IN-PHANTOM MEASUREMENT OF ABSORBED DOSE TO WATER IN MEDIUM ENERGY X-RAY BEAMS

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Abstract

Absorbed dose values in a water phantom derived by the formalism of the IAEA Code of Practice of Absorbed Dose Determination in Photon and Electron Beams are a few per cent higher than those based on the procedure following e.g. ICRU Report 23. The maximum deviation exceeds 10 % at 100 kV tube potential.

The correction factor needed to take into account the differences at the calibration in terms of air kerma free in air and at the measurement in the water phantom can be determined in different ways: In comparing the result of the absorbed dose measurement by means of the ionization chamber with an other, preferably fundamental method of measurement of absorbed dose in the water phantom or by evaluating all component parts of the correction factor separately. The values of the perturbation correction factor in the IAEA Code were determined in the former way by comparing against a graphite extrapolation chamber.

A review is given on a recent re-evaluation using former values of the extrapolation chamber measurements and on new determinations using an absorbed dose water calorimeter, a method based on calculated and measured air kerma values and a method of combining the component factors to the overall correction factor. Recent results achieved by the different methods are compared and a change of the data of the IAEA Code is recommended.

1. INTRODUCTION

When making measurements of absorbed dose, a distinction must be drawn between measurements under working conditions for regular clinical purposes such as output measurements in X-ray beams and the realization of the unit gray by means of primary standards. The equipment used as primary standards is designed to operate under defined and usually restricted conditions and would normally be inconvenient or even unsuitable for the measurements in practical routine. The instrument best suited for the regular clinical routine is without any doubt the ionization chamber calibrated directly or indirectly against a national primary standard. It is preferable that the calibration be carried out under conditions which are as close as possible to those under which the instrument will be used in practical routine measurements. This should favour primary standards of absorbed dose to water in a phantom, but in the X-ray energy region these standards are not yet commonly available. Therefore, the measurement chain starts from a calibration in air in terms of air kerma or exposure and formalisms have been developed to convert the meter reading M of an ionization chamber dosimeter to the absorbed dose to water.

The International Code of Practice of Absorbed Dose Determination in Photon and Electron Beams published in 1987 (IAEA 1987) [1] recommends essentially the same experimental procedure as the ICRU in its Report 23 (ICRU 1973) [2] . For the medium-energy X-ray region the absorbed dose dose to water is derived from a measurement with an *ionization* chamber on the beam axis , 5 cm deep in a water phantom irradiated with a 10 cm x 10 cm field. ICRU 23 provided the formalism and data to derive absorbed dose to water, assuming the calibration is in terms of exposure in röntgens. The data provided in the IAEA Code may be applied to ionization dosimeter calibrated in terms of air kerma in grays or exposure in röntgens, but the data of the IAEA Code produce significantly different values of absorbed dose to water, the difference can reach more than 10%. The difference in the IAEA and the ICRU procedures has been discussed by Schneider et al. (1988) [3] and a detailed analysis of the individual factors used has been given by Rosser (1991) [4]. It is the purpose of this paper to reconsider the data of the IAEA Code and to review new results for these data including their uncertainties. The uncertainties data in this paper are given as one standard deviation [1]. In the light of the values now available an assessment is made for the factors to be used with the IAEA Code TRS 277.

2. THE FORMALISM AND DATA OF THE IAEA CODE

2.1 The formalism

The formalism and the data of the IAEA Code are presented here briefly to enable the comparison with a more refined consideration of the procedures which evolved after the publication of the IAEA Code.

The air kerma at a depth in water is measured under reference conditions and is then given as the product of the meter reading M_u and the air kerma calibration factor N_K of the ionization dosimeter for reference ambient conditions (20 °C, 1013 mbar, 50 % rel. humidity) and for the radiatiom quality of the incident beam in air. This quantity is then converted to absorbed dose in the undisturbed water phantom (without the ionization chamber) by means of a conversion factor and applying correction factors to account for any changes in the conditions between the calibration in air and the measurement in the phantom. This results in the equation

$$D_w = M_u \cdot N_k \cdot k_u \cdot p_u \cdot (\bar{\mu}_{en}/\rho)_{w,air}$$

where k_u is the correction factor taking into account the change of the ionization chamber response due to the change of the spectral distribution of the photon fluence in the phantom compared to that in air during the calibration. p_u is the perturbation correction factor which takes into account the effect of displacement of the water in the phantom by an air volume given by the outer shape of the ionization chamber. Figure 1 taken from the IAEA Code illustrates the situation of what was meant by p_u.

2.2 The ratio of mass energy absorption coefficients of water to air $(\bar{\mu}_{en}/\rho)_{w,air}$

The conversion factor $(\bar{\mu}_{en}/\rho)_{w,air}$ is the ratio of the mass energy absorption coefficients of water and air averaged over the spectral energy fluence distribution at the depth of the phantom in the absence of the ionization chamber. For the condition given in the IAEA Code calculations by Grosswendt [5], Seutjens [6], Rosser [7] and Ma [8] agree well within 0,5 %. No information of the variation of the $(\bar{\mu}_{en}/\rho)_{w,air}$ ratio with field size has been given in the IAEA Code. The relevant range of variation may exceed 1 %.

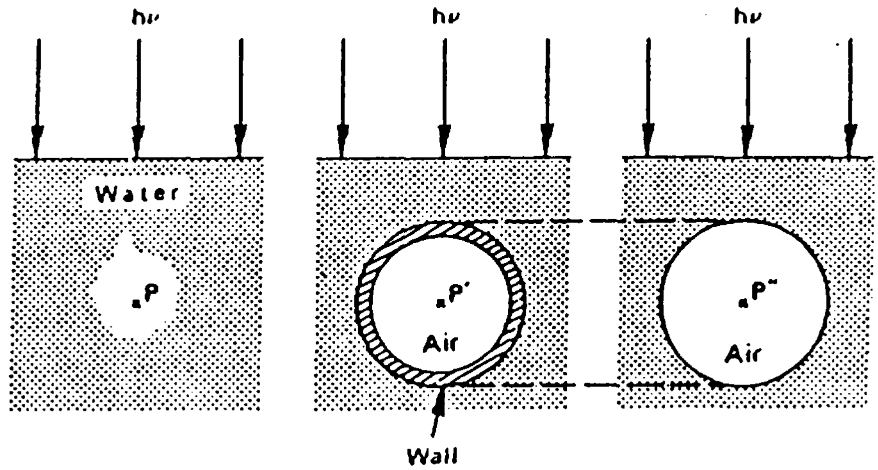


Fig.1. The absorbed dose at a point P in an undisturbed medium (water phantom) is to be determined. An exposure or air kerma calibrated chamber is placed with its centre P at that point. The chamber has been calibrated free in air. Included in the calibration factor are any disturbances due to the chamber material. In the phantom measurement, the calibrated chamber will therefore give the exposure or air kerma value in the centre P of an air cavity equal to the external size of the chamber. This figure caption is identical to that of Figure 12 in the IAEA Code. It should demonstrate the restricted definition of p_u which is the same as that of p_d in this publication.

2.3 The radiation quality correction factor k_u .

Under the assumption that the energy dependence of the response of the ionization chamber with regard to air kerma in air is less than 2% over the whole range of radiation qualities from 70 to 250 kV (2mm HVL in Al to 3 mm HVL in Cu) and the calibration factor N_K is taken for the relevant primary spectrum at the measurement in air the IAEA Code assumes for k_u a value close to unity for most practical situations. This implied that k_u was taken as one, an assumption which proved invalid (see section 7.1).

2.4 The perturbation correction factor p_u

The values of p_u were derived by comparing measurements in a phantom with a thimble chamber calibrated in terms of absorbed dose where the calibration was based on an extrapolation chamber method (Schneider 1980) [9] and the measurements with the same chamber calibrated in terms of air kerma in air. These p_u values vary with the radiation quality of the primary X-ray beam from 1.10 for 100 kV to 1.01 for 280 kV and are substantially different from the values for the procedures of the ICRU Report 23 where the effect of the water displacement was considered to be less than one percent and was neglected.

3. THE OVERALL CORRECTION FACTOR $k_{a,w}$

The correction factor needed to take into account all possible differences between the conditions at the calibration of the ionization chamber in terms of air kerma free in air and the measurement in the water phantom will be denoted by $k_{a,w}$. It can be determined in different ways: a) in comparing the result of the absorbed dose measurement by means of the ionization chamber with the results of an independent determination of the water absorbed dose in a water phantom (e.g. by a fundamental method of measurement as calorimetry) or b) by evaluating all component parts of the overall correction factor $k_{a,w}$ separately.

The values of the product $k_u \cdot p_u$ in the IAEA Code whose formalism followed mainly that described by Johns and Cunningham (1983) [10] correspond to the values of the overall correction factor $k_{a,w}$.

The values of the p_u factor in the IAEA Code were determined experimentally following the method explained under a) by comparsion against a graphite extrapolation chamber as the fundamental method of water absorbed dose determination. Using this method it has been implied that k_u is equal to one. This means that the p_u values in the Code may contain other influences and this has to be considered in comparing them with the results of more recent investigations.

4. RECONSIDERATION OF THE EXPERIMENT FOR DETERMINING THE p_u VALUES OF THE IAEA CODE

The values of p_u in the IAEA Code were derived from determinations of absorbed dose in a graphite phantom by means of an extrapolation chamber. This enables the measurement of absorbed dose to water in a water phantom by an ionization chamber calibrated in the graphite phantom applying the necessary correction factor $k_{c,w}$ for the transfer from the graphite to the water phantom. $k_{c,w}$ has a meaning which can be concluded from chapter 3. The comparison of measurement of absorbed dose in the water phantom under identical conditions by means of thimble ionization chambers calibrated to indicate air kerma and conversion to absorbed dose yielded the p_u values in the IAEA Code. Without repeating the very extensive measurements with the extrapolation chamber the individual steps of the whole procedure have been checked, giving rise to minor changes (Schneider 1992) [11]:

a) The extrapolation in chamber depth can now be extended to smaller mass layers of air in reducing the air density to 1/16 of atmospheric conditions in operating the extrapolation in an underpressure tank. No change in the extrapolated values can be seen within the stated uncertainty of 1 to 1.5 %.

b) The extrapolation of the diameter of the ionization volume to zero needed because of inhomogenity of the radiation field in the phantom was improved using new pistons of the extrapolation chamber. A decrease of about 1 % in the p_u values resulted independent on radiation quality.

c) For the determination of the p_u values in the IAEA Code one step is the transfer from a calibration in a graphite phantom to a calibration in a water phantom requiring a correction factor $k_{c,w}$. An energy independent value of unity for this correction factor $k_{c,w}$ was used up to now with an uncertainty assumed to be 1.5 %. Information on the energy dependence of $k_{c,w}$ was gained by Monte Carlo calculations. Incorporating this new information in the re-evaluation of the IAEA p_u values the data in the last column of table I result.

In table I the original input data for the IAEA Code are shown together with the recently corrected values (Schneider 1992) [11]. It must be noted that the values given apply only to the chambers used in the investigation.

A radiograph of the PTW M 23332 (with the highest p_u-values in table I) revealed in the meantime an inclined central electrode questioning the results obtained with this ionization chamber as characteristic for this chamber type. In addition this chamber has a comparably high energy dependence at low photon energies, so this chamber should be discounted.

Table I Re-consideration of the p_u value in the IAEA Code.

In column two to four the original data are shown from which the p_u values in the IEAE Code (column five) were derived. A radiograph of the PTW M23332 revealed later on an inclined central electrode questioning the results obtained with this ionization chamber. The NE 2561 ionization chamber was used in the graphite phantom within a protective PMMA sleeve, which may have an influence on the results predominantly at lower tube potentials.

U kV	PTWM23331 (1 cm^3)	PTWM23332 (0.3 cm^3)	NE 2561 (0.3 cm^3)	IAEA	PTWM23331 (1 cm^3)
100	1.09 ±0.045	1.115	1.11	1.10	1.07 ±0.04
120	1.08 ±0.045	1.105	1.09	1.09	1.06 ±0.04
140	1.07 ±0.035	1.095	1.07	1.08	1.05 ±0.03
150	1.05 ±0.03	1.08	1.05	1.06	1.035 ±0.025
200	1.03 ±0.03	1.055	1.03	1.04	1.02 ±0.025
250	1.015 ±0.03	1.04	1.02	1.02	1.01 ±0.025
280	1.005 ±0.03	1.02	1.01	1.01	1.00 ±0.025

The NE 2561 ionization chamber was used in the graphite phantom within a protective PMMA sleeve, which, after correction may still have a residual influence on the results predominantly at lower tube voltages.

The IAEA p_u values were taken from this table as an average value of the three investigated chambers. All values have the same uncertainty, since the values for the chambers in column 2 and 3 were achieved by a comparison of the chamber readings only. The stated uncertainty is due mainly to the extrapolation chamber method. Therefore the uncertainty could not be decreased by averaging the results of the ionization chambers, as it was done in the IAEA Code.

Further work using the extrapolation chamber technique is to be expected, also at other places. (Cszete 1992) [12].

5. DETERMINATION OF THE OVRERALL CORRECTION FACTOR $k_{a,w}$ USING WATER ABSORBED DOSE CALORIMETRY

The overall correction factor $k_{a,w}$ is given directly from comparing the absorbed dose to water measured using a water absorbed dose calorimeter with the results of measurements of air kerma using ionization chambers, converting the latter by means of the adequate (μ_{en}/ρ) ratios of water and air into absorbed dose to water. Seutjens et al. (1993) [13] describe the construction, operation and the correction factors of a water absorbed dose calorimeter used in a comparative study with a NE 2571 thimble ionization chamber at the reference depth of 5 cm for seven X-ray radiation qualities. Co 60 gamma radiation was included to enable the heat defect correction to be determined. Here the heat defect was found to amount to -1.5 %. This value was adopted for all radiation qualities used. The measurement were performed at the Physikalisch-Technische Bundesanstalt Braunschweig, Germany, using the water absorbed dose calorimeter constructed in Gent. The overall correction factor $k_{a,w}$ as a result of the calorimeter and ionization chamber measurements amounts to (1.007 ± 0.015) at 250 kV tube potential (HVL 2.5 mm Cu) up to (1.04 ± 0.02) at 100 kV (HVL 4.54 mm

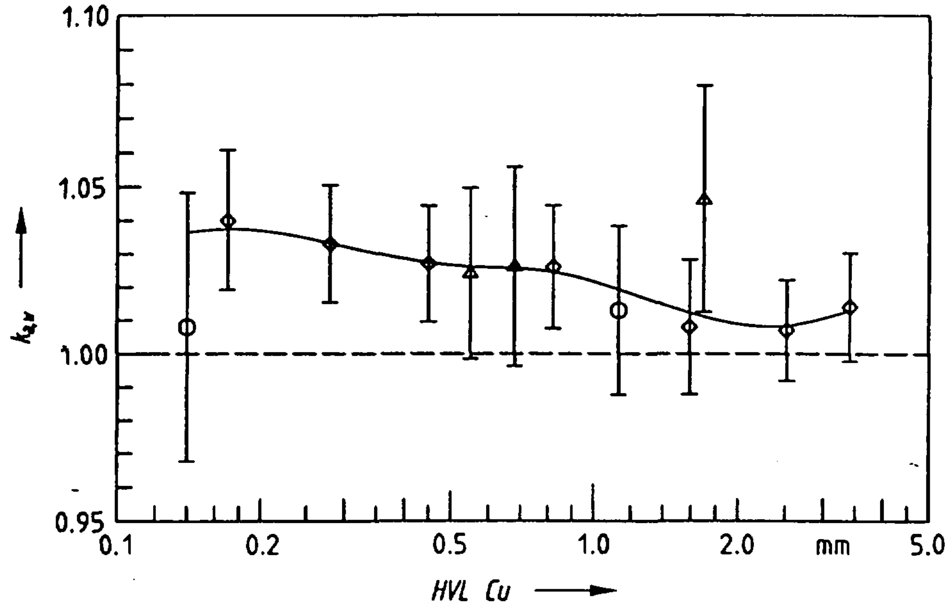


Fig. 2. Energy dependence of the correction factor $k_{a,w}$ derived from the comparison of water absorbed dose calorimetry and air kerma measurement with a Farmer-type ionization chamber. The squares indicate the results of Seuntjens et al., the circles those of Mattsson and the triangles the results from the work of Kubo. The solid curve represents a smoothed mean from all values averaged according to their uncertainties.

Al). It is shown in figure 2. The error bars correspond to the total uncertainty at the one standard deviation level.

The calorimetric work of Mattsson (1985) [14] and Kubo (1985) [15] has lended support to the p_u values of the IAEA Code. Both used Domen type water absorbed dose calorimeters (Domen 1982) [16] and compared with 0.6 cm^3 Farmer type ionization chambers. Mattson's measurements gave p_u values of 1.075 and 1.056 for 100 and 200 kV X-ray respectively, whereas Kubo's results were between 1.07 and 1.09. If their data are adjusted to correspond to the database of the IAEA Code and an exothermic heat defect correction of 3 % is applied to the calorimeter measurements this will give a lower bound to the $k_{a,w}$ values derived by both authors. The assumption of a 3 % heat defect for Co 60 gamma radiation is reasonable for the type of calorimeter and the water used in their investigations. The heat defect correction is dependent on the purity of the water and probably on the accumulated dose during the experiments. Furthermore, the heat defect is assumed to be almost constant for low LET radiation. An experimental proof for this assumption may now be possible. An example of such measurement has been given for the case when the defect is zero (Roos et al. 1992, Selbach et al. 1992) [17], [18]. As such informations were not available at that time the same 3 % correction is applied to the medium energy X-rays as it was evident for Co 60 gamma radiation.

In figure 2 the results of Mattsson and Kubo are also shown, despite the fact that the experimental conditions with respect to depth, field size and radiation quality are different. In general it can be concluded that the results are mutually consistent.

In contrast to that, Motakabbir et al. (1992) [19] found for 250 kV X-ray beams with HVL of 1.1 mm Cu and 2.1 mm Cu values of 1.05 and 1.07, respectively. This caused the authors to state that the values of the IAEA Code are too small by about 5 %.

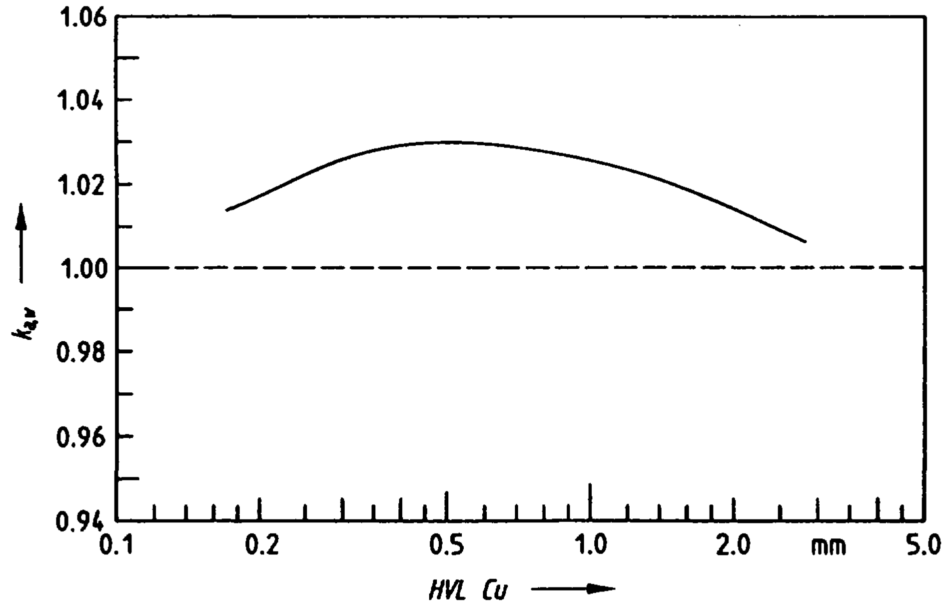


Fig.3. Correction factor $k_{a,w}$ for the PTW 23331 ionization chamber dependent on the radiation quality characterized by the HVL in Cu. The curve results from smoothed date taken from [3].

Similar values (up to 10 %) have been found by Seuntjens et al. (1988) [20], but owing to the uncertainties introduced by using separate phantoms, the accuracy of the values is rather poor (up to 5 %)

Further experimental work is to be expected (Rosser 1991, Schneider 1991) [20], [22] as water absorbed dose calorimeters are under development.

6. DETERMINATION OF THE OVERALL CORRECTION $k_{a,w}$ FROM MEASUREMENTS AND CALCULATIONS OF AIR KERMA

The overall correction factor $k_{a,w}$ for a given ionization chamber can be derived from measurements of the air kerma free in air and at the reference depth in the water phantom in the same radiation field comparing the ratio of the dosimeter readings with the calculated values of the ratio of air kerma free in air and in the phantom (Schneider et al. 1988) [3].

$$k_{a,w} = (K_{a,phantom}/K_{a,air})/(M_{phantom}/M_{air})$$

In figure 3 the overall correction factor $k_{a,w}$ for the ionization chamber PTW M23331 in the depht of 5 cm in the water phantom is shown as a smoothed curve derived from results by Schneider et al. 1988 [3]. More recently measurements have been carried out again with a PTW M23331 ionization chamber by Schneider and the corresponding air kerma values were calculated by Kramer [23]. In table II the results are given for eight radiation qualities and two depths in the phantom. The calculation is sensitive to the exact knowledge of the input spectra, as the low energy part will result in a contribution to the air kerma free in air whereas this will not be the case to the same extend in the 5 cm depth of the phantom due to the attenuation of the low-energy photons. The uncertainty of this method is difficult to assess and an estimate of at least 2.0 % appears reasonable, especially at low photon energies.

Table II The overall correction factor $k_{a,w}$ determined from measurement of the air kerma free in air and in the phantom and from Monte Carlo calculations of the same quantities [23].

Radiation quality	HVL in mm Cu	$k_{a,w}$ (2 cm)	$k_{a,w}$(5 cm)
TH 100	0.17	1.015	1.002
TH 120	0.28	1.020	1.002
TH 140	0.45	1.024	1.004
TH 150	0.82	1.028	1.005
TH 200	1.52	1.023	1.004
TH 250	2.52	1.013	1.001
TH 280	3.41	1.008	1.000

7. COMPONENTS OF THE OVERALL CORRECTION FACTQR $k_{a,w}$

The overall correction $k_{a,w}$ (in its values to be compared with k_u p_u in the IAEA Code, but the definition is slightly modified and extended) comprises the following components:

$k_{E,\theta}$ the correction factor which accounts for the effect of the difference in the spectral and angular distribution of the photon fluence at the calibration free in air and at the measurement in the water phantom, i.e. the correction factor for the energy and angular dependence of response of the ionization chamber (see figure 4),

p_d the displacement correction factor which accounts for the effect of displacement of water by an air volume with the shape of the ionization chamber (see figure 1),

k_{st} the correction factor which accounts for the effect of the difference in the photon fluence due to scattering and attenuation from the ionization chamber stem at the calibration free in air and the measurement in the water phantom, i.e. the correction factor for the influence of the stem,

k_{sl} the correction factor which accounts for the effect of the protective sleeve needed if a non water-tide ionization chamber is inserted into the water phantom,

k_β the correction factor which accounts for any unknown effects and the value of which is taken as unity. This will allow to incorporate other influences without changing the formalism.

In the following sub-sections these correction factors are discussed in detail.

7.1 The correction factor $k_{E,\theta}$ for the energy and angular dependence of response of the ionization chamber

The assumption in the IAEA Code that the value of k_u is close to unity has been verified by Seuntjens et al. (1988) [24]. In figure 5 a small deviation only of k_u from one will be recognized. Here, only the spectral change of the radiation in the phantom and the energy dependent response of the ionization chamber determined free in air in an unidirectional photon

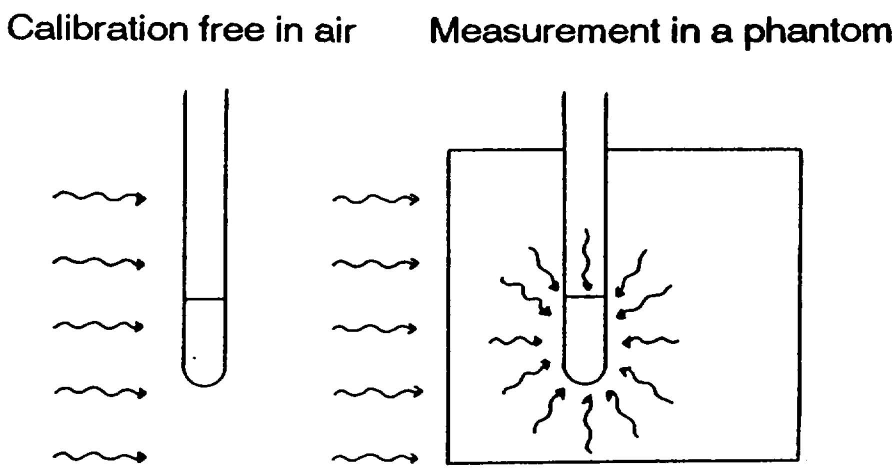


Fig.4. At the calibration of the ionization chamber in terms of air kerma free in air the chamber is exposed to an unidirectional radiation field of a given radiation quality. During the measurement at the depth in the water phantom the radiation field is modified with respect to its spectral and angular distribution.

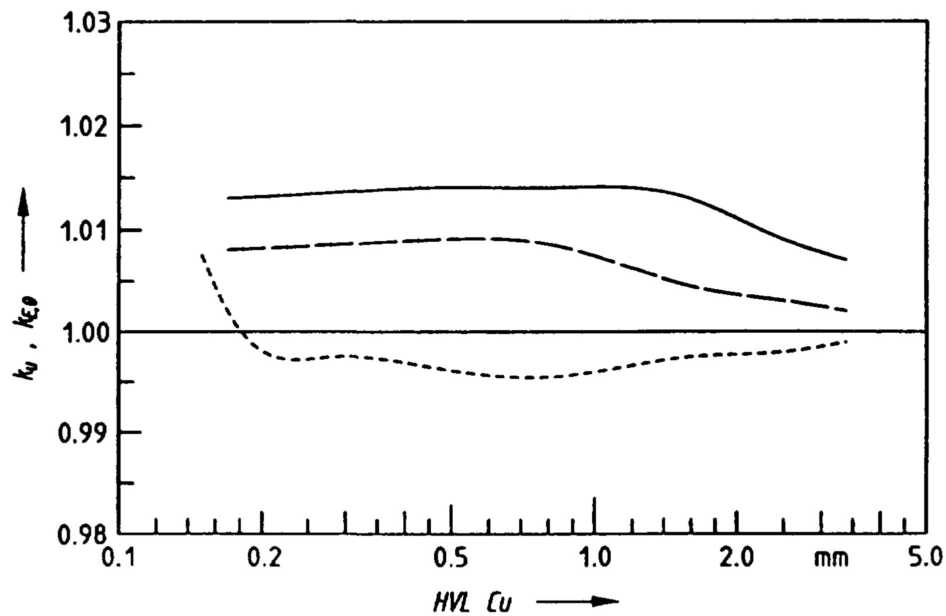


Fig.5. The component correction factor $k_{E,\theta}$ for the energy and angular dependence of response is shown for two ionization chamber types. For the NE 2571 (solid line) the curve is taken from Seuntjens at al. [13] and for the PTW M23331 the reference is Schneider and Kramer [29]. Seuntjens et al, have calculated k_u for the NE 2571 (dotted line) where only the change in radiation quality between the calibration situation and the in-phantom measurement is taken into account.

field have been taken into account in the calculation of k_u. However, as the angular distribution of the fluence must also be considered, the definition of k_u is to restricted. Therefore, the correction factor $k_{E,\theta}$ is definded as R_a/R_p, where R_a is the response of the ionization chamber free in air for a given radiation quality and R_p the response for the in-phantom situation (Schneider and Kramer 1989) [25]. Their notation will be used in what follows. R_p is defined by the following equation

$$R_p = \frac{\iint (\mu_{tr}(E)/\rho)_a \cdot E \cdot \phi_{E,\theta} \cdot R(E,\theta)\, dE \cdot \sin\theta \cdot d\theta}{\iint (\mu_{tr}(E)/\rho)_a \cdot E \cdot \phi_{E,\theta} \cdot dE \cdot \sin\theta \cdot d\theta}$$

where $(\mu_{tr}/\rho)_a$ is the mass energy transfer coefficient of air

r (E,θ) is the response in dependence on energy E and angle θ given as the ratio of the reading and the air kerma produced by a monoenergetic and unidirectional radiation field of energy E and direction θ

$\phi_{E,\theta}$ is the photon fluence spectrum differentiated with regard to energy E and angle θ

and θ is the angle between the direction of the incident photons and the axis of the ionization chamber

R_a is defined correspondingly

$$R_a = \frac{\int (\mu_{tr}(E)/\rho)_a \cdot E \cdot \phi_{E,\theta} \cdot R'(E)\, dE}{\int (\mu_{tr}(E)/\rho)_a \cdot E \cdot \phi_{E,\theta} \cdot dE}$$

r'(E) is the response as a function of photon energy E when the ionization chamber is irradiated free in air perpendicular to the chamber axis

Schneider and Kramer (1989) [25] determined the response R_p (E, θ) for the PTW M23331 ionization chamber and Seuntjens et al. (1993) [13] the response for the NE 2571 ionization chamber. In figure 6 an illustration of the results of both investigations is given. The dependence of the response on the direction of the monoenergetic incident radiation field normalized to its value for incidence perpendicular to the axis of the ionization chamber is shown.

The function $\phi_{E,\theta}$ was derived by the Monte-Carlo calculation of the transport of photons in water.

The resulting values of $k_{E,\theta}$ for radiation qualities with mean energies between 30 and 170 keV are presented in figure 7. The quality correction factor k_u for the NE 2571 chamber determined by Seuntjens et al (1988) [24]. $k_{E,\theta}$ behaves quite differently from k_u for the NE 2571 ionization chamber. It exceeds always unity and is at a maximum in the energy region, where the scattered radiation has its maximum, too. Seuntjens et al. (1993) [13] state an overall uncertainty of 0.6 % on the $k_{E,\theta}$ value for the NE 2571 ionization chamber. In deriving $k_{E,\theta}$ the ionization chamber is looked at as being symmetrical without stem and the stem effect is treated separately. It must be noted that in principle the influence of the chamber stem should be included in the correction factor $k_{E,\theta}$, but experimental difficulties using the above method and another possible approach suggest putting the influence of the stem into a separate correction factor.

7.2 The displacement correction factor p_d

The problem of the water volume displaced in the water phantom by the ionization chamber can be restricted to the study of the ratio of the air kerma at a point at the reference depth in the phantom to the air kerma at the center of an air cavity when its center placed at the same depth. The presence of the air filled cavity causes a decreased attenuation of both the primary and scattered radiation and decreases the scattering of radiation within the cavity. The two effects go in the opposite directions and the combined effect determines the p_d value.

The displacement correction p_d can be calculated as the ratio $K_{a,w}/K'_{a,w}$ where $K_{a,w}$ is the air kerma at the reference point and $K'_{a,w}$ is the air kerma in the center of the air filled

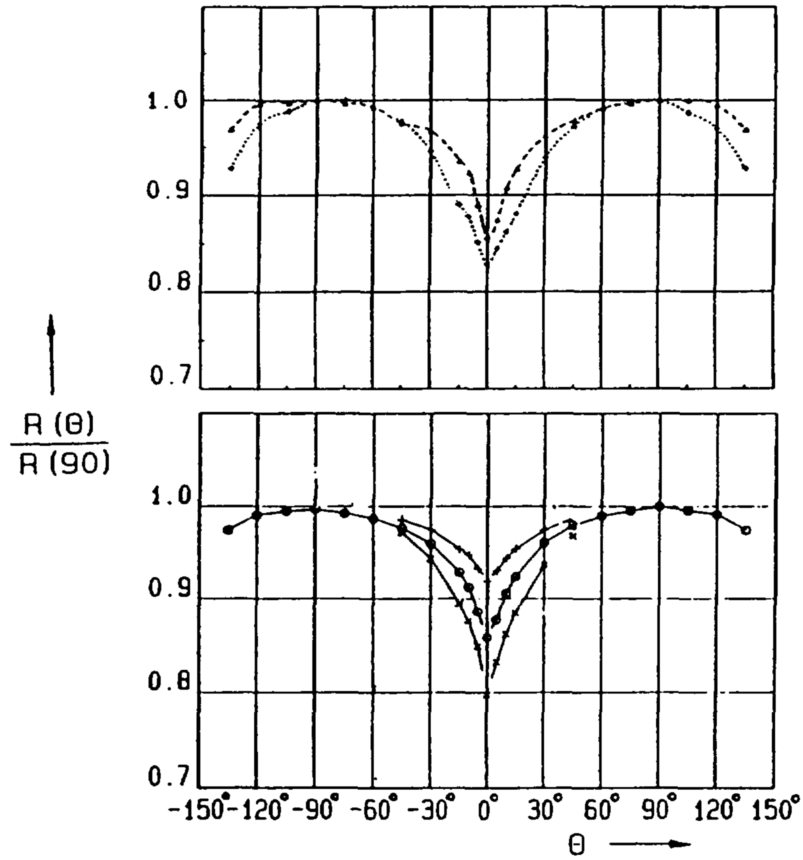


Fig.6. Illustration of the experimental data in the determination of $k_{E,\theta}$. As $k_{E,\theta}$ depends on two variables E and θ, only the angular dependence of response R (θ) of two ionization chamber types (NE 2571) and PTW M23331) is presented with the radiation quality as parameter. The curves are normalized to the radiation incidence perpendicular to the chamber axis (θ=90°). In the upper part of the figure the date for the NE 2571 ionization chamber obtained by Seuntjens et al. [13] are shown for two radiation qualities (triangles: HVL 0.17 mm Cu, crosses: 0.09 mm Cu). The curves for the PTW M23331 (lower part of the figure) are very similar [3]. Here the radiation qualities are characterized roughly by 0.09 mm Cu (lower curve), 0.24 mm Cu (curve in the middle) and 0.59 mm Cu (upper curve).

cavity at the reference depth in the water phantom. Seuntjens et al. (1993) [13] used the EGS4 Monte Carlo code and the correlated sampling variance reduction technique. A very detailed investigation was carried out by Ma and Nahum (Ma and Nahum 1993, Ma 1992) [26], [7]. They used a simple photon attenuation and scattering method to evaluate the displacement correction factor p_d following the method of Cunningham and Sontag (1980) [27].

A direct Monte Carlo calculation of the water kerma at the depth in water with and without the water volume replaced by a low-density (o equal to that of air) water cavity using the EGS4/DOSIMETER code together with the application of the correlated sampling variance reduction technique yielded almost perfect agreement between the two procedures in calculation the p_d correction factor for the NE 2571 ionization chamber. The same holds for the comparison with the results of Seuntjens et al. (1993) [13] for an ionization chamber with length 2.5 cm and a NE 2571 like chamber volume. In figure 4 the values of both calculations are plotted on one curve. The stated computational uncertainties of 0.2 % and 0.5 %, respectively, are confirmed by this excellent agreement. In the same figure the results of an independent Monte Carlo calculation carried out by Kramer (1992) [28] for a different ionization chamber (PTW 23331) are given for comparison. These calculations show that the correction

Table III Summary of the results of the $k_{a,w}$-values derived from four different methods and recommended values for $k_{a,w}$. These values should replace those of Table VI of TRS 277. The recommended values are average values weighted according to the inverse of the squared uncertainties. All uncertainties are given as one standard deviation. They are not always identical to those stated in the references.

U kV	HVL Cu mm	$k_{a,w}$-values derived from: Extrapol.Ch.	Calorimetry	Combination	MC/Measurem.	Recommended values
100	0.17	1.07 ± 0.04	1.04 ± 0.03	1.017 ± 0.025	0.998 ± 0.03	1.03
120	0.28	1.06 ± 0.04	1.033 ± 0.02	1.020 ± 0.025	1.002 ± 0.03	1.03
140	0.45	1.05 ± 0.03	1.027 ± 0.02	1.024 ± 0.02	1.004 ± 0.03	1.03
150	0.82	1.03 ± 0.025	1.026 ± 0.02	1.021 ± 0.02	1.005 ± 0.03	1.02
200	1.52	1.02 ± 0.025	1.008 ± 0.02	1.015 ± 0.02	1.004 ± 0.03	1.02
250	2.52	1.01 ± 0.025	1.007 ± 0.02	1.010 ± 0.02	1.004 ± 0.03	1.01
280	3.41	1.00 ± 0.025	1.014 ± 0.02	1.006 ± 0.02	1.000 ± 0.03	1.01

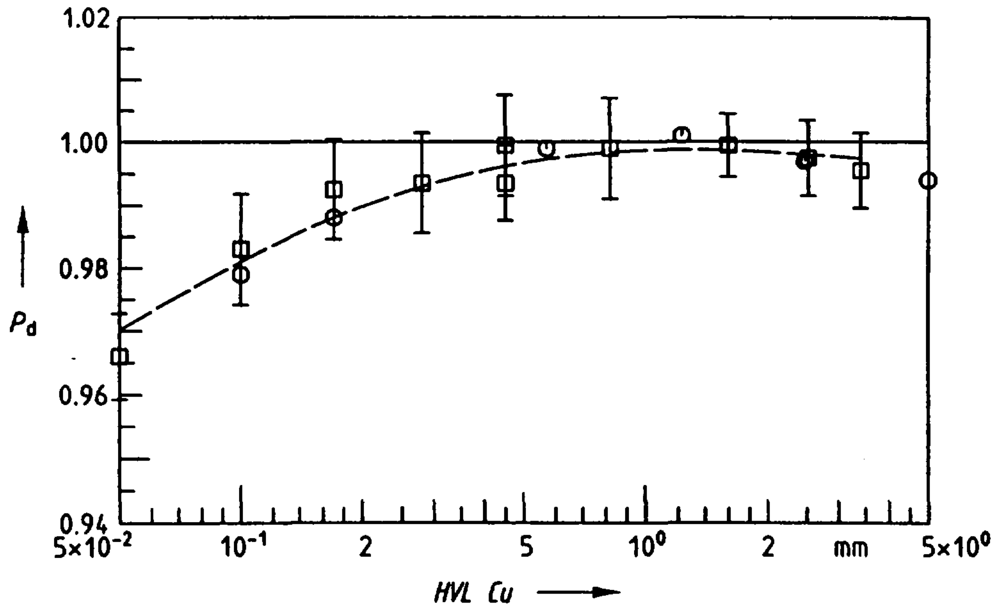


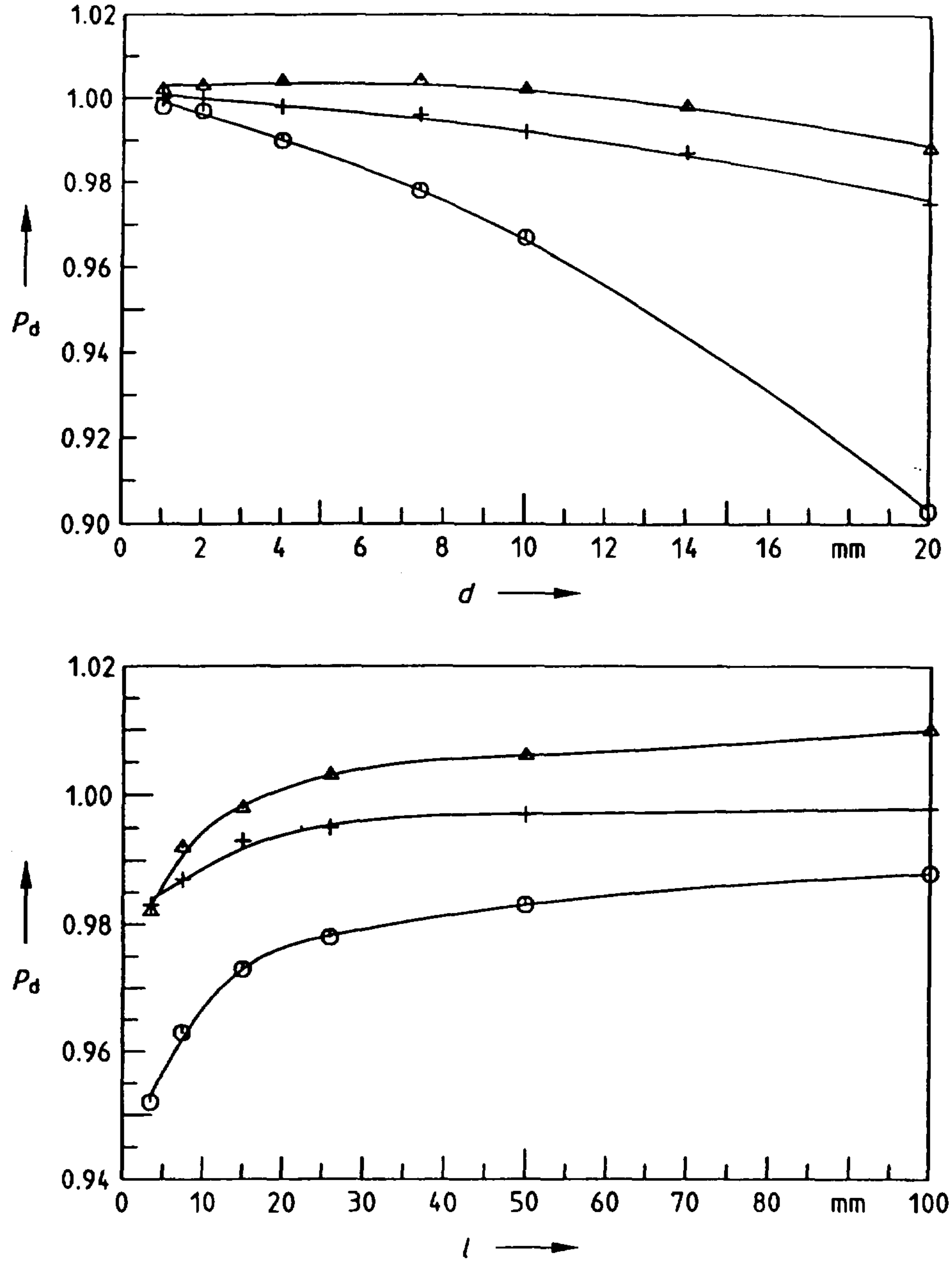
Fig. 7. The component correction factor p_d for the displacement of phantom material by the ionization chamber. Two Monte Carlo calculations (circles: Ma and Nahum [26]; squares. Seuntjens et al. [13] were carried out for the NE 2571 ionization chamber with statistical uncertainties of 0.2% and 0.5%, respectively. The dashed curve is a fit to the results by Seuntjens et al.

for the displacement of water by the chamber is not likely to exceed unity by more than a few tenths of a percent.

It must be noted that the displacement correction factor p_d depends both on the diameter and on the length of the ionization chamber volume. From the investigation by Ma and Nahum (1992) [26] the trend of the p_u value for a given shape of the ionization chamber can be deduced using the curves presented in figure 10.

7.3 The stem effect correction factor k_{st}

The response of an ionization chamber calibrated free in air is enhanced compared to the situation of a stemless ionization chamber due to additional scattering from the stem. Thus a correction factor $k_{st,air}$ smaller than unity is needed to compensate for the effect of the stem on the calibration factor N_K. The calibration factor for the stemless ionization chamber is $N'_K = N_K/k_{st,air}$. The experimental method using a dummy stem of the same size and material opposite the actual stem for the evaluation of the correction factor is well known and in widespread use. A similar correction factor $k_{st,w}$ can be defined for the stem effect of the "stemless" ionization chamber in the water phantom. Here the reading of the ionization chamber is likely to be reduced by the effect of displacement of phantom material (low Z material) by the chamber stem. The attenuation and scattering from the phantom and the stem is influenced by the stem, the material of which is mainly aluminium. The in-water correction factor $k_{st,w}$ exceeds one. The stem correction factor k_{st} is given as the ratio of the in-water stem effect corretion factor $k_{st,w}$ to the in-air stem effect correction factor $k_{st,air}$. Experimental results are available for the NE 2571 ionization chamber (Seutjens et al. 1993) [13], the NE 2561 ionization chamber (Rosser 1992) [7] and the PTW 23331 ionization chamber (Schneider and Kramer 1993) [29]. Figure 9 illustrates the variation of the experimentally determinated values of $k_{st,w}$ with radiation quality and phantom material.



Figs. 8(a) and 8(b). Variation of the displacement correction factor p_d with the outer diameter for an ionization chamber of 26 mm length (a) and (b) with the length for an ionization chamber with an outer diameter of 7.4 mm, respectively. The radiation qualities correspond to 0.1 mm Cu HVL (circles), 1.23 mm Cu (crosses) and 5.1 mm Cu (triangles). The curves are derived from the work of Ma and Nahum [26].

Ma and Nahum (1992) [30] have calculated the in-air and in-water stem correction factors as the ratios of the absorbed dose in the air cavity of the ionization chamber with and without a chamber stem using the EGS4 Monte Carlo code.The ratio of the in-water correction to the in-air correction gives the stem effect correction factor k_{st}. For the NE 2571, k_{st} varies from 1.012 ± 0.001 at 70kV (2.9 mm Al, mean energy 41 keV) to 1.005 ± 0.001 at 300 kV (21.5 mm Al, 207 keV mean energy) while for the NE 2561 it varies from 1.035 ± 0.002 to 1.010 ± 0.002 within the same radiation quality range. As can be seen from figure 10 this is in very good agreement with the recent experimental results by Seuntjens et al. [13] and Rosser [6].

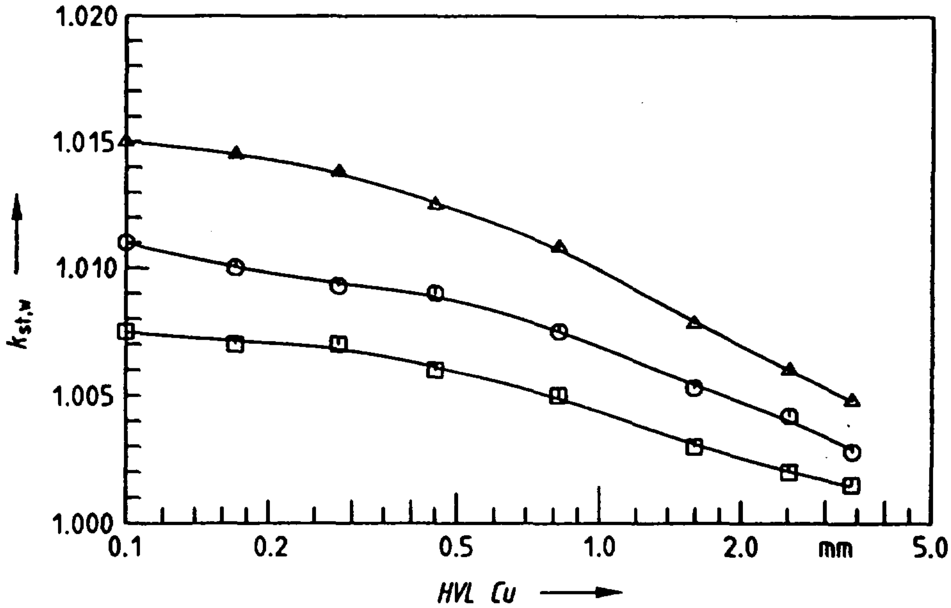


Fig.9. The energy dependence of the factor $k_{st,w}$ describing the influence of the stem in the water phantom was measured in different phantom materials (squares: SR6, circles: PMMA, triangles: graphite) for the PTW M23331 ionization chamber [29]. The measured values fall on a smooth curve indicating a small measurement uncertainty of about 0.2%.

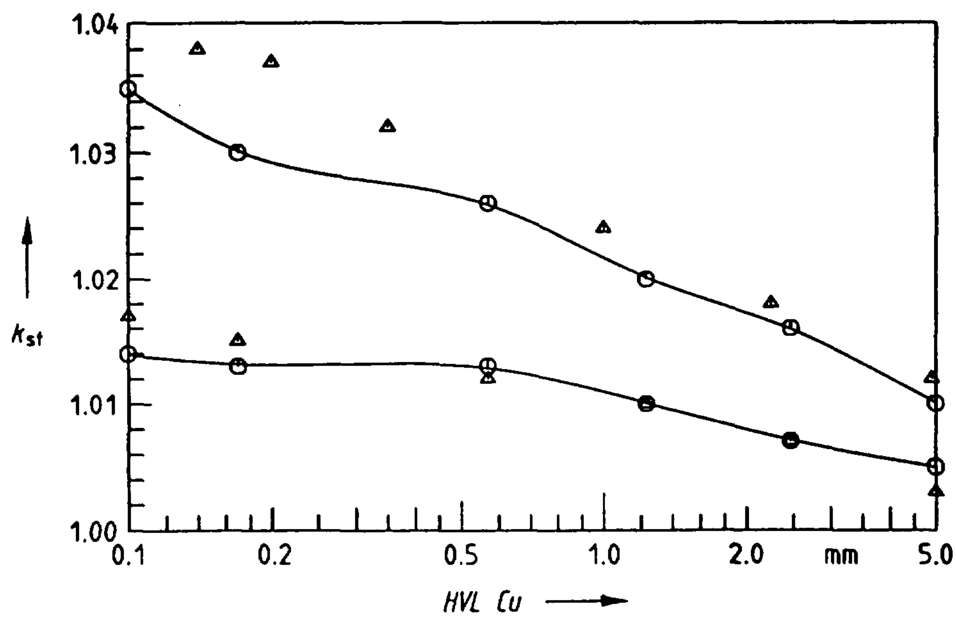


Fig.10. The stem effect correction factor k_{st} for the NE 2571 (upper curve) and NE 2561 (lower curve) ionization chamber calculated by Ma and Nahum [30] agree very well with measured values for the NE 2561 ionization chamber from Rosser [6] and for the NE 2571 ionization chamber determined experimentally by Seutjens et al. [13]. The maximum difference in the k_{st} values amount to roughly 2% at low energies.

7.4 The sleeve effect correction factor k_{sl}

The sleeve effect correction factor k_{sl} can be determined performing measurements with and without the protective sleeve in a solid water equivalent phantom. For a comparably thick-walled sleeve (mm of PMMA) the curve given in figure indicates an upper limit of this

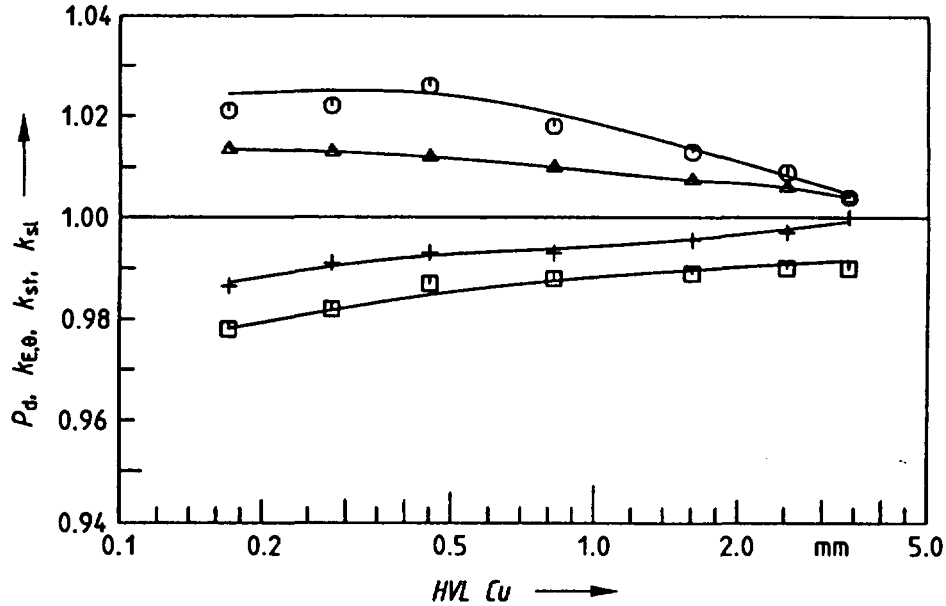


Fig.11. The component correction factor p_d, (squares) $k_{E,\theta}$, (circles) k_{st} (triangles) and k_{sl} (crosses) for the PTW M23331 ionization chamber determined by Schneider and Kramer [29].

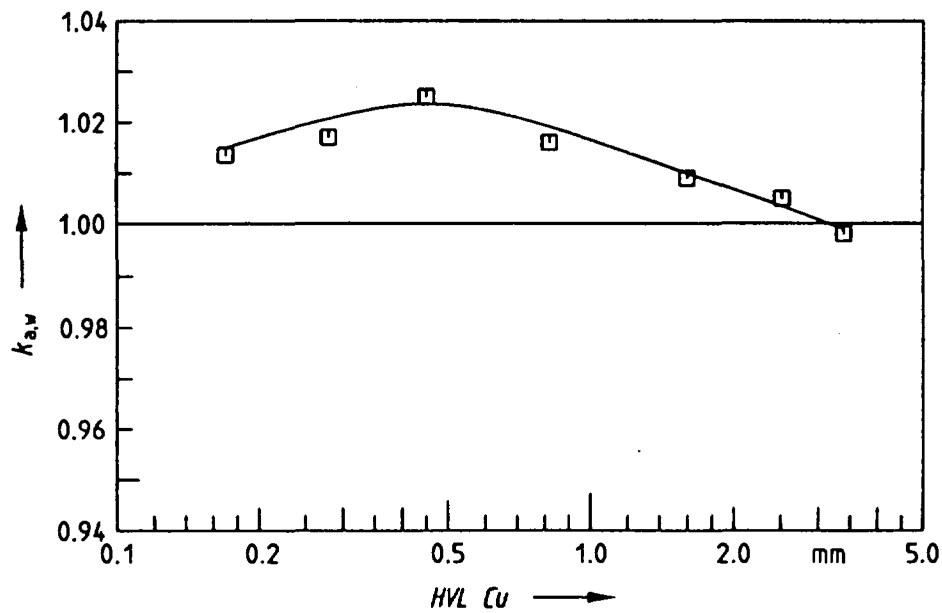


Fig.12. The correction factor $k_{a,w}$ for the PTW M23331 ionization chamber resulting from the multiplication of the curves given in figure 11. k_{sl} has not been taken into account, as the sleeve normally used with this chamber will have a much smaller wall thickness than that for which the curve in figure 11 is valid.

correction factor, as the thickness of the sleeve with normally be below the value stated above. The measurements were carried out in a SR6 phantom [31] by Schneider and Kramer [29].

7.5 Determination of the overall correction factor $k_{a,w}$ from its components

The overall correction factor $k_{a,w}$ is the product of its components $k_{E,\theta}$, p_d, k_{st} and k_{sl} which have been evaluated separately. Results of the component correction factors are available for two ionization chamber types namely for the PTW M23331 ionization chamber

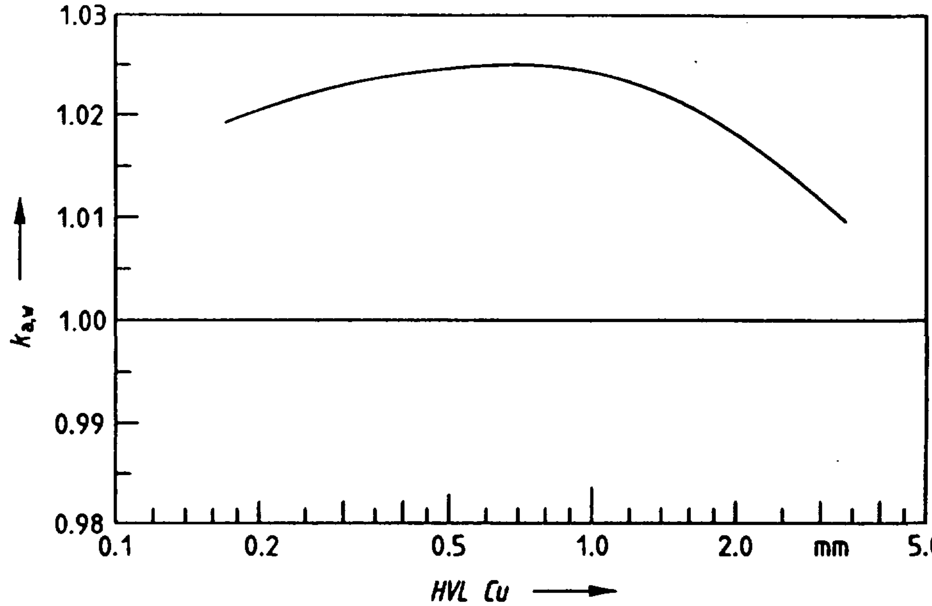


Fig.13. The correction factor $k_{a,w}$ for the NE 2571 ionization chamber as the product of p_d, $k_{E,\theta}$, and k_{st} from figures 5,7, and 10 respectively.

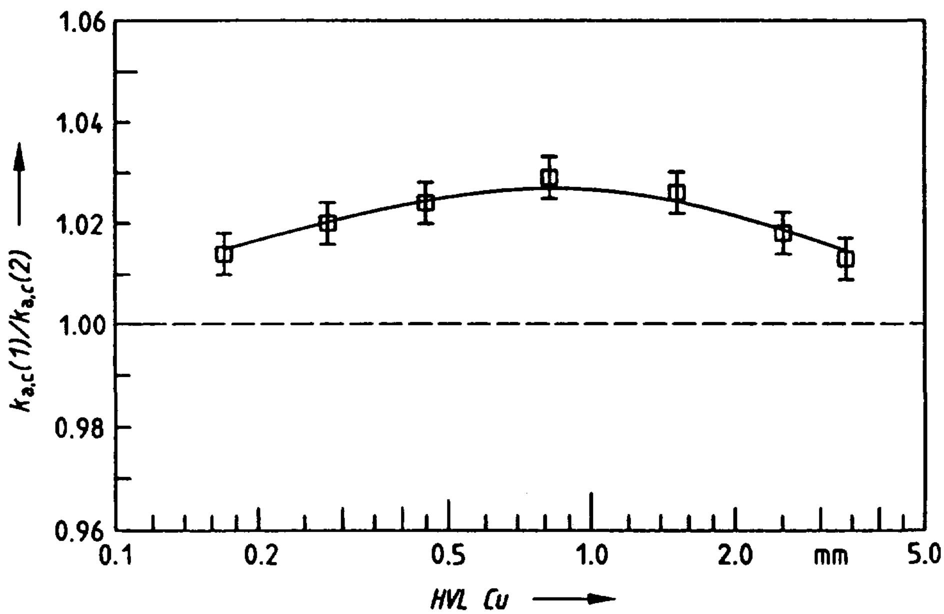


Fig.14. The ration of $k_{a,c}(1)/k_{a,c}(2)$ for two different ionization chambers (1:PTW M23331; 2: PTW M23332) as a function of radiation quality.

by the work of Schneider and Kramer and for the NE 2571 by the work of Seutjens et al and the work of Ma and Nahum on p_d and k_{st} for the latter ionization chamber. Figure 11 gives the component correction factors for the PTW M23331 ionization chamber type as a function of the radiation quality. In figure 12 the resulting overall correction factor is presented. The corresponding information for the NE 2571 ionization chamber can be taken from figures 5, 7 and 10, whereas the curve in figure 13 as the product is the overall correction factor $k_{a,w}$. Especially for the NE 2571 ionization chamber the input data from two groups are very consistent.

8. RESULTS AND DISCUSSION

Since the appearance of the IAEA Code, the diverging results arising when data recommended in the code are applied compared with those of other recommendations. e.g. ICRU 23, have led to further investigations on medium-energy x ray dosimetry. The results from different methods available at the time being are presented and summarized in this review.

The results of the extrapolation chamber method at low photon energies which entered into the IAEA Code have not been confirmed by other methods. Considering the re-evaluated values of $k_{a,w}$ (see table I) and the values derived by other methods the discrepencies are still obvious in the low energy range of the radiation qualities as can be seen from table III. Yet they are consistent with respect of the uncertainties stated.

The significant uncertainty associated with the water absorbed dose calorimeter for medium energy X-rays (see figure 2) is mainly due to the low dose rates, the heat defect and the heat conduction as the depth dose curves are steeper than those for high energy photons. the results presented are valid only for the NE 2571 ionization chamber against which the calorimeter measurements were compared. The correction factor $k_{a,w}$ derived from the calorimetric investigations exceeds unity at all photon energies with a maximum of nearly 4 %.

The result from the method of combining the component correction factor exhibit a different behavior in dependence on the radiation quality. The $k_{a,w}$ values decrease in the low photon energy range with decreasing photon energy, what is caused by the decreasing p_d values. The uncertainty of this method estimated from the uncertainties stated in evaluating the component correction factors amounts to about 2.0 % except for the low photon energy range where it may be about 2.5 %.

As a general remark, the results presented here are derived mainly for two types of ionization chambers. However, the displacement correction factor p_d depends on the outer shape of the ionization chamber. The stem correction factor k_{st} which accounts for scattering and attenuation effects depends on stem material and dimensions and probably on the design of the inside of the stem and the adjacent ionization chamber part. The $k_{E,\theta}$ values for different ionization chamber types will be different. Beyond that, some considerations may be necessary insofar as the individual energy and angular dependence of a single ionization chamber will affect $k_{a,w}$. The example in figure 14 underlines this fact.

9. CONCLUSION

The analysis of the status of the main methods of determining absorbed dose to water in the medium energy X-ray range yields that the values of the correction factor $k_{a,w}$ ($p_u \cdot k_u$ in the formalism of the IAEA Code) at the lowest photon energies are significantly lower than those given in the IAEA Code. The uncertainties of the new determinations are no better than 2 % or 3 % however. The results are assumed to apply to other ionization chambers of similar geometry, though this may be modified when more information becomes available.

It is clear that in principle different types of ionization chambers will have different $k_{a,w}$ values. Beyond this it is very probable that measured $k_{a,w}$ values are specific for the individual ionization chamber rather than for the ionization chamber type. As a final consequence of this, calibrations should be carried out in a water phantom against an ionization chamber whose $k_{a,w}$ value is well known. By this the individual $k_{a,w}$ correction factor can be incorporated into the calibration factor.

It is recommended to replace the values of table XV " Perturbation correction factor p_u for thimble ionization chambers for X-rays at 5 cm depth inside a water phantom" in the IAEA Code by the values of table III being aware that ongoing work in this field may bring up further improvements.

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