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Table 1. Filter/Tube potential combinations of the Gulmay D3225 unit.

Tube potential (kV)	**Filter**	**Reference field size**	**Focus-surface distance**
30	0.8 mm Al	3 cm diameter circular	20 cm
80	2 mm Al	3 cm diameter circular	20 cm
120	2 mm Al	10 x 10 cm^2 square	50 cm
200	0.5 mm Cu	10 x 10 cm^2 square	50 cm

Table 2. Summary of dosimeters used: Plane-parallel ionization chambers PTW type 23344 with serial numbers 622 and 0909 are denoted “PP (622)” and “PP (0909)”, respectively, the cylindrical ionization chamber Nuclear Enterprises type 2571 with serial number 650 is denoted “Cyl (650)”, and the cylindrical ionization chamber Scanditronix/Wellhöfer type FC65-G with serial number 1055 is denoted “Cyl 1055”. “Geometry” refers to the reference conditions for determination of absorbed dose to water: “in-air” represents air kerma measured free in air requiring the use of a back-scatter factor; “0 cm” represent air kerma or absorbed dose measured at the surface of a full-scatter phantom; “2 cm” represents air kerma or absorbed dose measured at 2 cm depth in water.

Protocol	**Geometry**	**30 kV**	**80 kV**	**120 kV**	**200 kV**
AAPM TG-61	In-air	PP (622)	PP (622)	Cyl (650)	Cyl (650)
	2 cm			Cyl (650)	Cyl (650)
IPEMB	In-air		PP (622)	Cyl (650)	Cyl (650)
	0 cm	PP (622)			
	2 cm				Cyl (650)
NCS-10	In-air	PP (622)	PP (622)		
	2 cm			Cyl (650)	Cyl (650)
DIN 6809	0 cm	PP (622)	PP (622)	PP (622)	
	2 cm			Cyl (650)	Cyl (650)
IAEA TRS-277	In-air	PP (622)	PP (622)		
	2 cm			Cyl (650)	Cyl (650)
IAEA TRS-398	0 cm	PP (0909)	PP (0909)	PP (0909)	
	2 cm				Cyl (1055)

Table 3. Measured first (HVL-1) and second (HVL-2) half-value layer.

Tube potential (kV)	**Added filtration**	**HVL-1**	**HVL-2**
30	0.8 mm Al	0.65 mm Al	0.88 mm Al
80	2 mm Al	2.35 mm Al	3.89 mm Al
120	2 mm Al	3.42 mm Al	5.97 mm Al
200	0.5 mm Cu	1.04 mm Cu	1.93 mm Cu

Table 4. Absorbed dose to water (Gy/100MU) at the surface of a full-scatter phantom; comparison between air kerma and absorbed dose to water based protocols. Measurements are normalised to the average of each column.

Protocol	**Geometry**	**30 kV**	**80 kV**	**120 kV**	**200 kV**
AAPM TG-61	In-air	1.004	1.001	0.963	0.982
	2 cm			0.994	1.001
IPEMB	In-air		1.001	0.953	0.982
	0 cm	0.994			
	2 cm				1.001
NCS-10	In-air	1.007	1.002		
	2 cm			1.005	1.004
DIN 6809	0 cm	0.993	0.988	1.018	
	2 cm			1.015	0.999
IAEA TRS-277	In-air	1.000	1.000		
	2 cm			1.017	1.006
IAEA TRS-398	0 cm	1.002	1.009	1.035	
	2 cm				1.025

Table 5. Percentage depth doses at 2 cm depth in water measured using various detectors. Two sets of data are presented in the British Journal of Radiology (BJR) Supplement 25 for the beam quality of the 200 kV beam, the first in the table refers to what is called “closed applicator” while the second refers to “diaphragm limited”. Open applicators were used in the present study.

Beam (kV)	**Diamond**	**Cyl. chamber (FC65-G)**	**Plane-parallel chamber (NACP)**	**Plane-parallel chamber (Roos)**	**British Journal of R. (Suppl 25)**
120	75.3	73.9	73.6	73.9	75.0
200	88.8	90.2	88.5	89.1	87.1 or 94.0

Table 6. Estimated uncertainties (1 SD) of the absorbed dose to water at the surface full-scatter phantom for $N_{D,w}$-based protocols.

Physical quantity or procedure	**Estimated uncertainties (%)**			
	30 kV	80 kV	120 kV	200 kV
$N_{D,w}$ factor from standards laboratory	1.4	1.4	1.4	1.8
Beam quality correction	1.5	1.5	1.5	1.5
Long-term stability of the dosimeter	0.3	0.3	0.3	0.3
Establishment of reference conditions	1.0	1.0	1.0	1.0
Dosimeter reading M_Q relative to monitor chamber	0.5	0.5	0.5	0.5
Correction for influence quantities	0.8	0.8	0.8	0.8
Difference of chamber sleeve at standards laboratory and clinical beam				0.5
Chamber field size dependence; difference between standards laboratory and clinical beam			1.0	
Renormalization using PDD data (transition from the reference point at 2 cm depth to the phantom surface)				1.0
Overall uncertainty (k=1)	**2.5**	**2.5**	**2.7**	**3.0**

Table 7. Estimated uncertainties (1 SD) of the absorbed dose to water at the surface full-scatter phantom for N_K-based protocols. The top seven posts in the uncertainty budget are applicable to both the in-air and the in phantom method. The remaining posts are applicable to either the in-air or the in phantom method; those applicable to the in-air method are italicized.

Physical quantity or procedure	**Estimated uncertainties (%)**			
	30 kV	80 kV	120 kV	200 kV
N_K factor from standards laboratory	0.5	0.5	0.4	0.4
Beam quality correction	2.0	2.0	2.0	2.0
Long-term stability of the dosimeter	0.3	0.3	0.3	0.3
Establishment of reference conditions	1.0	1.0	1.0	1.0
Dosimeter reading M_Q relative to monitor chamber	0.5	0.5	0.5	0.5
Correction for influence quantities	0.8	0.8	0.8	0.8
$(\mu_{en}/\rho)_{water,air}$	1.5	1.5	1.5	1.5
Back-scatter factor (B_w)	*1.5*	*1.5*	*1.5*	*1.5*
Stem perturbation effect (in-air)	*1.5*	*1.5*	*1.5*	*1.5*
Perturbation correction (*e.g.* $P_{Q,chamber}$ in AAPM TG-61)	1.5	1.5	1.5	1.5
Waterproofing sleeve correction (or lack of)	0.5	0.5	0.5	0.5
Renormalization using PDD data (transition from the reference point at 2 cm depth to the phantom surface)			1.0	1.0
Overall uncertainty (k=1): in phantom method	**3.3**	**3.3**	**3.4**	**3.4**
Overall uncertainty (k=1): ***in-air method***	***3.6***	***3.6***	***3.6***	***3.6***

Table 8. Monte Carlo calculated back-scatter factors (B_w) as a function of the thickness of the tally volume.

Volume thickness (mm)	**120 kV Beam**	**200 kV Beam**
0.01	1.340	1.325
0.05	1.340	1.326
0.10	1.341	1.326
0.50	1.357	1.335
1.00	1.372	1.353
AAPM TG-61	*1.332*	*1.364*

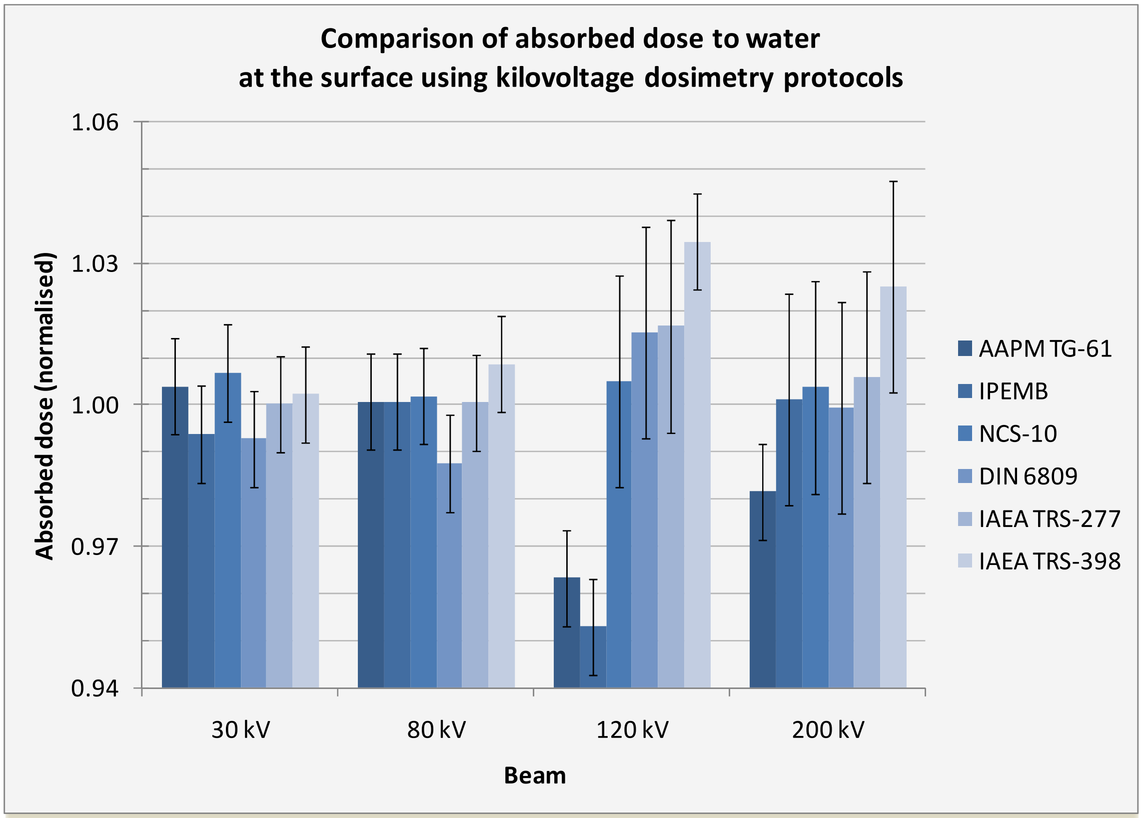

Figure 1. Comparison of absorbed doses to water at the surface of a full-scatter phantom obtained using kilovoltage dosimetry protocols: graphic presentation of the data in Table 4. Data using the recommended method are shown with reduced uncertainty estimates (k=2).

Kilovoltage x-ray dosimetry – an experimental comparison between different dosimetry protocols

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SHORT TITLE:

Kilovoltage x-ray dosimetry protocols compared

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Abstract

Kilovoltage dosimetry protocols by the IAEA (TRS 277 and 398), DIN (6809), IPEMB (with addendum), AAPM (TG-61) and NCS (report 10) were compared experimentally in four clinical beams. The beams had acceleration potentials of 30, 80, 120 and 200 kV, with half-value layers ranging from 0.6 mm Al to 1 mm Cu. Dosimetric measurements were performed and data were collected under reference conditions as stipulated within each separate protocol under investigation. The Monte Carlo method was used to derive back-scatter factors for the actual x-ray machine.

In general, the agreement of the dosimetric data at the surface of a full-scatter water phantom obtained using the guidelines of the various protocols was fairly good, i.e. within 1-2%. However, the in-air calibration method using the IPEMB and AAPM TG-61 protocols yielded an absorbed dose about 7% lower than the IAEA TRS-398 protocol in the 120 kV beam. By replacing the back-scatter factors given in the protocols with Monte Carlo calculated back-scatter factors the convergence between the protocols improved (within 4%). The internal consistency obtained for protocols supporting more than one geometry for dosimetry under reference conditions was better than 0.2% for the DIN protocol (120 kV beam), 2-3% for the AAPM TG-61 (120 and 200 kV beams) and about 2% for the IPEMB protocol (200 kV beam).

The present study shows that the current supported dosimetry protocols in the kilovoltage range were in fairly good agreement, and there were only a few exceptions of clinical significance.

Key words: absorbed dose, dosimetry protocol, kilovoltage x-ray, ionization chamber, diamond detector, Monte Carlo

1. Introduction

In recent years, several protocols for kilovoltage x-ray dosimetry have been published, and these have been promoted by various organisations: the AAPM, IPEMB, DIN, NCS and the IAEA. The protocols differ with respect to the choice of geometry for dosimetry under reference conditions; the fundamental quantity in which the reference instrument is calibrated is either absorbed dose to water or air kerma. In addition, the data provided in the protocols differ in range and in numerical values. As an additional complication for the medical physicist, some protocols offer multiple choices with respect to the geometry for dosimetry under reference conditions.

A theoretical inter-comparison of dosimetry protocols applicable in the kilovoltage x-ray range was presented previously by Peixoto and Andreo (2000), and they found that the dosimetric data of the dosimetry protocols studied were within about 1-2%. In that study, however, it was necessary to extrapolate dosimetric data to allow a comparison across the whole range of beam qualities. Therefore, the authors had to depart from strict adherence to the protocols in some instances. In many cases, the kilovoltage dosimetry protocols recommend different geometries for reference conditions for a certain range of beam qualities, i.e. (1) the ionization chamber placed free in-air, (2) the ionization chamber placed at the surface of a full-scatter phantom, or (3) the ionization chamber placed at a specific depth in a water phantom. Consequently, a dosimetric comparison can only be performed experimentally if one adheres strictly to the recommendations of individual protocols. Measurements in reference conditions where the detector is positioned (1) free in-air or (2) at the surface of a full-scatter phantom yield results that are directly comparable through the use of relevant dosimetric data, i.e. the absorbed dose to water at the surface of a full-scatter water phantom. Reference conditions in which the detector is placed at a depth in water yields the absorbed dose to water at that position. Therefore, relative dosimetric measurements are required in order to compare with conditions (1) and (2) which have been discussed in detail by Ma *et al*, 1998.

In the present study, dosimetric measurements according to the recommendations in the following protocols are presented and analyzed: DIN 6809 (1988), DIN 6809-5 (1996), NCS-10 (Grimbergen *et al,* 1997), IPEMB (Klevenhagen *et al*, 1996) with addendum (Aukett *et al*, 2005), IAEA TRS-398 (Andreo *et al,* 2000) and AAPM TG-61 (Ma *et al*, 2001). Superseded dosimetry protocols were not included in the analysis, except for the IAEA TRS-277 protocol (Andreo *et al,* 1987, updated 1997), which was included due to its historical importance and continued use.

2. Materials and methods

2.1 Equipment

2.1.1 The ortovoltage unit

A kilovoltage (ortovoltage) x-ray machine (Gulmay Medical model D3225, Gulmay Medical Limited, UK) was used in the present work. A thorough presentation of a Gulmay Medical D3300 unit was made previously by Evans *et al* (2001). That machine (D3300) has a higher maximum acceleration potential (300 kV) than the one used in the present study (D3225) but is otherwise of similar design. The D3225 unit has an acceleration potential ranging from 20 to 225 kV with an inherent filtration of 0.8 mm beryllium. The inherent filtration is fairly thin to accommodate the use of the soft beam qualities. The wolfram target is angled 20º relative to the beam axis. The D3225 machine is supplied with a series of open applicators constructed of steel and copper with an end-frame of clear PMMA defining the treatment aperture. The distances from the focal spot to the centre of the surface defined by the end of the applicators were within the manufacturer's specification, i.e. within 0.5 mm in all cases. The machine is equipped with a single transmission chamber controlling the beam output. The kV/filter combinations and the Focus Surface Distance (FSD) of the applicators used in the present study are presented in Table 1. They were chosen in order to match those of a decommissioned ortovoltage x-ray unit previously used for patient treatments at our department.

2.1.2 Detectors and electrometers.

Two cylindrical chambers, an NE type 2571 and a Scanditronix/Wellhöfer type FC65-G, and two PTW parallel plate chambers of type 23344, were used for the dosimetric measurements. Two electrometers, a Scanditronix/Wellhöfer Dose-1 and a PTW Unidos 10002 electrometer, were used. The ionization chambers had calibration certificates traceable to the primary standards dosimetry laboratory PTB, Braunschweig, Germany, and the electrometers were calibrated at the primary standards laboratory SP Sveriges Tekniska Forskningsinstitut (Borås, Sweden). Ionization chambers and electrometers were checked routinely in a ^{60}Co beam in a fixed geometry and using an instrument delivering a known charge (cf. Blad *et al,* 1998), respectively.

A PTW diamond detector type 60003 and a cylindrical Scanditronix/Wellhöfer FC65-G ionization chamber were used for the collection of relative depth dose data, as recommended by the AAPM TG-61 (Ma *et al,* 2001) and by the IAEA TRS-398 protocols (Andreo *et al,* 2000), respectively. The measurement with the diamond detector included a small correction for the dose-rate effect, with a Δ-value of 0.991 for the specific diamond detector used, and that value was taken from Björk *et al* (2000). The depth-dependent quality corrections for a diamond detector determined by Seuntjens *et al* (1999) were not applied due to the mismatch of acceleration potential and filtration of the beams under investigation. An NACP type 02 and a PTW Roos ionization chamber were also used for measurement of relative depth doses for comparative purposes.

2.2 Absolute dosimetry

2.2.1 HVL measurements.

The first and second Half-Value Layer (HVL) of the 30, 80, 120 and 200 kV beams were determined using a set of copper/aluminium foils. The attenuator was positioned at 20 cm or 50 cm from the focus, and the ionization chamber was positioned 20 cm and 50 cm from the attenuator for the two softer and harder beam qualities, respectively. The HVLs of the two softer qualities were also measured with 50 cm focus-attenuator and 50 cm attenuator-chamber distances. A parallel-plate PTW chamber type 23344 and a cylindrical NE chamber type 2571 were used with the Scanditronix/Wellhöfer Dose-1 electrometer for the measurement of HVLs for the two softer and the two harder beam qualities, respectively.

2.2.2 Dosimetry under reference conditions.

Reference conditions, i.e. geometries and detector types, for the beam qualities studied were chosen according to the protocol under investigation. Determination of absorbed dose to water was performed at least three times for each dosimetry protocol, and at each occasion a routine measurement of beam output was performed using the ion-chamber based dosimetry system for the weekly quality assurance programme.

Reference geometries and detectors used for the different beam qualities and dosimetry protocols are summarised in Table 2. The two plane-parallel PTW type 23344 ionization chambers were used for absorbed dose measurements in the three softer beam qualities. The plane-parallel chambers were positioned so that the surface of the entrance window coincided with the surface of a full-scatter phantom (30 x 30 x 30 cm^3), or free in air with the surface of the entrance window coinciding with the end of the applicator (depending on the recommendations given in each protocol). The chamber volume was placed centrally in the 3 cm diameter field for the 30 and 80 kV beams (Focus Surface Distance (FSD) 20 cm) and in the 10x10 cm^2 field for the 120 kV beam (FSD 50 cm), respectively.

An N_K-calibrated cylindrical NE type 2571 ionization chamber was used for dosimetric measurements in the two hardest beam qualities (i.e. the 120 and 200 kV beams), both free in air and with the centre of the chamber at 2 cm depth in a water phantom centred on the beam axis in a 10x10 cm^2 field. An $N_{D,w}$-calibrated cylindrical Scanditronix/Wellhöfer type FC65-G chamber was used in the hardest beam quality (200 kV beam) at 2 cm depth. The centre of the chamber volume coincided with the beam axis of the 10x10 cm^2 field. A PMMA sleeve with a 0.6 mm thick wall was used for the measurement in the water phantom.

Strict adherence to the dosimetry protocols studied was upheld except for:

(1) The “Low Range” recommendation in IAEA TRS-398 was used to calibrate the 120 kV beam quality, even though it is strictly within the “Medium Range” (above about 100 kV and a first HVL of 2-3 mm Al). The reason for this was that the cylindrical chamber was calibrated at 100 kV potential with an HVL of 4.52 mm Al, which was the lowest quality available at the standards laboratory for

cylindrical chambers. Alternatively, the calibration factor would have needed to be extrapolated, which seemed to be a somewhat inferior option compared to the chosen method.

(2) The Scanditronix/Wellhöfer FC-65G cylindrical ionization chamber was calibrated in terms of absorbed dose to water at 5 cm depth in water at the standards laboratory, while it was used at 2 cm depth in the present study. It is assumed that the calibration factor is identical at these two depths for the relevant beam qualities.

(3) In the IAEA TRS 277 protocol the reference depth in water is 5 cm, while in the present study measurements were made at 2 cm depth instead.

2.3 Relative dosimetry

Relative absorbed depth doses were collected at 0-20 cm using the diamond detector, the Roos, the NACP, and the cylindrical FC65-G ionization chambers in a water phantom (Scanditronix/Wellhöfer RFA-300) for the 120 and 200 kV beam qualities. Photon diodes were not used in the present study due to their strong spectral dependence (Li *et al,* 1997). Scans were taken three times for each beam, and the average was calculated. A measurement using the diamond detector and Roos chamber was performed after applying a bias voltage of 100 V and after a pre-irradiation at a single position until a stable signal was obtained. The NACP and the FC65-G chambers were operated at a bias voltage of 300V.

The results obtained were compared with tabulated reference data from BJR Suppl 25 (1996), interpolated to the actual HVL and FSD. Only data for the two harder beam qualities were of interest because only those were possible to calibrate at a depth in water according to the recommendations given by all protocols except for the IAEA TRS-398 protocol as described above.

2.4 Monte Carlo calculations of back-scatter factors

A Monte Carlo model of the x-ray machine has previously been benchmarked against experimental data (Knöös *et al,* 2007). The Monte Carlo model was constructed using the EGSnrc code packages BEAMnrc and FLURZnrc (Rogers *et al,* 1995).

Specifically, back-scatter factors (B_w) were calculated for the 120 and 200 kV beams using the formula given by Grosswendt (1984, 1990). We calculated primary and scattered photon fluences averaged in a volume of 0.01, 0.05, 0.1, 0.5 and 1 mm thickness and with a radius of 1 cm positioned centrally in the two beams. In the work by Grosswendt (1984, 1990), the photon fluence was derived from the number of photons penetrating the surface of a water phantom.

The 30 and 80 kV beams were considered to be of less interest to simulate using the Monte Carlo model than the 120 and 200 kV beams. This was due to the low back-scatter factor (as given by the AAMP TG-61 protocol), the difficulty to experimentally verify the percentage depth doses in a phantom with such soft beam qualities, and their limited clinical use. Therefore, the back-scatter factor of the 30 and 80 kV beams were not studied using the Monte Carlo method in this work.

3. Results and discussion

3.1 Absolute dosimetry

The first and second Half-Value Layer, HVL-1 and HVL-2, respectively, of the 30, 80, 120 and 200 kV beam qualities (i.e. filters 1, 3, 4 and 6) are presented in Table 3. The measurement of the two lowest beam qualities at 50 cm focus-attenuator and 50 cm attenuator-chamber distances yielded a 2.5% larger HVL than those presented in Table 3, which could be expected due to beam hardening (in air). Subsequently, the HVL measured at the smaller distance was used, considering that this is the distance used both clinically and for the other dosimetric measurements. It should be noted that this small difference in HVL has little impact on the subsequent determination of the absorbed dose

(~0.1% or less). Note also that the 120 kV has a comparatively low HVL for its acceleration potential due to the rather small amount of filtration materials used; this beam was matched to one available at the older decommissioned unit.

The measurement series were performed during a period of three weeks, during which time the machine output was constant within 0.6% or less for all beam qualities. The measurement geometry and the detectors used are presented in Table 2, and the results obtained are presented in Table 4. It should be noted that the normalization used in Table 4 was made against the average of each column. The IAEA TRS-398 protocol is based on absorbed dose to water standards; the results obtained using this protocol are interchangeable with the DIN protocol based on absorbed dose to water standards (for all beam qualities). Note also that the IAEA TRS-277 protocol accommodates the use of $N_{D,w}$ calibrations for soft beam qualities, which encompass the 30 and 80 kV beams in the present study. Percentage depth dose data (see Table 5) using a cylindrical ionization chamber were used to derive the absorbed dose at the surface of a full-scatter water phantom from the measurements at 2 cm depth.

In general, fairly similar results were obtained using the various dosimetry protocols as seen in Table 4. One notable exception was the in-air method of the AAPM TG-61 and IPEMB protocols, for which we found quite substantial deviations as compared to the IAEA TRS-398 protocol for the two harder beam qualities. The dosimetric deviations could be clinically relevant (Mijnheer *et al,* 1987). In the case of the IPEMB protocol, for the 120 kV beam, there are no back-scatter factors provided for FSD=50 cm, and therefore data for FSD=30 cm were used here. However, by taking the back-scatter factor from the AAPM TG-61 protocol, almost identical results were obtained using the IPEMB and the AAPM protocols (in-air method). Interestingly, the magnitude of the deviation correlated well with the magnitude of the back-scatter factor (B_w) as a function of HVL given by the AAPM TG-61 protocol. Basically, the protocols could be divided into two groups: one group that involves the use of a previously calculated back-scatter factor and in-air measurements, and the other that constitutes the majority of protocols, in which the back-scatter factor is measured by the user in a phantom.

The two methods suggested in the AAPM TG-61 protocol for the two harder beam qualities yielded somewhat inconsistent results. The deviations between these methods were greater than previously reported by Ma and Seuntjens (1998). However, by using the data in the AAPM TG-61 protocol and the measurement data in the same reference, deviations of only 3% were obtained, which are similar to those found in this study. Accordingly, when using the dosimetric data applicable for the actual unit studied by Ma and Seuntjens, the convergence between the in-air and in-phantom methods was improved as compared to using generic data from the AAPM TG-61 protocol.

The two IAEA protocols (TRS-277 and TRS-398) showed quite good agreement – within 1.6% – for all beam qualities. However, the dosimetric measurements were performed at 2 cm depth in a water phantom, while the recommended phantom depth is 5 cm in the TRS-277 protocol. Data applicable at 2 cm depth are provided in the TRS-277 protocol, and therefore, it is possible to use that depth in this situation also. Due to the uncertainty in the measured depth doses, the data in Table 4 for the IAEA TRS-277 protocol might be slightly different if the recommended reference point at 5 cm depth in water were used instead of 2 cm.

In Tables 6 and 7, a summary of the estimated dosimetric uncertainty involved in the determination of the absorbed dose of the present kilovoltage x-ray unit is presented; estimated values were taken from calibration certificates, experimental data, the IAEA TRS-398, and the protocols. The overall estimated uncertainties in the absorbed dose to water at the surface were about of 3-4% at the 1 SD-level. However, in the comparison of the dosimetric results obtained using the protocols, it was of interest to see if the observed deviations could be related to the experimental procedure or due to inherent differences in the protocols (*e.g.* back-scatter factors, chamber correction factors, etc). In Figure 1, the data from Table 4 for the recommended method are presented graphically (i.e. the in-air method of AAPM TG-61 is presented as absorbed dose at the surface is of interest). In Figure 1, each data point was assigned an uncertainty of 0.5% (1 SD) for the reproducibility of the measurements performed and a 1.0% (1 SD) uncertainty related to the normalization using PDD to yield the absorbed dose at the surface (in relevant cases cf. Tables 2 and 4) added in quadrature. Uncertainties in Figure 1 are plotted at the level of two standard deviations. Therefore, in cases where the uncertainty bars of two protocols do not overlap it can be considered to be likely that the differences between them are not related to the experimental procedure. As can be seen, in the 120 kV beam, the AAPM TG-61 and IPEMB protocols yielded results that deviated from the four others. In addition, in the 200 kV beam, the AAMP TG-61 and IAEA TRS-398 (and $N_{D,w}$-based DIN) yielded results that were outside the estimated uncertainty budget related to the experimental procedure of the present work.

In the case of the 120 kV beam, it should be noted that the plane-parallel chamber was calibrated in a beam of 3 cm diameter, while in this study it was used for measurements in a 10x10 cm^2 beam. Variations of the N_K factor for a PTW type 23344 chamber of about 2% for field sizes between 3 and 10 cm diameter have been observed (Grimbergen *et al*, 1997), presumably due to changes in in-scatter of photons by the large chamber housing. The field size variation of the $N_{D,w}$ factor is probably significantly less than 2%, although no information about this is available in the literature to the authors' knowledge. Some indication is given by the variation of the k_{ch} factor by about 1% within the same range of field sizes presented by Perrin *et al* (2001) (cf. the IPEMB protocol regarding the definition of the k_{ch} factor; Klevenhagen *et al,* 1996). However, in the study by Perrin *et al* (2001), the field size variation of the k_{ch} factor was determined in a much softer beam quality (a HVL of 0.56 mm Al) than the beam used in the present study. An additional uncertainty of 1% was included in Table 6 which accounts for the assumed constancy of the $N_{D,w}$-factor with field sizes ranging between the calibration and user beams.

3.2 Relative dosimetry

Table 5 shows measured relative absorbed dose for the 10x10 cm^2 applicator at 2 cm depth in water, including comparisons with tabulated data (British Journal of Radiology, Supplement 25: "BJR"). No data are available in the BJR Supplement 25 for the 120 kV beam quality at an FSD of 50 cm. Therefore data for FSD 30 cm were used and corrected using an inverse-square correction. Despite this simplistic treatment of the BJR data, it was in fair agreement with the measured data. Interestingly, the percentage depth doses obtained at 2 cm depth were fairly similar using three ionization chambers of different design: within 0.5% for the 120 kV beam and within 2% for the 200 kV beam. Including also the diamond detector, the measured PDDs at 2 cm depth were within 2% for both beams. The uncertainty of 3% (1 SD), stated in the AAPM TG-61 protocol, seems to be slightly over-estimated for the beams studied. An uncertainty of 1% (1 SD) in measured PDDs was assumed in Tables 6 and 7.

Two separate tables are provided in the BJR publication corresponding to the 200 kV beam in this study, referring to the type of field-delimiter device utilized. Both, i.e. “diaphragm limited” and “closed cone”, are included in Table 5. The measured data for the 200 kV quality fell in between these two data sets provided in the BJR Supplement, which seems reasonable considering that the applicators used in the present study were open-ended.

3.3 Monte Carlo calculations of back-scatter factors

Calculated back-scatter factors for the 120 and 200 kV beams are presented in Table 8 (data from the AAPM TG-61 protocol are included for reference). The calculated back-scatter factors decreased with decreasing thickness of the volume over which the photon fluence was averaged. This was presumably due to a build-up of the fluence with increasing phantom depth due to photon scattering. For the smaller thicknesses of the volume the build-up factor was practically constant and should be expected to converge towards the value obtained if the fluence were calculated as in the studies by Grosswendt (1984, 1990, 1993). The Grosswendt data were later used in the IPEMB (Klevhagen *et al*, 1996) and AAPM TG-61 (Ma *et al*, 2001) protocols.

The sets of back-scatter factors derived in this work were all within 3% of the factors given in the AAPM TG-61 protocol for both the 120 and 200 kV beams. It was shown previously that the calculated PDDs using the Monte Carlo model deviated somewhat from the measurements in the first few millimetres down to about 1 cm (Knöös *et al*, 2007). Therefore, the back-scatter factors can be assumed to be affected by similar deviations. It is difficult to judge which of the back-scatter factors presented in Table 8 should be selected for clinical use. However, the calculation in which the fluence was averaged over the first 1 mm probably correlates best with measured data. Hence, if our Monte Carlo calculated back-scatter factors were to be used instead of those found in the AAPM TG-61 and IPEMB protocols, the general convergence between the protocols would be improved for the 120 kV beam (Table 4). For instance, the “in-air” values given in Table 4 for the 120 kV beam would be 0.992 for both the AAPM TG-61 and the IPEMB protocol using B_w equal to 1.372 (using an unchanged normalization). However, for the 200 kV beam, the general convergence would deteriorate to some extent using the B_w calculated in the present work.

4. Summary and conclusions

A kilovoltage x-ray unit was calibrated in terms of absorbed dose to water at the surface of a full-scatter phantom using the guidelines of several different dosimetry protocols which are presently in use (summarised in Table 2). Both N_K- and $N_{D,w}$-based protocols were used and compared (see Table 4 and Figure 1). Therefore, not only the methodology and dosimetric data provided in each specific protocol, but also the inherent differences in the air kerma and absorbed dose to water standards were compared.

The dosimetric differences found in the present study were generally rather small and inside the estimated experimental uncertainty pertaining to the reproducibility of measurements (see Figure 1), except for the in-air methods using the AAPM TG-61 and IPEMB protocols in the 120 kV beam. In that case, results were obtained that were outside the estimated uncertainty budget as compared to the NCS-10, the DIN and IAEA TRS 277 and 398 protocols. Similarly, the in-air method for the AAPM TG-61 protocol yielded results that were outside the estimated uncertainty budget as compared to results obtained using the IAEA TRS-398 and ($N_{D,w}$-based) DIN protocols for the 200 kV beam. Note that the magnitude of the deviation correlated with the magnitude of the back-scatter factor (B_w) as a function of HVL given by the AAPM TG-61 protocol. This fact suggests that the deviations found can be related to uncertainties in the back-scatter factor, whether it was intrinsically included in the measurement made or taken from the protocol. In the present study we derived back-scatter factors for the 120 and 200 kV beams using a Monte Carlo model for the actual the x-ray machine studied. When using the Monte Carlo calculated back-scatter factors the convergence between the protocols improved, which indicates that applying generic back-scatter factors tends to increased dosimetric uncertainties. It is possible that the problem of using the HVL as the sole beam quality specifier might be the cause for the observed deviations.

The measured central percentage depth dose data using plane-parallel and cylindrical ionization chambers were shown to be in reasonably good agreement with the data from the British Journal of Radiology Supplement 25 for the same beam qualities, as specified in first half-value layers of aluminium and copper (see Table 5). Measured PDDs for both the 120 and 200 kV beams were in fair agreement (within 2%) at 2 cm depth, using plane-parallel and cylindrical ionisation chambers as well as a diamond detector. Taken together, the present study leans in favour of calibrating medium-range kilovoltage x-ray beams at 2 cm depth and using measured PDDs rather than using the in-air method with generic back-scatter factors.

In the specification/ordering of kilovoltage x-ray units it is advantageous if the beam qualities of the machine are matched to those available for calibration of dosimeters at the standards laboratory. By doing so, the dosimetric uncertainties in the commissioning phase can be reduced. In addition, the medical physicist needs to consider the limitations of the dosimetry protocol of choice in order to avoid the need to deviate from the methods stipulated therein.

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