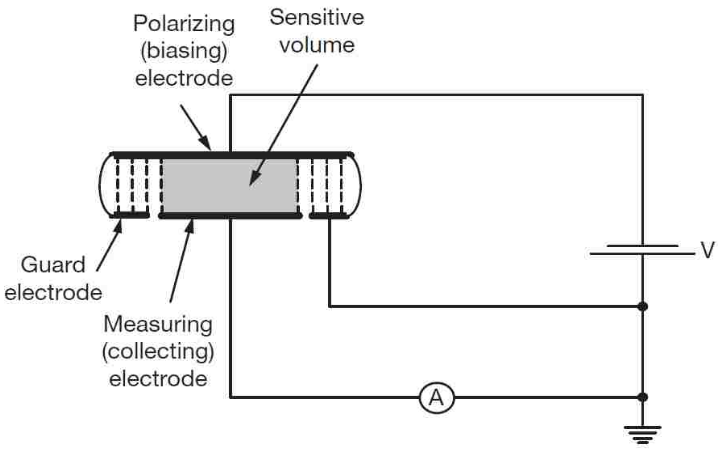

Figure 4: Circuitry of an ionization chamber based dosimetry system
(A) represents the electrometer and (V) is the power supply

There are two main types of ionization chamber that are used in clinical beam dosimetry:

i. Cylindrical or farmer chambers; typically for photons.

ii. Plane - parallel or parallel plate chambers; for electron beam and surface dose measurements.

Some examples of typical chambers used in clinical beams calibrations are shown in tables (1) & (2). (IAEA1, 2000)

Type of chamber	Cavity volume (cm^3)	Cavity length (mm)	Cavity radius (mm)	Wall material	Wall thickness (g/cm^2)	Build up cap material	Build-up cap thickness (g/cm^2)	Central electrode material	Waterproof
NE2571	0.6	24	3.2	Graphite	0.065	Delrin*	0.551	Aluminium	No
PTW 30013	0.6	23	3.1	PMMA**	0.057	PMMA**	0.541	Aluminium	Yes

Table 1: Characteristics of cylindrical ionization chamber types.
* Delrin: PolyOxy-Methylene (CH_2O) ** PMMA: polymethyl-methacrylate ($C_2H_8O_2$) or Acrylic or Perspex or Lucite

Type of chamber	Materials	Window thickness	Electrode spacing	Collecting electrode diameter	Guard ring width	Recommended phantom material
NACP01	Graphite window and rexolite housing	90 mg/cm^2 0.5 mm	2 mm	10 mm	3 mm	Polystyrene graphite water (with waterproof housing)
Roos chamber PPC40	PMMA, graphite electrodes	118 mg/cm^2 1 mm	2 mm	16 mm	4 mm	Water PMMA

Table 2: Characteristics of plane-parallel ionization chamber types

1.4 Clinical Chambers Calibration Chain

Ionization chambers used in clinical photon and electron beams calibration have calibration coefficients measured either in air or water and are traceable to a national Primary Standard Dosimetry Laboratory (PSDL). Traceability, precision and consistency of radiation measurements are needed in radiation dosimetry, especially in radiotherapy, since the outcome of treatments is highly dependent on the radiation dose delivered to patients.

The international measurement system supplies the framework for consistency by providing users around the world with calibrated instruments that are traceable to primary measurement standards. Figure 5 shows the international organizational chart for the measurement system where the traceability of user reference instruments to primary standards is achieved either by direct calibration in a PSDL or, more commonly, in a Secondary Standard Dosimetry Laboratory (SSDL) with direct link to the Bureau International des Poids et Mesures (BIPM)[1], a PSDL, or to the International Atomic Energy Agency (IAEA).

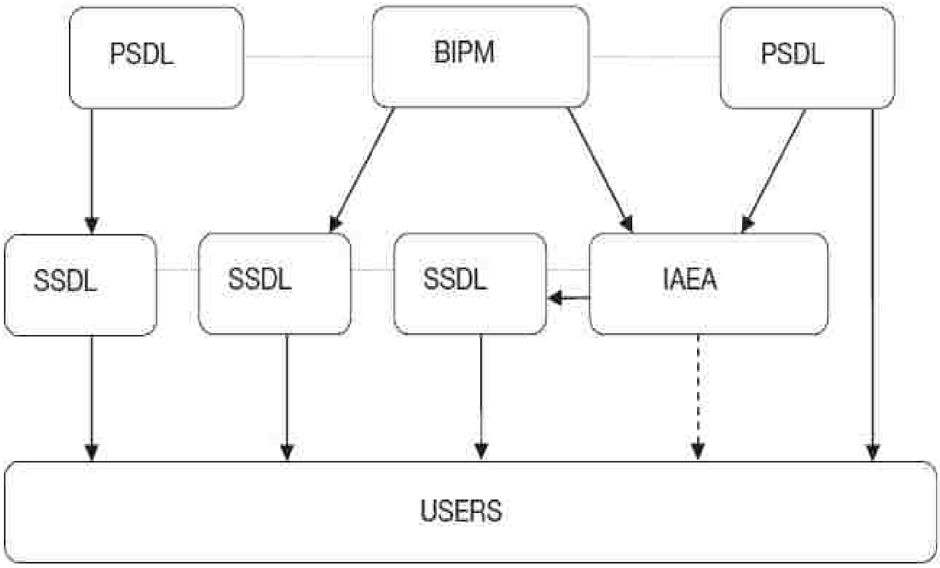

Figure 5: The international measurement system (IMS)
The dashed lines indicate inter-comparison of primary and secondary standards. The dashed arrow represents exceptional calibration of a user instrument by the IAEA in the event that a country has no SSDL and limited resources

There are only twenty countries in the world with PSDLs included in radiation dosimetry. As such, it is not possible for these centers to directly calibrate the large number of radiation dosimeters that are used around the world. As a result, the PSDLs calibrate the standards of Secondary Standard Dosimetry Laboratory (SSDLs), which in turn calibrate user reference instruments (WHO, 2009).

[1] The BIPM, located in Sèvres (near Paris), is an international laboratory set up under the Metre Convention of 1875 to act in matters of world metrology, particularly concerning the demand for measurement standards

1.5 Protocols and Codes of Practice

Having a reference for dose measurement in a water phantom under standard conditions is the main idea to calibrate the output of a clinical radiation beam. The procedures for the calibration of clinical photon and electron beams are described by different radiation dosimetry protocols or dosimetry codes of practice. Protocols aim to refine the accuracy and consistency of dose determination in order to standardize the radiation dosimetry around the world. The choice of which protocol to follow depends on the individual radiotherapy center.

During the last two decades many national and international organizations from different countries have published various codes of practice for the calibration of the clinical beams; for examples: Nordic Association of Clinical Physics (NACP1, 1980) and (NACP2, 1981); American Association of Physics in Medicine Task Group -21 (Dosimeters, 1983) and Task Group -39 (Almond, 1994); Hospital Physics Association (Lillicrap, S. C., Burns, J. E., Greene, D., & Williams, P. C., 1983) and (HPA, 1985); IAEA Technical Report Series No. 277 (IAEA2, 1997) and Technical Report Series No. 381 (Almond P. R., 1997). The above mentioned protocols are based on an air kerma (kinetic energy released per unit mass in air) calibration factor of an ionization chamber in a ^{60}Co gamma ray beam.

The recent codes of practice are: IAEA TRS-398 (IAEA1, 2000), AAPM TG-51 (Almond P. R., 1999), Institute of Physical Engineering in Medicine in UK (IPEM) for electron beams (Party, 2003) and Institute of Physical Science in Medicine in UK (IPSM) for photon beams (Lillicrap, S. C., Owen, B., Williams, J. R., & Williams, P. C., 1990). In these protocols, calibration has been changed from the air kerma based calibration to absorbed dose to water calibration (D_w). Since D_w

is strongly related to the biological effects of radiation, it is the main quantity of interest in radiation therapy.

These new standards provide a more robust system; i.e. the reproducibility is higher; than air kerma based standards which lead to reduce the uncertainty in the dosimetry of radiotherapy beams. In addition to these two advantages of D_w and most important to users, it also allows the use of a simple formalism (IAEA1, 2000).

Many studies have been carried out by different groups in different countries to examine the consistency of dosimetry codes of practice. The aim of these studies is to confirm the uniformity in the establishment of dosimetry of all radiation beam types used in cancer therapy in the world. The studies explain how those codes complement and extend in the different organizations. In this study three protocols will be reviewed.

Chapter 2: Theory

This chapter is an overview of the IAEA TRS-398, AAPM TG-51, IPEM-2003 and IPSM-1990 codes of practice for electron and photon beams dosimetry. All these codes are based on the calibration of ionization chambers in terms of absorbed dose to water as they offer the possibility of reducing the uncertainty in the dosimetry of radiotherapy beams, provide a more robust system of primary standards, and allow the use of a more straightforward formalism. The main differences among these protocols lie in the choice of quality index, calibration setup, standards of ionization chamber calibration and terminology. A brief comparison of these is carried out as this will form the main part of the present study.

2.1 Dosimetry Equipment

2.1.1 Phantom

All the codes recommend the water phantom to be used in dosimetry of high energy photon and electron beams. Both IAEA TRS-398 and the IPSM-1990 code point out that the phantom should be a full scatter phantom extending at least 5 cm outside the beam edges and at least 5 cm beyond the maximum measured depth. AAPM TG-51 code recommends the phantom dimension should be at least 30 × 30 × 30 cm^3. For horizontal beams, one should take the phantom's wall into account if it is greater than 2 mm thick, then all depths should be scaled to water equivalent depths.

IAEA TRS-398 and IPSM-1990 give secondary recommendations for the solid phantom, especially for low energy beams. The alternative phantoms considered by IPEM-1990 are epoxy-based solid water, PMMA and polystyrene. On the other hand, IAEA TRS-398 suggests PMMA, polystyrene and water equivalent plastics like solid water, virtual water and plastic water.

Reference dosimetry measurements in plastic phantoms are not allowed, because in general they give rise to the largest discrepancies in the determination of absorbed dose to water in clinical photon and electron beams. Plastic phantoms can be used for routine quality assurance checks, taking into account that the relationship between dosimeter readings in plastic and water has been established for the user beam at the time of calibration.

2.1.2 Ionization Chambers

As recommended by IAEA TRS-398, the chamber cavity volume needs to be between about 0.1 cm^3 and 1 cm^3 for reference dosimetry in clinical photon and electron beams This will provide a compromise between the need for sufficient sensitivity and the ability to measure a dose at a point. Therefore, it is designed with an air cavity of internal diameter not greater than around 7 mm and an internal length not greater than around 25 mm. The materials chosen for chambers play an important role in ensuring that the energy response of the chamber is uniform. The air cavity should rapidly reach equilibrium conditions with the ambient temperature and air pressure in about 5 minutes. The chamber should be homogeneous and as water equivalent as possible, to get mass stopping powers and linear scattering powers similar to those of water.

2.1.3 Water Sleeve for the Chamber

All the protocols point to the importance of using waterproof sleeves for chambers that are not designed to be used directly in water. An inherently waterproof chamber prevents the complications of extra waterproofing sleeves and the probability of air gaps.

For non-waterproof chambers there are recommendations to be followed when using a water phantom. The sleeve should be made of PMMA or similar low atomic number plastic material, with a sufficiently thin wall ($\leq$ 1 mm) to allow the chamber to achieve thermal equilibrium with the water. An air gap of 0.1 mm to 0.3 mm between the chamber and the sleeve is enough to allow the air pressure in the chamber to reach the ambient air pressure quickly. The waterproof sleeve should not be left in water longer than is necessary to carry out the measurements, to reduce the build-up of water vapour around the chamber.

2.2 Practical Considerations

Before the measurements start, some issues should be taken into consideration:

- The stability of the dosimeter system; i.e. chambers and electrometers; should be verified using a check source.
- Plane – parallel chamber should be fixed to its holder under water to make sure of not having air bubbles in the lower cavity.
- The reliability of the waterproofing sleeve needs to be checked.
- Enough time must be allowed for the dosimeters and phantoms to achieve thermal equilibrium, i.e. several hours before use.
- It is always preferable to pre-irradiate or warm up the ion chamber with 2-5 Gy to achieve charge equilibrium.
- The temperature of the air in the chamber should be taken as that of the water

phantom when in equilibrium as it is different than room temperature due to evaporation.

- Enough time must be allowed when the polarizing voltages are modified so that the ion chamber reading can reach equilibrium.
- The leakage current generated by the measuring system in the absence of radiation should always be measured before and after irradiation. The best practice is to zero the dosimeter system before using.
- Water phantoms should not be left full of water and ionization chambers not be left in water for longer than necessary; IPEM limits the practices to no longer than 8 hours as Perspex absorbs water and may change the dimensions.

2.3 Formulation

2.3.1 Determination of Absorbed Dose to Water

The absorbed dose to water at the reference depth for a beam of quality Q, $D_{w,Q}$, is calculated in the different protocols as follows:

2.3.1.1 IAEA TRS-398

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \qquad \text{Eq. 1}$$

where: M_Q : dosimeter reading corrected for the influence factors.

N_{D,w,Q_0}: calibration factor in terms of absorbed dose to water of the dosimeter obtained from a standards laboratory.

k_{Q,Q_0} : factor to correct for the effects of the difference between the reference beam quality Q_0 and the actual user quality Q. More details in section 2.3.2.

2.3.1.2 AAPM TG-51

$$D_{w,Q} = MN_{D,w}^{Co-60}k_Q \qquad \text{Eq. 2}$$

where: M : dosimeter reading corrected for the influence factors.

$N_{D,w}^{Co-60}$: calibration factor for absorbed dose for reference conditions in a ^{60}Co beam.

k_Q : quality conversion factor, converts the dose for a ^{60}Co beam into calibration factor for beam quality Q.

2.3.1.3 IPEM – 2003

$$D_w(z_{ref,w}) = M_{ch,w}N_{D,w}(R_{50,D}) \qquad \text{Eq. 3}$$

where: $M_{ch,w}$: dosimeter reading corrected for the influence factors.

$N_{D,w}(R_{50,D})$: calibration factor for absorbed dose to convert the reading in this quality beam to absorbed dose to water using National Physical Laboratory (NPL) factor.

2.3.1.4 IPSM-1990

$$D = RN_D \qquad \text{Eq. 4}$$

where: D : absorbed dose to water at the geometrical centre of the chamber

R : instrument reading corrected to a chamber air temperature of 20 ^oC, an ambient air pressure 1013.25 mbar, humidity of 50% and for loss due to ion recombination.

N_D : NPL factor for the quality. It converts the reading to absorbed dose.

2.3.2 Beam Quality Conversion Factor

The beam quality conversion factor (k_{Q,Q_0}) corrects the response of an ionization chamber in the reference beam quality Q_0 used for calibrating the chamber and in the actual user beam quality Q. k_{Q,Q_0} is determined as the ratio of the calibration factors at Q and Q_0 in terms of absorbed dose to water of the ionization chamber where:

$$k_{Q,Q_0} = \frac{N_{D,w,Q}}{N_{D,w,Q_0}} = \frac{D_{w,Q}/M_Q}{D_{w,Q_0}/M_{Q_0}} \qquad \text{Eq. 5}$$

Ideally, it must be calculated directly for each chamber at the same quality as user beam. But this is not always possible in most standard laboratories. For this reason the technique is limited to only a few PSDLs in the world. So, each protocol provides the users with its own tables and plots of k_{Q,Q_0} for photon and electron beams as ionization chamber type versus beam quality from tissue phantom ratio in water at depth of 20 and 10 g/cm^2 ($TPR_{20,10}$) or percentage depth dose (%DD) measurements; farther explanation will be in sections (2.4.1.2) and (2.4.2.2).

When no experimental values are available for k_{Q,Q_0}, it can be calculated theoretically using the Bragg-Gray theory. A general expression has been given in (Andreo P. , 1992) and (Medin, J; Andreo, P; Grusell, E; Mattsson, O; Montelius, A; Roos, M;, 1995)**:**

$$k_{Q,Q_0} = \frac{(S_{w,air})_Q (W_{air})_Q (P)_Q}{(S_{w,air})_{Q_0} (W_{air})_{Q_0} (P)_{Q_0}} \qquad \text{Eq. 6}$$

where $S_{w,air}$ is the Spencer-Attix water/air stopping power ratios, W_{air} is the mean energy expended in air per ion pair formed, and P is the perturbation factors which includes all departures (i.e. P_{wall}, P_{cav}, P_{cel} and P_{dis})[2]. Clinical electron and photon beams W_{air} are constant over the energies. The perturbation correction factors are only chamber dependent factors.

2.3.3 Corrections for Influence Quantities

All four codes recommend the chamber reading correction for a number of influence factors; to ensure that the measurements are not much affected by warm up effects, drift, leakage current and cable effects. Therefore, the dosimeter reading (M) should be corrected after considering the influence quantities as Eq. 7:

$$M_Q = M k_{T,P} k_{elec} k_{pol} k_s \qquad \text{Eq. 7}$$

where M_Q is the corrected reading and the other quantities are dealt with in the following subsections.

2.3.3.1 Temperature, Pressure and Humidity Correction Factors

The correction should be applied to convert the cavity air mass to the reference conditions by using:

$$k_{T,P} = \frac{273.15+T}{273.15+T_0}\frac{P_0}{P} \qquad \text{Eq. 8}$$

where T: is the cavity air temperature;

P: is the cavity air pressure;

T_0: is the manufacturer reference value for temperature;

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[2] P_{wall} corrects the non-medium equivalence of the chamber wall and waterproofing material. P_{cav} corrects effects related to the air cavity. P_{cel} corrects the effect of the central electrode during in-phantom measurements in high energy photon, electron and proton beams. P_{dis} corrects for the effect of replacing a volume of water with the detector cavity when the reference point of the chamber is taken to be at the chamber center.

P_0: is the manufacturer reference value for pressure.

It is assumed that the relative humidity is between 20% and 80%, and in this range the maximum deviation from the standard humidity (50%) is about 0.1% and can be neglected.

2.3.3.2 Electrometer Calibration

The electrometer calibration factor (k_{elec}) corrects the electrometer reading to true coulombs (C). It is required when the ionization chamber and the electrometer are calibrated separately and is considered as 1 if the electrometer and ionization chamber are calibrated together. It is in unit of nC/rdg[3] or nC/nC.

2.3.3.3 Polarity Effect

This is the difference in readings obtained under the same irradiation conditions, but taken with positive and negative polarizing voltages. It varies with beam quality and other conditions such as cable position, therefore it is necessary to correct for these effects in the case of electron beams but is negligible for photon beams. It can be given by:

$$k_{pol} = \frac{|M_+|+|M_-|}{2M} \qquad \text{Eq. 9}$$

where M_+ : electrometer's reading when applying a positive polarity ;

M_- : electrometer's reading when applying a negative polarity;

M : electrometer's reading obtained from the routine polarity;

[3] Arbitrary unit used for the reading of a dosimeter.

2.3.3.4 Ion Recombination

A correction is needed to account for incomplete collection of charge due to ion recombination in the volume of the chamber. There are two separate effects:

(i) Volume recombination: dose rate dependent.

(ii) Initial recombination: results from recombination of ions formed by a single ionizing particle track.

Both of the above depend on the chamber geometry and the applied voltage.

For pulsed beams, the recombination correction factor; can be derived using two voltage methods, given by:

$$k_s = a_0 + a_1\left(\frac{M_1}{M_2}\right) + a_2\left(\frac{M_1}{M_2}\right)^2 \qquad \text{Eq. 10}$$

where: a_i is given in table 3 for pulsed and pulsed-scan radiation;

M_1 is the collected charge at polarizing voltage V_1;

M_2 is the collected charge at polarizing voltage V_2.

$\frac{V_1}{V_2}$	Pulsed			Pulsed-scan		
	a_0	a_1	a_2	a_0	a_1	a_2
2.0	2.337	-3.636	2.299	4.711	-8.242	4.533
2.5	1.474	-1.587	1.114	2.719	-3.977	2.261
3.0	1.198	-0.875	0.677	2.001	-2.402	1.404
3.5	1.080	-0.542	0.463	1.665	-1.647	0.984
4.0	1.022	-0.363	0.341	1.468	-1.200	0.734
5.0	0.975	-0.188	0.214	1.279	-0.750	0.474

Table 3: Quadratic fit coefficients in pulsed and pulsed-scanned radiation as a function of voltages ratio (Weinhous, 1984)

For $k_s < 1.03$, the ion recombination correction can be approximated to within 0.1 % using the relation:

$$k_s - 1 = \frac{M_1/M_2 - 1}{V_1/V_2 - 1} \qquad \text{Eq. 11}$$

2.3.4 Corrections for Use of Non-Water Phantom

A water phantom is recommended by all the codes to be used in the clinical beam dosimetry, but both TRS-398 and IPEM allow the use of plastic phantoms if there are problems in using a water phantom and particularly at low energies. In this case the depths need to be scaled to water-equivalent depths and the chamber reading must also be multiplied by a fluence[4]-ratio correction.

For a given depth in a non-water phantom ($d_{non\text{-}w}$), an approximation of the equivalent depth in water phantom is given by:

$$z_w = d_{non-w} C_{pl} \quad g/cm^2 \qquad \text{Eq. 12}$$

where, C_{pl} is the depth scaling factor.

In addition, the dosimeter reading also needs to be scaled by using the following relation:

$$M_Q = M_{Q,pl} h_{pl} \qquad \text{Eq. 13}$$

where, h_{pl} is the fluence scaling factor where it equals to unity for water. Values of C_{pl} and h_{pl} for certain plastic phantom media are given by TRS-398 and IPEM are shown in table 4.

Plastic phantom	The value of C_{pl}		The value of h_{pl}	
	TRS-398	IPEM	TRS-398	IPEM
RMI-457	0.949	1.00	1.008	1.011
Clear polystyrene	0.922	0.98	1.026	1.025
White polystyrene	0.922	0.995	1.019	1.018
PMMA	0.941	1.13	1.009	1.008

Table 4: Values for depth scaling factor and fluence scaling factor by IAEA TRS-398 and IPEM-2003 for a number of plastic phantoms

[4] A stream of particles crossing a unit area, usually expressed as the number of particles per second per area.

2.4 Comparison between Protocols

2.4.1 Photons

The three codes of practice under study here are based on standards of absorbed dose to water; nevertheless, there are some peculiarities regarding the way calibrations are dealt with. The IPSM-1990 protocol is based on the UK National Physical Laboratory ion chamber calibration service, whose primary standard is a graphite calorimeter, and three ion chambers (NE 2561/2611, NE Technology Ltd, Reading, UK) are used as reference standards in graphite. This service provides calibration coefficients for a range of beam quality indices where a generic fit of k_Q versus $TPR_{20,10}$ (tissue phantom ratio at 20 cm deep, normalized to 10 cm) is generally used and the ion chamber to be calibrated is checked at several beam qualities. No generic fit is available for other chamber types, and measurements for a full range of beam qualities are carried out instead. AAPM TG-51 is based on ion chambers with absorbed dose to water calibration coefficients for ^{60}Co beam quality Q_0 and sets of beam quality conversion factors. IAEA TRS-398 provides the most general and flexible framework for calibration, allowing the use of experimental or theoretical beam quality conversion factors. IAEA TRS-398 recommends the use of generic experimental beam quality conversion factors provided that they have been determined in a standards laboratory, such as NPL.

2.4.1.1 Reference Conditions

The reference conditions to determine the absorbed dose to water for high energy photon beams in three protocols are summarized in table 5.

Influence quality	Code of practice	Reference conditions
Phantom material	IAEA TRS-398	Water
	IPSM-1990	
	AAPM TG-51	
Chamber type	IAEA TRS-398	Cylindrical
	IPSM-1990	
	AAPM TG-51	
Measurement depth z_{ref}	IAEA TRS-398	For $TPR_{20,10} < 0.7$; 10 g/cm^2 (or 5 g/cm^2) For $TPR_{20,10} \geq 0.7$; 10 g/cm^2
	IPSM-1990	For $0.58 \leq TPR_{20,10} \leq 0.75$; 5 cm For $0.75 < TPR_{20,10} \leq 0.81$; 7 cm
	AAPM TG-51	At 10 cm
Reference point of chamber	IAEA TRS-398	On the central axis at the center of the cavity volume
	IPSM-1990	
	AAPM TG-51	
Position of reference point of chamber	IAEA TRS-398	At z_{ref}
	IPSM-1990	
	AAPM TG-51	Shift $0.6r_{cav}$* upstream from z_{ref}
SSD	IAEA TRS-398	100 cm
	IPSM-1990	
	AAPM TG-51	
Field size at phantom surface	IAEA TRS-398	10 × 10 cm^2
	IPSM-1990	
	AAPM TG-51	

Table 5: Reference conditions for determination of absorbed dose to water in high energy photon beam in three protocols: TRS-398, IPSM and TG-51

* r_{cav}: radius of the chamber's cavity

The general formalisms for the absorbed dose calculation for each code of practice are given in section (2.3.1) at reference depth (z_{ref}). The values of the k_Q are given by each code for the used chambers as a function of beam quality. If we need to find the absorbed dose at the maximum depth (z_{max}), we have to use central axis %DD data for SSD set-ups and TMR[5] data for SAD set-ups.

[5] TMR stands for tissue maximum ratio that is a special case of TPR and defines as the ratio of the dose at a given point in phantom to the dose at the same point at the reference depth of maximum dose.

2.4.1.2 Beam Quality Index

For both IAEA TRS-398 and IPSM-1990, the beam quality for high energy photon beam is specified to be the tissue phantom ratio ($TPR_{20,10}$). The important characteristic of this beam quality is its independence of electron contamination. The experimental set-up for measuring $TPR_{20,10}$ is shown in figure 6 and the reference conditions of its measurements that are given by IAEA TRS-398 are illustrated in table 6.

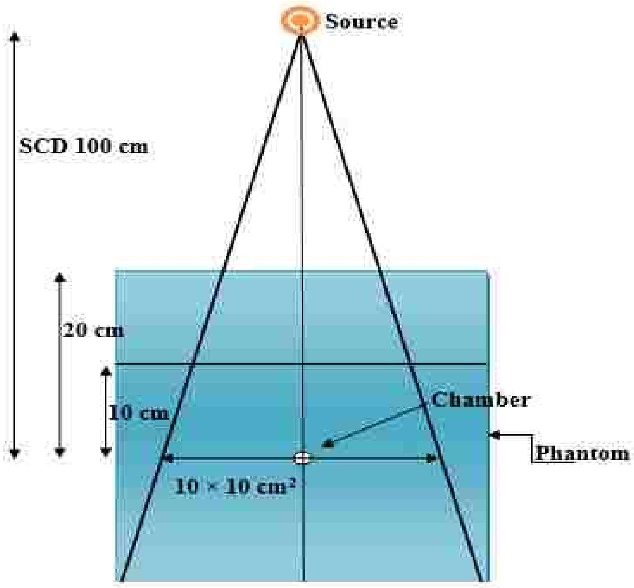

Figure 6: Experimental set up for the $TPR_{20,10}$ measurements
Either cylindrical or plane-parallel chamber can be used (IAEA1, 2000)

Influence quantity	Reference value
Phantom material	Water
Chamber type	Cylindrical or plane-parallel
Measurement depths	20 and 10 g/cm^2
Reference point of the chamber	For cylindrical, at centre of the chamber cavity. For plane-parallel, on the inner surface of the window at its centre.
Position of reference point of chamber	At the measurement depths
SSD	100 cm
Field size	10 × 10 cm^2

Table 6: Reference conditions to determine $TPR_{20,10}$

In regard to AAPM TG-51, the beam quality of the clinical photon beam is chosen to be the percentage depth dose at 10 cm depth ($\%DD(10)_x$) in a water phantom. The subscript 'x' means that the percentage depth dose is due to photons only (i.e. excluding electron contamination).

To measure $\%DD(10)_x$, the ionization chamber must be placed in a water phantom at 100 cm SSD from the surface with 10 × 10 cm^2 field size to produce the central axis percentage depth-ionization curve. For the cylindrical chamber, the measured depth needs to be shifted by $0.6r_{cav}$, while for the plane-parallel chamber no shift is required because there is no shift in the effective point of measurement.

At energies higher than 10 MV, the electron contamination may significantly affect the $\%DD(10)_x$, therefore 1 mm thick lead foil can be positioned below the accelerator head and 50 ± 5 cm or 30 ± 1 cm from a phantom surface to reduce this effect to a negligible level. Then, what has been measured is assigned as $\%DD(10)_{Pb}$.

Now to obtain $\%DD(10)_x$ when 50 ± 5 cm lead foil from a phantom surface is employed, eq. 14 is used (Rogers, 1999):

$$\%DD(10)_x = [0.8905 + 0.00150\%DD(10)_{Pb}]\%DD(10)_{Pb} \qquad \text{Eq. 14}$$

However, when 30 ± 1 cm lead foil from a phantom surface is employed, eq. 15 is used:

$$\%DD(10)_x = [0.8116 + 0.00264\%DD(10)_{Pb}]\%DD(10)_{Pb} \qquad \text{Eq. 15}$$

2.4.2 Electrons

The three codes of practice under study here are based on standards of absorbed dose to water and use R_{50} (the depth at which the dose in water is 50% of its maximum value) as the quality index. The IPEM-2003 protocol is based on the UK National Physical Laboratory ion chamber calibration service. This service provides calibration coefficients for a range of beam quality indices where a generic fit of k_Q versus R_{50} is generally used. AAPM TG-51 is based on ion chambers with absorbed dose to water calibration coefficients for ^{60}Co beam quality Q_0 and sets of beam quality conversion factors that is provided by the SSDL or a cross calibration. Also for electrons, IAEA TRS-398 provides the most general and flexible framework for calibration, allowing the use of experimental or theoretical beam quality conversion factors.

2.4.2.1 Reference Conditions

The reference conditions for determination of absorbed dose to water for high energy electron beams in the three protocols are summarized in table 7.

Influence quality	Code of practice	Reference value or reference characteristics
Phantom material	IAEA TRS-398	For $R_{50} \geq 4$ g/cm^2,water For $R_{50} < 4$ g/cm^2,water or plastic
	IPEM-2003	Water, plastic for low energy beams
	AAPM TG-51	Water
Chamber type	IAEA TRS-398	For $R_{50} \geq 4$ g/cm^2, plane-parallel or cylindrical For $R_{50} < 4$ g/cm^2, plane-parallel
	IPEM-2003	
	AAPM TG-51	For $R_{50} \geq 4.3$ cm, plane-parallel or cylindrical For $R_{50} < 4.3$ cm plane-parallel
Measurement depth z_{ref}	IAEA TRS-398	$0.6\ R_{50} - 0.1$ g/cm^2
	IPEM-2003	
	AAPM TG-51	
Reference point of chamber	IAEA TRS-398	For plane-parallel, on the inner surface of the window at centre; For cylindrical, on the central axis at center of the cavity volume
	IPEM-2003	
	AAPM TG-51	
Position of reference point of chamber	IAEA TRS-398	For plane parallel, at z_{ref}, For cylindrical chamber, $0.5r_{cav}$* downstream
	IPEM-2003	For plane parallel, at z_{ref}, For cylindrical, $0.6r_{cav}$ upstream
	AAPM TG-51	For plane parallel, at z_{ref}, For cylindrical, $0.5r_{cav}$ upstream.
SSD	IAEA TRS-398	100 cm
	IPEM-2003	
	AAPM TG-51	
Field size at phantom surface	IAEA TRS-398	For $R_{50} \leq 7$ g/cm^2, 10 × 10 cm^2 For $R_{50} > 7$ g/cm^2, 20 × 20 cm^2
	IPEM-2003	For $E \leq 15$ MeV, 10 × 10 cm^2 For $E > 15$ MeV, 20 × 20 cm^2
	AAPM TG-51	For $R_{50} \leq 8.5$ cm, 10 × 10 cm^2 For $R_{50} > 8.5$ cm, 20 × 20 cm^2

Table 7: Reference conditions for determination of absorbed dose to water in high energy electron beam in three codes; TRS-398, IPEM and TG-51

* r_{cav}: radius of the chamber's cavity

The general formalisms for the absorbed dose calculation for each code of practice are given in section (2.3.1) at reference depth (z_{ref}). The values of the k_Q are given by each code for the used chambers as a function of beam quality. If we need to find the absorbed dose at the maximum depth (z_{max}) for a SSD setup, we must divide the result of the absorbed dose at the reference depth by the central axis %DD data.

2.4.2.2 Beam Quality Index

All three codes choose the same beam quality index for high energy electron beams, which is the half value depth in water (R_{50}).

When we setup the equipment with measurement conditions as previously mentioned in section (2.4.2.1), the ionization chamber measures the depth ionization distribution in water ($R_{50,\ ion}$). From this depth ionization curve, one can extract the 50% half-value depth ionization where the ionization is 50% of its maximum value. Then we can find R_{50} by (Ding, 1995):

$$R_{eq} = 1.029\, R_{ion} - 0.06 \qquad (R_{ion} \leq 10\, \frac{g}{cm^2}) \qquad \text{Eq. 16}$$

$$R_{eq} = 1.059\, R_{ion} - 0.37 \qquad (R_{ion} > 10\, \frac{g}{cm^2}) \qquad \text{Eq. 17}$$

2.4.3 General Similarities and Differences

In general, there are similarities and differences between the three protocols in terms of beam quality index, calibration setup, standards of ionization chamber calibration and terminology. Both TRS-398 and TG-51 have already been discussed in great detail in the literature (Khan, 2003), (Huq, 2001) (Banjade, Tajuddin, & Shukri, 2001).

Examples of those similarities and differences are:

1. IAEA TRS-398, AAPM TG-51 and IPSM-1990 primarily all recommend the water phantom and only cylindrical chambers to be used in photon beam dosimetry. Also they all recommend the setup of 10 × 10 cm^2 and SSD of 100 cm, although IAEA TRS-398 and AAPM TG-51 allow either SSD or SAD of 100 cm.

2. IAEA TRS-398, AAPM TG-51 and IPEM-2003 recommend water as phantom material of choice for electron beam dosimetry. Although plastic phantoms are discouraged by the IAEA TRS-398 and IPEM-2003, their use is allowed for lower energies in case of difficulties in using water phantom. While, AAPM TG-51 does not allow plastic phantom use.

3. IAEA TRS-398 and IPEM-2003 recommend the use of plane-parallel ionization chambers for all energies and require its use at $R_{50} < 4$ g/cm^2, however cylindrical chamber can be used for $R_{50} = 4$ g/cm^2. On the other hand, AAPM TG-51 allows the use of cylindrical chamber for all energies above 6 MeV ($R_{50} = 4.3$ g/cm^2), recommends the use of plane-parallel chambers at all energies and require its use for energies at or less than 6 MeV.

4. The depth of measurements in reference condition is determined to be at 10 cm depth in both IAEA TRS-398 and AAPM TG-51, although IAEA TRS-398 allows 5 cm if $TPR_{20,10}$ is less than 0.7. On the other hand, according to IPSM-1990 protocol the depth should be at 5 cm for energy (E) equals to 10 MV and 7 cm for E > 10 MV.

5. Both IAEA TRS-398 and AAPM TG-51 provide sets of theoretically derived beam quality conversion factors ($k_{Q,Qo}$) for a number of ionization chambers used worldwide. The k_Q values are derived from Bragg-Gray theory, and the combined value of its uncertainty is 1.0% (Nuttbrown, Duane, Shipley, & Thomas, 2002) (Andreo P. , 2000). While IPSM-1990 does not use k_Q. Instead, NPL factor that is provided for the secondary standard chamber is used to convert the reading to absorbed dose.

6. The IAEA TRS-398 and IPSM recommended $TPR_{20,10}$ as the quality index for photon beams, while AAPM TG-51 uses $\%DD(10)_x$. In the IPSM-1990 code, the dose is measured at a depth of 5 or 7 cm depending on beam energy, but both IAEA TRS-398 and AAPM TG-51 chose 10 cm depth, although the IAEA TRS-398 allows 5 cm depth for $TPR_{20,10}$ < 0.7 g/cm^2.

7. For photon beams, $N_{D,w}$ factor for IAEA TRS-398 and AAPM TG-51 is taken from the calibration certificate of the used chamber that is calibrated in a standard laboratory with two years interval. On the other hand, IPSM-1990 recommends the cross calibration with a standard chamber to obtain $N_{D,w}$ factor. In the case of electron beams, $N_{D,w}$ factor for IAEA TRS-398 and IPEM-2003 is taken from the calibration certificate of the used chamber that is calibrated in a standard laboratory with two years interval. Alternatively, AAPM TG-51 mentions the cross calibration with a standard chamber to achieve $N_{D,w}$ factor.

8. The IPSM-1990 code does not contain recommendations in regard to several problems such as using alternatives for water phantom, wall thickness when a horizontal beam is used, design characteristics of ion chamber and waterproof sleeves.

9. IAEA TRS-398 provides an empirical relationship between $TPR_{20,10}$ and $\%DD_{20,10}$.

10. IAEA TRS-398 and IPEM-2003 provide detailed guidelines to estimate measurement uncertainty.

11. IPSM-1990 does not provide details about the chamber type to be used when measuring central axis depth dose distributions and the effective point of

measurement. Both IAEA TRS-398 and AAPM TG-51 recommend an upstream shift of 0.6 times the inner radius of a cylindrical chamber.

12. AAPM TG-51 mentions a shift of 0.5 times the inner radius of a cylindrical chamber (r_{cav}) for the cross calibration with a plane-parallel chamber used for electron beams measurements. IAEA TRS-398 recommends the reference point of the chamber to be positioned $0.6r_{cav}$ deeper than the reference depth. In IPEM-2003, a shift of $0.6r_{cav}$ towards radiation source is suggested.
13. In IPSM-1990 and IPEM-2003, ion recombination factor can be determined using two different ways: the experimental formula by Burns and Rosser (Burns & Rosser, 1990), and Boag's analytical formula (Boag & Currant, 1980).
14. IAEA TRS-398, AAPM TG-51 and IPEM-2003 are using R_{50} as beam quality index for electrons and calculating the reference depth at $0.6R_{50}$-0.1 cm depth.
15. Only IAEA TRS-398 gives the non-reference conditions to measure the absorbed dose.
16. IAEA TRS-398, AAPM TG-51 and IPEM-2003 show the calculation for the absorbed dose at z_{max} where the clinical dosimetry calculations are referenced to the depth of dose maximum.

2.5 Errors and Uncertainties

An error is defined as the difference between a measured value and the true value, and is a combination of both systematic and random errors. An error has a numerical value with a sign and can be corrected.

Trueness is the closeness of agreement between the average value obtained from a large number of measurements and the accepted true value. Precision is the closeness of agreement between repeated measurements. Precision is largely affected by random error, whereas, trueness is largely affected by systematic error. Accuracy is a representation of the lack of errors, both random and systematic.

On the other hand an uncertainty is a parameter that characterizes the dispersion of the values and expressed as standard deviation where it has no sign and is assumed to be symmetrical.

The measurement of relative dose data; target volume and delineation; equipment commissioning and quality assurance; treatment planning; delivery of dose; and the actual patient set-up on the treatment machine, all represent sources of uncertainty in dose delivery which may compromise the potential advantages of modern technologies. Therefore, it is important to understand levels of accuracy and consider the propagation of the uncertainties as part of the entire treatment optimization process.

Standard uncertainties are classified into two types:

● Type A uncertainties are obtained by a statistical analysis of a series of observations. They are evaluated in a straightforward manner as the standard deviation of the mean value. They can be improved by repeating the measurements.

● Type B uncertainties are systematic and are determined through other than statistical methods. It is assumed that this type has a probability density that corresponds to a rectangular, triangular or Gaussian distribution.

Type-A and type-B uncertainties are combined in quadrature to yield the combined standard uncertainty (u_c) and an expanded uncertainty can be built by multiplying u_c by a coverage factor (k), typically in the range of 2 to 3.

In our context, uncertainties of measurements are stated as relative standard uncertainties ($u_r(y)$), i.e. standard deviation of the measurement ($u(y)$) divided by the absolute value of the measurement ($|y|$).

The uncertainties in the different physical quantities or procedures that contribute to the determination of absorbed dose to water in the user beam can be divided into three steps. The first step made by the user considers the uncertainties in the determination of the chamber factor based on an $N_{D,W}$ calibration from a standard laboratory.

The second step to be considered is that of uncertainties in the measurements carried out by the user in the clinical beam. The components in this step, in addition to the long-term stability of the user's dosimeter, are the experimental set-up, the uncertainty of the readings of the dosimeter relative to a timer or beam monitor, and the necessary corrections for the influence quantities (polarity effect, temperature and pressure, humidity and ion recombination). The combined uncertainty varies with the beam type and ionization chamber.

The third step in the uncertainty estimate of the dose determination corresponds to the beam-quality correction factor, k_Q, and the most common approach is based on the use of theoretically determined k_Q factors, which includes ratios at the user's quality Q and at ^{60}Co of water/air stopping power ratios, $s_{w,air}$, the mean energy expended in air per ion pair formed (W_{air}), and the perturbation factor.

Combining the uncertainties in quadrature in the various steps yields the combined relative standard uncertainty (IAEA1, 2000) (Podgorsak, 2005).

Chapter 3: Methodology

Measurements were performed on a Varian Clinac iX (# 5233) linear accelerator from Varian Medical Systems at Tawam Hospital, United Arab Emirates. Photon energies used were 6MV and 15 MV whereas electron energies used were 6, 9, 12, 16 and 20 MeV. Equipment used to perform the measurements is shown in brief detail and the procedures used to measure the absorbed dose following each code of practice are explained.

3.1 Experimental Equipment

3.1.1 Phantoms

Three types of phantoms were used in this project. They are:

I. IBA one dimensional water phantom with smart control unit: the wall is made of PMMA with inner dimension of 40 cm length × 34 cm wide × 35 cm height. It is equipped with a motor control device to move the detector. It is used mainly for photon and electron beams stability, depth dose measurements in beam quality determination and quality assurance. The measurement depth can be adjusted by 0.1, 1, 10, 100 mm using smart control unit. Position reproducibility is ± 0.1 mm. Figure 7 illustrates the IBA 1D-WP (IBA, 2016).

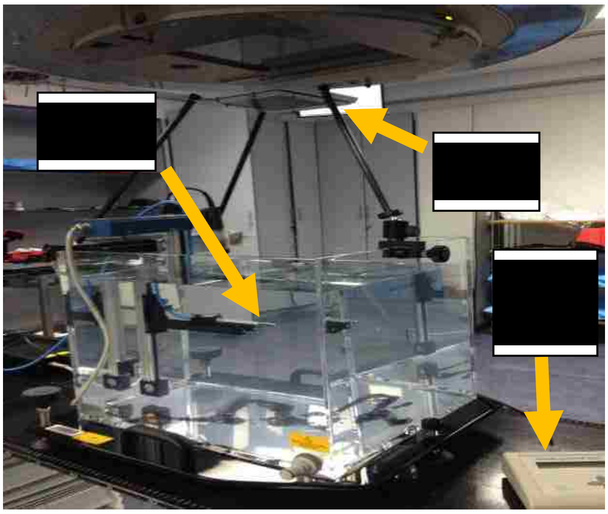

Figure 7: IBA one-dimensional water phantom

II. Brown solid water phantom: it is 30 × 30 cm, water equivalent material with density of 1.043 ± 0.005 g/cm^3. The phantom consists of layers or slabs of different thickness with adaptor plates for the chamber in-use (figure 8). This phantom can be used with photon and electron beam calibrations. It is usually used in the daily measurement or to get a quick result. It eliminates the inconvenience of transporting, setting up and filling water tanks (Litzenberg, 2011).

Figure 8: Brown, solid water-equivalent phantom

III. Perspex inter-comparison phantom: it is a water equivalent material phantom designed especially for cross calibration. One side is 5 cm in thickness and the other side is 7 cm thick. Holes for insertion of cylindrical ionization chambers are drilled into the phantom at the same distance from the central axis, where we can fix the two chambers, figure 9. It is safer for non-waterproof secondary standard chamber to be used with this phantom and the positioning is easily reproduced.

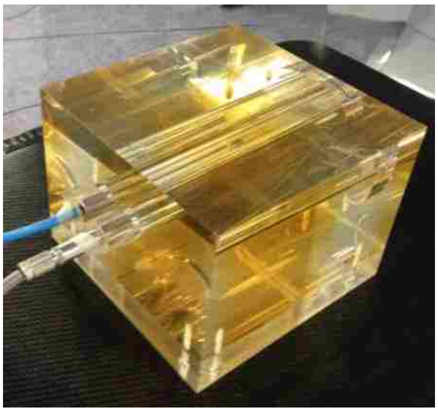

Figure 9: Perspex inter-comparison phantom

3.1.2 Ionization Chambers

Knowing the ionization chamber in-use is an essential step in applying any protocol because k_Q and $N_{D,W}$ factors are chamber dependent. A regular schedule of constancy checks with Sr-90 check sources is carried out for all our chambers. Different types of ionization chambers were used:

I. A water proof plane-parallel chamber from IBA (PPC40/ TNC, serial number: 680) was chosen to perform the electron measurements, figure 10. One should be aware of the reference point or the effective point of measurement that lies 1 mm below the front window; e.g. after setting the SSD to 100 cm on the front window we need to raise the chamber 1mm up to reach the reference point. In Appendix-A the technical description and the calibration certificate of the chamber are provided. One can note that the calibration certificate is due to be renewed; but constancy checks on a monthly basis and a cross calibration with the secondary standard chamber every two years are done within the medical physics department at Tawam Hospital ensure the validity of $N_{D,W}$ factor. Another note is that PPC40 chamber is similar to the Roos chamber that is mentioned in IAEA TRS-398 and AAPM TG-51 k_Q tables.

Figure 10: Plane-parallel chamber from IBA

II. A waterproof cylindrical chamber from PTW (TW30013, serial number: 04604) was chosen for photon dosimetry, figure 11. In Appendix-B the technical description and the calibration certificate of the chamber are provided. The reference point of measurement for this chamber is along the central axis and 1.3 cm from the tip of the chamber. One can note that the calibration certificate is due to be renewed, but constancy checks on a monthly basis and a cross calibration with the secondary standard chamber each two years are done within the medical physics department at Tawam Hospital ensure the validity of $N_{D,W}$ factor.

Figure 11: Cylindrical chamber from PTW

III. NPL secondary standard ionization chamber (type 2611A, serial number 121) is a non-waterproof, cylindrical chamber type that is traceable to the UK primary standard of absorbed dose for photon beams at NPL. The chamber is kept as a reference chamber in the department and not for clinical use. It is used for transferring ^{60}Co factors by cross calibration with cylindrical chambers using side-by-side method in a Perspex inter-comparison phantom, figure 9. The effective point of measurement is 5 mm from the tip of the chamber. Appendix-C shows the calibration certificate.

IV. A waterproof cylindrical chamber from PTW (TW30013, serial number: 008620) was used to transfer ^{60}Co factors by cross calibration with plane-parallel chamber (PPC40/ TNC, serial number: 680) using substitution method (section 3.2.2.2) in a water phantom. In Appendix-D the calibration certificate of the chamber is provided.

3.1.3 Electrometers

A PTW secondary standard reference class dosemeter, UniDos^{webline}, is used where dose, dose-rate, charge or current measurements can be taken, figure 12. It is common practice at Tawam to calibrate the ionization chamber and the electrometer together, as one set. In this case the calibration coefficient $N_{D,W}$ is expressed in the unit Gy/rdg or Gy/C and no separate electrometer calibration coefficient has to be applied. Appendix-E shows the calibration certificate of UniDos^{webline} (Serial No. 00146) electrometer.

Figure 12: Electrometer from PTW

3.2 Procedures

The project assesses the traceability of different codes of practice in measuring absorbed dose to water for high energy photon and electron beams. The gantry is set at 0^o. The temperature and pressure were measured and correct for. The average of three readings is taken, to reduce the uncertainty of the instrument reading.

3.2.1 Photon Beams

Experiments were performed using both a water phantom and a solid water phantom with a cylindrical ionization chamber and UniDos^{webline} electrometer. The experimental setup was 10 × 10 cm^2 field size and 100 cm SSD or 100 cm SAD depending on the recommendations of each code. The depth also varies according to the protocol requirements.

3.2.1.1 Quality Indices

In the IPSM-1990 and IAEA TRS-398, $TPR_{20,10}$ is used as a beam quality specifier. Figure 13 demonstrates the set up to measure $TPR_{20,10}$ where a brown, solid water phantom was used with 100 cm SAD. The readings were recorded at 10 and 20 cm depth for 6 and 15 MV.

Figure 13: $TPR_{20,10}$ setup for IPSM-1990 and IAEA TRS-398

Figure 14 shows the set up to measure $\%DD(10)_x$ for 15 MV using 1mm lead foil at 30 ± 1 cm from the phantom surface and 100 cm SSD. The readings were recorded from 0 to 11 cm depth. For 6 MV $\%DD(10)_x$, lead foil is not needed.

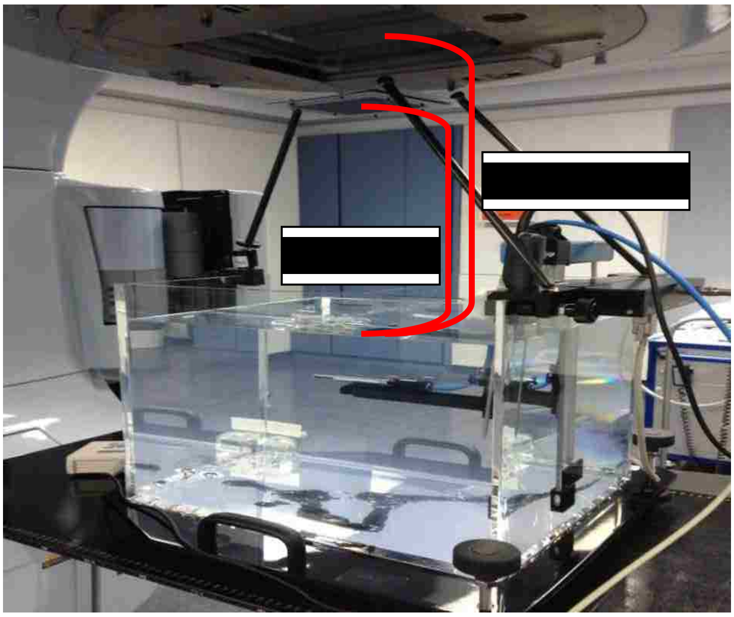

Figure 14: Percentage depth dose setup for AAPM TG-51 protocol

To determine the influence quantities, the setup conditions were 100 cm SSD, 10×10 cm^2 field size, and 10 cm depth[6] in water for IAEA TRS-398 and AAPM

[6] $0.6r_{cav}$ correction and the foil are not needed in measuring influence quantities in AAPM TG-51 because it has already been included while measuring the %DD.

TG-51. The measurements depths were 5 cm for 6 MV and at 7 cm for 15MV using IPSM-1990. Humidity was always within 20% to 70% so no humidity correction was necessary.

3.2.1.2 Absolute Dosimetry

A waterproof cylindrical chamber from PTW (TW30013, serial number: 04604) was chosen for these measurements in order to fulfil all three protocol recommendations.

The side-by-side method was used to cross-calibrate the PTW ionization chamber against the Secondary Standard leading to the corresponding $N_{D,W}$ field for each beam quality as described by IPSM-1990. The reference instrument in our institution is a NE 2611A Secondary Standard cylindrical chamber as recommended by the National Physical Laboratory (Teddington, Middlesex, UK), along with a PTW UniDos^{webline} electrometer. Both ion chambers were placed in a perspex phantom, with two built-in holes and appropriate perspex inserts to allow ion chambers to fit in. four sets of measurements were performed; after each, the inserts were exchanged and measurements repeated. Cross-calibrations were carried out at two different depths, corresponding to the reference conditions for absolute dose measurements of 5 cm depth for 6 MV and 7 cm depth for 15 MV at 100 cm SSD for a 10 × 10 cm^2 field size. Since the PTW ionization chamber was cross-calibrated with the Secondary Standard for each beam, only k_Q factors for the Secondary Standard NE 2611A are needed for IPSM-1990. Measurements were taken at 10 cm depth in water for IAEA TRS-398 and AAPM TG-51where $N_{D,W}$ is taken from the calibration certificate of the selected chamber.

3.2.2 Electron Beams

Experiments were performed using a water phantom with the IBA plane parallel chamber (PPC 40) and UniDos^{webline} (Serial No. 00146) electrometer. The experimental setup was 10 × 10 and 20 × 20 applicator at 100 cm SSD. The measurement depth is at z_{ref} which varies according to energy of the beam.

3.2.2.1 Quality Indices

According to IAEA TRS-398 and AAPM TG-51, the beam quality in electron beams is specified by R_{50}, the depth in water in cm at which the absorbed dose falls to 50% of the maximum dose for a beam. For IAEA TRS-398, the field size on the phantom surface is 10 × 10 cm^2 for 6, 9, 12, 16 and 20 MeV but for AAPM TG-51, the field size is 20 × 20 cm^2 for 20 MeV at an SSD of 100 cm, figure 15. The same applies to the IPEM-2003 except it recommends 10 × 10 cm^2 applicator with 6, 9 and 12 MeV and 20 × 20 cm^2 applicator for 16, 20 MeV. The readings were recorded from 0; i.e. on the surface; to different depths according to different energy beams. In order to measure the influence quantities, the plane parallel chamber is placed at z_{ref} depending on the energy at 100 cm SSD.

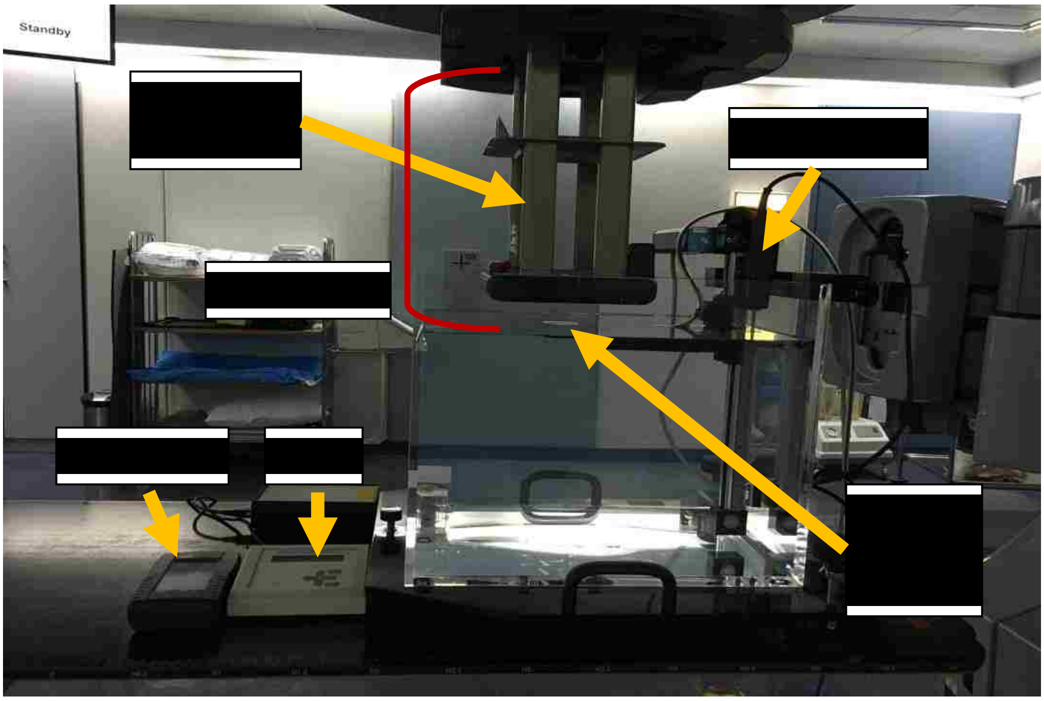

Figure 15: Depth- ionization measurement

3.2.2.2 Absolute dosimetry

For IAEA TRS-398 protocol, $N_{D,w}$ was taken from the calibration certificate of the selected chamber.

For AAPM TG-51, $N_{D,w}$ was calculated from cross calibrating the plane parallel chamber with a recently calibrated cylindrical chamber in water by the substitution method using 20 MeV beam at reference depth of 4.85 cm. The cylindrical chamber was shifted upstream by $0.5r_{cav}$.

IPEM-2003 needs the calibration factor for absorbed dose to be obtained by cross calibration with chamber has a NPL factor where in the time of measurement was not available.

Chapter 4: Results

This chapter summarizes the collected data, the statistical analysis and data processing that were performed according to the procedures described in the previous chapter. Linear accelerators at Tawam Hospital are calibrated to deliver 1 cGy per monitor units (MUs) at $z_{max,}$ at 100 cm SSD and 10 × 10 cm^2 field size or electron applicator.

In this chapter, we will collect the percentage depth dose data (%*DD*) for photon beams and percentage depth ionization data (%*DI*) for electron beams with different depths. Quality indices with be obtained from the curves, $\%DD(10)_x$ and R_{50} respectively. Also, $TPR_{20,10}$ will be measured as a quality index for photon beams. Quality indices help us to find the beam quality conversion factor ($k_{Q,Qo}$) from the used protocols.

The reference depth for photon beams is predetermined by each protocol but the reference depth for electron beams will be calculated depending on R_{50} for each energy.

Cross calibration with the secondary standard chamber will be used to obtain a calibration coefficient for the chamber in use. Also the influence quantities will be measured for the different energies in the mentioned protocols to correct for the dosimeter readings.

At the end, absorbed dose to water will be calculated at the reference depth and at the maximum depth where the absorbed dose at z_{max} will be compared to the 100 MUs which is expected to give 100 cGy, to find out the percentage error.

The relative standard uncertainties will be mentioned according to the source of each uncertainty and the total relative standard uncertainties will be summed and combined with the absorbed dose results.

4.1 Photons

Percentage depth dose curves are an indication about the beams penetration capability. In clinical situations, the %*DD* helps to decide the beam of choice depending upon how deep the tumor is located. Figures 16 and 17 illustrate the measured %*DD* distribution in water for 6 and 15 MV combined with the reference data set for %*DD* from Varian Medical System. The two distributions are consistent. The %*DD* at z_{ref} = 10 cm is used later in absorbed dose calculation at z_{max}.

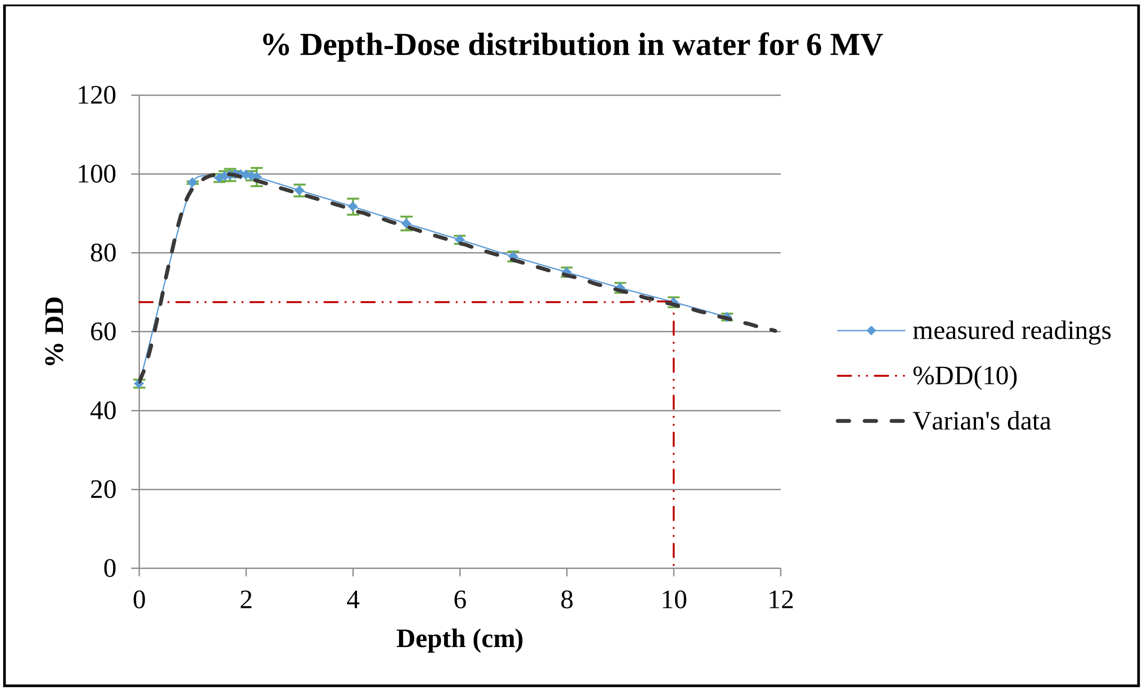

Figure 16: %Depth-Dose distribution in water for 6 MV

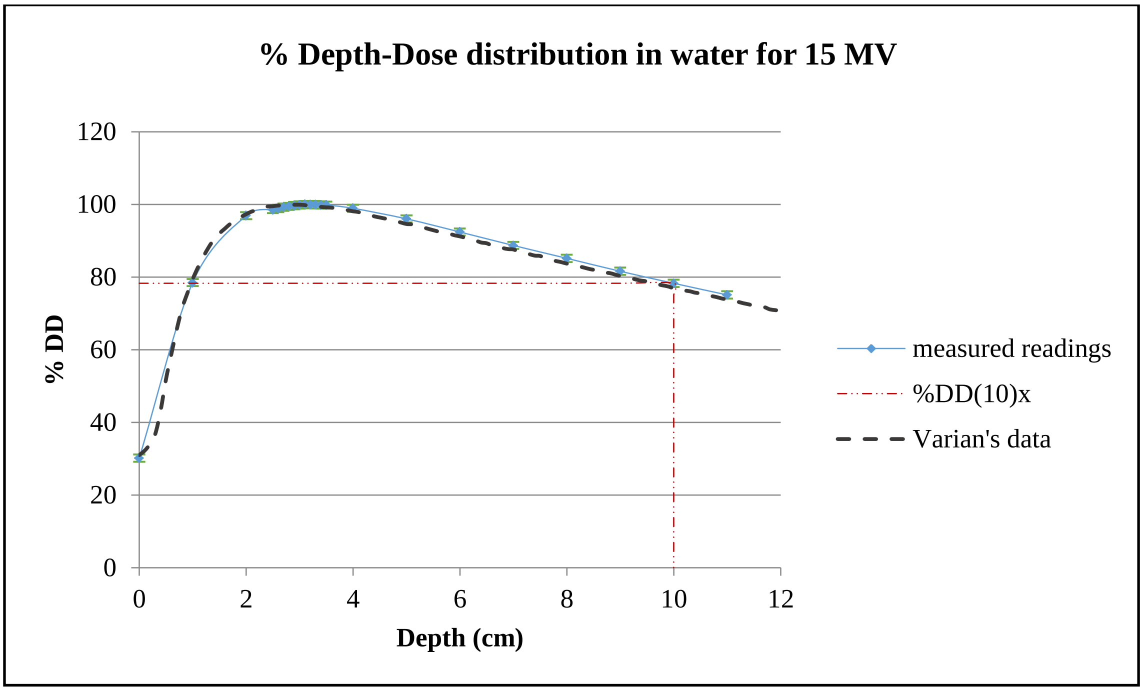

Figure 17: %Depth-Dose distribution in water for 15 MV

Table 8 demonstrates the absorbed dose measurements at z_{max} for 6 and 15 MV photon energies using three different international protocols. We delivered 100 MUs for all energies with the same setup and the dose was calculated by the three different protocols. The results indicate less than 2% error in the dose at the depth of z_{max}. The detailed measurements and calculations for photon beams using IAEA TRS-398, AAPM TG-51 and IPSM-1990 are listed in Appendix-F/G/H, respectively.

	6 MV		15 MV	
	Absorbed Dose at Z_{max} (cGy)	% error	Absorbed Dose at Z_{max} (cGy)	% error
IAEA TRS-398	99.440 ± 1.5	**0.56%**	100.085± 1.5	**0.08%**
IPSM-1990	98.784 ± 1.9	**1.22%**	101.816 ± 1.9	**1.82%**
AAPM TG-51	99.125 ± 1.5	**0.87%**	99.291 ± 1.5	**0.71%**

Table 8: Absorbed Dose at z_{max} comparison for 6 and 15 MV, calculated from different protocols

The estimated relative standard uncertainties of $D_{W,Q}$ at the maximum depth in water, based on a chamber calibration in ^{60}Co gamma radiation with level of confidence of approximately 95%, are listed in table 9 and 10 below. The expanded uncertainty in $N_{D,W}$ is estimated to be about 1.1% for TW300013/04604 cylindrical chamber and 1.4 % for the secondary standard chamber (2611A/121) in a ^{60}Co beam of a secondary standard lab (SSDL), based on standard uncertainty multiplied by coverage factor, k=2. Concerning photon beam quality conversion factors k_Q, IAEA TRS-398 reports uncertainty estimates of 1.0% for theoretical k_Q.

Relative standard uncertainty (%)	Source of uncertainty using k_Q calculated
1.1	$N_{D,W}$ calibration of the user dosimeter
1.0	Beam quality correction (calculated k_Q)
0.05	Pressure uncertainty for the Barometer
0.1	Temperature uncertainty for the Thermometer
0.2	Polarity uncertainty for the user dosimeter
0.1	Recombination correction for the user dosimeter
0.4	Establishment of reference conditions
0.006	Dosimeter reading relative to MUs
1.5	Quadratic Summation

Table 9: Relative standard uncertainties for photon beams using calculated k_Q

Relative standard uncertainty (%)	Source of uncertainty using cross calibration
1.1	$N_{D,W}$ calibration of the user dosimeter
1.4	$N_{D,W}$ calibration of the secondary standard
0.05	Pressure uncertainty for the Barometer
0.1	Temperature uncertainty for the Thermometer
0.2	Polarity uncertainty for the user dosimeter
0.1	Recombination correction for the user dosimeter
0.4	Establishment of reference conditions
0.00875	Dosimeter reading relative to MUs
1.9	Quadratic Summation

Table 10: Relative standard uncertainties for photon beams using cross calibration with a secondary standard chamber

4.2 Electrons

For electron measurements, we measured percentage depth ionization curves which were later converted to percentage depth dose by the IBA 3D water phantom OmniPro software. Figures 18 to 22 illustrate the measured percentage depth ionization distribution in water for 6, 9, 12, 16 and 20 MeV combined with the reference data set from Varian Medical System. The distributions are a close match. The Figures also show how to find $R_{50,}$ value of 50% ionization which is used later to find the reference depth, z_{ref}.

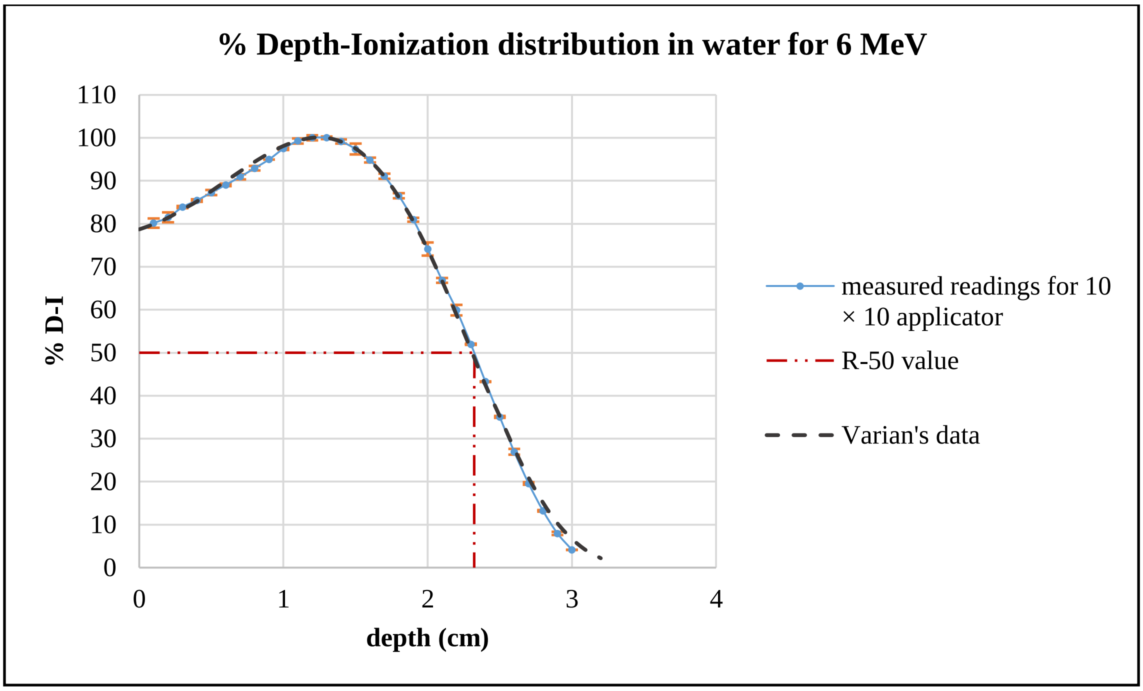

Figure 18: %Depth-Ionization distribution in water for 6 MeV

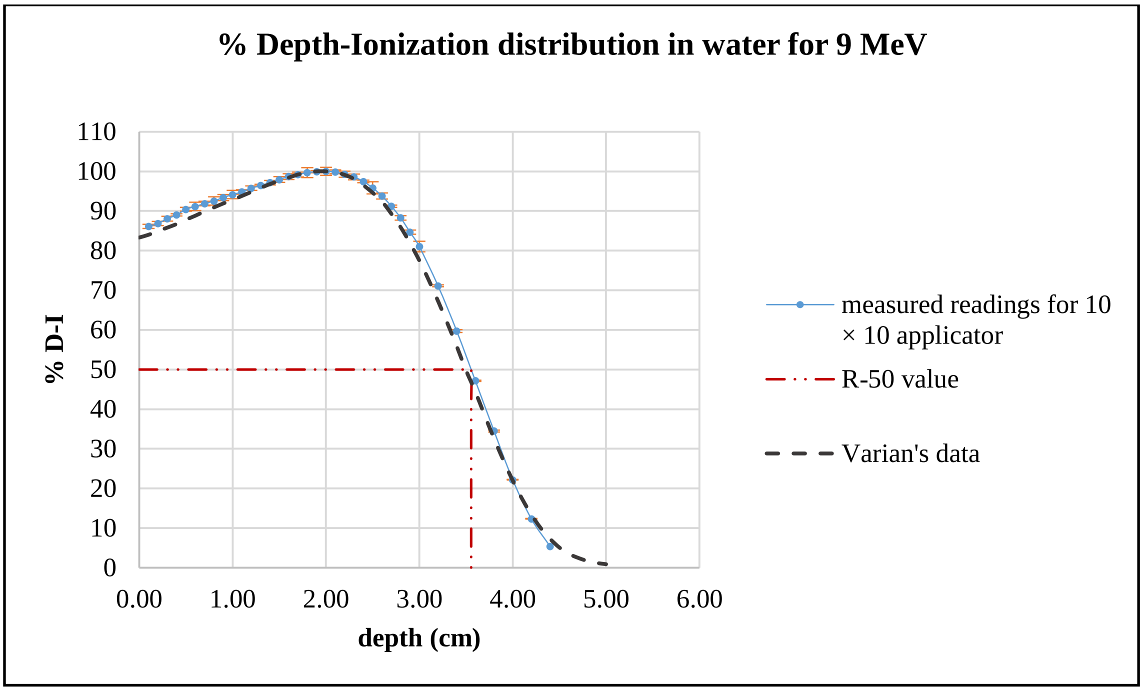

Figure 19: %Depth-Ionization distribution in water for 9 MeV

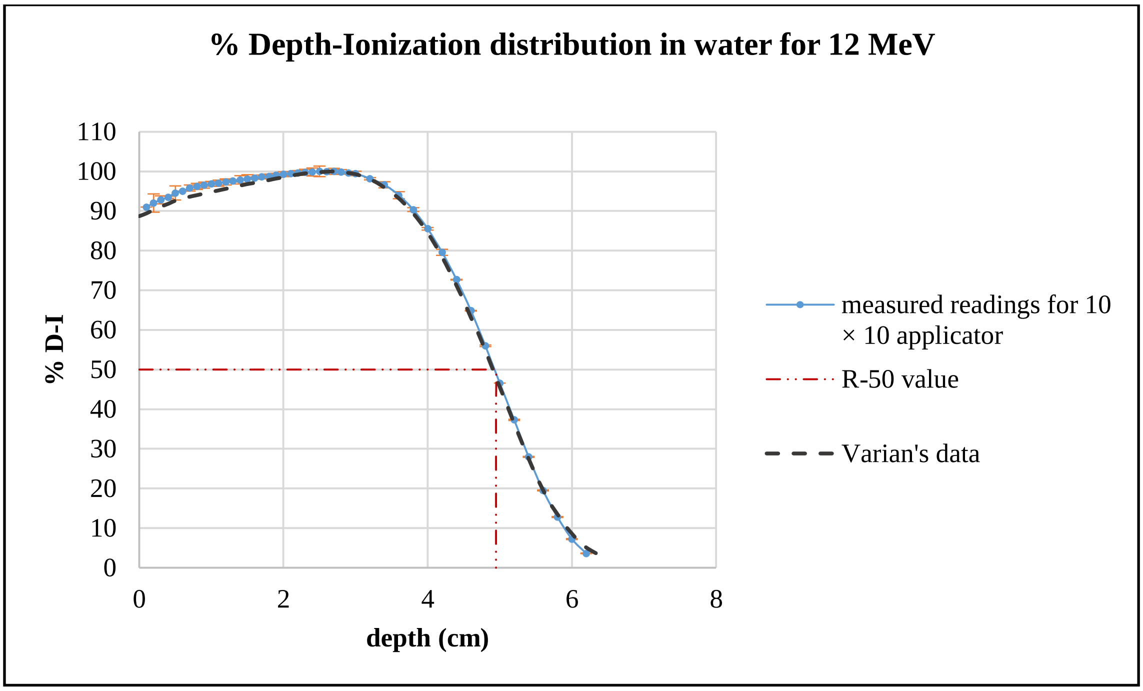

Figure 20: %Depth-Ionization distribution in water for 12 MeV

Following the guideline recommendations for the field size at phantom surface in section 2.4.2; in addition to the 10 × 10 cm^2, we also measured with 20 × 20 cm^2, for 16 and 20 MeV energies; the difference in %D-I curves is practically negligible. The calculated percentage error between z_{ref} is 0.4% and 0.2% for 16 and 20 MeV respectively; refer to figures 21 and 22.

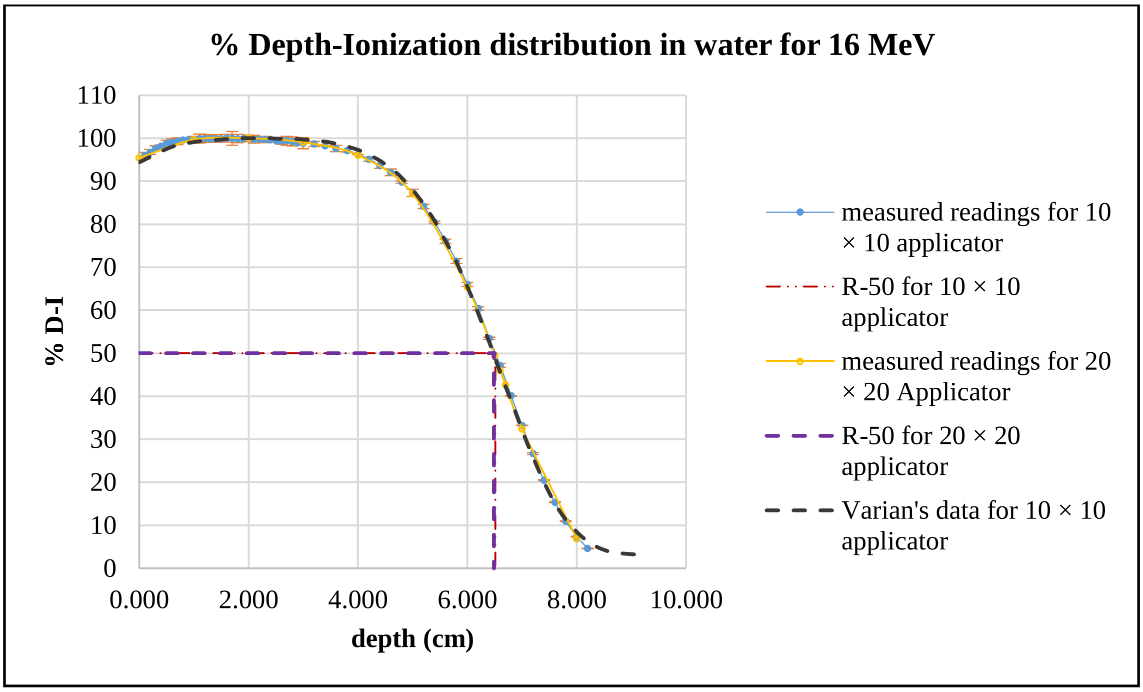

Figure 21: %Depth-Ionization distribution in water for 16 MeV

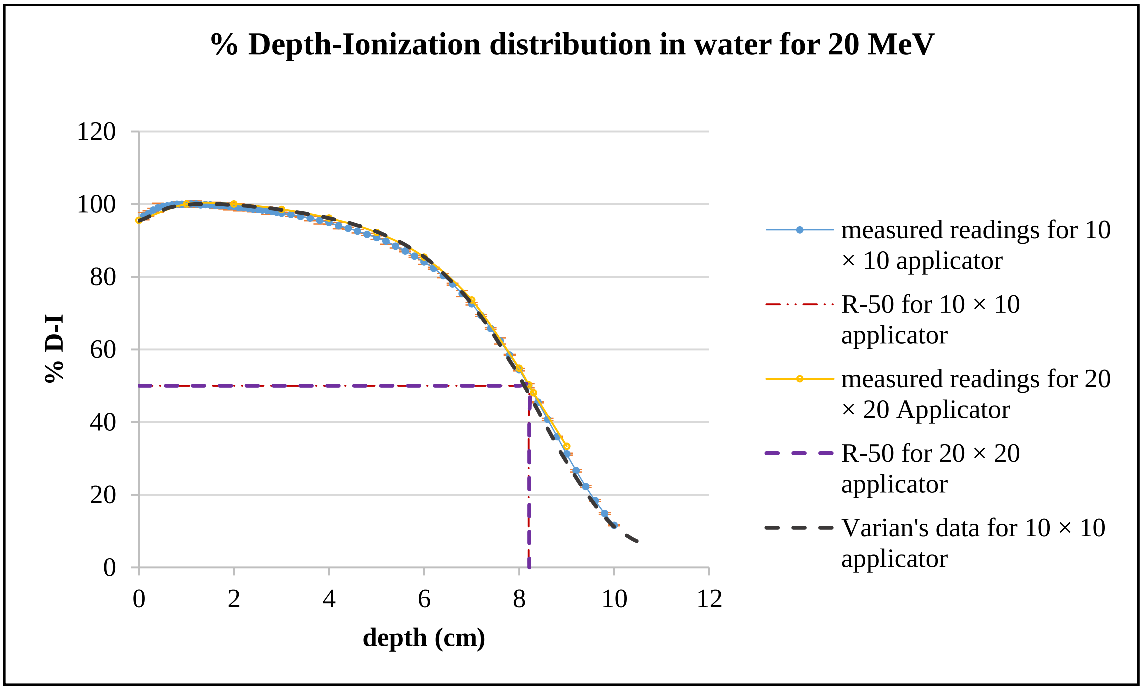

Figure 22: %Depth-Ionization distribution in water for 20 MeV

Table 9 shows the absorbed dose measurements at z_{max} for 6, 9, 12, 16 and 20 MeV electron energies by IAEA TRS-398 and AAPM TG-51 protocols. We delivered 100 MUs at 100 cm SSD and varying depths with varying energies. The results were found to have a maximum error of 3.76% in the dose measurement at depth, z_{max}. AAPM TG-51 shows less deviation with electron beams.

Absorbed dose measurements for electron beams with IPEM-2003 were not carried out because of the unavailability of NPL calibration factor for the chamber in use. The detailed measurements and calculations for electron beams using IAEA TRS-398 and AAPM TG-51 are listed in Appendix-I/J.

		IAEA TRS-398	AAPM TG-51
6 MeV	Absorbed Dose at z_{max} (cGy)	103.762 ± 2.9	102.337 ± 2.6
	% error	**3.76%**	**2.34%**
9 MeV	Absorbed Dose at z_{max} (cGy)	103.165 ± 2.9	101.691 ± 2.6
	% error	**3.17%**	**1.69%**
12 MeV	Absorbed Dose at z_{max} (cGy)	102.038 ± 2.9	102.120 ± 2.6
	% error	**2.04%**	**2.12%**
16 MeV	Absorbed Dose at z_{max} (cGy)	102.837 ± 2.9	101.404 ± 2.6
	% error	**2.84%**	**1.40%**
20 MeV	Absorbed Dose at z_{max} (cGy)	101.508 ± 2.9	100.155 ± 2.6
	% error	**1.51%**	**0.16%**

Table 11: Absorbed Dose at z_{max} comparison for 6, 9, 12, 16 and 20 MeV, calculated from different protocols

The expanded uncertainty in $N_{D,W}$ is estimated to be about 2.2% for IBA PPC40/680 parallel-plate chamber and 1.1 % for TW300013/008620 cylindrical chamber in a ^{60}Co beam of a secondary standard lab (SSDL), based on standard uncertainty multiplied by coverage factor, k=2. Regarding beam quality conversion factors k_Q for electron beams, IAEA TRS-398 reports uncertainty estimates of 1.7% for theoretical k_Q.

The estimated relative standard uncertainties of $D_{W,Q}$ at the maximum depth in water, based on a chamber calibration in ^{60}Co gamma radiation with level of confidence of approximately 95%, are listed in table 12 and 13 below.

Relative standard uncertainty (%)	Source of uncertainty using k_Q calculated
2.2	$N_{D,W}$ calibration of the user dosimeter
1.7	Beam quality correction (calculated k_Q)
0.05	Pressure uncertainty for the Barometer
0.1	Temperature uncertainty for the Thermometer
0.2	Polarity uncertainty for the user dosimeter
0.1	Recombination correction for the user dosimeter
0.4	Establishment of reference conditions
0.015	Dosimeter reading relative to MUs
2.9	Quadratic Summation

Table 12: Relative standard uncertainties for electron beams using calculated k_Q

Relative standard uncertainty (%)	Source of uncertainty using cross calibration
2.2	$N_{D,W}$ calibration of the user dosimeter
1.1	$N_{D,W}$ calibration of the secondary standard
0.05	Pressure uncertainty for the Barometer
0.1	Temperature uncertainty for the Thermometer
0.2	Polarity uncertainty for the user dosimeter
0.1	Recombination correction for the user dosimeter
0.4	Establishment of reference conditions
0.006	Dosimeter reading relative to MUs
2.6	Quadratic Summation

Table 13: Relative standard uncertainties for electron beams using cross calibration with a secondary standard chamber

Chapter 5: Discussion

The previous chapter shows how our %DD and %DI results are very close to Varian's data, the small differences are due to the difference in the equipment that was used. The consistency indicates in my opinion two things:

1. The quality assurance program for the equipment in Tawam Hospital, radiotherapy department is effective. The equipment showed stability in their performance.
2. The protocols are easy to be followed and applied by the end user in the work place.

If the equipment are reliable, then personal errors are the main source of the uncertainties like measuring the wrong depth, using different voltage than the recommended in the electrometer, inappropriate fixing of the chamber, etc.

The calculated absorbed doses at z_{max} for photon and electron beams are within the ± 5 % internationally suggested accuracy by ICRU using the different protocols.

The uncertainty values for the electrons in table 11; are larger than those for photons in table 8. This should be expected due to the charged particle nature versus uncharged electromagnetic radiation. One can also notice that photon's %DD curves, figures 16 and 17, show gradual and slower decrease than Electron's %DI curves, figure 18 to 22. So mis-positioning the chamber in electron measurements leads to more counts for the uncertainty.

The percentage error in the measured dose for electrons decreases, table 11, with the electron's energy (except for energy 16 MeV for the IAEA TRS-398 protocol and 12 MeV for the AAPM TG-51 protocol). This confirms that the main source of error in the determination of the measured dose is statistical. Furthermore, looking carefully at the differences between the measured data and the Varian's data for the electrons, figures 18 to 22, show that these differences are larger at smaller depths of water than at larger depths. The dose measured at shallow depth is obviously more sensitive to mis-positioning of the chamber both in depth and in angular orientation.

While the error in electron dose calculation averaged over all energies is smaller for the IAEA protocol than that of the AAPM protocol, the trend is reversed for the photon dose. It is difficult to make conclusions from these limited data sets about the accuracy of the various protocols. Further studies regarding this issue may be useful.

IAEA TRS-398 and AAPM TG-51 are self-contained protocols and provide detailed work sheets for the users with tabulated reference conditions for different situations. On the other hand, IPSM-1990 needs some more practical explanations.

IAEA TRS-398 is the most recent, general and flexible outline for calibration with a great details from the background of the work until the comprehensive explanation of the different quantities and formulas.

Chapter 6: Conclusion

This research offers an introduction to the radiotherapy treatment and basic background of the dosimetry. Then it gives the worldwide steps that are shadowed by the international and regional organizations in the dosimetry measurements system.

This study presents a detailed comparison of the differences and the similarities in the basic data included in the IAEA TRS-398, AAPM TG-51, IPSM-1990 (for photon beams only) and IPEM-2003 (for electron beams only) protocols for high energy beams dosimetry. It also demonstrates the measurements done on water phantom according to the different protocols.

Consequently, the followed protocols are very similar in their formalisms, correcting the dosimeter readings for influence quantities and all are based on absorbed dose to water calibration of the ionization chamber. There are minor differences between the protocols in beam quality indices, ways to obtain beam quality correction and using different notation. Overall, measurements obtained are in very good agreement with each other as well as with the values from Varian Medical System.

The chosen protocols simplify the clinical reference dosimetry which leads to improve the accuracy. IAEA TRS-398 and AAPM TG-51 provide worksheets, which guide the user in a step by step implementation of the protocol.

In conclusion, this work has showed generally consistent radiotherapy dosimetry for photon and electron beams, i.e. percentage error in the measured absorbed dose for photon and electron beams is less than 2% and 4% respectively for all codes of practice involved. The study provides estimation for relative standard uncertainties where in future studies more accurate details can be given.

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Appendix-A

Technical description and the calibration certificate for plane-parallel chamber from IBA (PPC40/ TNC, serial number: 680)

SCANDITRONIX
WELLHÖFER

Technical description

Parallel Plate Chamber PPC40

Material

- outer electrode
  PMMA (1.18 g/cm³)
- inner electrode
  PMMA graphitised (1.18 g/cm³)

Cable & Connector

connector type	TNC or BNC triaxial
cable length	1.40 m

Application

- absolute dosimetry of electron, photon and proton beams in radiotherapy
- measurements in air, in solid or in water phantoms

Active Dimensions

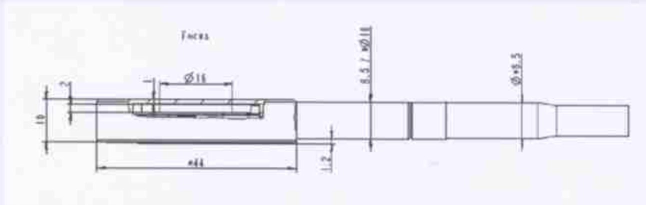
volume (nominal)	0.40 cm³
cylinder height	2.0 mm
front window thickness	1.0 mm
diameter of inner electrode	16.0 mm

Operational Data

leakage current	< ± 4 x 10^{-15} A
sensitivity	12 x 10^{-9} C/Gy
radiation quality (e^-)	> 2 MeV
polarising voltage	+ 300 V
reference point in water	1.0 mm below the outer surface

Features

- air ionisation chamber
- waterproof
- vented through waterproof sleeve
- fully guarded
- superior physics characteristics:
  - stabilisation time after polarity change approx. 30 s
  - perturbation correction approx. equal to unity
  - polarity effect < 1 % for all usable energies, field sizes and depths at linear accelerators
- supplied with individual factory calibration certificate and user's guide



* add 0.2 mm for tolerance if you intend to make adapters
dimensions in mm

Technical data subject to change without prior notice.

Sweden: Scanditronix Medical AB - Stålgatan 14 - SE-754 50 Uppsala
Tel.: +46 18 18 07 00 ❑ Fax: +46 18 12 75 52 ❑ info@scxmedical.se

Germany: Wellhöfer Dosimetrie GmbH - Bahnhofstr. 5 - DE-90592 Schwarzenbruck
Tel.: +49 9128 607 0 ❑ Fax: +49 9128 607 10 ❑ info@wellhofer.com

USA: Scanditronix Wellhofer North America - 3150 Stage Post Drive, Suite 110 - Bartlett, TN 38133
Tel.: +1 901 386 2242 ❑ Fax: +1 901 382 9453 ❑ swna@iba-group.com

Homepage: www.iba-ar.com

IBA
GRIFFITH MICRO SCIENCE SteriGenics RDI SCANDITRONIX WELLHOFER

CE

DFI000 12001 0

Calibration Certificate

Calibration mark	010617
	10-12

Calibration laboratory for ionising radiation quantities

Object : Ionization chamber

Manufacturer : IBA Dosimetry, Germany

Type : PPC40

Serial number : 680

Beam quality : **Co-60**

Absorbed dose to water calibration factor : $N_{D,w} = 8.585 \times 10^{7}$ **Gy/C**

Measurement uncertainty : $U = 2.2\ \%$

Reference conditions : T_0: 20.0 °C p_0: 101.325 kPa R.H.: 50 %

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k = 2, which for a normal distribution provides a level of confidence of approximately 95%.

The secondary standard of this laboratory is traceable to the PTB in Braunschweig (German Federal Institute of Physics and Metrology).

Calibration reported in this certificate was carried out in accordance with the procedures described in the IAEA TRS 398 Code of Practice.

Measuring conditions:

Phantom size :	30 cm × 30 cm × 30 cm
Phantom material :	water
Source to phantom surface distance (SSD) :	100 cm
Field size at the phantom surface :	10 cm × 10 cm
Depth in phantom of the reference point of the chamber :	5 g·cm^{-2}
Reference point of the IC :	on the inner surface of the window at its centre
Chamber orientation :	the beam axis perpendicular to the chamber axis
If the chamber stem has a mark, the mark is oriented towards the radiation source	
Waterproof sleeve (PMMA) :	NO
Sleeve Serial Number:	-
Polarizing potential of collecting (central) electrode :	300 V
Dose rate :	0.4 Gy·min^{-1}
Recombination correction coefficient (k_s) with standard uncertainty:	1.000 ± 0.1%
Polarity correction has not been applied.	

Date of calibration	Calibration approved by	Calibration performed by
12.10.2012	Dipl.Ing. Pavol Pribylsky	Andreas Schmiech

Calibration certificate without signature is not valid. This calibration certificate may not be reproduced other than in full.

BA Dosimetry GmbH Bahnhofstraße 5 | 90592 Schwarzenbruck | Deutschland | Tel.: + 49 9128 607 0 | Fax: + 49 9128 607 10

Appendix-B

Technical description and the calibration certificate for cylindrical chamber from PTW (TW30013, serial number: 04604)

Farmer Chamber
Type 30013

Waterproof therapy chamber for absolute dosimetry in high-energy photon, electron and proton beams

Features

- Waterproof, fully guarded chamber
- Sensitive volume 0.6 cm³, vented to air
- Acrylic wall, graphited
- Aluminum central electrode
- Radioactive check device (option)

The 30013 Farmer chamber is the standard ionization chamber for absolute dose measurements in radiation therapy. Correction factors needed to determine absorbed dose to water or air kerma are published in the pertinent dosimetry protocols. Its waterproof design allows the chamber to be used in water or in solid state phantoms. The acrylic chamber wall ensures the ruggedness of the chamber.

Specification

Type of product	vented cylindrical ionization chamber acc. IEC 60731
Application	absolute therapy dosimetry in water, solid state phantoms and air
Measuring quantities	absorbed dose to water, air kerma, exposure
Reference radiation quality	^{60}Co
Nominal sensitive volume	0.6 cm³
Design	waterproof, vented, fully guarded
Reference point	on chamber axis, 13 mm from chamber tip
Direction of incidence	radial
Nominal response	20 nC/Gy
Long-term stability	≤ 0.5 % per year
Chamber voltage	400 V nominal ± 500 V maximal
Polarity effect at ^{60}Co	< 0.5 %
Photon energy response	≤ ± 2 % (70 kV ... 280 kV) ≤ ± 4 % (200 kV ... ^{60}Co)
Directional response in water	≤ ± 0.5 % for rotation around the chamber axis and for tilting of the axis up to ± 5°
Leakage current	≤ ± 4 fA
Cable leakage	≤ 1 pC/(Gy·cm)

Materials and measures:

Wall of sensitive volume	0.335 mm PMMA, 1.19 g/cm³ 0.09 mm graphite, 1.85 g/cm³
Total wall area density	56.5 mg/cm²
Dimension of sensitive volume	radius 3.05 mm length 23.0 mm
Central electrode	Al 99.98, diameter 1.1 mm
Build-up cap	PMMA, thickness 4.55 mm

Ion collection efficiency at nominal voltage:

Ion collection time	140 µs
Max. dose rate for ≥ 99.5 % saturation ≥ 99.0 % saturation	 5 Gy/s 10 Gy/s
Max. dose per pulse for ≥ 99.5 % saturation ≥ 99.0 % saturation	 0.46 mGy 0.91 mGy

Useful ranges:

Chamber voltage	± (100 ... 400) V
Radiation quality	30 kV ... 50 MV photons (10 ... 45) MeV electrons (50 ... 270) MeV protons
Field size	(5 x 5) cm² ... (40 x 40) cm²
Temperature	(10 ... 40) °C (50 ... 104) °F
Humidity	(10 ... 80) %, max 20 g/m³
Air pressure	(700 ... 1060) hPa

Ordering Information

TN30013 Farmer type chamber 0.6 cm³, waterproof, connecting system BNT

TW30013 Farmer type chamber 0.6 cm³, waterproof, connecting system TNC

TM30013 Farmer type chamber 0.6 cm³, waterproof, connecting system M

Options

T48012 Radioactive check device ^{90}Sr

T48002.3.003 Chamber holding device for check device

CALIBRATION CERTIFICATE
No. 1002785

PTW-Freiburg, Lörracher Str. 7, 79115 Freiburg, Germany ☎ +49-(0)761- 49055-0 FAX +49-(0)761- 49055-70 E-Mail info@ptw.de

Calibration Object

Radiation Dosemeter	
Electrometer	**UNIDOS webline T10022-00146**
Detector	**TW30013-04604**
Detector Type	Ionization Chamber
Manufacturer	PTW-Freiburg
Customer	Advance Management Services LLC Office 1309 UAE- Dubai

Order No. : AU1003349
Order Date : 2010-06-29

Calibration Results

Measuring Quantity: Absorbed Dose to Water (D_w)

Detector Calibration Factor: $N_{D,w}$ = **5.317 · 10^7 Gy / C**

Electrometer Calibration Factor: k_{elec} = **1.000 +/- 0.5 %**

Beam Quality Correction

Beam Quality	Correction Factor k_Q	Uncertainty
^{60}Co	1.000	1.1 %

Reference Conditions	
Beam Quality:	^{60}Co
Temperature:	293.2 K (20°C)
Air Pressure:	1013.2 hPa
Relative Humidity:	50%
Chamber Voltage/Polarity:	+ 400 V
Ion Collection Efficiency:	100 %

Calibration Date: **2010-07-28**

Recalibration Interval: 2 years (recommended)

Freiburg, 2010-07-28

PTW-Freiburg
Physikalisch-Technische
Werkstätten Dr. Pychlau GmbH

i. A. Petra Heisl

(Signature)

Appendix-C

Calibration certificate for Secondary standard chamber (type 2611A, serial number 121)

NATIONAL PHYSICAL LABORATORY
Teddington Middlesex UK TW11 0LW Telephone +44 20 8977 3222

Certificate of Calibration

of an

Ionisation Chamber
in terms of Absorbed Dose to Water

UKAS CALIBRATION
0478

This certificate is issued in accordance with the laboratory accreditation requirements of the United Kingdom Accreditation Service. It provides traceability of measurement to recognised national standards, and to units of measurement realised at the National Physical Laboratory or other recognised national standards laboratories. This certificate may not be reproduced other than in full, except with the prior written approval of the issuing laboratory.

FOR:
Medical Physics Department
Tawam Hospital
P.O. Box 15258
Al Ain
Abu Dhabi
United Arab Emirates
15258

For the attention of Mr Anthony Beal

DESCRIPTION: NPL Secondary Standard Ionisation Chamber

DATE OF RECEIPT: 17 January 2012

DATE OF CALIBRATION: 24 January 2012 - 7 March 2012

IDENTIFICATION:

Ionisation chamber: N.E.TECH./N.P.L., type 2611A, serial number 121

Waterproof sheath: Perspex, labelled 121A

Reference: 2011120181-4
Date of Issue: 9 March 2012
Checked by: [signatures]

Signed: [signature]
Name: R F Nutbrown

Page 1 of 8
(Authorised signatory)
on behalf of NPLML

NPLC02-06/07

NATIONAL PHYSICAL LABORATORY
Continuation Sheet

Table 1 – Absorbed dose to water calibration coefficients
N.E.TECH./N.P.L., type 2611A, serial number 121

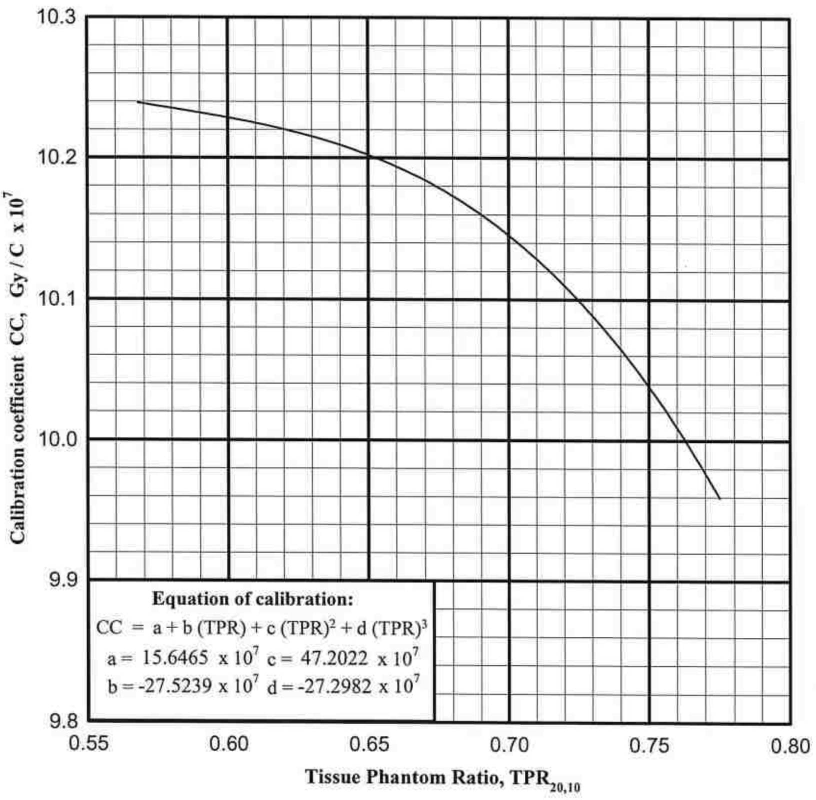
Quality index ($TPR_{20,10}$)	Beam energy (MV)	Depth in water (g/cm^2)	Calibration coefficient, N_D (Gy/C)
0.568	(^{60}Co)	5	10.24×10^7
0.633	4	5	10.21×10^7
0.682	6	5	10.17×10^7
0.713	8	5	10.12×10^7
0.733	10	5	10.08×10^7
0.758	15	7	10.02×10^7
0.775	18	7	9.96×10^7

Uncertainties

The expanded uncertainty for each calibration coefficient is 1.4%. This uncertainty is based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95%. The uncertainty is calculated according to UKAS requirements. More detailed information is available on request.

NATIONAL PHYSICAL LABORATORY
Continuation Sheet

Figure 1 – Absorbed dose to water calibration coefficient
(corrected to 20 °C, 1013.25 mbar and 50% RH)
N.E.TECH./N.P.L., type 2611A, serial number 121



NPLCS00 06/07

Appendix-D

Calibration certificate for cylindrical chamber from PTW (TW30013, serial number: 008620)

CALIBRATION CERTIFICATE
No. 1503951

PTW

PTW-Freiburg, Lörracher Str. 7, 79115 Freiburg, Germany ☎ +49-(0)761- 49055-0 FAX +49-(0)761- 49055-70 E-Mail info@ptw.de

Calibration Object

Radiation Detector

Detector	**[REF] TW30013 [SN] 008620**
Detector Type	Ionization Chamber
Manufacturer	PTW-Freiburg
Customer	Precimed Medical Supplies LLC Unit 8 & 10, G-06 Morocco Cluster UAE- Dubai

Order No. : AU1502810
Order Date : 2015-08-19

Calibration Results

Measuring Quantity	Absorbed Dose to Water (D_w)
Detector Calibration Factor	$N_{D,w}$ = **5.341 · 10^7 Gy / C**

Beam Quality Correction

Beam Quality	Correction Factor k_Q	Uncertainty
^{60}Co	1.000	1.1 %

Reference Conditions

Beam Quality:	^{60}Co
Temperature:	293.2 K (20°C)
Air Pressure:	1013.25 hPa
Relative Humidity:	50%
Chamber Voltage/Polarity:	+ 400 V
Ion Collection Efficiency:	100 %

Calibration Date	**2015-09-07**
Recalibration Interval	2 years (recommended)

Freiburg, 2015-09-07

PTW-Freiburg
Physikalisch-Technische
Werkstätten Dr. Pychlau GmbH

(Signature)

Page 1 / 2

Calibration Conditions and Set-up

Climatic Conditions

Temperature Range:	(294.2 ± 3) K / (21 ± 3) °C
Air Pressure Range:	(1000 ± 50) hPa
Rel. Humidity Range:	(40 ± 20) %

Beam Quality and Geometry

Quality	Filter [mm]	HVL [mm]	SDD [cm]	Size [cm]
^{60}Co	-	-	100	10 x 10

Quality:	Beam qualities according to DIN 6809-5 / DIN 6809-4
Filter:	Total filtration (inherent and additional filters)
HVL:	Half value layer at the point of measurement
SDD:	Distance between radiation source and reference point
Size:	Field size at reference point, diam. = Field Diameter
Reference depth:	5 g cm^{-2} H_2O

Detector Arrangement

Chamber axis perpendicular to radiation beam axis
Line on chamber stem faced towards the radiation source
Reference point position at stated measuring depth / distance to the radiation source (For further information see manual and data sheet of detector.)

Dose and Dose Rate

Absorbed Dose To Water : min.: $5.0 \cdot 10^{-2}$ Gy / max.: 5.0 Gy
Absorbed Dose To Water rate : min.: 50 mGy/min / max.: 300 mGy/min

Polarity Effect $\leq$ 0.2 % (not accounted for in the detector calibration factor)

Saturation Correction Factor k_S = 1.000

Leakage Negligible during calibration

Remarks

1. The uncertainty stated corresponds to the double standard deviation (k=2). The standard deviation was calculated according to ISO GUM from the partial uncertainties arising from the standard used, the calibration procedure, the environmental conditions and short time effects of the object of measurement. The uncertainties stated are composed of the uncertainties of the calibration procedure and those of the specimen during calibration. A share for the long-term instability of the object under calibration is not included.
2. The calibration is traceable to national standards of the German National Laboratory, PTB, Braunschweig. This calibration certificate may not be reproduced other than in full except with the permission of the issuing laboratory. This certificate is valid only with the ionization chamber showing the intact sticker with the certificate number. Calibration factors of chambers having been opened for repair are not comparable to previous calibrations. Calibration certificates without signature are not valid.
3. The components of the calibration object fully comply with the respective specifications given in the data sheet and user manual.
4. The calibration factor presented in this certificate can be equally used for Absorbed-Dose-To-Water determination with dosimetry protocols IAEA TRS 398, AAPM TG-51 and DIN 6800-2. However, it must be guaranteed that the reference temperature given in this certificate is in agreement with the reference temperature of the chosen dosimetry protocol. In the case of disagreement of reference temperatures an appropriate correction of the presented calibration factor with respect to the dosimetry protocols reference temperature must be applied.

Appendix-E

Calibration certificate of UniDos-webline 00146 electrometer

NACHWEIS DER KALIBRIERUNG
Certificate of Calibration

PTW

PTW-Freiburg, Lörracher Str. 7, 79115 Freiburg, Germany ☎ +49-(0)761- 49055-0 FAX +49-(0)761- 49055-70 E-Mail info@ptw.de

Elektrometer / *Electrometer* : UNIDOS webline T10022-00146

Hiermit wird bestätigt, dass das oben genannte Messsystem unter Beachtung eines Qualtitätssicherungssystems nach **DIN EN ISO 9001:2000** kalibriert wurde.

Die für die Kalibrierung verwendeten Messeinrichtungen werden regelmäßig kalibriert und sind rückführbar auf die nationalen Normale der Physikalisch Technischen Bundesanstalt (PTB).

Das Gerät entspricht vollständig den Spezifikationen des Datenblatts und der Gebrauchsanweisung.

Das Gerät ist erfolgreich auf seine elektrische Sicherheit geprüft worden.

Die für diesen Vorgang angefertigte Dokumentation kann bei Bedarf eingesehen werden.

Linearitätsabweichung im Messbereich ≤ ± 0,25%
Wiederholbarkeit im Messbereich ≤ ± 0,25%

Nullpunktwanderung ≤ ±1 Count (bei 1 fA, 50 fA, 5 pA)

Abweichung der Kammerspannung vom Sollwert ≤ ±1 V (bei 0 V ≤ ± 0,5 V)
Abweichung der Verhältnisse zweier Kammerspannungen ≤ ±2 %

We hereby confirm that the above mentioned measuring system was calibrated according to **DIN EN ISO 9001:2000** *under the observation of a certified quality assurance system.*

The measuring installations used for calibration are regularly calibrated. The calibration of these systems is traceable to standards of the German National Laboratory (PTB).

The instrument fully complies with the specifications given in the data sheet and the user manual.

The instrument has been successfully checked for electrical safety.

The documents established for this procedure are available for inspection on request.

Non-linearity in total measuring range ≤ ± 0.25%
Repeatability in total measuring range ≤ ± 0.25%

Zero drift ≤ ±1 count (at 1 fA, 50 fA, 5 pA)

Deviation of nominal bias voltage ≤ ±1 V (at 0V ≤ ± 0.5 V)
Deviation of the relations between 2 bias voltages was ≤ ±2 %

Freiburg, 28-Jul-2010

PTW-Freiburg
Physikalisch-Technische
Werkstätten Dr. Pychlau GmbH

i. A. Petra Heise

(Unterschrift/Signature)

Appendix-F

Determination of the absorbed dose to water for photon beams using IAEA TRS-398 protocol

$D_{D,W}$ (z_{max})= 100 × $D_{D,W}$ (z_{ref})/PDD where PDD from Appendix-G

- 6 MV

Readings	10 cm depth	20 cm depth	TPR_{10}^{20}
1	14.35	9.49	0.661
2	14.36	9.51	
3	14.39	9.50	
mean	14.37	9.50	

from table 6.III IAEA page 65

	TPR_{10}^{20}	k_Q	
	0.65	0.994	
measured	0.661	0.992	interpolation
	0.68	0.99	

$N_{D,W}$ from certificate	5.32	cGy/nC
Uncorrected reading, M	12.03	nC
Pressure, P	974.7	kPa
Temperature, T	23.35	^{o}C
$k_{t,p}$	1.051	
k_{elec}	1	
k_{pol}	1	
k_s	1.006	
M1	17.06	nC
M2	16.96	nC
V1(normal)	400	V
V2(reduced)	200	V
M+	17.06	nC
M-	17.053	nC
a_o	2.337	
a_1	-3.636	
a_2	2.299	
Corrected reading, M_Q	12.719	nC
z_{ref}	10	cm
z_{max}	1.8	cm
$D_{D,W}$ (z_{ref})	67.122	cGy/MU
$D_{D,W}$ (z_{max})	99.440	cGy/MU

- 15 MV

Readings	10 cm depth	20 cm depth	TPR_{10}^{20}
1	16.85	12.72	0.754
2	16.87	12.72	
3	16.86	12.70	
mean	16.86	12.71	

from table 6.III IAEA page 65

	TPR_{10}^{20}	k_Q	
	0.74	0.98	
measured	0.754	0.976	interpolation
	0.76	0.975	

$N_{D,W}$ from certificate	5.32	cGy/nC
Uncorrected reading, M	14.26	nC
Pressure, P	974.7	kPa
Temperature, T	23.35	^oC
$k_{t,p}$	1.051	
k_{elec}	1	
k_{pol}	1.002	
k_s	1.005	
M1	18.14	nC
M2	18.05	nC
V1(normal)	400	V
V2(reduced)	200	V
M+	18.14	nC
M-	18.20	nC
a_o	2.337	
a_1	-3.636	
a_2	2.299	
Corrected reading, M_Q	15.092	nC
z_{ref}	10	cm
z_{max}	3.1	cm
$D_{D,W}$ (z_{ref})	78.356	cGy/MU
$D_{D,W}$ (z_{max})	100.085	cGy/MU

Appendix-G

Determination of the absorbed dose to water for photon beams using AAPM TG-51 protocol

$D_{D,W}(z_{max}) = 100 \times D_{D,W}(z_{ref})/PDD$ where PDD from Appendix-G

- 6 MV with no lead foil

	Reading (nC)					
Depth (cm)	1	2	3	Mean	Max	Normalized reading
0	8.45	8.44	8.46	8.45		46.81
1	17.65	17.66	17.65	17.65		97.80
1.5	17.84	17.87	17.88	17.86		98.97
1.6	17.92	17.95	17.97	17.95		99.43
1.7	17.97	18.01	18.03	18.00		99.74
1.8	18.05	18.03	18.06	18.05	18.05	99.98
1.9	18.03	18.02	18.02	18.02		99.85
2	18.01	18.02	18.01	18.01		99.80
2.1	17.98	17.94	17.98	17.97		99.54
2.2	17.86	17.94	17.94	17.91		99.24
3	17.27	17.30	17.33	17.30		95.84
4	16.53	16.53	16.60	16.55		91.71
5	15.75	15.78	15.82	15.78		87.44
6	15.04	15.02	15.06	15.04		83.32
7	14.24	14.27	14.29	14.27		79.04
8	13.54	13.54	13.58	13.55		75.09
9	12.81	12.84	12.86	12.84		71.12
10	12.16	12.18	12.21	12.18		67.50
11	11.49	11.49	11.52	11.50		63.71

From AAPM TG-51 protocol page 1857

	$\%DD(10)_x$	k_Q	
	66	0.992	
measured	67.498	0.990	interpolation
	71	0.984	

$N_{D,W}$ from certificate	5.32	cGy/nC
Uncorrected reading, M	12.03	nC
Pressure, P	972.7	kPa
Temperature, T	23.6	^oC
$k_{t,p}$	1.05	
k_{elec}	1	
k_{pol}	0.9996	
k_s	1.0028	
M1	12.20	nC
M2	12.10	nC
V1(normal)	400	V
V2(reduced)	200	V
M+	12.21	nC
M-	12.20	nC
Corrected reading, M_Q	12.72	nC
z_{ref}	10	cm
z_{max}	1.8	cm
$D_{D,W}$ (z_{ref})	66.907	cGy/MU
$D_{D,W}$ (z_{max})	99.125	cGy/MU

- 15 MV with lead foil

	Readings (nC)					
Depth (cm)	**1**	**2**	**3**	**Mean**	**Max**	**Normalized reading**
0	5.16	5.15	5.15	5.15		30.21
1	13.40	13.39	13.40	13.40		78.49
2	16.53	16.54	16.55	16.54		96.84
2.5	16.83	16.83	16.81	16.82		98.55
2.6	16.89	16.87	16.88	16.88		98.89
2.7	16.93	16.95	16.94	16.94		99.24
2.8	16.97	16.97	16.99	16.98		99.45
2.9	17.00	17.03	17.02	17.02		99.69
3	17.05	17.04	17.03	17.04		99.82
3.1	17.07	17.07	17.06	17.07	17.07	99.98
3.2	17.05	17.07	17.06	17.06		99.94
3.3	17.06	17.05	17.05	17.05		99.90
3.4	17.05	17.05	17.04	17.05		99.86
3.5	17.03	17.04	17.04	17.04		99.80
4	16.89	16.88	16.89	16.89		98.93

5	16.40	16.38	16.39	16.39		96.02
6	15.77	15.77	15.78	15.77		92.40
7	15.14	15.14	15.14	15.14		88.69
8	14.54	14.53	14.54	14.54		85.16
9	13.92	13.93	13.93	13.93		81.59
10	13.37	13.36	13.36	13.36		78.29
11	12.82	12.82	12.81	12.82		75.08

From AAPM TG-51 protocol page 1857

	$\%DD(10)_x$	k_Q	
	71	0.984	
measured	78.29	0.972	interpolation
	81	0.967	

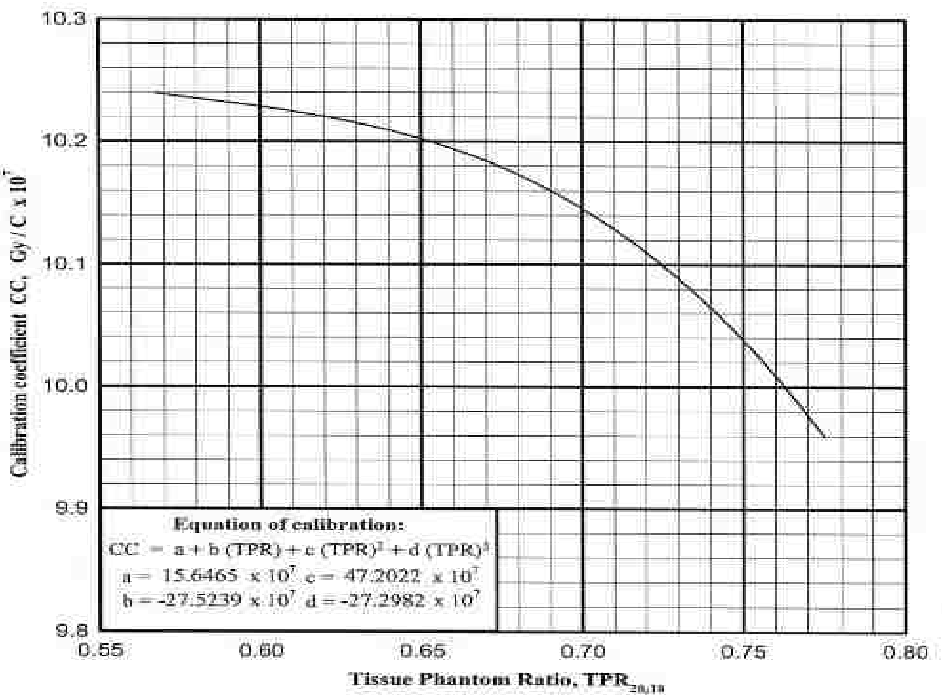
$N_{D,W}$ from certificate	5.32	cGy/nC
Uncorrected reading, M	14.26	nC
Pressure, P	972.7	kPa
Temperature, T	23.6	^oC
$k_{t,p}$	1.05	
k_{elec}	1	
k_{pol}	1.0011	
k_s	0.9995	
M1	14.27	nC
M2	14.29	nC
V1(normal)	400	V
V2(reduced)	200	V
M+	14.26	nC
M-	14.29	nC
Corrected reading, M_Q	15.05	nC
z_{ref}	10	cm
z_{max}	3.1	cm
$D_{D,W}$ (z_{ref})	77.731	cGy/MU
$D_{D,W}$ (z_{max})	99.291	cGy/MU

Appendix-H

Determination of the absorbed dose to water for photon beams using IPSM-1990 protocol

$D_{D,W}$ (z_{max})= 100 × $D_{D,W}$ (z_{ref})/TMR where TMR from Appendix-L

To Find $N_{D,W,Qo}$ which also called calibration coefficient (CC) for the secondary standard chamber is by applying the cubic polynomial that is provided by NLP, look at the next plot.



- 6 MV

TPR_{10}^{20}	0.6610
Calibration Coefficient for the secondary standard chamber	10.193 **cGy/nC**

working chamber	Readings	mean	**standard chamber**	Readings	mean
V1	17.09	17.063	V1	8.77	8.762
	17.06			8.757	
	17.04			8.758	
V2	17.04	17.053	V2	8.737	8.735
	17.05			8.735	
	17.07			8.734	
V3	16.95	16.957	V3	8.681	8.676
	16.94			8.666	
	16.98			8.68	

	k_{pol}	k_s	V1	V2	V3
Standard Chamber	0.9985	1.0098	200	-200	100
Working Chamber	0.9997	1.0061	400	-400	200

	Standard chamber	mean	Working chamber	mean	Ratio
Position A	8.770	8.762	17.090	17.063	0.513
	8.757		17.060		
	8.758		17.040		
Position B	8.729	8.735	16.880	17.563	0.497
	8.732		16.890		
	8.745		18.920		
Position A	8.692	8.703	16.950	16.970	0.513
	8.701		16.970		
	8.715		16.990		
Position B	8.725	8.736	16.880	16.903	0.517
	8.738		16.910		
	8.744		16.920		

Arithmetic mean for Position A = 0.513 arithmetic mean for Position B = 0.507

Geometric mean for Position A & B = 0.510

$$N_{D,w}^{W} = Geometric\ mean \times CC^{S} \times \frac{k_s^S \times k_{pol}^S}{k_s^W \times k_{pol}^W} \qquad \text{Eq. 18}$$

$N_{D,W}$ for working chamber by Eq. 18	5.212	cGy/nC
Uncorrected reading, M	17.06	nC
Pressure, P	974.7	kPa
Temperature, T	23.35	^{o}C
$k_{t,p}$	1.015	
z_{ref}	5	cm
z_{max}	3.1	cm
$D_{D,W}$ (z_{ref})	90.881	cGy/MU
$D_{D,W}$ (z_{max})	98.784	cGy/MU

- 15 MV

$\boldsymbol{TPR_{10}^{20}}$	0.754
Calibration Coefficient for the secondary standard chamber	10.027 **cGy/nC**

working chamber	Readings	mean	standard chamber	Readings	mean
V1	18.140	18.143	V1	9.308	9.305
	18.150			9.306	
	18.140			9.300	
V2	18.200	18.207	V2	9.311	9.316
	18.210			9.317	
	18.210			9.320	
V3	18.040	18.047	V3	9.204	9.197
	18.050			9.192	
	18.050			9.196	

	k_{pol}	k_s	V1	V2	V3
Standard Chamber	1.0006	1.0115	200	-200	100
Working Chamber	1.0017	1.0052	400	-400	200

	Standard chamber	mean	Working chamber	mean	Ratio
Position A	9.308	9.305	18.140	18.143	0.513
	9.306		18.150		
	9.300		18.140		
Position B	9.310	9.308	18.160	18.157	0.0.513
	9.313		18.160		
	9.301		18.150		
Position A	9.319	9.311	18.150	18.147	0.513
	9.311		18.130		
	9.304		18.160		
Position B	9.289	9.292	18.140	18.143	0.512
	9.293		18.140		
	9.293		18.150		

arithmetic mean for Position A = 0.513 arithmetic mean for Position B = 0.512

Geometric mean for Position A & B = 0.513

$N_{D,W}$ for working chamber by Eq. 18	5.167	cGy/nC
Uncorrected reading, M	17.06	nC
Pressure, P	974.7	kPa
Temperature, T	23.35	^oC
$k_{t,p}$	1.015	
z_{ref}	7	cm
z_{max}	3.1	cm
$D_{D,W}$ (z_{ref})	95.910	cGy/MU
$D_{D,W}$ (z_{max})	101.816	cGy/MU

Appendix-I

Determination of the absorbed dose to water for electron beams using IAEA TRS-398 and AAPM TG-51 protocols

$*R_{eq}$: use Eq. 16/17 $**z_{ref} = 0.6\ R_{50} – 0.1\ g/cm^2$

$D_{D,W}\ (z_{max}) = 100 \times D_{D,W}\ (z_{ref})/PDD$ where PDD from Appendix-M

- 6 MeV

	R_{ion} (nC)							
depth (cm)	1	2	3	mean	$*R_{eq}$	Normalized reading	R_{50}	$**Z_{ref}$
0.10	9.90	9.90	9.86	9.88	10.097	80.176	2.323	1.294
0.20	10.01	10.05	10.05	10.04	10.259	81.463		
0.30	10.32	10.32	10.33	10.32	10.562	83.873		
0.40	10.52	10.51	10.51	10.51	10.758	85.428		
0.50	10.75	10.73	10.73	10.74	10.988	87.253		
0.60	10.95	10.96	10.96	10.96	11.214	89.051		
0.70	11.18	11.18	11.20	11.19	11.451	90.930		
0.80	11.44	11.42	11.43	11.43	11.701	92.918		
0.90	11.68	11.68	11.68	11.68	11.959	94.961		
1.00	11.99	11.99	11.98	11.99	12.274	97.467		
1.10	12.20	12.22	12.20	12.21	12.501	99.265		
1.20	12.29	12.31	12.29	12.30	12.593	100.000		
1.30	12.30	12.29	12.30	12.30	12.593	100.000		
1.40	12.19	12.18	12.20	12.19	12.484	99.128		
1.50	11.95	12.00	11.98	11.98	12.264	97.385		
1.60	11.67	11.65	11.67	11.66	11.942	94.825		
1.70	11.21	11.21	11.19	11.20	11.468	91.066		
1.80	10.64	10.64	10.66	10.65	10.895	86.518		
1.90	9.97	9.99	9.97	9.98	10.196	80.967		
2.00	9.13	9.17	9.19	9.17	9.337	74.144		
2.10	8.28	8.30	8.31	8.30	8.415	66.822		
2.20	7.45	7.48	7.50	7.47	7.544	59.904		
2.30	6.53	6.52	6.53	6.53	6.543	51.955		
2.40	5.49	5.50	5.50	5.50	5.450	43.274		
2.50	4.52	4.52	4.52	4.52	4.415	35.058		
2.60	3.54	3.56	3.57	3.55	3.394	26.951		
2.70	2.67	2.68	2.68	2.68	2.465	19.576		
2.80	1.92	1.92	1.92	1.92	1.664	13.213		
2.90	1.29	1.30	1.30	1.30	1.003	7.966		
3.00	0.84	0.84	0.84	0.84	0.523	4.157		

$N_{D,W}$ from certificate	8.585	cGy/nC
Uncorrected reading, M	12.28	nC
Pressure, P	988.8	kPa
Temperature, T	23	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	1.000	
k_s	1.006	
M1	12.280	nC
M2	12.140	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.280	nC
M-	12.270	nC
a_o	1.198	
a_1	-0.875	
a_2	0.677	
Water phantom correction h_{pl}	1	
Corrected reading, M_Q	12.779	nC
z_{ref}	1.294	cm
z_{max}	1.3	cm
IAEA TRS-398/ $D_{D,W}$ (z_{ref})	103.762	cGy/MU
IAEA TRS-398/ $D_{D,W}$ (z_{max})	104.210	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{ref})	102.337	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{max})	102.779	cGy/MU

Page 80 from IAEA TRS-398

	R_{50}	k_q	
	2.000	0.951	
	2.500	0.943	
measured	2.323	0.946	interpolated

Page 1859 from AAPM TG-51

$$k'_{R_{50}} = 1.2239 - 0.145 \times (R_{50})^{0.214}$$

k'_{R50}	1.050
$(K_{ecal}\ N_{D,w})^{pp}$ from Appendix-J	7.625
P_{gr}^{Q} : gradient correction for Plane-Parallel chamber	1

- 9 MeV

depth (cm)	R_{ion} (nC) 1	2	3	mean	*R_{eq}	Normalized reading	R_{50}	**Z_{ref}
0.10	10.64	10.65	10.66	10.65	10.90	86.12	3.555	2.033
0.20	10.74	10.73	10.75	10.74	10.99	86.85		
0.30	10.90	10.88	10.88	10.89	11.14	88.05		
0.40	11.00	11.01	11.01	11.01	11.27	89.02		
0.50	11.18	11.17	11.19	11.18	11.44	90.43		
0.60	11.29	11.25	11.26	11.27	11.53	91.14		
0.70	11.37	11.35	11.35	11.36	11.63	91.87		
0.80	11.46	11.42	11.43	11.44	11.71	92.52		
0.90	11.53	11.54	11.56	11.54	11.82	93.39		
1.00	11.66	11.63	11.62	11.64	11.91	94.15		
1.10	11.73	11.71	11.71	11.72	12.00	94.80		
1.20	11.84	11.84	11.82	11.83	12.12	95.74		
1.30	11.92	11.91	11.92	11.92	12.20	96.42		
1.40	12.00	12.00	12.02	12.01	12.29	97.15		
1.50	12.12	12.09	12.10	12.10	12.39	97.94		
1.60	12.21	12.18	12.19	12.19	12.49	98.67		
1.70	12.25	12.27	12.25	12.26	12.55	99.19		
1.80	12.34	12.29	12.31	12.31	12.61	99.65		
1.90	12.35	12.35	12.34	12.35	12.64	99.92		
2.00	12.38	12.35	12.34	12.36	12.66	100.00		
2.10	12.35	12.34	12.33	12.34	12.64	99.86		
2.20	12.28	12.25	12.26	12.26	12.56	99.24		
2.30	12.20	12.18	12.17	12.18	12.48	98.59		
2.40	12.05	12.04	12.04	12.04	12.33	97.45		
2.50	11.87	11.85	11.81	11.84	12.13	95.83		
2.60	11.61	11.58	11.59	11.59	11.87	93.79		
2.70	11.28	11.28	11.27	11.28	11.54	91.22		
2.80	10.92	10.92	10.90	10.91	11.17	88.26		
2.90	10.48	10.46	10.47	10.47	10.71	84.66		
3.00	10.05	10.00	10.01	10.02	10.25	81.00		
3.20	8.84	8.85	8.85	8.85	9.00	71.13		
3.40	7.49	7.48	7.49	7.49	7.56	59.73		
3.60	5.98	5.98	5.99	5.99	5.97	47.16		
3.80	4.48	4.47	4.47	4.47	4.37	34.50		
4.00	3.00	3.00	3.00	3.00	2.81	22.19		
4.20	1.82	1.82	1.82	1.82	1.56	12.33		
4.40	0.99	0.99	1.00	0.99	0.68	5.40		

$N_{D,W}$ from certificate	8.585	cGy/nC
Uncorrected reading, M	12.34	nC
Pressure, P	988.8	kPa
Temperature, T	23	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	1.000	
k_s	1.005	
M1	12.34	nC
M2	12.22	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.34	nC
M-	12.35	nC
a_o	1.198	
a_1	-0.875	
a_2	0.677	
Water phantom correction h_{pl}	1	
Corrected reading, M_Q	12.841	nC
z_{ref}	2.033	cm
z_{max}	2.00	cm
IAEA TRS-398/ $D_{D,W}$ (z_{ref})	102.680	cGy/MU
IAEA TRS-398/ $D_{D,W}$ (z_{max})	103.165	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{ref})	101.213	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{max})	101.691	cGy/MU

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	R_{50}	k_q	
	3.5	0.932	
	4.0	0.927	
measured	3.555	0.931	interpolated

Page 1859 from AAPM TG-51

$$k'_{R_{50}} = 1.2239 - 0.145 \times (R_{50})^{0.214}$$

k'_{R50}	1.034
$(K_{ecal}\ N_{D,w})^{pp}$ from Appendix-J	7.625
P_{gr}^{Q} : gradient correction for Plane-Parallel chamber	1

- 12 MeV

depth (cm)	R_{ion} (nC) 1	2	3	mean	*R_{eq}	Normalized reading	R_{50}	**Z_{ref}
0.1	11.300	11.300	11.300	11.300	11.568	90.989	4.927	2.856
0.2	11.480	11.400	11.400	11.427	11.698	92.014		
0.3	11.550	11.520	11.510	11.527	11.801	92.823		
0.4	11.610	11.610	11.600	11.607	11.883	93.471		
0.5	11.750	11.700	11.770	11.740	12.020	94.550		
0.6	11.800	11.800	11.800	11.800	12.082	95.036		
0.7	11.910	11.890	11.880	11.893	12.178	95.791		
0.8	11.930	11.950	11.960	11.947	12.233	96.223		
0.9	12.000	11.990	11.970	11.987	12.274	96.547		
1	12.030	12.030	12.010	12.023	12.312	96.843		
1.1	12.060	12.030	12.050	12.047	12.336	97.032		
1.2	12.100	12.070	12.080	12.083	12.374	97.329		
1.3	12.120	12.110	12.110	12.113	12.405	97.572		
1.4	12.130	12.170	12.140	12.147	12.439	97.842		
1.5	12.170	12.160	12.200	12.177	12.470	98.084		
1.6	12.200	12.210	12.210	12.207	12.501	98.327		
1.7	12.240	12.250	12.230	12.240	12.535	98.597		
1.8	12.270	12.250	12.250	12.257	12.552	98.732		
1.9	12.280	12.290	12.300	12.290	12.586	99.002		
2	12.330	12.310	12.330	12.323	12.621	99.272		
2.1	12.340	12.350	12.330	12.340	12.638	99.406		
2.2	12.370	12.370	12.350	12.363	12.662	99.595		
2.3	12.390	12.370	12.400	12.387	12.686	99.784		
2.4	12.410	12.370	12.390	12.390	12.689	99.811		
2.5	12.430	12.380	12.420	12.410	12.710	99.973		
2.6	12.410	12.400	12.410	12.407	12.706	99.946		
2.7	12.410	12.430	12.400	12.413	12.713	100.000		
2.8	12.390	12.390	12.410	12.397	12.696	99.865		
2.9	12.370	12.360	12.370	12.367	12.665	99.622		
3	12.360	12.340	12.340	12.347	12.645	99.460		
3.2	12.190	12.190	12.180	12.187	12.480	98.165		
3.4	11.990	11.980	12.010	11.993	12.281	96.601		
3.6	11.690	11.660	11.660	11.670	11.948	93.984		
3.8	11.220	11.210	11.230	11.220	11.485	90.341		
4	10.620	10.620	10.630	10.623	10.871	85.512		
4.2	9.910	9.884	9.910	9.901	10.116	79.566		
4.4	9.073	9.077	9.076	9.075	9.241	72.686		
4.6	8.135	8.134	8.133	8.134	8.244	64.845		

4.8	7.066	7.072	7.075	7.071	7.118	55.990		
5	5.940	5.940	5.940	5.940	5.920	46.569		
5.2	4.832	4.830	4.826	4.829	4.744	37.317		
5.4	3.707	3.708	3.703	3.706	3.555	27.960		
5.6	2.693	2.688	2.691	2.691	2.479	19.503		
5.8	1.882	1.886	1.886	1.885	1.626	12.789		
6	1.218	1.222	1.218	1.219	0.921	7.247		
6.2	0.782	0.780	0.783	0.782	0.458	3.601		

$N_{D,W}$ from certificate	8.585	cGy/nC
Uncorrected reading, M	12.41	nC
Pressure, P	988.8	kPa
Temperature, T	23	^oC
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	1.000	
k_s	1.006	
M1	12.41	nC
M2	12.26	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.41	nC
M-	12.42	nC
a_o	1.198	
a_1	-0.875	
a_2	0.677	
Water phantom correction h_{pl}	1	
Corrected reading, M_Q	12.929	nC
z_{ref}	2.856	cm
z_{max}	2.7	cm
IAEA TRS-398/ $D_{D,W}$ (z_{ref})	101.957	cGy/MU
IAEA TRS-398/ $D_{D,W}$ (z_{max})	102.038	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{ref})	100.551	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{max})	100.631	cGy/MU

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	R_{50}	k_q	
	4.5	0.922	
	5.0	0.918	
measured	4.927	0.919	interpolated

Page 1859 from AAPM TG-51

$$k'_{R_{50}} = 1.2239 - 0.145 \times (R_{50})^{0.214}$$

k'_{R50}	1.0199
$(K_{ecal}\ N_{D,w})^{pp}$ from Appendix-J	7.625
P_{gr}^{Q} : gradient correction for Plane-Parallel chamber	1

- 16 MeV

depth (cm)	R_{ion} (nC) using 10 × 10 applicator				$*R_{eq}$	Normalized reading	R_{50}	$**Z_{ref}$
	1	2	3	mean				
0.1	12.460	12.480	12.450	12.463	12.765	95.927	6.511	3.807
0.2	12.560	12.580	12.580	12.573	12.878	96.778		
0.3	12.700	12.680	12.690	12.690	12.998	97.680		
0.4	12.760	12.750	12.750	12.753	13.063	98.170		
0.5	12.850	12.820	12.840	12.837	13.149	98.814		
0.6	12.890	12.860	12.870	12.873	13.187	99.098		
0.7	12.910	12.900	12.880	12.897	13.211	99.278		
0.8	12.940	12.930	12.940	12.937	13.252	99.588		
0.9	12.940	12.950	12.950	12.947	13.262	99.665		
1.0	12.960	12.950	12.930	12.947	13.262	99.665		
1.1	13.000	12.970	12.960	12.977	13.293	99.897		
1.2	12.990	12.990	12.960	12.980	13.296	99.923		
1.3	12.990	12.970	12.960	12.973	13.290	99.871		
1.4	12.990	12.990	12.960	12.980	13.296	99.923		
1.5	12.990	12.970	12.980	12.980	13.296	99.923		
1.6	12.980	12.980	13.010	12.990	13.307	100.000		
1.7	13.020	12.960	12.970	12.983	13.300	99.948		
1.8	13.000	12.960	12.980	12.980	13.296	99.923		
1.9	12.980	12.970	12.970	12.973	13.290	99.871		
2.0	13.000	12.970	12.980	12.983	13.300	99.948		
2.1	12.980	12.950	12.950	12.960	13.276	99.768		
2.2	12.960	12.960	12.980	12.967	13.283	99.820		
2.3	12.970	12.940	12.950	12.953	13.269	99.716		
2.4	12.960	12.940	12.940	12.947	13.262	99.665		
2.5	12.920	12.910	12.920	12.917	13.231	99.433		
2.6	12.920	12.910	12.890	12.907	13.221	99.356		
2.7	12.910	12.940	12.900	12.917	13.231	99.433		
2.8	12.910	12.900	12.870	12.893	13.207	99.252		
2.9	12.860	12.850	12.860	12.857	13.170	98.969		
3.0	12.870	12.830	12.820	12.840	13.152	98.840		
3.2	12.810	12.830	12.810	12.817	13.128	98.660		
3.4	12.760	12.760	12.760	12.760	13.070	98.221		
3.6	12.700	12.670	12.680	12.683	12.991	97.629		

3.8	12.620	12.620	12.610	12.617	12.923	97.113		
4.0	12.500	12.500	12.500	12.500	12.803	96.211		
4.2	12.370	12.360	12.350	12.360	12.658	95.128		
4.4	12.170	12.150	12.170	12.163	12.456	93.607		
4.6	11.950	11.980	11.970	11.967	12.254	92.087		
4.8	11.670	11.680	11.670	11.673	11.952	89.818		
5.0	11.370	11.340	11.340	11.350	11.619	87.318		
5.2	10.940	10.930	10.950	10.940	11.197	84.147		
5.4	10.470	10.460	10.460	10.463	10.707	80.461		
5.6	9.916	9.909	9.897	9.907	10.122	76.066		
5.8	9.337	9.317	9.320	9.325	9.505	71.429		
6.0	8.655	8.641	8.635	8.644	8.784	66.009		
6.2	7.948	7.935	7.933	7.939	8.037	60.398		
6.4	7.068	7.077	7.078	7.074	7.122	53.520		
6.6	6.275	6.291	6.276	6.281	6.281	47.203		
6.8	5.393	5.393	5.395	5.394	5.342	40.144		
7.0	4.526	4.528	4.528	4.527	4.424	33.250		
7.2	3.699	3.697	3.705	3.700	3.549	26.668		
7.4	2.929	2.925	2.927	2.927	2.730	20.514		
7.6	2.281	2.283	2.278	2.281	2.045	15.370		
7.8	1.725	1.728	1.728	1.727	1.459	10.964		
8.0	1.278	1.278	1.281	1.279	0.984	7.398		
8.2	0.931	0.933	0.933	0.932	0.617	4.639		

$N_{D,W}$ from certificate	8.585	cGy/nC
Uncorrected reading, M	12.6	nC
Pressure, P	988.8	kPa
Temperature, T	23	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	1.001	
k_s	1.005	
M1	12.6	nC
M2	12.48	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.6	nC
M-	12.62	nC
a_o	1.198	
a_1	-0.875	
a_2	0.677	
Water phantom correction h_{pl}	1	
Corrected reading, M_Q	13.115	nC
z_{ref}	3.807	cm

z_{max}	1.6	cm
IAEA TRS-398/ $D_{D,W}$ (z_{ref})	102.168	cGy/MU
IAEA TRS-398/ $D_{D,W}$ (z_{max})	102.837	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{ref})	100.745	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{max})	100.404	cGy/MU

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	R_{50}	k_q	
	6.0	0.911	
	7.0	0.904	
measured	6.511	0.907	interpolated

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$$k'_{R_{50}} = 1.2239 - 0.145 \times (R_{50})^{0.214}$$

k'_{R50}	1.0074
$(K_{ecal}\, N_{D,w})^{pp}$ from Appendix-J	7.625
P_{gr}^{Q} : gradient correction for Plane-Parallel chamber	1

	R_{ion} (nC) using 20 × 20 applicator							
depth (cm)	1	2	3	mean	*R_{eq}	Normalized reading	R_{50}	**Z_{ref}
0	12.090	12.120	12.090	12.100	12.391	95.405	6.486	3.792
1	12.630	12.640	12.630	12.633	12.940	99.630		
2	12.690	12.680	12.670	12.680	12.988	100.000		
3	12.550	12.570	12.560	12.560	12.864	99.049		
4	12.180	12.180	12.180	12.180	12.473	96.039		
5	11.050	11.050	11.050	11.050	11.310	87.086		
6	8.366	8.369	8.349	8.361	8.485	65.328		
6.5	6.419	6.435	6.429	6.428	6.437	49.561		
6.6	5.988	5.994	5.992	5.991	5.975	46.004		
6.7	5.563	5.587	5.598	5.583	5.542	42.671		
7	4.321	4.333	4.332	4.329	4.214	32.446		
8	1.198	1.198	1.200	1.199	0.899	6.925		

- 20 MeV

depth (cm)	R_{ion} (nC) using 10 × 10 applicator 1	2	3	mean	$*R_{eq}$	Normalized reading	R_{50}	$**Z_{ref}$
0.1	12.770	12.750	12.730	12.750	13.060	96.649	8.199	4.820
0.2	12.860	12.830	12.850	12.847	13.159	97.385		
0.3	12.980	12.970	12.960	12.970	13.286	98.325		
0.4	13.060	13.080	13.030	13.057	13.375	98.985		
0.5	13.100	13.090	13.120	13.103	13.423	99.340		
0.6	13.120	13.130	13.130	13.127	13.447	99.518		
0.7	13.160	13.160	13.150	13.157	13.478	99.746		
0.8	13.160	13.190	13.180	13.177	13.499	99.898		
0.9	13.180	13.190	13.180	13.183	13.506	99.949		
1	13.180	13.170	13.200	13.183	13.506	99.949		
1.1	13.200	13.170	13.200	13.190	13.513	100.000		
1.2	13.170	13.200	13.200	13.190	13.513	100.000		
1.3	13.160	13.170	13.150	13.160	13.482	99.772		
1.4	13.170	13.180	13.170	13.173	13.495	99.873		
1.5	13.160	13.160	13.160	13.160	13.482	99.772		
1.6	13.130	13.130	13.160	13.140	13.461	99.619		
1.7	13.150	13.120	13.140	13.137	13.458	99.594		
1.8	13.150	13.120	13.120	13.130	13.451	99.543		
1.9	13.130	13.110	13.090	13.110	13.430	99.391		
2	13.100	13.120	13.090	13.103	13.423	99.340		
2.1	13.050	13.070	13.090	13.070	13.389	99.086		
2.2	13.080	13.050	13.070	13.067	13.386	99.061		
2.3	13.050	13.030	13.060	13.047	13.365	98.908		
2.4	13.030	13.000	13.010	13.013	13.331	98.655		
2.5	13.010	13.000	12.980	12.997	13.314	98.528		
2.6	12.970	12.990	12.970	12.977	13.293	98.375		
2.7	12.930	12.970	12.950	12.950	13.266	98.172		
2.8	12.930	12.920	12.930	12.927	13.242	97.995		
2.9	12.890	12.910	12.890	12.897	13.211	97.766		
3	12.860	12.860	12.850	12.857	13.170	97.462		
3.2	12.820	12.810	12.800	12.810	13.121	97.106		
3.4	12.750	12.740	12.750	12.747	13.056	96.624		
3.6	12.680	12.670	12.700	12.683	12.991	96.142		
3.8	12.600	12.580	12.620	12.600	12.905	95.507		
4	12.510	12.530	12.530	12.523	12.827	94.923		
4.2	12.420	12.390	12.420	12.410	12.710	94.060		
4.4	12.320	12.320	12.310	12.317	12.614	93.349		
4.6	12.210	12.220	12.200	12.210	12.504	92.537		

4.8	12.090	12.090	12.100	12.093	12.384	91.649		
5	11.970	11.990	11.980	11.980	12.267	90.786		
5.2	11.830	11.850	11.860	11.847	12.130	89.770		
5.4	11.660	11.680	11.670	11.670	11.948	88.425		
5.6	11.490	11.500	11.500	11.497	11.770	87.105		
5.8	11.300	11.300	11.310	11.303	11.571	85.633		
6	11.100	11.100	11.080	11.093	11.355	84.034		
6.2	10.880	10.870	10.870	10.873	11.129	82.358		
6.4	10.590	10.610	10.590	10.597	10.844	80.251		
6.6	10.300	10.290	10.300	10.297	10.535	77.967		
6.8	9.978	9.945	9.960	9.961	10.179	75.328		
7	9.606	9.604	9.618	9.609	9.806	72.572		
7.2	9.193	9.195	9.202	9.197	9.369	69.338		
7.4	8.744	8.739	8.734	8.739	8.885	65.751		
7.6	8.288	8.292	8.319	8.300	8.419	62.308		
7.8	7.811	7.806	7.812	7.810	7.900	58.468		
8	7.302	7.288	7.296	7.295	7.356	54.437		
8.2	6.733	6.736	6.714	6.728	6.755	49.988		
8.4	6.155	6.150	6.147	6.151	6.144	45.466		
8.6	5.545	5.552	5.539	5.545	5.503	40.722		
8.8	4.941	4.945	4.940	4.942	4.864	35.993		
9	4.322	4.333	4.331	4.329	4.214	31.186		
9.2	3.740	3.744	3.754	3.746	3.597	26.620		
9.4	3.188	3.199	3.192	3.193	3.011	22.286		
9.6	2.692	2.700	2.690	2.694	2.483	18.375		
9.8	2.233	2.244	2.238	2.238	2.000	14.804		
10	1.830	1.826	1.829	1.828	1.566	11.591		

$N_{D,W}$ from certificate	8.585	cGy/nC
Uncorrected reading, M	12.1	nC
Pressure, P	988.8	kPa
Temperature, T	23	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	0.999	
k_{s}	1.007	
M1	12.1	nC
M2	11.94	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.1	nC
M-	12.08	nC
a_o	1.198	

a_1	-0.875	
a_2	0.677	
Water phantom correction h_{pl}	1	
Corrected reading, M_Q	12.598	nC
z_{ref}	4.82	cm
z_{max}	1.2	cm
IAEA TRS-398/ $D_{D,W}$ (z_{ref})	97.011	cGy/MU
IAEA TRS-398/ $D_{D,W}$ (z_{max})	101.508	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{ref})	95.719	cGy/MU
AAPM TG-51/ $D_{D,W}$ (z_{max})	100.155	cGy/MU

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	R_{50}	k_q	
	8.0	0.898	
	10.0	0.888	
measured	8.199	0.897	interpolated

Page 1859 from AAPM TG-51

$$k'_{R_{50}} = 1.2239 - 0.145 \times (R_{50})^{0.214}$$

k'_{R50}	0.9964
$(K_{ecal}\, N_{D,w})^{pp}$ from Appendix-J	7.625
P_{gr}^{Q} : gradient correction for Plane-Parallel chamber	1

	R_{ion} (nC) using 20 × 20 applicator							
depth (cm)	1	2	3	mean	*R_{eq}	Normalized reading	R_{50}	**Z_{ref}
0	11.980	11.980	11.980	11.980	12.267	95.488	8.213	4.828
1	12.540	12.560	12.530	12.543	12.847	100.000		
2	12.550	12.520	12.560	12.543	12.847	100.000		
3	12.360	12.390	12.340	12.363	12.662	98.558		
4	12.070	12.040	12.060	12.057	12.346	96.102		
5	11.570	11.570	11.560	11.567	11.842	92.177		
6	10.720	10.730	10.710	10.720	10.971	85.396		
7	9.274	9.281	9.285	9.280	9.458	73.616		
8	6.992	6.998	7.007	6.999	7.042	54.814		
8.2	6.448	6.443	6.456	6.449	6.459	50.280		
8.3	6.185	6.169	6.195	6.183	6.178	48.087		
9	4.390	4.400	4.400	4.397	4.286	33.362		

Appendix-J

Cross calibration by substitution method between cylindrical chamber from PTW (TW30013, serial number: 008620) with plane-parallel chamber (PPC40/ TNC, serial number: 680)

Note that: the cylindrical chamber is shifted upstream by $0.5r_{cav}$ = 0.1375 cm= 14mm

The nominal electron energy is 20 MeV

*R_{eq} : use Eq. 16/17 **$z_{ref} = 0.6\ R_{50} - 0.1$ g/cm^2

	R_{ion} (nC)							
depth (cm)	1	2	3	mean	*R_{eq}	Normalized reading	R_{50}	**z_{ref}
0.0	19.280	19.280	19.330	19.297	19.796	94.083	8.545	5.027
0.5	19.490	19.510	19.500	19.500	20.006	95.077		
1.0	20.320	20.390	20.390	20.367	20.897	99.315		
1.5	20.520	20.470	20.530	20.507	21.041	100.000		
2.0	20.460	20.480	20.490	20.477	21.010	99.853		
2.5	20.380	20.410	20.350	20.380	20.911	99.381		
3.0	20.250	20.240	20.300	20.263	20.791	98.810		
3.5	20.060	20.050	20.080	20.063	20.585	97.832		
4.0	19.840	19.840	19.800	19.827	20.342	96.675		
4.5	19.520	19.510	19.520	19.517	20.023	95.159		
5.0	19.170	19.200	19.230	19.200	19.697	93.610		
5.5	18.670	18.670	18.660	18.667	19.148	91.002		
6.0	18.090	18.030	18.050	18.057	18.520	88.019		
6.5	17.180	17.230	17.210	17.207	17.646	83.862		
7.0	16.010	16.010	16.060	16.027	16.431	78.091		
7.5	14.540	14.510	14.540	14.530	14.891	70.772		
8.0	12.700	12.720	12.740	12.720	13.029	61.920		
8.5	10.500	10.490	10.500	10.497	10.741	51.047		
9.0	8.127	8.116	8.124	8.122	8.298	39.436		
9.5	5.838	5.852	5.864	5.851	5.961	28.330		
10.0	3.787	3.790	3.790	3.789	3.839	18.244		

$N_{D,W}$ from certificate for cylindrical chamber	5.341	cGy/nC
Uncorrected reading, M	19.17	nC
Pressure, P	987.7	kPa
Temperature, T	22.5	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	1.001	
k_{s}	1.008	
M1	19.17	nC
M2	19.01	nC
V1(normal)	400	V
V2(reduced)	200	V
M+	19.17	nC
M-	19.2	nC
P_{gr} (cylindrical)= M at (z_{ref} + 0.5r_{cav})/ M at (z_{ref})	1.0074	
M at (z_{ref})	19.03	nC
M at (z_{ref} + 0.5r_{cav})	19.17	nC
Corrected reading, M_Q	20.018	nC
$D_{D,W}$ (z_{ref})	96.465	cGy
Dose/MU at z_{ref}	0.964654	cGy/MU

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k'_{R50}	0.997419

Page 1858, Table II from AAPM TG-51

K_{ecal}	0.898

Plane-parallel chamber at Z_{ref} of the cylindrical chamber = 5.027 cm

Uncorrected reading, M	12.24	nC
Pressure, P	987.7	kPa
Temperature, T	22.5	^{o}C
$k_{t,p}$	1.035	
k_{elec}	1	
k_{pol}	0.999	
k_{s}	1.005	
M1	12.24	nC
M2	12.11	nC
V1(normal)	300	V
V2(reduced)	100	V
M+	12.24	nC
M-	12.22	nC
P_{gr}	1.0	
Monitor units	100	MU

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k'_{R50}	0.994414

By applying the following equation: $\left(k_{ecal} N_{D,w}^{60Co}\right)^{pp} = \frac{\left(D_w/_{MU}\right)^{cyl}{}_{MU}}{\left(M k'_{R_{50}}\right)^{pp}}$

We obtain the cross calibration factor for the plane parallel chamber $\left(k_{ecal} N_{D,w}^{60Co}\right)^{pp} = 7.625\ cGy/nC$

Appendix-K

Reference Data Set for high energy CLINAC from Varian medical systems, Inc. 2005. 3100 Hasen way, Bldg. 4A Palo Alto, CA 94304-1030, USA.

Typical Beam Data: Open field percentage depth doses, normalized to z_{max}

	10 X 10 Applicator							20 X 20 Applicator	
	%DD		%DI						
Depth (cm)	6 MV	15 MV	6 MeV	9 MeV	12 MeV	16 MeV	20 MeV	16 MeV	20 MeV
0.0	47.3	31.0	78.7	83.3	88.7	94.4	95.4	94.5	94.7
0.1	50.6	32.2	79.9	84.0	89.4	95.0	95.9	95.1	95.2
0.2	55.2	34.0	81.4	84.9	90.3	95.7	96.5	95.7	95.8
0.3	60.9	36.8	83.3	85.8	91.1	96.3	97.2	96.4	96.5
0.4	67.2	43.2	85.2	86.7	91.8	96.9	97.8	97.0	97.2
0.5	73.8	51.8	87.6	87.8	92.6	97.5	98.3	97.6	97.8
0.6	79.6	58.7	89.9	88.8	93.1	98.0	98.9	98.1	98.3
0.7	85.5	65.4	92.2	89.9	93.6	98.4	99.2	98.5	98.8
0.8	90.4	71.3	94.4	90.9	94.0	98.7	99.5	98.8	99.1
0.9	94.0	75.5	96.4	91.9	94.4	98.9	99.7	99.0	99.3
1.0	96.3	79.4	98.1	92.8	94.8	99.1	99.8	99.2	99.5
1.1	97.6	82.7	99.3	93.8	95.2	99.3	99.9	99.4	99.6
1.2	98.7	85.6	100.0	94.8	95.6	99.4	100.0	99.5	99.8
1.3	99.4	88.2	100.0	95.8	96.0	99.5	100.0	99.6	99.9
1.4	99.8	90.4	99.1	96.8	96.4	99.6	100.0	99.7	99.9
1.5	100.0	92.0	97.5	97.6	96.8	99.7	100.0	99.8	99.9
1.6	100.0	93.3	94.7	98.4	97.1	99.8	100.0	99.8	100.0
1.7	99.9	94.6	91.0	99.2	97.4	99.8	100.0	99.8	99.9
1.8	99.7	95.6	86.2	99.6	97.8	99.9	99.9	99.9	99.9
1.9	99.3	96.5	80.6	100.0	98.2	100.0	99.8	99.9	99.9
2.0	99.0	97.3	74.0	100.0	98.5	100.0	99.8	100.0	99.8
2.1	98.7	98.0	66.7	99.8	98.9	100.0	99.7	100.0	99.8
2.2	98.3	98.5	58.8	99.1	99.2	100.0	99.6	100.0	99.7
2.3	97.9	99.1	50.7	98.1	99.5	100.0	99.5	100.0	99.6
2.4	97.5	99.4	42.5	96.5	99.7	100.0	99.3	99.9	99.5
2.5	97.1	99.5	35.2	94.6	99.8	99.9	99.2	99.9	99.4
2.6	96.6	99.7	27.7	92.4	99.9	99.9	99.1	99.9	99.3
2.7	96.2	99.7	20.9	89.3	100.0	99.9	98.9	99.8	99.2
2.8	95.8	100.0	15.1	85.9	99.9	99.8	98.8	99.8	99.1
2.9	95.4	99.9	10.3	81.9	99.6	99.8	98.6	99.7	99.0
3.0	95.0	99.9	6.7	77.5	99.3	99.7	98.4	99.6	98.8
3.1	94.6	99.8	4.0	72.6	98.7	99.6	98.2	99.4	98.6
3.2	94.2	99.6	2.2	67.3	98.0	99.5	98.0	99.3	98.5

3.3	93.8	99.5	1.1	61.7	97.1	99.4	97.8	99.1	98.3
3.4	93.4	99.3	0.6	55.9	95.9	99.2	97.6	98.9	98.1
3.5	93.0	99.2	0.4	49.8	94.6	99.0	97.4	98.7	97.9
3.6	92.6	99.1	0.3	44.4	93.2	98.7	97.1	98.5	97.7
3.7	92.2	98.8	0.3	38.4	91.4	98.5	96.9	98.2	97.4
3.8	91.8	98.6	0.3	32.6	89.4	98.1	96.7	97.8	97.2
3.9	91.3	98.4	0.4	27.1	87.1	97.7	96.4	97.5	96.9
4.0	90.9	98.1	0.4	22.0	84.5	97.3	96.1	97.0	96.7
4.1	90.4	97.9	0.4	17.4	81.6	96.8	95.8	96.5	96.4
4.2	90.1	97.4	0.4	13.4	78.4	96.2	95.5	95.9	96.1
4.3	89.6	97.2	0.5	10.0	74.9	95.5	95.2	95.3	95.8
4.4	89.2	96.7	0.5	7.3	71.2	94.8	94.9	94.5	95.5
4.5	88.8	96.4	0.4	5.1	67.3	93.9	94.5	93.7	95.1
4.6	88.4	96.1	0.4	3.5	63.1	93.0	94.1	92.7	94.7
4.7	87.9	95.9	0.4	2.5	59.2	92.0	93.8	91.8	94.3
4.8	87.5	95.4	0.4	1.7	54.8	90.8	93.4	90.6	93.9
4.9	87.1	95.0	0.4	1.2	50.2	89.4	92.9	89.3	93.5
5.0	86.7	94.6	0.4	0.9	45.6	88.0	92.4	87.8	93.1
5.1	86.2	94.5	0.4	0.8	41.0	86.4	91.9	86.3	92.6
5.2	85.8	94.0	0.5	0.8	36.4	84.7	91.3	84.6	92.0
5.3	85.3	93.7	0.4	0.8	31.9	82.8	90.8	82.8	91.5
5.4	84.9	93.3	0.4	0.8	27.5	80.8	90.1	80.8	90.9
5.5	84.5	92.9	0.4	0.8	23.4	78.5	89.5	78.6	90.3
5.6	84.1	92.5	0.4	0.8	19.6	76.1	88.8	76.3	89.6
5.7	83.7	92.1	0.4	0.8	16.2	73.8	88.0	74.1	88.9
5.8	83.3	91.9	0.4	0.9	13.5	71.2	87.2	71.5	88.2
5.9	82.9	91.5	0.4	0.9	10.8	68.4	86.4	68.8	87.3
6.0	82.4	91.2	0.4	0.8	8.6	65.5	85.5	65.9	86.4
6.1	82.1	90.8	0.4	0.9	6.6	62.4	84.5	62.8	85.5
6.2	81.6	90.3	0.4	0.8	5.1	59.2	83.4	59.6	84.4
6.3	81.2	90.0	0.3	0.8	4.0	55.9	82.3	56.3	83.3
6.4	80.8	89.5	0.3	0.8	3.1	52.6	81.0	52.9	82.0
6.5	80.3	89.3	0.3	0.8	2.6	49.1	79.7	49.5	80.8
6.6	79.9	88.7	0.3	0.8	2.2	45.6	78.4	46.0	79.4
6.7	79.5	88.5	0.4	0.8	2.0	42.2	77.0	42.6	78.1
6.8	79.1	88.0	0.4	0.8	1.9	39.0	75.7	39.5	76.7
6.9	78.6	87.7	0.4	0.8	1.8	35.6	74.2	36.1	75.2
7.0	78.2	87.6	0.4	0.7	1.7	32.2	72.5	32.8	73.5
7.1	77.8	87.0	0.4	0.7	1.7	28.9	70.8	29.6	71.9
7.2	77.4	86.6	0.3	0.7	1.7	25.9	69.0	26.5	70.1
7.3	77.0	86.3	0.3	0.8	1.6	22.9	67.2	23.6	68.3
7.4	76.6	85.9	0.3	0.8	1.6	20.1	65.4	20.8	66.4
7.5	76.2	85.8	0.3	0.8	1.6	17.5	63.3	18.1	64.5
7.6	75.8	85.2	0.3	0.8	1.6	15.1	61.2	15.7	62.4

7.7	75.4	84.7	0.3	0.8	1.6	13.1	59.1	13.7	60.3
7.8	75.1	84.4	0.3	0.8	1.6	11.3	56.9	11.7	58.1
7.9	74.7	84.1	0.3	0.8	1.5	9.9	54.9	10.3	56.0
8.0	74.3	83.7	0.3	0.8	1.5	8.5	52.6	8.8	53.7
8.1	74.0	83.5	0.3	0.7	1.5	7.3	50.3	7.5	51.3
8.2	73.6	83.0	0.3	0.7	1.5	6.3	47.8	6.5	48.8
8.3	73.2	82.7	0.3	0.7	1.5	5.5	45.4	5.7	46.4
8.4	72.8	82.3	0.3	0.7	1.5	4.8	43.1	5.1	44.0
8.5	72.3	82.0	0.3	0.7	1.5	4.3	40.6	4.6	41.6
8.6	71.9	81.8	0.3	0.7	1.5	3.9	38.2	4.2	39.1
8.7	71.6	81.2	0.3	0.7	1.5	3.7	35.8	3.9	36.6
8.8	71.2	81.1	0.3	0.6	1.4	3.5	33.4	3.7	34.2
8.9	70.8	80.7	0.3	0.6	1.4	3.4	31.1	3.5	31.9
9.0	70.4	80.3	0.3	0.7	1.5	3.3	29.0	3.4	29.8
9.1	70.1	80.1	0.3	0.7	1.5	3.2	26.8	3.4	27.6
9.2	69.7	79.7	0.3	0.7	1.5	3.2	24.7		
9.3	69.3	79.3	0.3	0.6	1.5	3.1	22.7		
9.4	68.9	79.0	0.3	0.6	1.5	3.1	20.8		
9.5	68.5	78.8	0.3	0.6	1.4	3.1	18.9		
9.6	68.3	78.3	0.3	0.6	1.4	3.1	17.1		
9.7	67.9	78.0	0.3	0.6	1.4	3.0	15.4		
9.8	67.5	77.7	0.3	0.6	1.4	3.0	13.9		
9.9	67.2	77.4	0.3	0.6	1.3	3.0	12.5		
10.0	66.9	76.9	0.3	0.5	1.3	3.0	11.2		

Appendix-L

ViX1 – Tissue Maximum Ratio generated from SSD data, 10 × 10 field size.

Medical Physics Department / Tawam Hospital.

Depth (mm)	6 MV	15 MV
0	0.530	0.322
5	0.834	0.588
10	0.972	0.799
15	0.999	0.905
20	0.996	0.960
30	0.974	0.986
40	0.947	0.998
50	0.920	0.100
60	0.891	0.997
70	0.862	0.983
80	0.832	0.962
90	0.803	0.942
100	0.773	0.919

Appendix-M

ViX1 – Percentage Depth Dose at 100 cm SSD generated from Percentage Depth Ionization data using 10 × 10 applicator. Medical Physics Department / Tawam Hospital.

Depth [cm]	6 MeV	9MeV	12 MeV	16 MeV	20 MeV
0	73.88	79.30	84.60	89.92	91.77
0.1	74.63	79.83	85.04	90.52	92.38
0.2	77.02	81.74	86.88	92.38	94.04
0.3	79.28	83.11	88.22	93.60	95.41
0.4	81.34	84.50	89.16	94.53	96.33
0.5	83.32	85.46	89.92	95.17	97.19
0.6	85.46	86.42	90.73	95.95	97.57
0.7	87.75	87.30	91.37	96.39	98.05
0.8	89.98	88.44	91.86	96.72	98.42
0.9	92.41	89.25	92.48	97.12	98.85
1	94.69	90.27	92.93	97.44	99.01
1.1	96.74	91.25	93.46	97.62	99.25
1.2	98.62	92.29	93.81	98.00	99.40
1.3	99.57	93.38	94.32	98.14	99.44
1.4	99.99	94.25	94.73	98.32	99.52
1.5	99.49	95.35	95.26	98.49	99.73
1.6	98.23	96.40	95.45	98.54	99.68
1.7	95.70	97.31	95.85	98.90	99.94
1.8	92.14	98.11	96.43	99.08	99.90
1.9	87.51	98.97	96.90	99.09	99.88
2	81.75	99.53	97.19	99.19	99.80
2.1	74.87	99.93	97.68	99.39	99.82
2.2	67.23	99.97	97.92	99.42	99.79
2.3	58.83	99.64	98.49	99.67	99.77
2.4	49.68	98.82	98.72	99.58	99.80
2.5	40.68	97.57	98.86	99.72	99.89
2.6	31.94	96.20	99.50	99.69	99.67
2.7	23.69	93.75	99.66	99.81	99.42
2.8	16.60	91.10	99.80	99.87	99.42
2.9	10.85	87.74	99.92	99.94	99.37
3	6.43	83.92	99.81	99.91	99.27
3.1	3.44	79.74	99.59	99.87	99.31
3.2	1.64	74.76	99.22	99.91	99.02
3.3	0.61	69.57	98.58	99.84	98.84

3.4	0.15	63.78	97.92	99.71	98.80
3.5	0.04	57.81	97.20	99.63	98.56
3.6	0.10	51.46	95.96	99.66	98.57
3.7	0.12	45.12	94.54	99.40	98.17
3.8	0.13	38.68	93.03	99.35	98.16
3.9	0.14	32.41	91.06	99.20	97.90
4	0.16	26.38	88.84	98.79	97.64
4.1	0.17	21.06	86.40	98.48	97.42
4.2	0.18	15.94	83.44	97.97	97.20
4.3	0.19	11.89	80.11	97.52	97.15
4.4	0.21	8.27	76.89	96.94	96.59
4.5	0.22	5.62	73.01	96.33	96.34
4.6	0.23	3.71	68.98	95.69	96.06
4.7	0.24	2.35	65.00	94.66	95.80
4.8	0.24	1.48	60.78	93.80	95.57
4.9	0.25	0.98	55.98	92.83	95.12
5	0.26	0.73	51.31	91.53	94.76
5.5	0.30	0.38	27.75	83.33	92.35
6	0.34	0.32	9.82	70.89	89.02
6.5	0.37	0.26	2.66	55.44	84.44
7	0.40	0.20	1.43	37.58	78.09
7.5	0.46	0.13	1.29	21.47	69.88
8	0.46	0.08	1.21	10.12	59.96
8.5	0.50	0.04	1.11	4.61	48.28
9	0.51	0.00	1.01	3.11	35.66
10	0.55	0.09	0.86	2.69	14.61
13	0.64	0.28	0.49	2.02	4.41
15	0.71	0.42	0.31	1.66	3.80