

**Air Kerma Calibration Factors and  $k_{ch}$  Values for PTW Soft X-ray, NACP and Roos  
Ionization Chambers at Very Low X-ray Energies  
(0.035 mm - 1.0 mm Al HVL)**

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**Abstract:**

Several national and international protocols have been established for the dosimetry of x-ray beams used in radiotherapy. For the very low energy x-rays (0.035 mm- 1.0 mm Al HVL) only two codes are available: the UK IPEMB Code of Practice and the German standard, DIN 6809 Part 4. The measurement of very low energy x-ray beams is normally performed with parallel plate ionization chambers calibrated at a standards laboratory and characterized by an air kerma calibration factor  $N_k$ . According to the IPEMB Code of Practice the absorbed dose in the user's beam should be determined by taking measurements with the parallel plate chamber positioned such that its entrance window is at the surface of a full-scatter water equivalent phantom. The absorbed dose to water can then be determined using an equation which includes a factor,  $k_{ch}$ , which accounts for the change in response of the ionization chamber between the calibration in air and measurement at the surface of the phantom.  $N_k$  and  $k_{ch}$  values for the PTW soft X-ray, NACP and Roos ionization chambers are reported. It was found that  $k_{ch}$  values varied from about 1.01 to 1.08 depending on the chamber, beam quality and phantom material. It is recommended that the IPEMB Code of Practice should be revised to incorporate these values.

## **1 INTRODUCTION**

Several national and international protocols have been established for the dosimetry of X-ray beams used in radiotherapy. For the very low energy X-rays (0.035 mm - 1.0 mm Al HVL) only two codes are available: the IPEMB Code of Practice [1] and the German standard, DIN 6809 Part 4 [2]. The measurement of very low energy X-ray beams is normally performed with parallel plate ionization chambers calibrated at a standards laboratory and characterized by an air kerma calibration factor  $N_k$ . According to the IPEMB Code of Practice the absorbed dose in the user's beam should be determined in the following way. Measurements should be taken with the parallel plate chamber positioned such that its entrance window is at the surface of a full-scatter water equivalent phantom. The absorbed dose to water can then be determined using an equation that

includes a chamber-specific correction factor  $k_{ch}$ . This factor accounts for the change in response of the ionization chamber between the calibration in air and measurement at the surface of the phantom. However, at the time the code was written no  $k_{ch}$  values were available for very low energy X-rays, so a value of unity was assumed.

In this paper we report the results of measurements performed at NPL to determine calibration factors  $N_k$  and chamber correction factors  $k_{ch}$  for various ionization chambers (small and large PTW soft X-ray, NACP and Roos). Measurements were performed using Perspex and solid water phantoms.

## 2 IPEMB CODE OF PRACTICE

### 2.1 Scope of the Code of Practice

The IPEMB Code of Practice [1] for the determination of absorbed dose for X-rays below 300 kV is primarily intended for measurements on X-ray beams for radiotherapy treatment. Three separate energy ranges are defined in the code with very specific procedures for each range. The energy range is divided as follows: medium energy (0.5 - 4 mm Cu, HVL), low energy (1.0 - 8 mm Al, HVL) and very low energy (0.035 - 1.0 mm Al, HVL).

### 2.2 Low-energy X-rays

The code specifies that for low energy X-rays the dose determination should be performed with the ionization chamber free in air. The absorbed dose in water is then given by the following equation:

$$D_{w,z=0} = MN_K B_w \left[ \left( \frac{\bar{\mu}_{en}}{\rho} \right)_{w/air} \right]_{air} \quad 1$$

where

- $D_{w,z=0}$  is the dose to water in grays at the water (or water equivalent) phantom surface when the surface of the phantom material is positioned at the same focal distance as the chamber center,
- $M$  is the instrument reading obtained with a chamber in air corrected to the standard pressure and temperature,
- $N_K$  is the chamber calibration factor in grays per scale reading to convert the instrument reading at the beam quality (HVL) concerned to air kerma free in air at the reference point of the chamber with the chamber assembly replaced by air,
- $[(\bar{\mu}_{en}/\rho)_{w,air}]_{air}$  is the mass energy absorption coefficient ratio, water to air, averaged over the photon spectrum in air,
- $B_w$  is the back-scatter factor, defined as the ratio of the water collision kerma at a point on the beam axis at the surface of a full scatter water phantom, to the water collision kerma at the same point in the primary (incident) beam with no phantom present for the field size and focal distance concerned.

The recommended secondary standard for these X-ray qualities is either an NE2561, NE2611 or NE2571 ionization chamber<sup>1</sup> connected to an electrometer of secondary standard quality. The chambers should be calibrated in terms of air kerma, at appropriate radiation qualities, at a standards laboratory.

The recommended field instrument is any thimble ionization chamber with a volume less than 1.0 cm<sup>3</sup> for which N<sub>K</sub> varies smoothly and by less than 5% over the energy range of interest, connected to any suitable electrometer. The chamber must be vented to the atmosphere and no materials with an atomic number greater than that of aluminum may be used in the vicinity of the chamber.

### 2.3 Very low-energy X-rays

The code requires that parallel plate ionization chambers be used in this energy range since thimble chambers have an unsatisfactory energy response. Since parallel plate chambers are normally mounted in small blocks of materials, there is a substantial amount of backscatter from the material itself, thus leading to undesirable variations in response with field size. Hence, the code recommends that the instrument is placed, and the output measurements made with the front surface of the chamber at the surface of a full-scatter phantom.

The absorbed dose to water can then be determined using the following equation:

$$D_{w,z=0} = MN_k k_{ch} \left[ \left( \frac{\bar{\mu}_{en}}{\rho} \right)_{w/air} \right]_{z=0,\phi} \quad 2$$

where

- $D_{w,z=0}$  is the dose to water in grays at the phantom surface at the position of front face of the chamber when the chamber is replaced by phantom material,
- $M$  is the instrument reading corrected to standard pressure and temperature obtained with a chamber embedded in the full-scatter phantom,
- $N_K$  is the parallel-plate chamber calibration factor in grays per scale reading to convert the instrument reading at the beam quality (HVL) concerned to air kerma free in air at the reference point of the chamber with the chamber assembly replaced by air,
- $[(\bar{\mu}_{en}/\rho)_{w/air}]_{z=0,\phi}$  is the mass energy absorption coefficient ratio, water to air, averaged over the photon spectrum at the surface of the water phantom for a field diameter  $\phi$
- $k_{ch}$  is the factor that accounts for the change in response of the ionization chamber between the calibration in air and measurement at the surface of a full scatter, water equivalent phantom.

At the time the code was written there was very little information available on the values of the correction factors represented by  $k_{ch}$  for parallel plate ionization chambers. Hence the historic practice of assuming a value of unity for  $k_{ch}$  was endorsed by the code. It was expected that  $k_{ch}$

<sup>1</sup> NE Technology Limited, Bath Road, Beenham, Reading, Berkshire RG7 5PR England

would include the effect of stem scatter, displacement correction, energy response of the chamber and back scatter from the chamber housing. It was postulated that these factors could significantly alter the value obtained for absorbed dose.

The code specifically discouraged the use of a Perspex phantom in place of a water phantom. Additionally, the code recommended that the secondary standard dosimeter should be either a PTW23342<sup>2</sup> (0.02cm<sup>3</sup>) or a PTW23344 (0.2 cm<sup>3</sup>) soft X-ray ionization chamber connected to an electrometer of secondary standard quality. The chambers should be calibrated in terms of air kerma at appropriate radiation qualities at a standards laboratory.

The recommended chambers for the field instruments are parallel plate chambers with volumes in the range 0.02 – 0.8 cm<sup>3</sup> and N<sub>K</sub> values which varies smoothly and by less than 5% over the energy range of interest. Further, the code recommends that the chambers be used with build up material so that the wall thickness is at least 8.5 mg cm<sup>-2</sup> (corresponding to the thickness of the epidermis). This amount of material is sufficient to remove any electron contamination and places the depth of measurement at the critical layer of the skin.

### 3 DETERMINATION OF k<sub>ch</sub>

For the range of energies over which a chamber has a flat energy response (i.e, N<sub>K</sub> varies smoothly and by less than 5%) one can set equation 1 equal to equation 2 and obtain an expression for k<sub>ch</sub>. Knight [3] has shown that the  $[(\bar{\mu}_{en}/\rho)_{w/air}]_{air}$  values are negligibly different from the  $[(\bar{\mu}_{en}/\rho)_{w/air}]_{Z=0,\phi}$  values. Hence setting these two quantities equal, the following equation for k<sub>ch</sub> is obtained:

$$k_{ch} = B_w \frac{M_{air} N_K}{M_{ph} N_K} \quad 3$$

where:

- M<sub>air</sub> is the free air instrument reading,
- N<sub>K</sub> is the calibration factor in terms of air kerma
- M<sub>ph</sub> is the instrument reading at the surface of the phantom.

The values for B<sub>w</sub> can be obtained from work reported by Grosswendt [4] and Knight [5]. The k<sub>ch</sub> values can be determined three ways: 1) relative to the Farmer chamber, where [M<sub>air</sub>. N<sub>K</sub>] represents the free air Farmer reading times its calibration factor, 2) relative to the free air ionization chamber, where [M<sub>air</sub>.N<sub>K</sub>] is the air kerma measured using the free air chamber, and, 3) relative to the instrument itself, where [M<sub>air</sub>.N<sub>K</sub>] represents the instrument reading (M<sub>air</sub>) times its calibration factor (N<sub>K</sub>). In all cases, M<sub>ph</sub>.N<sub>K</sub> represents the instrument (for which k<sub>ch</sub> is to be determined) reading (M<sub>ph</sub>) at the surface of the phantom times the calibration factor for the instrument. Equation 3 reduces to equation 4 in the third case, since N<sub>K</sub> cancels out (assuming that the spectrum is the same in air and at the surface of the phantom):

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<sup>2</sup> Physikalisch Technische Werkstätten, Lorracher Str. 7, 79115 Freiburg, Germany

$$k_{ch} = \frac{B_w M_{air}}{M_{ph}} \quad 4$$

The second and third methods (which are essentially equivalent) are more accurate than the first method since the energy dependence of the detector response (not the backscatter) is eliminated in the determination of  $k_{ch}$ . The value of  $k_{ch}$  determined using the first method is flawed because it includes the difference in energy response between the Farmer and the instrument.

For measurements performed at the surface of a solid water phantom (WT1) and at the surface of a Perspex (PMMA) phantom, the  $k_{ch}$  values will be referred to as  $k_{ch}(WT1)$  and  $k_{ch}(Perspex)$ , respectively. It should be noted that the values of  $B_w$  for Perspex and WT1 maybe different from that of water. However, at the present time only values of  $B_w$  [6,4] for water are widely available and will be adopted in this report.

#### 4 STANDARD DIN 6809 PART 4

The Deutsches Institut für Normung (DIN) standard [2] contains specifications for the determination of absorbed dose during the therapeutic application of X-rays with tube voltages from 10 to 100 kV in medicine and also applies in soft tissues diagnostics such as mammography (25 to 50 kV). The determination of absorbed dose is described in the standard for a) a pancake type chamber calibrated in a Perspex phantom to display the water absorbed dose  $D_w$ , b) a pancake type chamber calibrated in free air to display the standard ion dose (exposure), and, c) a pancake type chamber calibrated in free air to display the air kerma.

Since the ionization chambers used to measure very low energy X-rays cannot be immersed in water without a water tight covering, the code allows for the use of Perspex phantoms. The standard specifies that only the pancake type ionization chambers are to be used. The chamber window should be thick enough so that secondary electrons which are generated outside the sensitive volume cannot penetrate the measuring volume but at the same time provide minimal attenuation for the photons. A reference depth of  $z_0$  equal to 0.03 mm (in water) can be met by using a window made of a low atomic number material with thickness of 3mg/cm<sup>2</sup>. According to the standard, if a flat chamber calibrated in free air to display air kerma is used, the chamber should be positioned flush with the surface in a Perspex phantom in order to determine the absorbed dose to water at a reference depth of  $z_0$  equal to 0.03 mm. The following equation applies:

$$D_w = f \cdot k_{a \rightarrow w} N_K \cdot k \cdot M \quad 5$$

where

- $D_w$  is absorbed dose to water at reference depth  $z_0$ ,
- $f$  is the ratio of mean mass energy absorption coefficients for water and air, respectively, measured over the photon spectrum at the measurement point,  $(\mu_{en}/\rho)_w/(\mu_{en}/\rho)_{air}$ ,
- $k_{a \rightarrow w}$  is the correction factor for the transition from the measurement in free air to the measurement in the water phantom,

- $N_K$  is the calibration factor for air kerma at the reference beam quality,
- $M$  is the measuring device display (instrument reading),
- $k$  is the product of the correlation factors  $k_i$  for influence factors and equipment properties.

The parameter  $k_{a \rightarrow w}$  can be determined for a specific chamber if the back-scatter factor for water,  $B_w$ , is known [7] and is given by

$$k_{a \rightarrow w} = B_w M_{FL} / M_{PH} \quad 6$$

where

- $M_{FL}$  is the instrument reading in free air,
- $M_{PH}$  is the instrument reading when placed in a phantom with its surface flush with the phantom surface.

Here  $B_w$  is defined as the ratio of the dose in the phantom to the dose in free air. Values of  $k_{a \rightarrow w}$  are given in the code for the small and large PTW soft X-ray chambers (PTW23342, PTW23344) using back-scatter factors from Grosswendt [8] for a field size of 3 cm diameter and a focal spot to chamber distance of 100 cm. This approach to the determination of  $k_{a \rightarrow w}$  is equivalent to using equation 4 to determine  $k_{ch}$  in the IPEMB code.

## 5 COMPARISON BETWEEN THE IPEMB CODE AND THE DIN STANDARD

The following are noted from a comparison of the IPEMB Code of Practice and the DIN standard:

1. Both codes recommend the use of parallel plate ionization chambers.
2. DIN 6890 allows the use of Perspex phantoms whereas the IPEMB code does not endorse its use.
3. DIN 6890 recommends a window thickness of 3 mg/cm<sup>2</sup> for the ionization chamber while the IPEMB code recommends that the chamber be used with build up material of thickness 8.5 mg/cm<sup>2</sup> for the in-phantom measurement.
4. DIN 6890 allows for free-air calibration in terms of exposure or kerma, while the IPEMB code recommends calibration in terms of air kerma only.
5. Equation 4 (for  $k_{ch}$ ) is identical to equation 6 (for  $k_{a \rightarrow w}$ ).

In the determination of  $k_{a \rightarrow w}$ , the  $B_w$  values used from Grosswendt are based on kerma (K) and not collision kerma  $K_c$ . At low energies, the collision water kerma and the absorbed dose to water are effectively the same [9].

## 6 EXPERIMENTAL CONDITIONS

Table 1 shows the soft X-ray qualities available with the NPL 50 kV X-ray generator.

**Table 1** X-ray Qualities

Generating Potential (kV)	Added Filtration (mm Al)	HVL (mm Al)
8.77	none	0.024
10.32	0.025	0.036
11.85	0.050	0.050
13.47	0.11	0.070
16.35	0.20	0.100
20.87	0.30	0.150
25.35	0.45	0.250
33.90	0.47	0.350
40.48	0.56	0.50
45.53	0.74	0.70
49.73	1.01	1.0

The NPL primary standard free air chamber (FAC) for X-rays generated at energies up to 50 kV was used to determine air kerma. The FAC is a parallel-plate, guarded-field, free air ionization chamber and is described in detail elsewhere [10,11]. Air attenuation corrections were determined using the NPL low energy air attenuation chamber built with two collecting electrodes. When using this chamber the center of the first electrode is at the same focal distance as the reference plane of the primary standard, the second at the same distance as the primary standard collecting electrode. A comparison of the current from the two electrodes yields the air attenuation correction.

Table 2 lists the characteristics of the chambers used in this investigation. Even though the Roos, NACP, NE2561 and NE2571 chambers are not intended for use in this entire energy range, we investigated the feasibility of their use.

**Table 2** Chamber Characteristics

Chamber	Serial Numbers	Sensitive volume (cm <sup>3</sup> )	Chamber Geometry	Reference Point	Wall Thickness	Polarizing Potential (V)
PTW soft X-ray type 23342 (small)	1257	0.02	parallel plate	Centre of window	0.03 mm polyethylene	-200
PTW soft X-ray type 23344 (large)	565 792	0.2	parallel plate	Centre of window	0.03 mm polyethylene	-200
NE2561 (NPL secondary standard)	225	0.325	thimble	Axis of rotation, 5 mm from tip	0.5 mm graphite	-200
NE2571 (Farmer)	2304	0.69	cylindrical	Axis of rotation, 12 mm from tip	0.36 mm graphite	-250
PTW 34001 (Roos electron chamber) <sup>4</sup>	0133	0.35	parallel plate	Centre of window	1 mm graphite	-100
NACP electron chamber <sup>3</sup>	37-02	0.16	parallel plate	Centre of window	0.5 mm graphite + 0.1 mm Mylar	-100

## 7 EXPERIMENTAL PROCEDURE

The 50 kV X-ray calibration facility is equipped with a motorized carriage on which the primary standard and ionization chambers can be mounted. The carriage can be controlled remotely.

The X-ray beam was aligned so that it was parallel with the carriage rails and its major axis was coincident with the beam monitor and the FAC. The setting up telescope was aligned and made

<sup>3</sup> Scanditronix AB, Husbyborg, S-752 29 Uppsala, Sweden

<sup>4</sup> PTW type 34001, Physikalisch Technische Werkstätten, Lorracher Str. 7, 79115 Freiburg, Germany and  
Wellhöfer type PPC35, Wellhöfer Dosimetrie, Bahnhofstr. 5, D-90592 Schwarzenbruck, Germany



parallel with the carriage rails. Alignments for telescope and X-ray beam were conducted in accordance with NPL standard procedures. The alignments were checked by taking a radiograph using a high contrast, high definition X-ray film. The measured beam diameter on the film was 5.4 cm at a focal distance of 50 cm.

The reference plane (effective point of measurement) of the FAC was set at a focal distance (distance from the focal point of the X-ray tube stand) of 50 cm. The reference plane of the FAC is 0.71 mm downstream from the front face of the aperture. The ionization chambers were mounted on the carriage system above the FAC. The reference point of each chamber was set up to be at the same focal distance as the FAC reference plane. Polarizing potential was applied to all the chambers as shown in Table 2.

For the free-in-air calibrations, measurements were made with several ionization chambers for each set of primary standard measurements; only one chamber was calibrated in-phantom at a time. In the latter case the chamber was placed so that its front face was flush with the surface of the phantom. The temperature of the chambers was measured using thermistors. All chambers were given a pre-calibration irradiation of at least 0.1 Gy. This was done to eliminate any charge that may have been built up on the insulator while the chamber has not been in use. The Derived Factor Calibration Program was used to perform the calibrations at each beam quality. At the end of each quality a printout is obtained giving the calibration factors for each chamber. A set of measurements consists of the mean of three readings where the ionization charges from the standard and monitor chambers are measured, integrated over a pre-set time. For each chamber the leakage current was also measured. In order for the readings to be accepted the standard error of the ratio of chamber reading to monitor reading must be within 0.06% and the leakage current of the chamber and monitor must be less than 0.3% of the collected value. The temperatures of the monitor and the chamber are used to correct for any temperature difference between them. The calibration room was maintained at a temperature of approximately 20 °C and at a relative humidity of between 20% and 70%. The atmospheric pressure was also measured. The measurements were corrected to standard atmospheric conditions of 20 °C, 101.325 kPa and 50% relative humidity.

## **8 RESULTS AND DISCUSSION**

### **8.1 In-air Measurements**

Table 3 summarizes the results of the in-air measurements. Figures 1-4 show the calibration factors as a function of half value layer (HVL) in mm of aluminum for the various ionization chambers. It should be noted that the variation in response of chamber serial number 1257 (Figure 1) and chamber serial number 0792 (Figure 2) is outside the manufacturer's specification.

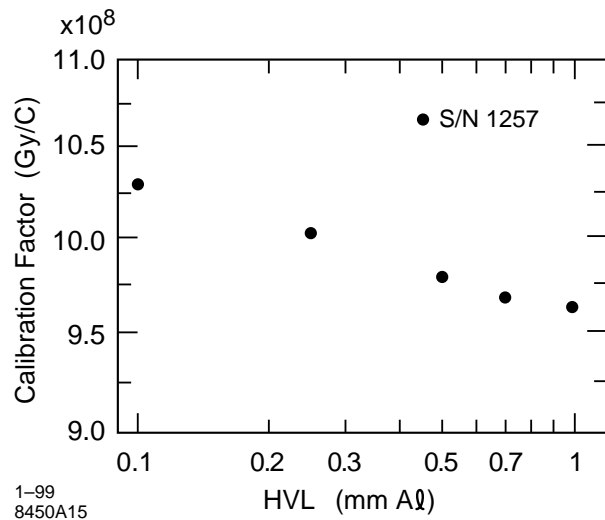


Figure 1. Calibration Factor as a Function of HVL for PTW 23342

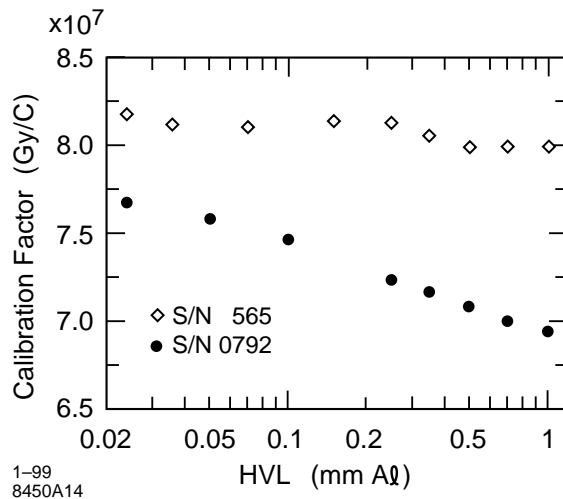


Figure 2. Calibration Factor as a Function of HVL for PTW 23344

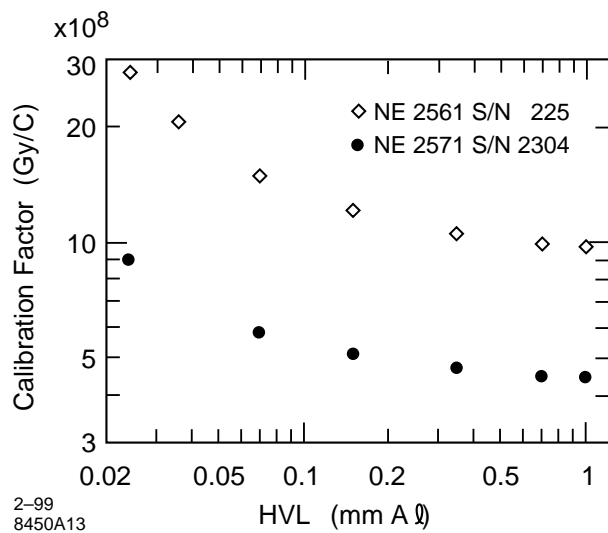


Figure 3. Calibration Factor as a Function of HVL for NE 2561 and NE 2571

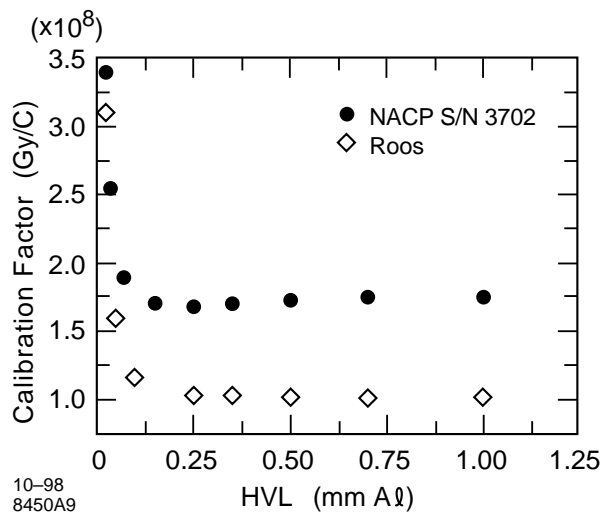


Figure 4. Calibration Factor as a Function of HVL for NACP and Roos (PTW 34001)

**Table 3** Summary of the in air measurements.

Chamber type	Chamber Serial Number	Recommended useable energy range*	Figure	Comments
PTW soft X-ray type 23342	1257	0.25 - 1.0 mm Al HVL	1	Calibration factor decreases smoothly but by more than 5% over the energy range
PTW soft X-ray type 23344 (large)	565	0.024 - 1.0 mm Al HVL	2	Calibration factor is within 2.5% over this range of energies.
PTW soft X-ray type 23344 (large)	792			Calibration factor changes smoothly, but by more than 5% over the energy range
NE 2571 (Farmer)	2304	0.7 - 1.0 mm Al HVL	3	Calibration factor decreases rapidly with increasing HVL up to 0.15 mm Al and then decreases smoothly thereafter
NE2561 (NPL secondary standard)	225	0.7 - 1.0 mm Al HVL	3	Calibration factor decreases rapidly with increasing HVL up to 0.15 mm Al and then decreases smoothly thereafter
NACP electron chamber	37-02	0.15 - 0.25 mm Al HVL	4	Calibration factor decreases rapidly with increasing HVL between 0.15 and 0.25 mm Al and then decreases smoothly thereafter
PTW 34001 (Roos electron chamber)	0133	0.15 - 0.25 mm Al HVL	4	Calibration factor decreases rapidly with increasing HVL between 0.15 and 0.25 mm Al and then decreases smoothly thereafter

\* A chamber is recommended for use in this energy range if its response in air varies smoothly by less than 5%

## 8.2 Determination of $k_{ch}$

Table 4 shows the back-scatter factors for water as a function of HVL, used in the determination of  $k_{ch}$  values. The values shown were interpolated (log-log) from Grosswendt's data for a field diameter (d) of 5.4 cm at a source to phantom surface distance (SSD) of 50 cm [4].

**Table 4** Back-scatter Factors for Water as a Function of HVL  
(d = 5.4 cm, SSD = 50 cm)

HVL (mm Al)	$B_w$
0.07	1.011
0.10	1.019
0.25	1.052
0.35	1.065
0.50	1.085
0.70	1.106
1.0	1.135

Table 5 shows the back-scatter factors for Perspex ( $B_{Perspex}$ ) and water ( $B_w$ ) as a function of HVL used in the determination of the  $k_{a \rightarrow w}$  values (hereafter referred to as  $k_{ch}(\text{Perspex})$  DIN Standard). For all beam qualities  $B_{Perspex}$  is higher than  $B_w$ .

**Table 5** Back-scatter Factors for Perspex and Water as a Function of HVL  
(d = 3 cm, SSD = 100 cm)

HVL (mm Al)	$B_{Perspex}$	$B_w$
0.07	1.005	1.000
0.11	1.020	1.010
0.36	1.065	1.045
0.71	1.105	1.080
0.94	1.120	1.100

Table 6 shows the calculated chamber correction factor,  $k_{ch}$ , values (using equation 3) based on FAC measurements for the various ionization chambers. It is important to note that in-phantom measurements with the PTW soft X-ray chambers were performed with the addition of 7.6 mg/cm<sup>2</sup> of Kapton (polyimide) film on the chamber window. The NACP and Roos chambers have sufficient build-up material and consequently the additional material was not necessary.

**Table 6** Chamber correction factors,  $k_{ch}$  as a Function of HVL for various Ionization Chambers

HVL (mm Al)	$k_{ch}$					
	Small PTW soft X-ray	Large PTW soft X-ray			NACP	Roos
	S/N 1257	S/N 0792		S/N 565	S/N 2304	
	Perspex	Perspex	WT1	Perspex	Perspex	Perspex
0.25	1.048	1.048	1.048	1.037	1.028	
0.35	1.040	1.046	1.051	1.045	1.030	1.011
0.50	1.049	1.051	1.063	1.048	1.037	1.010
0.70	1.049	1.056	1.074	1.059	1.046	1.017
1.0	1.056	1.068	1.090	1.066	1.080	1.027

### 8.3 Discussion of $k_{ch}$ Results

Figures 5-8 and 10 show the  $k_{ch}$  values for the various chambers as a function of HVL.

In all cases, there is good agreement between the data based on Farmer and FAC at 0.70 mm Al, however, there is a large difference between the  $k_{ch}(\text{Perspex})$  relative to Farmer and relative to the FAC at 1 mm Al HVL. This discrepancy is not fully understood. The Farmer should really only be used at energies near the cross-over between very-low and low-energy X-rays (1 mm Al HVL). Fig.5 shows the  $k_{ch}(\text{Perspex})$  values for the small PTW soft X-ray chamber. Also shown are the DIN Standard  $k_{ch}(\text{Perspex})$  data [2]. The  $k_{ch}(\text{Perspex})$  for the small PTW soft X-ray chamber is relatively constant compared to the DIN Standard data between 0.25 and 1.00 mm Al HVL.

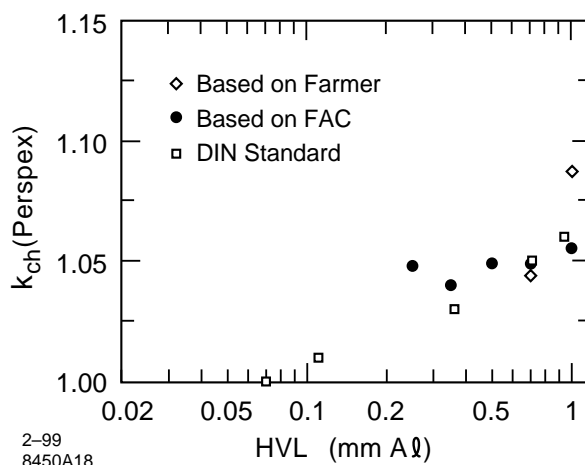


Figure 5.  $k_{ch}(\text{Perspex})$  as a Function of HVL for PTW 23342 S/N 1257

From Figures 6 and 7 it is observed that the  $k_{ch}(\text{Perspex})$  values for the two large soft X-ray chambers increase slowly with HVL and differ at the most by 1% while the PTW values increase more rapidly with increasing HVL. Since back-scatter factors for a given HVL and field diameter vary with the spectral shape (tube potential, filter thickness and material), SSD, and the anode angle, there will be differences between the  $k_{ch}$  and  $k_{a \rightarrow w}$  values for the soft X-ray chambers [12].

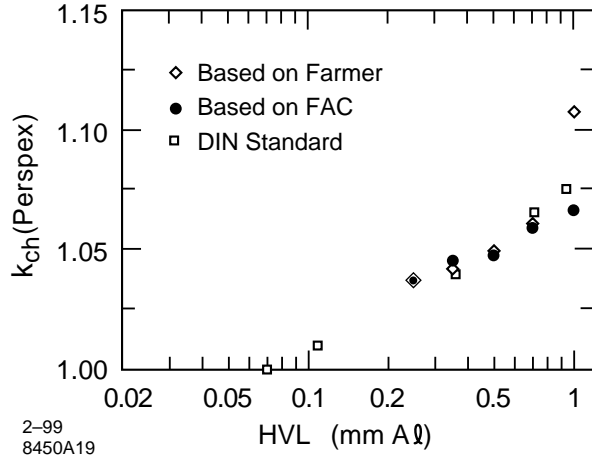


Figure 6.  $k_{ch}(\text{Perspex})$  as a Function of HVL for PTW 23344 S/N 565

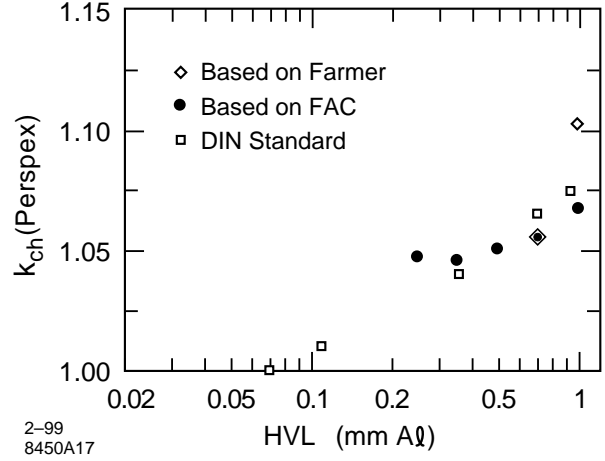


Figure 7.  $k_{ch}(\text{Perspex})$  as a Function of HVL for PTW 23344 S/N 0792

Figure 8 shows the  $k_{ch}(\text{WT1})$  for the large soft X-ray chamber (S/N 0792). Also shown is the DIN standard data. The NPL  $k_{ch}(\text{WT1})$  values are higher than the  $k_{ch}(\text{Perspex})$  values and the DIN standard data.

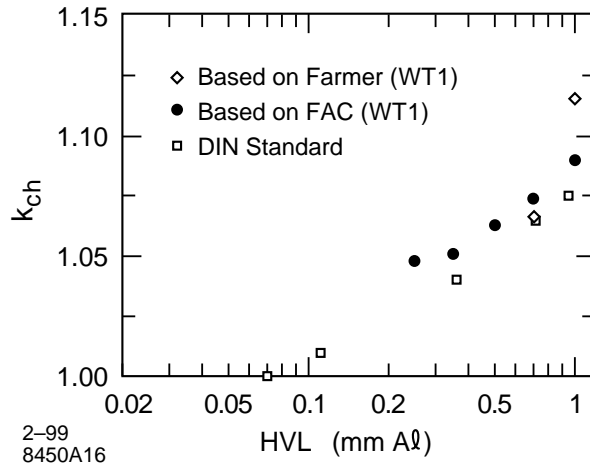


Figure 8.  $k_{ch}$  as a Function of HVL for PTW 23344 S/N 0792

Figure 9 shows the ratio of  $k_{ch}(\text{WT1})$  to  $k_{ch}(\text{Perspex})$  as a function of HVL for the large soft X-ray chamber (S/N 0792). The NPL  $k_{ch}(\text{WT1})$  values exceed the  $k_{ch}(\text{Perspex})$  values at HVLs greater than 0.25 mm Al and the difference between the two values increases with increasing HVL. To a first approximation this data can be used to obtain  $k_{ch}(\text{WT1})$  values from the  $k_{ch}(\text{Perspex})$  for the

small soft X-ray chamber, since both the large and small soft X-ray chambers are made of Perspex and scattering from the detector material is significant. In order to obtain true  $k_{ch}(WT1)$  and  $k_{ch}(Perspex)$  values, the back-scatter factors for WT1 and Perspex, should be used, respectively, instead of the back-scatter factors for water. Since the back-scatter factors are higher for Perspex than for water, the true  $k_{ch}(Perspex)$  values will be higher than those reported in this paper.

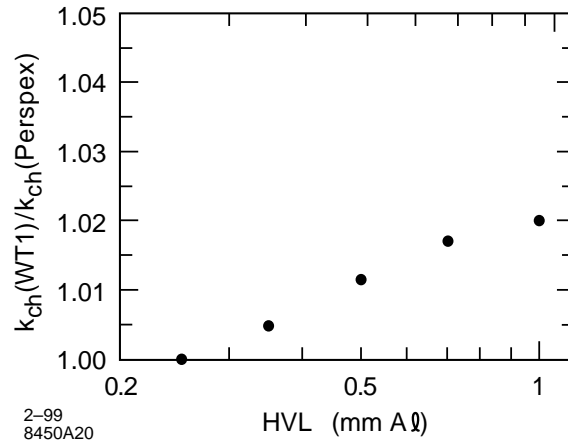


Figure 9.  $k_{ch}(WT1)/k_{ch}(Perspex)$  as a Function of HVL for PTW 23344 S/N 0792

Figures 10 and 11 show the  $k_{ch}(Perspex)$  values for the NACP and Roos chambers. The  $k_{ch}$  values for the Roos chamber are fairly small.

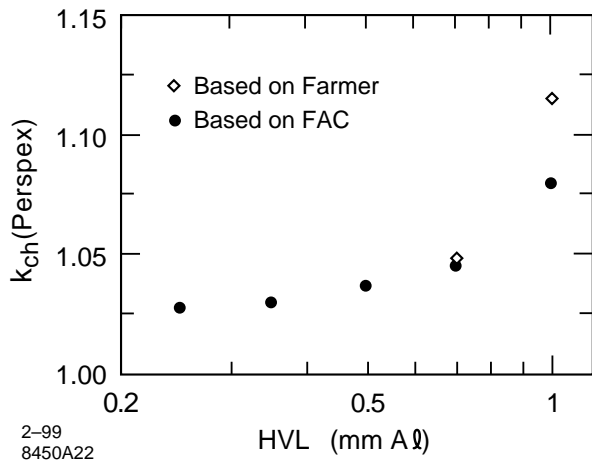


Figure 10.  $k_{ch}(Perspex)$  as a Function of HVL for NACP S/N 3702

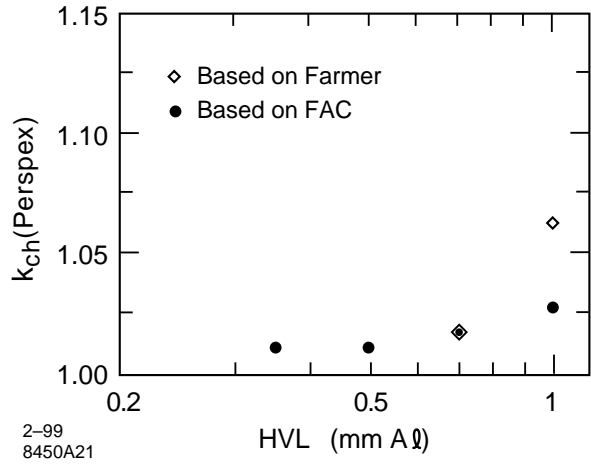


Figure 11.  $k_{ch}(Perspex)$  as a Function of HVL for Roos (PTW 34001) S/N 0133

The results of these measurements indicate that  $k_{ch}$  cannot be assumed to be equal to one, but that it depends on the X-ray spectra, the phantom and the ionization chamber used. The  $k_{ch}(WT1)$  values for the large soft X-ray can be used in the determination of absorbed dose to water at very low energies. However, the  $k_{ch}(Perspex)$  values for the small soft X-ray, NACP and Roos should

be used with the caveat that true  $k_{ch}$  values for these instruments will be higher and therefore the absorbed dose will be underestimated.

### **8.3     Uncertainties**

The sources of uncertainty in the  $k_{ch}$  values are listed in Table 7. The overall uncertainty in the determined values of  $k_{ch}$  is estimated to be  $\pm 3.0\%$  at the 95% confidence level, using a coverage factor of  $k$  equal to 2.

## **9        CONCLUSIONS**

Calibration factors for the small and large soft X-ray chambers (0.25-1.0 mm Al HVL) and the NACP and Roos ionization chambers were determined. Besides the soft X-ray chambers, the NACP (0.15-1.00 mm Al HVL) and Roos chambers (0.25-1.0 mm Al HVL) can be used for very low-energy X-ray dosimetry.

The chamber correction factors,  $k_{ch}$ , for various ionization chambers were determined using a Perspex phantom. To our knowledge apart from the data in the DIN standard these are the only published  $k_{ch}$  data. The  $k_{ch}$  factors were also determined for the large soft X-ray chamber using a solid water phantom. Future work should include a) experimental determination of back-scatter factors for Perspex and WT1 for the energy spectra that were used, b) measurement of  $k_{ch}(WT1)$  for the small soft X-ray, NACP and Roos chambers, and, c) determination of variation of  $k_{ch}$  with field size. The IPEMB Code should then be revised to include these  $k_{ch}$  values as currently the use of  $k_{ch}$  set equal to 1 in clinical dosimetry leads to an underestimate of absorbed dose to water.

Since back-scatter factors depend on the energy spectra, monoenergetic X-rays from synchrotron radiation facilities can also be used to determine back-scatter factors as a function of energy. The experimental results can then be compared with Monte Carlo calculations. These factors can then be averaged over the energy spectra of interest.



**Table 7** Uncertainty budget for  $k_{ch}$ 

Source	Value $\pm$ %	Probability distribution	Divisor	$c_i$	$u_i$	$v_i$
<b>Uncertainties in the in air-measurements</b>						
Reference chamber measurements	0.48	normal	2	1	0.242	$\infty$
Voltage	0.01	rectangular	$\sqrt{3}$	6	0.035	$\infty$
Temperature	0.15	rectangular	$\sqrt{3}$	1	0.087	$\infty$
Leakage current	0.05	rectangular	$\sqrt{3}$	1	0.029	$\infty$
Humidity	0.1	rectangular	$\sqrt{3}$	1	0.058	$\infty$
Distance	0.02	rectangular	$\sqrt{3}$	1	0.012	$\infty$
Angular	0.02	rectangular	$\sqrt{3}$	1	0.012	$\infty$
Monitor	0.01	rectangular	$\sqrt{3}$	1	0.006	$\infty$
Repeatability	0.1	normal	1	1	0.100	4
Combined uncertainty		normal			0.286	$\infty$
Expanded uncertainty		normal (k=2)			0.571	$\infty$
<b>Uncertainties in the in-phantom measurements</b>						
Reference chamber measurements	0.48	normal	2	1	0.242	$\infty$
Depth in phantom	0.0	rectangular	$\sqrt{3}$	1	0.000	$\infty$
Voltage	0.01	rectangular	$\sqrt{3}$	6	0.035	$\infty$
Temperature	0.15	rectangular	$\sqrt{3}$	1	0.087	$\infty$
Leakage current	0.05	rectangular	$\sqrt{3}$	1	0.029	$\infty$
Humidity	0.1	rectangular	$\sqrt{3}$	1	0.058	$\infty$
Distance	0.02	rectangular	$\sqrt{3}$	1	0.012	$\infty$
Beam size	0.5	rectangular	$\sqrt{3}$	1	0.289	$\infty$
Monitor	0.01	rectangular	$\sqrt{3}$	1	0.006	$\infty$
Repeatability	0.1	normal	1	1	0.100	4
Combined uncertainty		normal			0.406	$\infty$
Expanded uncertainty		normal (k=2)			0.812	$\infty$
<b>Uncertainties in the determination of <math>k_{ch}</math></b>						
In-air measurements	0.57	normal	2	1	0.286	$\infty$
In-phantom measurements	0.81	normal	2	1	0.406	$\infty$
Phantom water equivalence	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
$B_w$	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
Interpolation of $B_w$ for HVL	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
Interpolation of $B_w$ for field size	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
Difference in $N_k$ , in air/in phantom	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
Equivalence of $[(\mu_{en}/\rho)_{air,water}]_{air}$ and phantom surface	1.0	rectangular	$\sqrt{3}$	1	0.577	$\infty$
Combined uncertainty		normal			1.499	$\infty$
Expanded uncertainty		normal (k=2)			2.998	$\infty$

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## 11 REFERENCES

- 1 IPEMB Code of Practice for the determination of absorbed dose for X-rays below 300 kV generating potential (0.035mm Al – 4 mm Cu HVL; 10-300 kV generating potential), Phys. Med. Biol. 41 (1996), prepared by a working party of the Institute of Physics and Engineering in Medicine and Biology,  
  
The IPEMB is now known as The Institute of Physics and Engineering in Medicine (IPEM), Fairmont House, 230 Tadcaster Road, York, YO24 1ES, UK
- 2 DIN6809 Part 4: "CLINICAL DOSIMETRY – Application of X-radiation with tube voltages of 10 to 100 kV in radiotherapy and soft tissue diagnostics", Deutsches Institut für Normung, Berlin, Germany, 1988. In German
- 3 Knight R. T., "Absorbed dose conversion factors for therapeutic kilovoltage and megavoltage X-ray beams calculated by the Monte Carlo method", Royal Marsden NHS Trust Internal Report ICR-PHYS-1/96, 1996.
- 4 Grosswendt, B. "Dependence of the photon back scatter factor for water on source-to-phantom distance and irradiation field size", Phys. Med. Biol., 35 (9), 1990.
- 5 Knight, R. T., "Backscatter factors for low- and medium-energy X-rays calculated by Monte Carlo method", Royal Marsden NHS Trust Internal Report ICR-Phys-1/93, 1993.
- 6 Knight R. T., "Absorbed dose conversion factors for therapeutic kilovoltage and megavoltage X-ray beams calculated by the Monte Carlo method", Royal Marsden NHS Trust Internal Report ICR-PHYS-1/96, 1996.
- 7 Dierker, J., "Calibration correction with soft X-ray measurements using a phantom", in: Medizinische Physik 1981 (ed E Bunde), pp 111-116, Heidelberg 1982, In German
- 8 Grosswendt, B., "Backscatter factors for X-rays generated at voltages between 10 and 100 kV", Phys. Med. Biol, 29(5), 1984.

- 9 Klevenhagen, S. C., Aukett, J. E., Harrison, R. M., Knight, R. T., Nahum, A. E., and Rosser, K. E., "Report of the IPSM working party on low- and medium-energy X-ray dosimetry", *Phys. Med. Biol.* 36 (8), 1991.
- 10 Moretti, C. J., Heaton, J. A., Laitanao, R. F., and Toni, M. P, "Intercomparison of the low energy primary standards for X-ray exposure of NPL and ENEA, Italy", NPL Report RSA (EXT) 19, National Physical Laboratory, Teddington, UK, May 1991.
- 11 Marsh, A. R. S., and Williams, T. T., "50 kV Primary Standard of Exposure, 1978 Design of Free-Air chamber", NPL Report RS(EXT) 54, National Physical Laboratory, Teddington, UK, May 1991.
- 12 Carlsson, C.A., "Differences in reported backscatter factors for low-energy X-rays: a literature study", *Phys. Med. Biol.* 38, 1993.

## **APPENDIX 1.** Phantom construction.

The PTW Perspex phantom consisting of 10 plates of area 130 mm<sup>2</sup>, and thicknesses of 1 mm (1 plate), 2 mm (2 plates), 5 mm (2 plates) and 10 mm (5 plates) was used for all the parallel plate chambers. For each chamber, a special plate in which the chamber could recessed, was used. The solid water phantom (WT1)<sup>5</sup> was also made of plates of thickness 14.5 mm and was used only for the large soft X-ray chamber.

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<sup>5</sup> Supplied by St. Batholomews Hospital, London UK.