Master of Science Thesis

Dose Determination at kV X-ray Qualities Using Different Protocols

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Abstract

Absorbed dose was determined under reference conditions at four x-ray qualities; 30, 80, 120 and 200 kV using five different dosimetry protocols and codes of practice; IAEA TRS-398, AAPM, IPEMB, NCS and DIN. The dose determined by the IAEA protocol was chosen as reference.

The dosimetry protocols use different formalisms for determining the absolute dose in a reference point. The IAEA and DIN protocols are based on a dose-to-water calibration factor, $N_{\mathrm{D,w}}$. The other protocols (including DIN) are air kerma based, with calibration factor N_{K}. Some standard laboratories can provide the user with both types of calibration factors. The reference conditions for the different codes are either "in water" or "in air". In the latter case the dose has to be recalculated into dose to water. The use of plane parallel ionization chambers are generally recommended for low energy photon beams, but at an interval from about 80 kV to 160 kV both plane parallel and cylindrical chambers may be used depending on protocol.

The measurements for dose determination were carried out three times at different occasions to minimize uncertainties. The results were generally very stable with a total mean variation of 0.5 %, and in any single measurement series never exceeding 1 %. A mean value from the three measurements was used to calculate the dose.

For low energy x-rays the correlation in absolute dose per MU using the different protocols was good. For 30 kV the general deviation was only fractions of a percent. For 80 kV the deviation was around 1 %. At medium energy, however, the different formalisms resulted in larger deviations and could be explained by different reference conditions for the different protocols, for example use or no use of phantom and type of ionization chamber.

The DIN protocol was the one that best correlated with the IAEA protocol. DIN uses both formalisms. AAPM dose determinations at medium energy x-rays in phantom and NCS were also well correlated, probably due to similar reference conditions. To be able to better compare doses calculated using the different protocols, more uniformity between the protocols is needed.

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1 Introduction

Low and medium x-rays, approximately 10 – 400 kV generating potential, are used clinically in external radiation therapy. This report will focus on the dosimetry protocols used internationally by IAEA (TRS-398 [1]), the national European protocols (IPEMB [3], NCS Report 10 [4] and DIN [5,6]) and one American protocol (AAPM TG-61 [2]). These protocols are meant to represent methodology through out the world. Most of the protocols state that there is renewed interest in the latter years for radiotherapy treatment with the energy ranges in question. They also seem to agree that it is a field of dosimetry where standard methods are notably lacking.

The energy ranges, low and medium x-rays, are often categorized as superficial and deep (orthovoltage) respectively. They are used in radiation therapy to deliver doses to the skin or a few millimeters down to a few centimeters depth in tissue. There is definitely a need for dedicated dosimetry protocols for x-ray photons in the low and medium energy ranges. There is also need for dedicated ionization chambers calibrated in the energy ranges in question, to avoid extrapolation. Both dedicated protocols and chambers are in use.

All radiotherapy dosimetry determine the dose to water as water is a good tissue equivalent material. As of now there is a limited experience of absolute dosimetry for kilovoltage x-rays in the primary standard dosimetry laboratories [1]. This applies especially for absolute dosimetry to water. The older standards for low energy x-rays are based on measurements in air of exposure or air kerma, but of course dose to water is more relevant in radiotherapy. Dose to water is converted from air kerma [1]. Some laboratories provide the user with an already converted calibration factor, $N_{\mathrm{D,w}}$, which determine the dose to water directly from the measurement. But still a majority of laboratories in the world provide the user with a calibration factor, N_{K}, to measure air kerma. The user has to convert air kerma into absorbed dose to water and subsequently tissue. For each step the user has to perform, a small uncertainty is introduced [1]. In consequence, results by any other user may needlessly differ. Also, many different quantities that are handled by the user introduce uncertainties. These uncertainties become even greater in the kilovoltage range due to lack of good experimental data. As a consequence due to lack of experimental data, lack of common standards and for other various practical reasons, the protocols differ slightly although calibration factors from the standard dosimetry laboratories are provided almost exclusively based on calibration in air, but as mentioned above sometimes converted to calibration factors for dose directly to water. This means that some factors, like the backscatter factor and other correction factors may not be consistent in all protocols, and it takes an effort to trace the consistency in detail between the protocols [8]. The purpose of this report is to go through the different protocols and measure absolute dosimetry on the radiation qualities 30, 80, 120 and 200 kV generating potentials to see how much they differ and seek out uniformity in the end result. The IAEA TRS-398 will be taken as a reference for comparison since it uses a simple formalism.

1.1 Calibration and Measurement with Ionization Chambers

The ionization chamber which is used to measure absorbed dose must be properly calibrated for the beam quality used, and a calibration factor is then obtained. There are also several correction factors that may need to be applied by the user to correct for other influences for example different atmospheric conditions, use of other beam qualities and presence of phantoms. The specific factors involved in each protocol will be presented later.

1.1.1 Calibration Factors

The calibration factor that is calculated by the standards laboratory is given together with all relevant information about the geometry, radiation quality, voltage applied on the ionization chamber's electrodes and atmospheric conditions. The atmospheric conditions; air pressure and water or air temperature, are standardized and all laboratories give the calibration factor at these standardized conditions. The actual measurement conditions at the standards laboratory are also given. The measurement geometry is also given so that the user can replicate these as far as practically possible, though often not completely accurately. For the protocols used there are two types of calibration factors that have been used. Calibration free in air, N_K, and calibration in a water or water equivalent phantom, $N_\mathrm{D,w}$. The main difference is that for calibration made in air, certain corrections must be applied by the user in order to calculate the dose given at reference depth in water [2,3,4,5]. The measurement is, however, done in water. Some of the protocols comment on poor knowledge in the low energy x-ray range. The most commonly used method is to use Monte Carlo calculated factors at these energies. Monte Carlo calculated backscatter factors has an uncertainty of 1 % at best [3], but it will remain the most commonly used method until the standards of kilovoltage x-ray dosimetry is more examined. The accuracy is lower at these energies anyway in comparison to high energy photons. The protocols which use the $N_\mathrm{D,w}$-factor, and not the N_K-factor, argues that the uncertainty is lower and that it is a simpler formalism [1]. The uncertainty with an $N_\mathrm{D,w}$-factor is 1 % and an N_K-factor that is later converted to $N_\mathrm{D,w}$ has about three times higher uncertainty, which means the user conversion from N_K to $N_\mathrm{D,w}$ contributes with the main uncertainty of the measurements [1]. The individual ionization chamber is not accounted for when converting air kerma to dose to water. If the laboratory applies the conversion from air kerma to dose to water, this problem is avoided. Even tough air kerma is the traditional standard for low and medium x-rays the main interest is in fact the absorbed dose to water.

1.1.2 Beam Quality

All calibration factors must be corrected with a correction factor k_Q for the specific beam quality used.

$$k_{Q,Q_0} = \frac{N_{D,w,Q}}{N_{D,w,Q_0}}$$

This factor is the ratio of measured calibration factors for the reference quality Q_0 and the quality, Q, which is used. For high energy photons the reference quality is generally Co-60, but dedicated low energy ionization chambers are calibrated in x-ray qualities. The reference quality must then be chosen. It is preferable to use empirical k_Q-factors for each ionization chamber used since the cavity theory is inadequate in the energy ranges in question. The data which all protocols use do determine the beam quality, Q, is half value layer, HVL [1-6]. It is defined as the thickness (usually in mm) of an absorber which reduces the air kerma rate of a narrow x-ray beam at a reference point distant from the absorbing layer to 50 % compared with the air kerma rate for the non-attenuated beam. The absorber is usually pure Al for generating potentials up to about 120 kV and pure Cu for higher energies up to 400 kV. HVL roughly describes an attenuation curve for a given primary spectrum in a given medium. However, different spectra can have the same HVL [7] and it is therefore preferable to combine HVL with generating potentials as a beam specifier, but due to different filtration, geometry etc., it is not always easy to match both kV and HVL for the individual clinical beam to that of the calibration laboratory. The HVL alone is often taken as a primary beam specifier. It may also be possible to use attenuation data in the same manner as in dosimetry protocols for high energy photons as the ratio of ionization at two different depths.

1.2 Dosimetry Protocols

All protocols use HVL as beam specifier. All protocols except the IPEMB divide the kV x-rays into two categories, low (or superficial) and medium (or orthovoltage). IPEMB makes an additional distinction in the low energy region of low and very low energy. As discussed above all measurement readings must be corrected with a factor to account for different atmospheric conditions than those of the calibration situation at the standards laboratory. The equation for correcting for air pressure and temperature is:

$$k_{TP} = \frac{273,2 + T \quad P_0}{273,2 + T_0 \quad P}$$

Reference air pressure, P_0, is 101,325 kPa and temperature, T_0, is 20° C (22° C for AAPM). The correction is needed because higher pressure or lower temperature than the reference conditions means more possible ionizations in the ionization chamber which leads to a higher measurement reading of collected charges. Relative humidity is also a factor which may be corrected for, but is only needed at extreme conditions. Since measurements are made indoors, this correction is not needed. Ion recombination is a factor which one should be aware of, but that is most likely not needed to be corrected for considering that the loss of signal due to ion recombination is generally small for continuous radiation [1]. Sometimes the correction has already been made at the standards laboratory and is included in the calibration factor for the ionization chamber. Polarity of the electrodes in the ionization chamber may also influence readings, but correction for this is most often not needed either if the user makes sure to use the same polarity and potential as the standards laboratory. The electrometer used needs to have a correction factor for its accuracy. There are also several things that needs to be corrected for only if the setup is changed from that of the calibration of the chamber, such as geometrical arrangement; distance, depth, field size, phantom material and phantom size [2-6]. It is best if all controllable variables are kept the same as the calibration laboratory since there might be other influences which are not yet completely understood or charted for kV x-rays.

1.2.1 IAEA

The IAEA TRS-398 code of practice is based on a calibration factor in terms of absorbed dose to water $N_{D,w}$ [1]. The entire spectrum of generating potentials and HVLs which the protocol addresses is from low energy x-rays with the lower limit determined by what the ionization chamber can handle up to any generating potential used in medium x-ray therapy. The low energy x-rays reach up to 100 kV and HVL of 3 mmAl. Medium energy x-rays begin at 80 kV and HVL 2 mmAl. There is an overlap between 80 and 100 kV (2 and 3 mmAl) where both methods are equally satisfactory to determine absorbed dose. The one method which is most convenient should be used. The dosimetry formalism for IAEA TRS-398 is very simple and the equation to be used is as follows:

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0}$$

This equation gives the dose at reference depth in water, $D_{w,Q}$, from a measurement reading at a given beam quality, M_Q, calibration factor for the ionization chamber at reference quality,

$N_{\text{D,w,Q0}}$, and a correction factor from reference quality to the beam quality of interest, $k_{\text{Q,Q0}}$. In the case of low energy x-rays the reference depth is at the surface in a water equivalent phantom (PMMA). The medium energy uses reference depth 2 cm in a water phantom. The calibration includes calibration in phantom and addition of effects of backscatter. Reference point in the ionization chambers is at the center of the cavity for the cylindrical chamber and at the center of the inside front window in the plane parallel chamber. Other recommended settings can be found in table 1.

Table 1: IAEA TRS-398 reference settings

	Low energy	**Medium energy**
Phantom material	PMMA	Water
Chamber type	Pp	Cyl
Calibration factor	$N_{\text{D,w}}$	$N_{\text{D,w}}$
Measurement depth	Surface	2 g/cm2
Field size	3 cm diameter	10 x 10 cm2

1.2.2 AAPM

Dosimetry in the AAPM TG-61 is based on an ionization chamber calibration factor in terms of air kerma, N_{K} [2]. AAPM addresses generating potentials from 40 kV up to 300 kV. The HVL is the beam quality specifier, but it is not included in the definition of the intervals. The boundary between low and medium energy x-rays is at 100 kV. Just like IAEA the formalism for both low and medium energy is the same:

$$D_{w,z=0} = MN_K B_w P_{\text{stem,air}} \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)^{w}_{\text{air}} \right]_{\text{air}}$$

The measurements are carried out in air and converted to dose to water at reference depth at the surface, $D_{\text{w,z = 0}}$. As the calibration factor is based on air kerma, N_{K}, the user has to apply a backscatter factor, B_{w}, which accounts for the effect of phantom scatter. $P_{\text{stem,air}}$ corrects for chamber stem scatter if the field size is different from when the chamber was calibrated. If the field size is the same, which is highly recommended, then this correction is equal to unity. The final correction factor is a transition factor for conversion from air to water and is the ratio for water-to-air of the mean mass energy-absorption coefficients averaged over the photon spectrum.

For medium energy x-rays the in-phantom method can also be used, in which dose is determined at 2 cm in a water phantom, $D_{\text{w,z = 2}}$. The formalism is as follows:

$$D_{w,z=2\text{ cm}} = MN_K P_{Q,\text{cham}} P_{\text{sheath}} \left[\overline{\mu}_{en}/\rho \; {}^{w}_{\text{air}} \right]_{\text{water}}$$

The in-phantom method replaces the backscatter factor and the chamber stem factor with a correction factor for overall chamber response $P_{\text{Q,cham}}$. This factor corrects for the chamber stem as well as for displacement of the ionization chamber in water, change in energy, angular distribution of the photon beam in the phantom compared to that used for the calibration in air. If measurements are done in water, a waterproof sleeve must be used unless the chamber is waterproof. Since the ionization chamber is calibrated without it a correction must be added,

P_{sheath}. The reference point of the ionization chambers in AAPM code of practice is in the middle of the sensitive volume in both plane parallel and cylindrical chambers. A summary of reference conditions for the AAPM protocol can be found in table 2.

Table 2: AAPM TG-61 reference settings

	Low energy	**Med. energy (in-air)**	**Med. energy (in-phantom)**
Phantom material	Air	Air	Water
Chamber type	Pp	Cyl	Cyl
Calibration factor	N_K	N_K	N_K
Measurement depth	-	-	2 g/cm2
Field size	-	-	-

The field size in the AAPM TG-61 code of practice should be the same as the one used when calibrating the ionization chamber, but effects of changes in field size is taken into account when determining the correction factors. Changes in field size are mainly due to practical reasons.

1.2.3 IPEMB

Like the AAPM protocol, IPEMB code of practice is based on an air kerma calibration factor [3]. The protocol covers the range from 8 kV of generating potential and 0,035 mmAl up to 300 kV and 4 mmCu. It acknowledges three different types of significant radiobiological intervals. The lowest being called very low energy x-rays. It spans from 8 kV and 0,035 mmAl to 50 kV and 1 mmAl. Low energy x-rays are defined as 50 kV and 1 mmAl to 160 kV and 8 mmAl. The medium energy interval is from 160 kV and 0,5 mmCu to 300 kV and 4 mmCu. Each energy range has its own formalism. Starting with the dosimetry equation for very low energy x-rays:

$$D_{w,z=0} = MN_K k_{ch} \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=0,\phi}$$

The dose is determined at the surface of a water equivalent phantom (PMMA), $D_{\text{w,z = 0}}$. Like AAPM there is a correction factor to account for the change from the calibration in air to the measurement in a phantom, k_{ch}, and a factor of mass energy absorption ratio which is similar to that in AAPM. It is field size dependent, ϕ, due to scatter in the phantom. The dose is measured with a plane parallel chamber.

For low energy x-rays the formalism is as follows:

$$D_{w,z=0} = MN_K B_w \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w/air} \right]_{air}$$

Measurements in the low energy range are done free in air and a backscatter factor, B_{w}, is needed. It is defined as the ratio of measurements of water collision kerma done at the surface of a full scatter phantom and measurements done at the same geometrical conditions but without a phantom. Since a kerma calibrated chamber is used, the mass energy absorption ratio correction factor is needed to calculate dose in water. This factor is not field size dependent unlike the one for very low energy x-rays because the measurements are carried out in air. The recommended type of ionization chamber in the low energy region is a cylindrical chamber.

Medium energy x-rays has the following formalism:

$$D_{w,z=2} = MN_K k_{ch} \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=2,\phi}$$

A water phantom is used and the chamber placed at reference depth 2 cm. The equation is very similar to the one for very low energy x-rays and utilizes the same correction factors. A cylindrical chamber is used and reference points in both cylindrical and plane parallel chambers are the same as in the IAEA protocol. A plane parallel chamber is needed for low energies which is one of the reasons for introducing a third energy range (very low) to be handles separately. The reference conditions for the IPEMB code of practice is summarized in table 3.

Table 3: IPEMB reference settings

	Very low energy	**Low energy**	**Medium energy**
Phantom material	PMMA	Air	Water
Chamber type	Pp	Cyl	Cyl
Calibration factor	N_K	N_K	N_K
Measurement depth	Surface	-	2 g/cm2
Field size	-	-	-

1.2.4 NCS

NCS Report 10 is also based on the air kerma standard [4], and the distinction of energy ranges is given only as generating potentials from 50 kV to 300 kV. The low energy range is 50 kV to 100 kV, and the medium energy range is from 100 kV to 300 kV.

The formalism is the same as for IPEMB low and medium energy. For low energy:

$$D_{w,z=0} = MN_K B_w \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w/air} \right]_{air}$$

For medium energy:

$$D_{w,z=2} = MN_K k_{ch} \left[\left(\frac{\overline{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=2,\phi}$$

The correction factors are the same but there are slight differences in the numerical value. The reference settings for the NCS code of practice can be found in table 4.

Table 4: NCS Report 10 reference settings

	Low energy	**Medium energy**
Phantom material	Air	Water
Chamber type	Pp	Cyl
Calibration factor	N_K	N_K
Measurement depth	-	2 g/cm2
Field size	-	10 x 10 cm2

1.2.5 DIN

Like the other protocols, DIN has the energy ranges low [5] and medium [6]. The entire range for which the protocol addresses is 10 kV to 400 kV. HVL is the beam quality specifier, but is not included in the definition of the energy ranges. For low energy x-rays (10 to 100 kV) DIN suggests two methods of measurement based on both water calibrated, $N_{D,w}$, and in-air, N_K, calibrated ionization chambers. Both measurements are done at the surface, or rather 0,03 mm depth, in a water equivalent (PMMA) phantom. The formalism for low energy with a water calibrated ionization chamber is as follows:

$$D_w = N_D kM$$

This is a simple formalism like the IAEA TRS-398. The dose to water, D_w, is given by multiplication of calibration factor, N_D, beam quality correction factor, k, and measurement of collected charges in the ionization chamber, M, corrected for atmospheric conditions.

The air-kerma based formalism:

$$D_w = t_{w/a}^{en} k_{a \to w} N_{K_a} kM$$

The correction factors are the same as for other protocols using an air kerma calibrated ionization chamber, but the symbols are different. t^{en} is the mass energy absorption ratio and $k_{a \text{ -> } w}$ is the conversion factor for measuring in a phantom with an N_K-calibrated ionization chamber.

Medium energy x-rays has the $N_{D,w}$-based formalism:

$$D_w = kNM$$

The measurement is done at 2 cm depth in water. Other reference settings can be found in table 5.

Table 5: DIN reference settings

	Low energy ($N_{D,w}$)	**Low energy (N_K)**	**Medium energy**
Phantom material	PMMA	PMMA	Water
Chamber type	Pp	Pp	Cyl
Calibration factor	$N_{D,w}$	N_K	$N_{D,w}$
Measurement depth	0,03 mm	0,03 mm	2 g/cm2
Field size	3 cm diameter	3 cm diameter	10 x 10 cm2

DIN has a reference point at 0,03 mm depth, but they have included a conversion factor to extrapolate to depth 0 mm, which is useful when dose determination at the surface is needed.

2 Materials and Methods

The machine which was used to generate x-rays was a Gulmay D3225 therapy system at the University Hospital in Lund. The system is capable of generating x-rays in the range of low and medium energy x-rays. The qualities that are used in daily x-ray radiation therapy are 30, 80, 120 and 200 kV. The choice of those qualities for the dosimetry measurements is good since they cover both the low and medium ranges described in the protocols, as well as the very low range described in the IPEMB protocol. Before the use of the system, warm up must be carried out to establish an even output from the x-ray tube. This procedure is automatically carried out when starting the machine.

2.1 Materials Used

Most of the dosimetry protocols correlate quite well with each other with respect on phantom sizes, applicator sizes, water depth, etc. Details about the specific recommended setup conditions can be found in the previous part of this report. The irradiations were carried out using two of the standard applicators, since they are the closest matches to the protocols. The specifics of the applicators can be found in table 6.

Table 6: Characteristics for the applicators

Shape	SSD/cm	Field size
Circular	20	3 cm diameter
Rectangular	50	10 x 10 cm^2

The plane parallel ionization chambers are calibrated at SSD 30 cm, but the applicator has only a SSD of 20 cm. This change was considered negligible.

2.1.1 Ionization Chambers

To cover both water and air calibration requirements and cylindrical and plane parallel chambers, four different chambers were needed. The type of chambers and other useful information is presented in table 7.

Table 7: Ionization chambers used

Type	Geometry	Manufacturer	Serial no	Calibration factor	Numerical value/(Gy/C)	Calibration quality	Calibration laboratory
TB 23344	Plane parallel	PTW	#0909	$N_{D,w}$	$9{,}783 \cdot 10^7$	0,370 mmAl	PTB (Germany)
B23344	Plane parallel	PTW	#622	N_K	$6{,}934 \cdot 10^7$	0,340 mmAl	PTB (Germany)
FC 65-G	Cylindrical	SW	#1055	$N_{D,w}$	$4{,}900 \cdot 10^7$	1,53 mmCu	PTB (Germany)
NE 2571	Cylindrical	NE	#650	N_K	$4{,}12 \cdot 10^7$	0,47 mmCu	SSI (Sweden)

All chambers, especially the cylindrical ones, have a mark which should always point upwards in accordance with they rotation of the chambers at the calibration laboratory. This helps replicate the reference conditions used. However, cylindrical chambers have a symmetrical geometry. This implies that there should be no major measuring error if the chamber should be accidentally rotated. To make sure of this, measurements of one of the cylindrical chambers was done at different rotation angles and the output at different angles was found to be non-existent.

The chambers were used as far as possible in accordance to the recommended reference conditions. However, some changes were necessary to make.

- The cylindrical chamber #1055 was calibrated at depth 5 cm, but the dose was determined with the chamber at 2 cm. The error was considered negligible.
- A cylindrical $N_{D,w}$-chamber is recommended by IAEA to be used at 120 kV, but the #1055 was not calibrated at those low HLVs. The plane parallel chamber #0909 was used instead as it was calibrated in that HVL range.
- A cylindrical N_K-chamber is recommended by the AAPM at 80 kV, but the #650 is only calibrated down to 120 kV. The #622 plane parallel chamber was used at 80 kV.

In addition to this, the plane parallel chamber #622 is calibrated up to 120 kV generating potential and therefore two additional dose determinations was possible to do using this chamber at 120 kV together with the AAPM and the DIN protocols.

The ionization chambers should be pre irradiated before use with about 500 MU to ensure stable measurement readings.

2.1.2 Phantoms

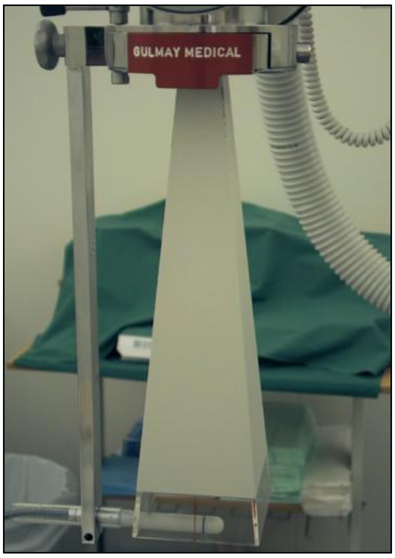
The phantoms used were cubical PMMA-containers that were filled with water and smaller PMMA-phantoms where plane parallel chamber can be mounted. The water phantoms have a built in water proof sleeve in which the ionization chamber is positioned. The phantoms are large enough to allow full photon scatter. When using the water phantom, it is important to level it. The applicator must also be leveled in correlation to the phantom. The applicator must then be positioned just at the surface of the water and with the central axis precisely over the ionization chamber’s sensitive volume. The phantom was filled with water close to room temperature to ensure stable water temperature. The depth should be 2 cm with little margin for error. The phantom for plane parallel chambers had a bit easier setup since no water surface had to be leveled. The chamber is leveled with the phantom when in position, and the applicator is then leveled with the other components.

2.1.3 The Electrometer

A separately calibrated electrometer, with an electrometer correction factor, was used. The electrometer should be switched on at least 15 min before it is needed. This is to create a stable field inside the ionization chamber between its electrodes at the existing atmospheric conditions. All readings should be corrected for background, and a background measurement is done for 60 s. This measurement is then stored in the electrometer and automatically corrects all readings. A voltage of +350 V is used by all calibration laboratories and therefore is the suitable voltage to be used in the measurements as well.

2.2 Output Test

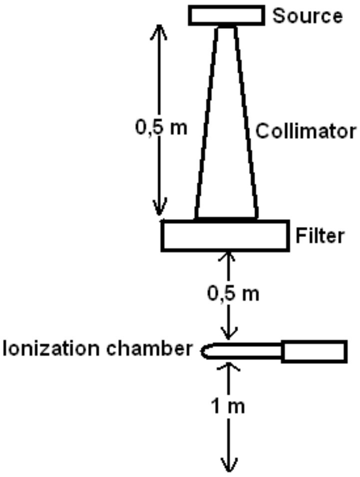
At the beginning of each day, an output test of 100 MU to check the machine output stability was carried out on all energies used. This test is normally carried out on a weekly basis on the x-ray machine. During the test, both output value and dose rate is checked to be the expected value. The test must be set up in the same way every time it is done. To make that simple there is a certain ionization chamber holder that is mounted directly on the x-ray machine head. To be able to run the different energies the applicator must be changed. One setup is done for 30 and 80 kV with the circular 20 cm SSD applicator and one for 120 and 200 kV with the square 50 cm SSD applicator. The setup can be seen in the following images:



A deviation of more than 1 % from the reference output for more than a few weeks is an indication that a recalibration of the machine is needed. A deviation of more than 2 % for one single output measurement is also considered bad.

2.3 HVL Measurements

The beam quality was determined for each of the used energies. To determine beam quality, HVL, the filtration device should ideally be placed at half the distance between source and ionization chamber. The SSD of the collimator define the distance from source to ionization chamber as can be seen in the following image:



There should preferably be 1 m of air free from any scattering material behind the ionization chamber. In general there should be as little scattering material as possible in the setup to avoid any electron contamination to the ionization chamber. The same ionization chamber can be used for determination of all energies since no calibration factor is needed to be considered, since it is in principle a relative measurement. Irradiations should first be made without the filtering device to determine the exposure (or air kerma) at a non attenuated beam. The collected charges in the chamber volume were registered and a mean value of three measurements was taken. Layers with varying thickness of pure Al (for 30, 80 and 120 kV) or Cu (120 and 200 kV) were inserted into the beam. The filtration device can measure layer thickness in steps of 0,1 mm. HVL has to be determined more accurately, and a linear interpolation between the closest values to the actual HVL was made. Air pressure and temperature corrections are unnecessary because k_{TP} will be eliminated by division. It is still important to keep an eye on them anyway so that they do not change during the measurement series.

2.4 Dosimetry Measurements

Absolute dosimetry was done 3 times for each energy and protocol to calculate a mean value. Irradiation was 100 MU. Each measurement for one certain energy together with one certain ionization chamber was done at different occasions so that different atmospheric conditions were present. All readings were then corrected with the k_{TP}-factor. The measurement data and atmospheric correction factor can be found in appendix 3. One series of measurements is the number of measurements needed when determining dose to one of the energies together with one of the protocols. The number of measurements for each series was about 10. This number was sometimes varied depending on how stable the output was during the measurement series. Sometimes no more than 5 measurements were needed due to stable output. At most 3 extra measurements (a total of 13 measurements) were needed to confirm a statistically good mean value. The series needed to be able to perform dosimetry on all energies with all protocols were:

- Three series with N_K-calibrated pp-chamber in phantom; 30, 80 and 120 kV
- Three series with $N_{D,w}$-calibrated pp-chamber in phantom; 30, 80 and 120 kV
- Three series with N_K-calibrated pp-chamber in air; 30, 80 and 120 kV
- Two series with N_K-calibrated cyl-chamber in air; 120 and 200 kV
- Two series with N_K-calibrated cyl-chamber in phantom; 120 and 200 kV
- One series with $N_{D,w}$-calibrated cyl-chamber in phantom; 200 kV

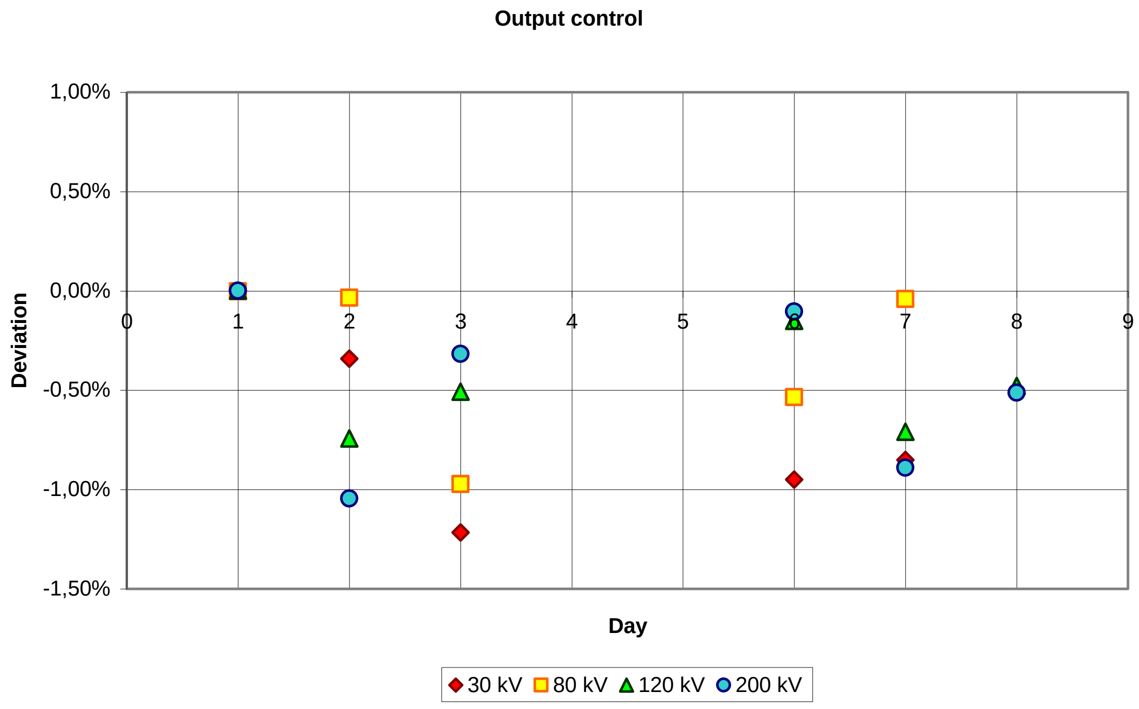
All measurements were arranged as closely as possible to the descriptions in the protocols and the actual setups for all the protocols are listed in appendix 4. The reference settings and other settings are already mentioned in this report except that inverse square was needed to convert dose to the surface in the plane parallel chamber to dose at reference point in the AAPM-protocol. Since the HVL for the Gulmay x-ray machine rarely correspond to the qualities used by the standards laboratory one must interpolate the k_Q-values. A linear interpolation is probably enough, but in the IAEA TRS-398 another mathematical interpolation is given which approximates the HVL as a function of k_Q-values as an exponential expression. This interpolation method was used for all interpolated k_Q-values. All other relevant correction factors were taken from tables in each protocol. Linear interpolation was used when determining correction factors (except for the k_Q-values). All calibration and correction factors used can be found in appendix 5. Doses were then calculated according to the formalisms in each code of practice.

3 Results

Results from the measurements for the output control, beam quality and dosimetry are presented below. The specific readout values are presented in appendix 1 for HVL and appendix 3 for dosimetry measurement data. Please note that the tabled values in appendix 3 are mean values from three different measurements each.

3.1 Output Control

The internal deviations for the output measurements are quite low, no more than 1 % depending on which measurement you take as reference. In comparison to the uncertainty of the protocols this can be considered negligible. This is one reason why output corrections to the measurements are not necessary. Another reason is which output measurement you should take as a reference. All measurements could be equally good. Rather than eliminating output differences for each day, you might add errors to the doses. You must also consider the fact that one output measurement for each day is not always representative for all dosimetry measurements done during that day. This can actually be observed during the proceedings of one day. The output can vary almost one percent during a series of dose measurements at its worst, but the variation is usually not that high. A variation when measuring a series could be expected to be around 0,5 %. A mean value of an entire series usually eliminates this problem, as can be seen as correlation between mean values when comparing measurements from different days. The final results are also mean values of the calculated dose since absorbed dose was measured at three independent occasions. This also helps to eliminate output errors and the need for independent output corrections.



The reference measurement in the figure for each potential is the measurement from day one. It seems like the output for day one is unusually high, which means that all other measurements have negative deviations in comparison to the reference. As discussed above, the choice of reference measurement is arbitrary. All in all the output deviation is reasonably low. The dose rate at each output check was stable.

3.2 HVL

Results of measurements in relative terms can be found in appendix 1. Linear interpolation was done to obtain specific HVL. The HVL for all energies are presented in table 8.

Table 8: HVL at different energies

Pot./kV	mmAl	mmCu
30	0,648	-
80	2,335	-
120	3,432	0,143
200	-	1,036

The HVL at 120 kV was measured both in terms of mmAl and mmCu. Only the HVL in terms of mmAl was used in the dose determination. The HVL was used to identify k_Q-factors for the different energies. The k_Q-factors were tabled in the calibration specifications for each ionization chamber.

3.3 Dosimetry

To calculate dose at surface from measurements done at depth in water, the values of percentage depth dose given in table 9 were used.

Table 9: Percentage depth dose

Depth	120 kV	200 kV
0 cm	100,00 %	100,00 %
2 cm	73,86 %	90,17 %

Doses determined by each protocol are given in table 10.

Table 10: Absolute dose in Gy/100 MU

	30 kV	80 kV	120 kV	200 kV
IAEA/DIN ($N_{D,w}$)	1,01	1,01	1,08	1,05
AAPM (in air)	1,01	1,00	1,02	0,98
AAPM (in phantom)	-	-	1,04	1,02
IPEMB	1,00	1,00	1,01	1,03
NCS	1,01	1,00	1,04	1,02
DIN (N_K)	1,00	1,00	1,07	-

The results are also converted to percentage deviation from reference doses. The reference dose is taken to be the IAEA protocol. IAEA and DIN protocols use the same formalism based on the $N_{D,w}$-factor, and therefore the absolute dose was the same for both protocols.

The relative dose deviations from IAEA-determined doses are listed in table 11.

Table 11: Relative dose deviations

	30 kV	**80 kV**	**120 kV**	**200 kV**
IAEA/DIN ($N_{D,w}$)	0,00 %	0,00 %	0,00 %	0,00 %
AAPM (in air)	-0,01 %	-1,09 %	-5,47 %	-6,05 %
AAPM (in phantom)	-	-	-4,10 %	-2,51 %
IPEMB	-0,68 %	-1,05 %	-6,58 %	-1,03 %
NCS	0,28 %	-0,98 %	-3,53 %	-2,25 %
DIN (N_K)	-0,51 %	-1,08 %	-0,95 %	-

A graphic representation of table 11 can be found in appendix 2.

4 Discussion and Conclusions

The purpose of this report was to compare absorbed doses in water at kilovoltage quality x-rays using different protocols, IAEA TRS-398, AAPM TG-61, NCS Report 10, DIN and IPEMB. The code of practice for each protocol has also been compared to some extent. The qualities used were 30, 80, 120 and 200 kV and HVL for each quality was determined. The HVL is the primary beam quality specifier and is individual for the x-ray machine used. In this report, both HVL and kV are used to specify beam quality as recommended in the protocols. The dose was determined three times at separate occasions for all energies together with each protocol and the mean value of those three measurements was presented in terms of absolute dose per 100 MU and in terms of a relative comparison between the protocols with IAEA as a reference. Only IAEA and DIN are based on absorbed dose to water standards [1,5]. All other protocols use the traditional air-kerma based standards [2-6].

HVL is used by all protocols as beam quality specifier, but some protocols are titled with only generating potential. It would be welcomed to have both HVL and kV included in titles and in the text. HVL would be easier to embrace if it was consequently connected with kV, since kV is often more familiar to most users. The energy ranges could be better matched between the protocols if more than one protocol is used. It could also be useful to have overlap of energy ranges, like in the IAEA protocol, to make better use of the user’s equipment.

A relative comparison is more useful than a comparison with absolute values. When evaluating the protocols both uniformity within the protocol and uniformity in comparison to other protocols were considered. The AAPM and NCS protocols generated the most uniform results throughout the entire kV-range with the most deviating results at 120 kV. In general, the biggest differences in dose between the different protocols lay in the medium energy range (120 and 200 kV). The coherence in dose for the low energies (30 and 80 kV) between the different protocols is good. For 30 kV the results are only fractions of a percent difference between the different protocols. At 80 kV differences from the reference (IAEA) is -1,0 % to -1,1 %, which is to be expected. At 120 kV there is a major difference in doses. In general the IPEMB protocol differ the most. At 120 kV the deviation from the IAEA protocol is almost 7 %. Possible measurement errors have been considered, but the general measurement stability for the ionization chamber used at different occasions was good with a total mean variation in measurements of 0,5 %, and in any single measurement series never exceeding 1 %. At 120 kV the difference in reference conditions is at its largest between IAEA and IPEMB. IAEA uses the plane parallel chamber with $N_{\mathrm{D,w}}$ calibration factor and measurement in phantom. IPEMB uses the cylindrical chamber with N_{K} calibration factor and measurement in air. The DIN protocol is the best matched result with only 1,0 % deviation. The DIN protocol uses both N_{K} and $N_{\mathrm{D,w}}$ based formalism parallel to each other [5], and that is probably why the two formalisms in DIN seem to be well correlated. As can also be seen, the phantom measurements in the AAPM protocol are better correlated with the IAEA reference than the in-air measurements. The deviation for both types of AAPM measurements is large and that is probably because of different formalisms. AAPM in phantom and NCS seem to be well correlated due to similar reference conditions and formalism. The deviations become smaller again at 200 kV, where the IPEMB protocol is the best correlated result in comparison to the reference with 1,0 % difference. This is probably because the IPEMB measurement at 200 kV is carried out in-phantom. In fact, the one measurement that is off most, AAPM, is the only one measured without a phantom. All other protocols recommend phantom measurements for 200 kV. Once again there is correlation between AAPM measured in phantom and NCS. The results at 200 kV are still not as uniform over all. Peixoto and Andreo found that doses at all energies calculated with data from different protocols were around 1 % [8]. However, they used N_K-based formalisms only, including the earlier IAEA protocol TRS-277. At least 1 % is to be expected, even more if you compare different formalisms. In conclusion to that, it is important to be careful when comparing doses determined by different formalisms. Any further comparisons of different protocols should be aware of the effect in dose between the different formalisms. In this report, however, the main purpose was to evaluate the most commonly used protocols, and the focus on type of formalism was given lower importance.

The medium energy x-rays (120 and 200 kV) seem to be affected more than low energy x-rays (30 and 80 kV) by different setups. The reason why the doses for low energy x-rays seem to correlate better, independent of setup variables, is that there really are no major differences in the setups. All protocols recommend plane parallel chambers and the lack or presence of a phantom is not so different from one and other physically. The entrance window is completely exposed in both cases since the ionization chamber used together with a phantom is at the surface. For measurements in-air a backscatter factor is used, but the numerical value is much closer to unity for the low energies than for the medium energies. This means that a measurement with a phantom can almost be approximated to a measurement in air.

It can be concluded that presence of phantom, type of formalism (N_K or $N_{D,w}$ based) and type of ionization chamber (plane parallel or cylindrical) make a big effect on dose determination.

5 References

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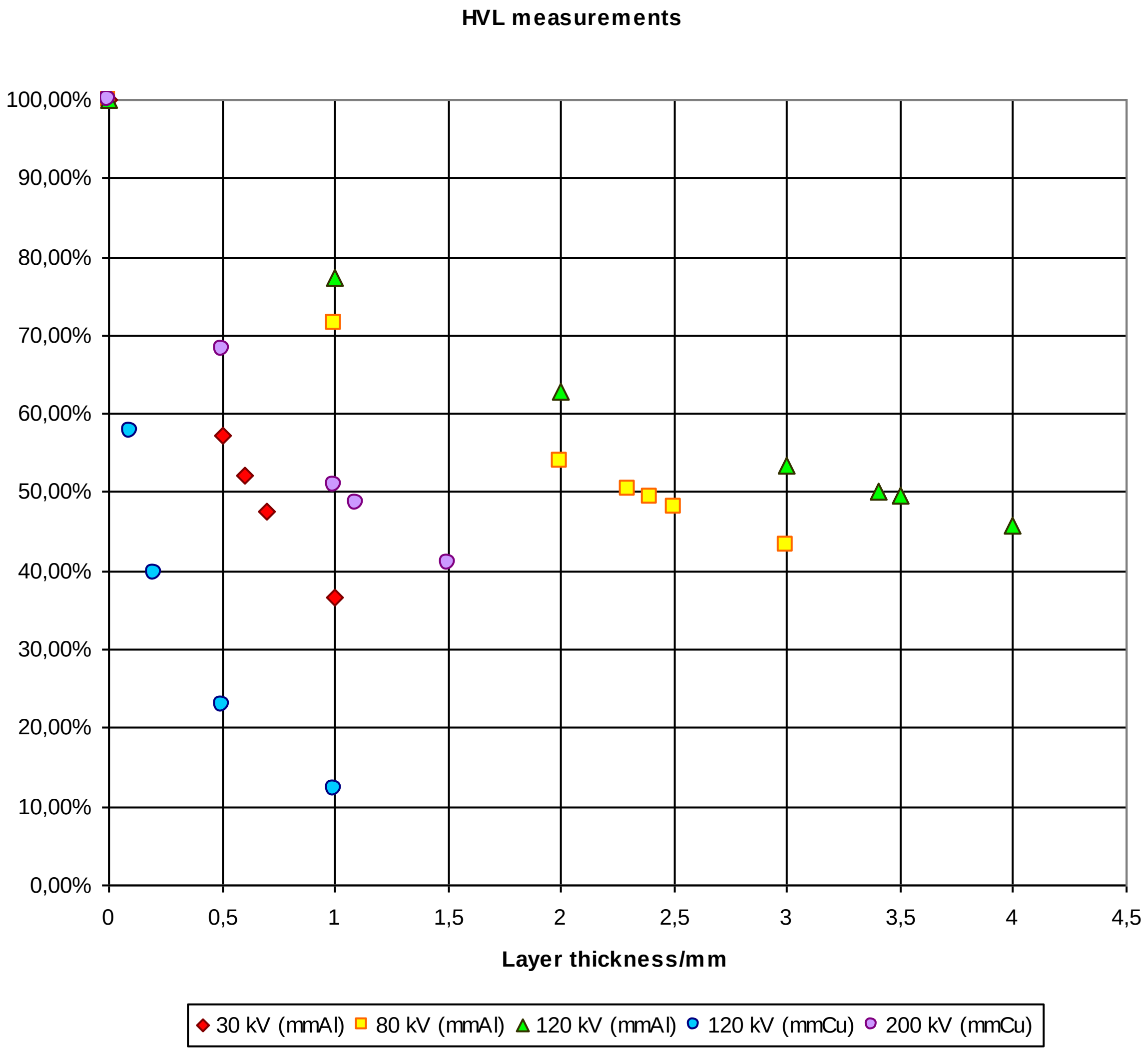
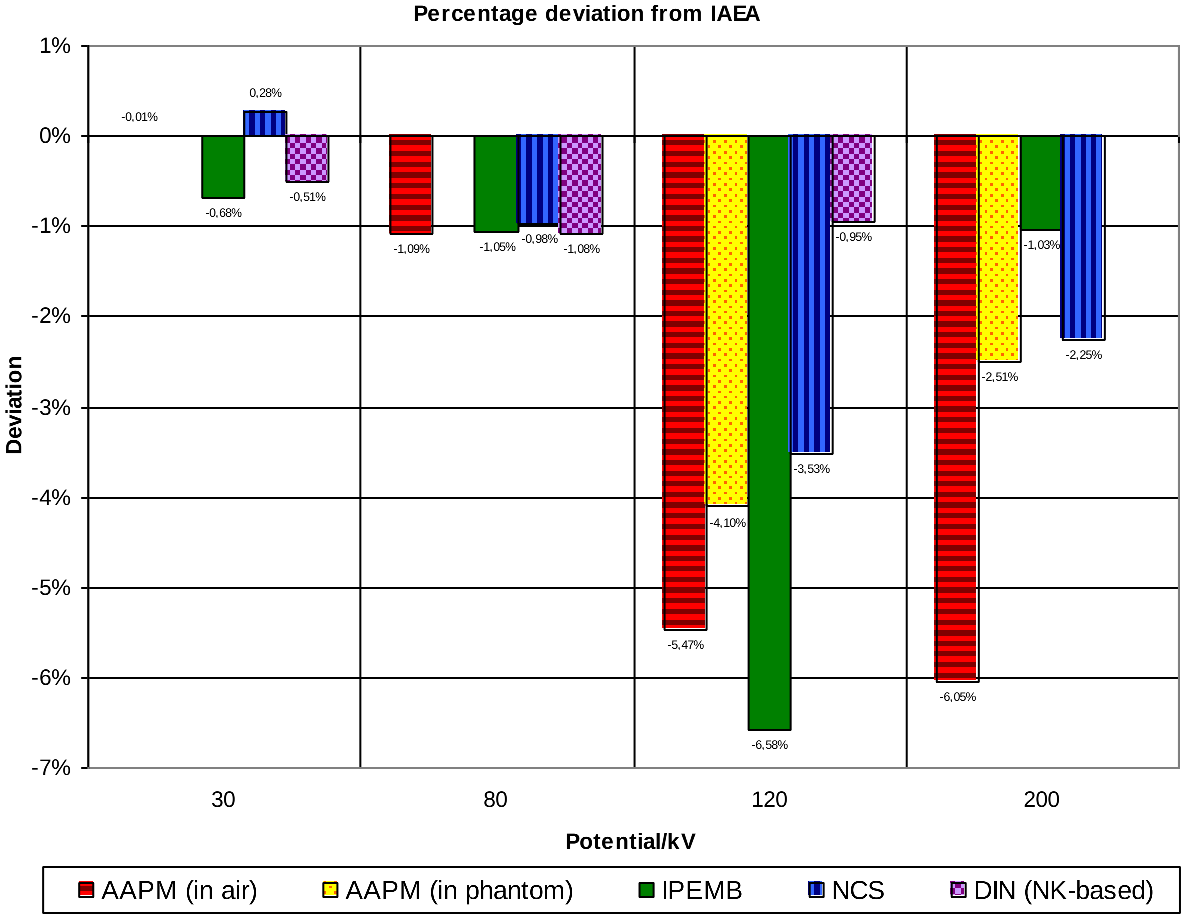
Appendix 1: Determination of HVL



Appendix 2: Relative Dose Values with IAEA as Reference



Appendix 3: Raw Data

All corrections are carried out using electrometer correction factor, k_{elec} = 0,9997.

Measurement series 1	**<M>/nC**	**k_{TP}**	**M_{corr}/nC**
pp in-air 30 (N_K)	13,26	1,0021	13,28
pp in-air 80 (N_K)	12,69	1,0023	12,72
pp in-air 120 (N_K)	11,21	1,0031	11,24
cyl in-air 120 (N_K)	17,29	1,0029	17,34
cyl in-air 200 (N_K)	16,23	1,0029	16,27
pp in-phantom 30 (N_K)	13,40	1,0033	13,44
pp in-phantom 80 (N_K)	13,24	1,0028	13,27
pp in-phantom 120 (N_K)	14,07	1,0030	14,11
cyl in-phantom 120 (N_K)	17,71	1,0072	17,83
cyl in-phantom 200 (N_K)	20,49	1,0072	20,64
pp in-phantom 30 ($N_{D,w}$)	10,30	1,0035	10,34
pp in-phantom 80 ($N_{D,w}$)	10,08	1,0032	10,11
pp in-phantom 120 ($N_{D,w}$)	10,73	1,0032	10,77
cyl in-phantom 200 ($N_{D,w}$)	18,96	1,0092	19,13

Measurement series 2	**<M>/nC**	**k_{TP}**	**M_{corr}/nC**
pp in-air 30 (N_K)	13,19	1,0039	13,23
pp in-air 80 (N_K)	12,57	1,0039	12,62
pp in-air 120 (N_K)	11,21	1,0039	11,25
cyl in-air 120 (N_K)	17,39	1,0017	17,41
cyl in-air 200 (N_K)	16,27	1,0021	16,30
pp in-phantom 30 (N_K)	13,34	1,0045	13,40
pp in-phantom 80 (N_K)	13,18	1,0047	13,24
pp in-phantom 120 (N_K)	14,03	1,0055	14,10
cyl in-phantom 120 (N_K)	17,83	0,9995	17,82
cyl in-phantom 200 (N_K)	20,61	0,9995	20,59
pp in-phantom 30 ($N_{D,w}$)	10,30	1,0030	10,33
pp in-phantom 80 ($N_{D,w}$)	10,09	1,0048	10,13
pp in-phantom 120 ($N_{D,w}$)	10,72	1,0048	10,77
cyl in-phantom 200 ($N_{D,w}$)	19,11	1,0004	19,12

Measurement series 3	**<M>/nC**	**k_{TP}**	**M_{corr}/nC**
pp in-air 30 (N_K)	13,17	1,0057	13,24
pp in-air 80 (N_K)	12,60	1,0060	12,68
pp in-air 120 (N_K)	11,18	1,0053	11,23
cyl in-air 120 (N_K)	17,21	1,0130	17,43
cyl in-air 200 (N_K)	16,09	1,0130	16,30
pp in-phantom 30 (N_K)	13,33	1,0060	13,41
pp in-phantom 80 (N_K)	13,15	1,0061	13,23
pp in-phantom 120 (N_K)	13,99	1,0077	14,09
cyl in-phantom 120 (N_K)	17,67	1,0116	17,87
cyl in-phantom 200 (N_K)	20,33	1,0112	20,55
pp in-phantom 30 ($N_{D,w}$)	10,23	1,0070	10,30
pp in-phantom 80 ($N_{D,w}$)	10,06	1,0070	10,13
pp in-phantom 120 ($N_{D,w}$)	10,69	1,0068	10,76
cyl in-phantom 200 ($N_{D,w}$)	18,87	1,0113	19,08

Appendix 4: Setup Parameters

Characteristics for ionization chambers and applicators are listed in table 6 and 7 in the report.

IAEA and DIN ($N_{D,w}$)					**DIN (N_K)**		
Pot./kV	30	80	120	200	30	80	120
Chamber	#0909	#0909	#0909	#1055	#622	#622	#622
Applicator	Circular	Circular	Square	Square	Circular	Circular	Square
Phantom	PMMA	PMMA	PMMA	Water	PMMA	PMMA	PMMA
Depth	Surface	Surface	Surface	2 cm	Surface	Surface	Surface

AAPM (in-air)				**AAPM (in-phantom)**	
Pot./kV	30	80	120	120	200
Chamber	#622	#622	#622	#650	#650
Applicator	Circular	Circular	Square	Square	Square
Phantom	Air	Air	Air	Water	Water
Depth	-	-	-	2 cm	2 cm

IPEMB				
Pot./kV	30	80	120	200
Chamber	#622	#622	#622	#650
Applicator	Circular	Circular	Square	Square
Phantom	PMMA	Air	Air	Water
Depth	Surface	-	-	2 cm

NCS				
Pot./kV	30	80	120	200
Chamber	#622	#622	#650	#650
Applicator	Circular	Circular	Square	Square
Phantom	Air	Air	Water	Water
Depth	-	-	2 cm	2 cm

Appendix 5: Calibration and Correction Factors

IAEA and DIN ($N_{D,w}$)

Pot./kV	30	80	120	200
$N_{D,w}$/(Gy/nC)	0,09783	0,09783	0,09783	0,04900
k_Q	0,997	1,020	1,028	1,007

AAPM

Pot./kV	30	80	120	120	200
N_K*k_Q/(Gy/nC)	-	-	-	0,0414	0,0412
N_K/(Gy/nC)	0,06934	0,06934	0,06934	-	-
k_Q	0,989	0,975	0,972	-	-
B_w	1,081	1,145	1,321	-	-
$P_{stem,air}$	1	1	1	-	-
$P_{Q,cham}$	-	-	-	1,014	1,023
P_{sheath}	-	-	-	0,995	0,999
(μ_{en}/ρ)	1,025	1,019	1,023	1,029	1,061

IPEMB

Pot./kV	30	80	120	200
N_K/(Gy/nC)	0,06934	0,06934	0,06934	-
k_Q	0,989	0,975	0,972	-
N_K*k_Q	-	-	-	0,0412
k_{ch}	1,06	-	-	1,022
B_w	-	1,147	1,306	-
(μ_{en}/ρ)	1,025	1,019	1,022	1,077

NCS

Pot./kV	30	80	120	200
N_K/(Gy/nC)	0,06934	0,06934	-	-
k_Q	0,989	0,975	-	-
N_K*k_Q	-	-	0,0414	0,0412
B_w	1,082	1,146	-	-
k_{ch}	-	-	1,015	1,023
P_{sheath}	-	-	0,997	0,999
(μ_{en}/ρ)	1,026	1,019	1,031	1,064

DIN (N_K)

Pot./kV	30	80	120	
N_K/(Gy/nC)	0,06934	0,06934	0,06934	
k_Q	0,989	0,975	0,972	
$t_{en,w/a}$	1,024	1,019	1,023	
$k_{a \text{-->} w}$	1,061	1,094	1,102	
D_{corr}	1,003	1,001	1,001	(0,03 mm to surface)