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Review of data and methods recommended in the international code of practice IAEA Technical Reports Series No. 277, Absorbed Dose Determination in Photon and Electron Beams

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FOREWORD

In its Report 24 on *Determination of Absorbed Dose in a Patient Irradiated by Beams of X or Gamma Rays in Radiotherapy Procedures*, the International Commission on Radiation Units and Measurements (ICRU, 1976) concluded "although it is too early to generalize, the available evidence for certain types of tumor points to the need for an accuracy of ±5% in the delivery of an absorbed dose to a target volume if the eradication of the primary tumor is sought". The limit was given in a context where uncertainties were estimated at 95% confidence limits, and therefore corresponds to approximately two standard deviations.

It is considered today that the above goal of ±2.5% (one standard deviation) in dose delivery to the patient might be too strict and the figure should probably be increased, but there are no definite recommendations in this respect. What modern radiobiology has confirmed is the need for high accuracy in dose delivery if new techniques in radiotherapy, including the increase of prescribed doses to values with no precedent in the past (dose escalation in conformal radiotherapy), are to be applied. The present possibilities in radiotherapy, using modern diagnostic tools for determination of the target volume and advanced accelerators for irradiation, can only be utilized in an adequate way if there is high accuracy in absolute dose determination. There are many steps involved in the dosimetry of a patient undergoing radiotherapy treatment, starting with the determination of primary standards of absorbed dose or kerma at Primary Standard Dosimetry Laboratories (PSDLs), followed by the calibration of ionization chambers at Secondary Standard Dosimetry Laboratories (SSDLs), and ending with calculations of irradiation time or accelerator monitor units for the patient treatment. All the different steps include uncertainties, and great care is needed in all the procedures to minimize these uncertainties in order to ensure that the radiation treatment has an acceptable quality.

So-called dosimetry protocols, describing procedures to determine the absorbed dose in reference conditions at radiotherapy treatment facility, were published by various national medical physicist associations in the seventies and early eighties. These protocols improved the consistency in dosimetry within a country but differences between the protocols resulted in deviations, in some cases of several per cent, among different countries. An International Code of Practice was published by the IAEA in 1987 (IAEA Technical Reports Series No. 277), in order to promote a world wide consensus in dose determination for radiotherapy. Authors were chosen who had already had been involved in writing the different national protocols and a large advisory group was consulted before the publication. The most up-to-date data on interaction coefficients and correction factors were used. The report therefore represented the highest possible accuracy in the field of dosimetry for ^{60}Co γ-beams and photon and electron beams from accelerators; for kilovoltage X rays the uncertainty was larger due to the intrinsic uncertainties in some correction factors not sufficiently known at that time.

After an initial period of use of TRS 277, research in the field of radiotherapy dosimetry indicated the need for a review of the data and procedures recommended in the International Code of Practice, and an analysis of the possible impact of new developments. An international working group was formed, which met at the end of 1992, to review the status of the Code of Practice. The working group surveyed scientific results on topics related to TRS 277, recommending that in certain cases important changes ought to be made, whereas in other situations it was considered that ignoring new developments would not significantly

affect the dosimetry of radiotherapy patients. The dosimetry of kilovoltage X rays deserved special attention, and the recommendations included changes in the data of TRS 277 up to 7% which could have important clinical consequences. In all cases the users of the Code of Practice should be made aware of the changes in dosimetry recommendations resulting from the new findings.

A booklet entitled "Working material", which included a summary with main recommendations and reviews on different topics of ionization chamber dosimetry (used as sources for the recommendations), was prepared by the IAEA Dosimetry Section responsible for the preparation of the publication of the International Code of Practice. In order to expand the dissemination of the changes to the recommendations of TRS 277 this material is now published as the present IAEA-TECDOC.

EDITORIAL NOTE

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CONTENTS

REVIEW OF DATA AND METHODS RECOMMENDED IN THE INTERNATIONAL CODE OF PRACTICE IAEA TECHNICAL REPORTS SERIES No. 277, ABSORBED DOSE DETERMINATION IN PHOTON AND ELECTRON BEAMS

P. Andreo, A. E. Nahum, K. Hohlfeld, H. Svensson

The validity of the recommended procedures, data and dosimetry correction factors given in the International Code of Practice: IAEA Technical Reports Series No. 277, Absorbed Dose Determination in Photon and Electron Beams, were analysed by a working group in December 1992. The main conclusions and recommendations for changes in TRS 277 are summarized in this status report and categorized according to radiation quality. Details on the recommendations can be found in the papers following this summary.

1. HIGH ENERGY ELECTRONS

The absorbed dose to water over a range of electron energies determined according to TRS 277 agrees within 1% with determinations based on non-ionometric methods. The values of the fluence perturbation factors for cylindrical chambers, p_u, have been found to be somewhat too high, but the change in dose would be less than 0.4%. Possible changes in the basic stopping-power data due to alternative derivations of the density-effect correction have been found to have a minor effect (below 0.5%) on $(s_{w,air})_u$. Similarly, recomputations of $s_{w,air}(E_0,z)$ using 3 different Monte Carlo codes have not revealed any significant differences from the data base of values given in TRS 277 despite the discovery of a major error in the particular Monte Carlo code used to derive these values. The method of choosing $s_{w,air}(E_0,z)$ based on the $E_0 = 2.33\ R_{50}$ formula has been thoroughly investigated for a range of clinical qualities varying from *clean* to *very contaminated* beams and found to be accurate to within 0.5% at $z = D_{max}$ in the worst case. The central-electrode correction factor p_{cel} for chambers with aluminium electrodes appears to be too high in TRS 277; this gives a small correction and the improved value results in a dose only 0.4% lower for electron beams when the central electrode has 1 mm diameter.

2. PLANE-PARALLEL CHAMBERS

For low energy electrons ($E_0 \leq 10$ MeV) it has been confirmed that a plane-parallel chamber is the instrument of choice. The N_D factor of a plane-parallel chamber should preferably be determined in a high energy electron beam; it may be determined in a ^{60}Co beam but in this case larger uncertainties must be accepted. It has been confirmed in recent experimental investigations that values of the perturbation factor $p_{u,pp}$ for properly designed plane-parallel chambers are negligibly different from unity at energies down to $E_x = 2$ MeV.

The use of plane-parallel chambers to determine the absorbed dose to water in a photon beam cannot be recommended as a result of the lack of consistency among the various determinations of the p_{wall} factor.

3. HIGH ENERGY PHOTONS

For ^{60}Co radiation the dose to water determined according to TRS 277 for most ionization chambers specified in the Code agrees within 1% with the calorimetric determinations of absorbed dose recently reported by several PSDLs. Furthermore, for the

different megavoltage X ray beam qualities the dose determined according to TRS 277 is within $\pm$ 1% of that given by non-ionometric methods, e.g. Fricke and water calorimetry.

A study of the separate factors given in TRS 277 for the conversion from K_{air} to $D_{w,u}$ has revealed the following. Concerning the shift of the effective point of measurement, P_{eff}, a single value of $0.6r$ is more consistent with experimental work than the separate values of $0.75r$ recommended in TRS 277 for high energy photon beams and $0.5r$ for ^{60}Co. Concerning $(s_{w,air})_u$, the use of alternative formulations of the density-effect correction parameter δ makes at most 0.5% difference and only at the highest energies. The $(s_{w,air})_u$-TPR^{20}_{10} correlation given in TRS 277 has been thoroughly investigated using 3 independent Monte Carlo codes, with much reduced statistical noise through the exploitation of a convolution-based depth-dose computation; differences from the TRS 277 values are never more than 0.5% at any TPR for typical *clinical* beams.

4. MEDIUM ENERGY X RAYS: 100 TO 300 kV

Absorbed dose values determined according to TRS 277 are a few per cent higher than those determined according to ICRU Report 23, which most national codes follow. The maximum deviation exceeds 10% at 100 kV tube potential.

A thorough analysis has been made of the main methods of determining the correction factors needed when an ionization chamber calibrated free in air is used in a water phantom. The four methods considered to evaluate the correction factors are:

(a) extrapolation chamber measurements in a graphite phantom and transfer of the calibration factor to the conditions of the water phantom;

(b) water absorbed dose calorimetry;

(c) Monte Carlo calculation of kerma values free in air and in the phantom, and comparison with ionization chamber measurements;

(d) determination of all separate factors contributing to a global correction factor.

Comparing the ratio N_w/N_K of the calibration factors determined according to the methods mentioned above, for two ionization chamber types (NE 2571 and PTW M 23331), values of the global factor that are significantly lower than the 1.10 in TRS 277 at the lowest energies (HVLs) can now be recommended. However, the uncertainties on these new determinations are no better than 2 and 3% (1 standard deviation). The results are assumed to apply to other chambers of similar geometry within the given uncertainties, though this may be modified when more information becomes available.

An amendment sheet will be issued with TRS 277 to replace Table XV of the International Code of Practice. The changes are according to the following table:

Tube potential kV	HVL mm Cu	Perturbation correction factor p_u	
		from TRS 277, Table XV to be replaced	new recommended values
100	0.17	1.10	1.03
120	0.30	1.09	1.03
140	0.49	1.08	1.03
150	0.83	1.06	1.02
200	1.70	1.04	1.02
250	2.47	1.02	1.01
280	3.37	1.01	1.01

5. LOW ENERGY PHOTONS

It should be recalled that in the calibration procedure (b) described in TRS 277 the ionization chamber is positioned free in air. In this context, the term "at the surface of the phantom", quoted in TRS 277 in relation to values of $(\mu_{en}/\rho)_{w,air}$ and k_u, should be understood as the material in which the ion chamber is embedded, i.e., any wall material present at the N_K calibration, and not as an extra phantom used for dosimetry purposes.

Recent work at PTB (Germany) and at RMH (UK) has yielded $(\mu_{en}/\rho)_{w,air}$ data calculated free in air. The values are exclusively based on the incident primary spectra (field-size or depth-dependence are not relevant) and therefore are consistent with the geometry used for the calibration procedure (b). The following table is the average of the values obtained by the two groups (discrepancies within -1.4%/+0.6%), and corresponds to typical clinical spectra. These data should be used together with the data in Table XVI of TRS 277 to yield the dose at the surface according to Equation (15) in the protocol. They should not be confused with the $(\mu_{en}/\rho)_{w,air}$ data given in Table XIV which corresponds to in-phantom calibrations.

Energy absorption coefficient ratios in free-air $[(\mu_{en}/\rho)_{w,air}]^{free\ air}$, for X rays as a function of the half-value thickness (Kramer and Hohlfeld, 1993; Knight and Nahum, 1993)

HVL (mm Al)	$[(\mu_{en}/\rho)_{w,air}]^{free\ air}$
0.1	1.048
0.15	1.045
0.2	1.041
0.3	1.036
0.4	1.033
0.5	1.030
0.6	1.027
0.8	1.024
1.0	1.021
1.5	1.018
2.0	1.017
3.0	1.023
4.0	1.028

THE STATUS OF HIGH-ENERGY PHOTON AND ELECTRON BEAM DOSIMETRY FIVE YEARS AFTER THE PUBLICATION OF THE IAEA CODE OF PRACTICE

(Abstract)

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The status of the dosimetry of high-energy photon and electron beams is analyzed taking into account the main developments in the field since the publication of the IAEA Code of Practice (TRS 277) and most modern dosimetry protocols. In electron beam dosimetry, energy-range relationships are discussed; Monte-Carlo results with different codes are compared with the experimentally derived empirical expression used in most protocols. Updated calculations of water to air stopping-power ratios following the changes in the Monte-Carlo code used to compute actual $s_{w,air}$ values are compared with the data included in most dosimetry protocols. The validity of the commonly used procedure to select stopping-power ratios for a clinical beam from the mean energy at the phantom surface and the depth of measurement, is analyzed for "realistic" electron beams. In photon beam dosimetry, calculated correction factors including the effect of the wall plus waterproofing sleeve, and existing data on the shift of the effective point of measurement of an ionization chamber are discussed. New calculations of medium-to-air stopping-power ratios and their correlation with the quality of the beam obtained from the convolution of Monte-Carlo kernels are presented together with their possible practical implications in dosimetry. Trends in Primary Standard Dosimetry Laboratories towards implementing calibrations in terms of absorbed dose to water are presented, emphasizing controversial proposals for the specification of photon beam qualities. Plane-parallel ionization chambers are discussed regarding aspects that affect determinations of absorbed dose, either through the different methods used for the calibration of these chambers or by means of correction factors. Recent studies on the effect of the central electrode in Farmer-type cylindrical chambers are described.

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TESTING OF THE IAEA CODE OF PRACTICE AT ^{60}CO GAMMA RAYS

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Abstract

The IAEA Code of Practice for Absorbed Dose Determination in Photon and Electron Beams TRS 277 gives recommendations for the absorbed dose determination in high energy photon and electron beams based on the use of ionization chambers calibrated in terms of air kerma. It was the task of the present work to test the validity of the Code for ^{60}Co gamma radiation for ten different types of ionization chambers. The absorbed dose as determined in accordance with the Code was compared with the absorbed dose derived from calorimteric measurements. The results show excellent agreement between the two methods.

1. INTRODUCTION

The IAEA Code of Practice [1] provides the methodology necessary for the accurate determination of the absorbed dose to water from radiation beams used for radiotherapy. The formalism is based on the use of ionization chamber dosimeters which are calibrated in terms of air kerma. The calibration quality for the use of the dosimeters in high energy photon and electron beams is recommended to be ^{60}Co gamma radiation. The task of the present work was to test the methodology of the Code for ten different types of ionization chambers at ^{60}Co gamma rays: The ionometrically determined absorbed dose to water based on an air kerma calibration of the ionization chamber was compared with the absorbed dose derived from calorimetric measurements. The investigations were performed at the Austrian dosimetry laboratory which is operated as a co-operative project of the BEV and the Austrian Research Centre Seibersdorf (OeFZS) [2].

2. MATERIALS AND METHODS

2.1 Radiation source and reference standards

The measurements were carried out in the beam of the teletherapy unit PICKER C8M/80 of the BEV/OeFZS dosimetry laboratory. The nominal air kerma rate in the reference distance (100 cm) was about 0,35 Gy/min during the period of measurements. The field size in the reference plane was 10 cm x 10 cm.

The air kerma rate was determined by means of the national primary standard which is a cylindrical graphite cavity ionization chamber with a nominal volume of 1 cm^3. Details of the chamber and results of international comparisons are given in [3].

The absorbed dose rate to water (in the water phantom) was derived from the national primary standard graphite calorimeter. The calorimeter is based on the design of Domen [4]. The details of its construction and operation are given in [5]. Two methods are employed to derive the absorbed dose rate to water from the absorbed dose rate to graphite, both making use of a photon fluence scaling theorem [6]. Two comparions of the standards of absorbed dose of PTB (Physiaklisch Technische Bundesanstalt, Germany) and BEV were carried out with PTB Fricke ampoules irradiated in the BEV cobalt beam and lead to the following result:

$$D_w(BEV)/D_w(PTB) = 0,998$$

where

D_w(BEV) is the absorbed dose to the Fricke ampoules as stated by BEV,
D_w(PTB) is the absorbed dose to the Fricke ampoules as evaluated by PTB.

The uncertainty of this ratio is stated by PTB to be 0,7 % (one sigma, excluding the uncertainty of the realization of the unit of absorbed dose at PTB).

Table 1: Characteristics of ionization chambers

Chamber	Internal radius mm	Material wall	cap
NE 2561 (NPL)	3,7	GRAPHITE	DELRIN
NE 2571	3,15	GRAPHITE	DELRIN
NE 2581	3,15	A-150	PMMA
PTW M 233641	2,75	PMMA	PMMA
PTW M 233642	2,75	PMMA	PMMA
PTW M 23332	2,5	PMMA	PMMA
CAPINTEC PR-06	3,2	C-552	PMMA
1C 10 (WELLH.)	3,0	C-552	PMMA
ÖFZS TK 01	3,5	DELRIN	DELRIN
ÖFZS TK 01	5,5	GRAPHITE (4 mm)	

Table 2: Results of the comparison of the ionometric and calorimetric method for absorbed dose determination

Chamber	$D(N_k)/D(call)$
NE 2561 (NPL)	1,001
NE 2571	1,003
NE 2581	1,005
PTW M 233641	1,001
PTW M 233642	1,004
PTW M 23332	1,003
CAPINTEC PR-06	1,003
IC 10 (WELLH.)	1,002
OeFZS TK 01	1,000
OeFZS CC1	1,001

Mean ration $D(N_k)/D(cal)$: 1,002
Standard deviation: 0,2 %

2.2 Ionization chambers

Ten different types of ionization chambers of certain manufacturers were available for the investigations. Characteristics of the chambers (internal radii and the wall and build-up-cap materials) are given in table 1. Three of the chambers (PTW M 233642, Wellhöfer IC 10, OeFZS CC1) are not contained in the respective tables of the Code. The chamber OeFZS CC1 is thickwalled (wall thickness 0,7 g/cm^2 of graphite) for the given radiation quality (^{60}Co), its internal radius is 5,5 mm, its internal height is 11 mm, the nominal volume is 1 cm^3. Thus it does not fully meet the requirements of the Code, but nevertheless it was included in the investigations.

2.3 Measurement procedure

The basic equation of the Code of Practice for the determination of the absorbed dose to water D_w (P_{eff}) at the point of interest (i.e. at the effective point of measurement) is given by

$$D_w (P_{eff}) = M N_D (s_{w,air})_u p_u \qquad (1)$$

where

M is the meter reading,
N_D is the absorbed dose to air chamber factor,
$(s_{w,air})_u$ is the stopping-power ratio water to air at the user's quality,
p_u is the perturbation correction factor.

N_D is related to the air kerma calibration factor N_K by

$$N_D = N_K (1 - g) k_{att} k_m \qquad (2)$$

where

g is the fraction of the energy of the secondary electrons lost to bremsstrahlung in air,
k_{att} corrects for the attenuation and scatter of photons in the chamber material,
k_m corrects for the lack of air equivalence of the chamber material.

The validity of Eq. (1) had to be tested in the ^{60}Co beam, that means the absorbed dose determined according to this equation was compared with the absorbed dose determined by some other independent method (namely by the calorimeter).

The first step was to calibrate the ionization chambers with build-up caps in terms of air kerma free in air against the primary standard. The N_D factors were then calculated using the k_{att} and k_m data of the Code. For the chambers PTW M 233642, IC 10, and CC1 k_m was calculated according to chapter 8 of the Code, k_{att} for these chambers was taken to be 0,990.

The next step was to place the chambers in the water phantom with the effective point of measurement in the refernce depth (5 cm) of the phantom without build-up caps. The phantom was the IAEA cubic phantom (30 cm x 30 cm x 30 cm) modified in such a way that the carriage for the chamber holder was continuously adjustable. For each type of chamber a special holder of PMMA was designed with a wall thickness of 1,5 mm in the active region. (Experiments with chambers sealed in polyethylene foil were carried out to assure that no correction for the PMMA holder is necessary: The influence on the reading of a Farmer chamber in the ^{60}Co beam was less than 0,1 percent.) From the measured current the absorbed dose to water $D(N_K)$ was determined for each chamber using the data of the Code for $s_{w,air}$ and p_u. For the chambers TK01 and CC1 p_u was calculated upon the basis of chapter 8 of the Code.

3. RESULTS AND DISCUSSION

Table 2 gives the results as ratios of $D(N_K)$ to D(cal), where $D(N_K)$ is the absorbed dose to water as derived ionometrically from the air kerma calibration in accordance with the Code, and D(cal) is the absorbed dose to water as derived from the calorimeter. The results are based on two chambers

of the types NE 2561, NE 2571, M 23332, M 233641 and on one chamber of the other types. The $D(N_K)$ values for one type of chamber did not differ by more than 0,1 % from each other. The differences between the respective values of $D(N_K)$ and D(cal) are well within the total uncertainty of D(cal) which is estimated to be 0,6% . This is valid even for the chamber CC1 (which is thick-walled without additional build-up cap and has dimensions larger than recommended in the Code). The mean ratio $D(N_K)/D(cal)$ is 1,002 with a standard deviation of 0,2 %. The conclusion can be drawn that following the IAEA Code of Practice the absorbed dose from a ^{60}Co beam can be determined with sufficient accuracy by the types of ionization chambers which have been under investigation. Furthermore one can conclude that it practically does not matter whether one determines the absorbed dose from an accelerator beam using equations (1) and (2) and a ^{60}Co air kerma calibration factor N_K or whether one starts with an absorbed dose to water calibration in a ^{60}Co beam and determines the absorbed dose
D_w (P_{eff}) according to

$$D_w (P_{eff}) = M N_w (s_{w,air} p_u)_u / (s_{w,air} p_u)_c \qquad (3)$$

where

M is the meter reading,

N_w is the absorbed dose to water calibration factor at ^{60}Co,

$(s_{w,air} p_u)_u$ is the product of the stopping-power ratio and the perturbation factor at the user's quality, and

$(s_{w,air} p_u)_c$ is the product of the stopping-power ratio and the perturbation factor at the calibration quality (i.e. ^{60}Co).

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THE USE OF PLANE-PARALLEL CHAMBERS FOR THE DOSIMETRY OF ELECTRON BEAMS IN RADIOTHERAPY

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Abstract

This paper reviews the use of plane-parallel chambers for the absolute determination of absorbed dose in water at the reference depth in low-energy electron beams. The geometrical and electrical properties of the most commonly used commercial designs of chamber are described. It is shown that there is now firm experimental evidence that the perturbation factors for two commonly used chamber designs differ significantly from unity below $\bar{E}_z \approx 5$ *MeV. Furthermore, there is also mounting evidence that the material behind the air cavity can influence the chamber signal due to differences in backscattering compared to that of the phantom material. The theoretical work on the perturbation in electron beams caused by gas cavities in condensed media has been critically examined. It is argued that none of the existing analytical approaches convincingly models the physics except at small depths, but that these limitations will be overcome by Monte-Carlo simulations in the near future. The different approaches to calibration of plane-parallel chambers are discussed. The failure of simple models to give* $k_{u,pp}$ *and* p_{wall} *values at* ^{60}Co *which agree with experimental determinations is emphasised. A recent compilation of the measured values of these correction factors for a wide range of chamber types and experimental conditions is given. New Monte-Carlo work which largely explains and correctly predicts the experimentally observed behaviour of chambers of non-homogeneous construction in a* ^{60}Co *beam is described. It is concluded that the most reliable method of obtaining the* $N_{D,pp}$ *factor is still by intercomparison with a cylindrical chamber in a high-energy electron beam. Finally problems with the use of non-water, i.e. plastic, phantoms are reviewed, including charge-storage effects and fluence conversion factors.*

1. INTRODUCTION

Plane-parallel chambers have a long history in radiation dosimetry [1,2]. There have been a number of important designs, including *free-air* chambers for the absolute determination of *exposure* and now *air kerma*, and extrapolation chambers in which one can gradually reduce the distance between the electrodes by mechanical means.

This report is concerned with a special type of plane-parallel chamber designed for use in electron beams, especially at low energy. Electron beams down to as low as 2 MeV are used in radiotherapy. The practical range in water of such beams can be as small as 1 cm. Clearly it is difficult to fulfil the requirements of a *Bragg-Gray* detector, which should cause a negligible disturbance of the electron fluence present in the medium; the dimensions of even the smallest detector will inevitably be a significant fraction of the electron range. Cylindrical or *thimble* ion chambers such as the widely used *Farmer* chamber have internal diameters of

the order of 6 mm. One should expect that such chambers will cause an appreciable *perturbation* in low-energy electron beams.

Morris and Owen [3] designed a plane-parallel chamber which was intended for accurate dose determination in electron beams below 5 MeV in incident energy. The front *entry* window was an aluminized Melinex film only 0.006 mm thick. The air volume was a disc-shaped cavity 26 mm in diameter and 2 mm long in the beam direction. There was an outer guard area 3mm in width. Morris and Owen considered that they had demonstrated that the chamber exhibited a *perturbation* effect of only 0.5% at an electron energy at the depth of the chamber of 0.5 MeV. They stated that this very low value was due to the guard ring which excluded from the measured signal those electrons scattered in through the sides of the air cavity. Figure 1 illustrates this important point. This chamber, originally known as the Pitman Model 631 and later re-christened the *Vinten Model 631*, formed the basis of the HPA code of practice [4].

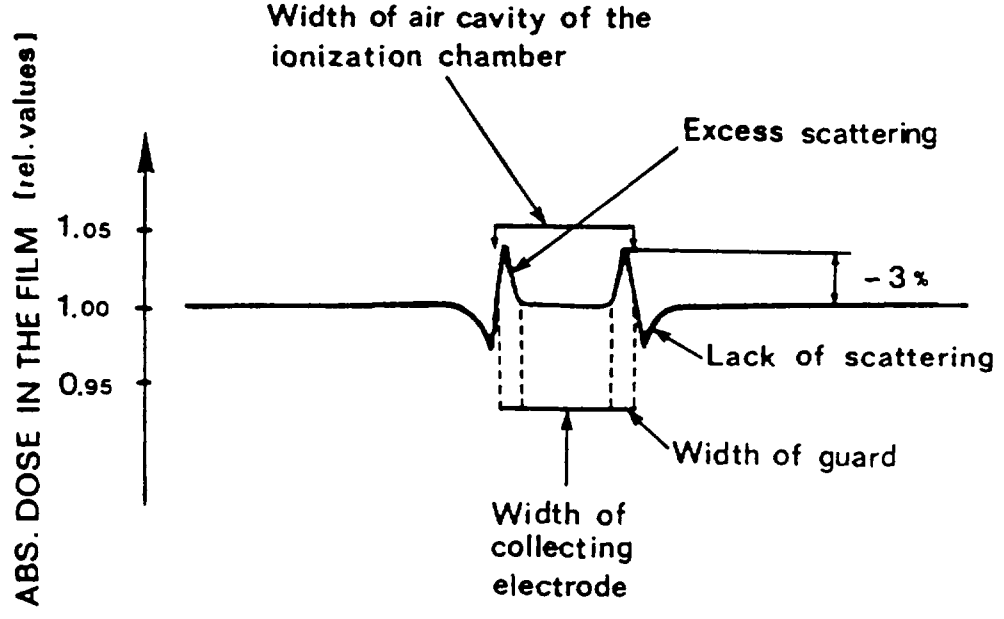

FIGURE 1. *Film measurements across the front surface of an cavity in a PMMA phantom at the depth of maximum dose in an E_o = 6 MeV electron beam; the effect of the guard ring in reducing the perturbation is clearly demonstrated (from [8]).*

Other designs of plane-parallel chamber for use in low-energy electron beams soon followed [5-7] and a great deal of work has since been done on investigating the properties of such chambers, e.g. [8-10]. The use of plane-parallel chambers in low-energy electron beams is now specified in all national dosimetry protocols e.g. [7, 11-14]. Plane-parallel chambers can, in principle, also be used in photon beams. They are particularly useful where one requires to make measurements very close to the phantom surface such as in the build-up region in high-energy beams. However, large perturbation effects have been demonstrated in such cases [15].

The IAEA protocol [16] also recommended the use of plane-parallel chambers in low-energy electron beams but was not very specific, merely referring the reader to the procedure in [7]. This present work describes the current status of the use of plane-parallel chambers. It will cover, in particular, the problematic aspects of the subject such as the seemingly unpredictable behaviour of current chamber designs in the ^{60}Co radiation often used for calibration, summarized recently by Rogers [17], the different options for the calibration of such chambers e.g. [11,18], and the fact that some of the widely used commercial models exhibit a distinctly non-negligible perturbation effect at the lowest electron energies e.g. [9].

It will help in what follows to set down the expression for absorbed dose to water derived from measurements with a plane-parallel chamber. Using the notation in the IAEA [16] protocol, we have

$$D_w(P_{eff}) = M_u\, N_D\, (s_{w,air})_u\, p_u \qquad (1)$$

where the perturbation correction factor p_u is specific to the effective point of measurement, P_{eff}, that is assumed for the chamber in question. In the case of plane-parallel chambers, P_{eff} is always taken to be the centre of the inside surface of the entrance window. The factor p_u is generally assumed to be unity i.e. there is no perturbation of the electron fluence at the depth of P_{eff} by the air cavity, or by the body of the chamber. We shall see in later sections that this is not always a justified assumption.

The factor N_D is the absorbed-dose-to-air chamber factor; N_D is shorthand for $N_{D,air}$ (known as N_{gas} in [11]). For cylindrical (thimble) chambers this is derived directly from the air-kerma calibration factor N_K. For plane-parallel chambers the situation is much less straightforward and forms the subject of section 7 on *Calibration Methods*.

2. PROPERTIES OF COMMONLY USED PLANE-PARALLEL CHAMBERS

Table I gives the material, geometrical and radiation performance characteristics of a number of commonly used commercially available plane-parallel chambers designed for use in low-energy electron beams. The table does not contain any data on non-unity perturbation correction factors in electron beams, nor on the behaviour in ^{60}Co beams at calibration; these are dealt with in later sections. It can be noted that the IAEA protocol [16] gives the following recommendations for plane-parallel chamber design for use with electrons where $\bar{E}_0 < 10$ MeV: front window thickness preferably < 1 mm; collecting electrode diameter ≤ 20 mm; guard width > 3mm; polarity effect (% difference in response between the two polarities) < 1%; negligible polarity effect; water immersible.

A detailed scale drawing of the widely used NACP chamber is shown in Figure 2. The following description, taken from [7], illustrates the points that need to be considered when designing a chamber for measurement in low-energy electron beams. The very narrow air gap (2 mm) and the presence of the guard ring minimize perturbation effects. The collecting

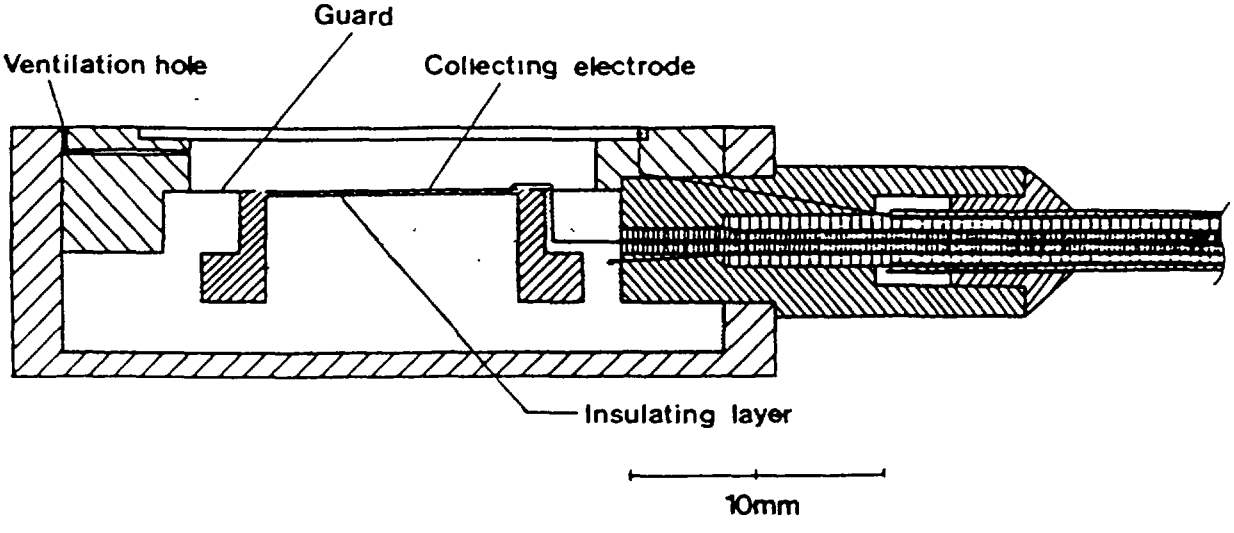

FIGURE 2. *The NACP chamber design (from [7]). See text for description.*

TABLE I. THE SPECIFICATIONS OF COMMERCIALLY AVAILABLE PARALLEL-PLATE IONIZATION CHAMBERS DESIGNED FOR USE IN LOW-ENERGY ELECTRON BEAMS.

CHAMBER	MATERIALS	WALL THICK.	PLATE SEP'N	EFF. DIAM	GUARD RING	POLARITY EFFECT	LEAKAGE
Vinten 631 [3]	aluminised melinex wall graphited melx. electrode styrene copolymer back wall	0.006 mm	2x1mm	20mm	3mm	<0.2%	$<10^{-14}$A
NACP [8] (Scandetronix, Dosetek)	graphite window, graphited rexolite electrode, rex. body	0.5mm	2mm	10mm	3.2mm	<0.5%	$<10^{-14}$A
PTW M23343 (Markus) [5]	graphited polyethylene window, graphited polystyrene electrode, PMMA body	~2.5 $mgcm^{-2}$	2mm	4.5mm	0.7mm	<0.5% spec. larger reported	$<10^{-14}$A
Holt/Memorial [6]	graphited polystyrene wall and electrode, polystyrene body	4mm	2mm	25mm	5mm	<1% spec. larger reported	$<10^{-14}$A
Capintec PS-033	aluminised polyethylene wall, carbon-impregnated air-equ. plastic electrode	25μm	2.4mm	16mm	2.4mm /0.5mm (?)	~1%	$<10^{-14}$A
Exradin	air-, polystyrene or tissue-equ. conducting plastic wall and electrode	0.5mm	1mm	20mm	5mm	n/a	$<10^{-15}$A
PTW/Roos Type 34001	graphited PMMA window and electrode	1mm	2mm	15mm	4mm	<0.5%	n/a

electrode is very thin (<0.1 mm) and is mounted on a thin insulating layer (≈0.2 mm) in order to achieve a negligible polarity effect. The front wall (0.5 mm thick to enable measurements to be made at small depths) and back wall are made of one single material (in this case graphite). The other material (slanted lines) is Rexolite, a form of polystyrene.

The guard ring plays a crucial role in minimizing the perturbation as discussed in the previous section (see also section 5). The widths given in Table I are all greater than the plate separation except for the PTW/Markus chamber and the Capintec PS-033 for which one might expect some measurable perturbation at the lowest energies. The electrical effect of the guard is illustrated in Figure 3 from [1]. The NACP design corresponds to *d*. The PTW/Markus design is similar to *a* except that the guard width is actually less than indicated in the figure.

Gerbi and Khan [19] measured the polarity effect of the Holt/Memorial [6], PTW/Markus [5] and Capintec PS-033 plane-parallel chambers in 6-24 MV x-ray beams and in 9- and 22-MeV electron beams. In the electron beams they found a 1-2% effect at d_{max} but this increased to as high as 4.5% at greater depths. In the buildup region of the high-energy x-ray beams a difference in collected charge between the two polarities as high as 30% was measured. Earlier, Mattsson et al [8] had shown that only the NACP [7] and the Vinten Model 631 chamber [3] had negligible polarity effects at d_{max} in electron beams.

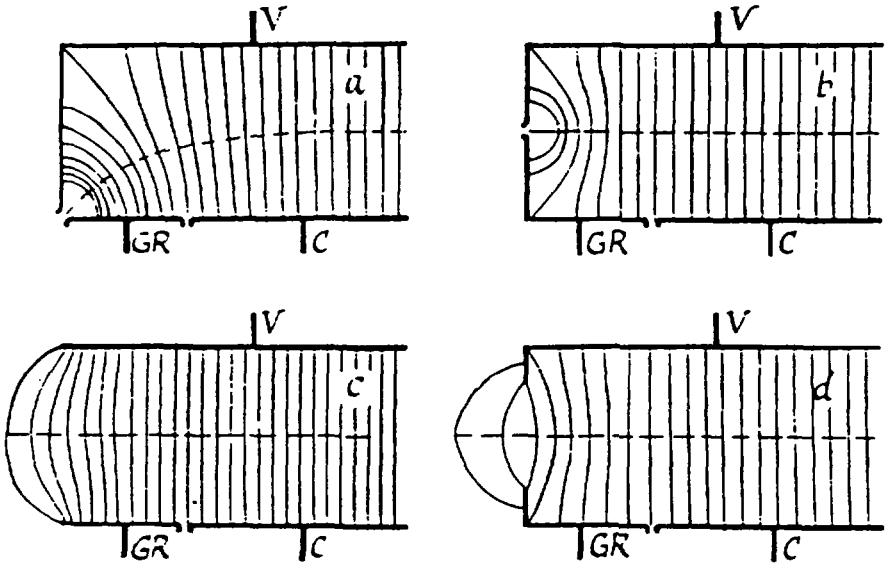

FIGURE 3. *Electric field patterns near the edge of a plane-parallel chamber for various guard ring (GR) configurations; charge-collecting electrode denoted by C. (from [1]).*

3. MEASUREMENTS OF p_u IN ELECTRON BEAMS

Measurements with plane-parallel chambers in electron beams have been made by a number of workers in order to investigate whether the perturbation correction factor p_u in Equ. 1 really is negligibly different from unity at $z = d_{max}$. The bulk of the experimental work on determining p_u (P_{repl} in [11]) has been carried out by comparing plane-parallel chambers against cylindrical chambers in electron beams with their effective points of measurement placed at the same depth. A number of experiments have been carried out on the PTW/Markus chamber which has a narrower guard ring than is believed to be necessary to ensure that p_u is unity [20,21]. Some of this work has indeed yielded p_u values as low as around 0.95 at $\bar{E}_z$ = 2 or 3 MeV [9]. However, the problem with such measurements is that the use of cylindrical chambers at these energies involves the large uncertainties in the values of the corresponding p_u for the cylindrical chambers [21,22].

Other experimental methods have involved comparing one plane-parallel chamber against another one, the latter being assumed to have unity perturbation correction factor. The instrument usually used as a *reference* is the NACP chamber (see above). Alternatively, comparisons have been made against the Fricke dosimeter [9,23]. These latter measurements are consistent with the assumption that the NACP chamber has an energy independent response down to $\bar{E}_z$ = 2 MeV. However, measurements with the Fricke system in low-energy electron beams are technically very difficult due to the relatively large volume of Fricke solution, which naturally can only yield a dose averaged over the volume, and the possible effects of the wall material of the vessel containing the solution [24].

It must be realised that all such measurements provide estimates not just of the perturbation due to the effect of the air cavity, but rather a *composite correction factor* which includes all components not explicitly taken into account, e.g. any electron backscatter deficiency effects - see section 5. Furthermore, there may even be other effects of the guard ring due to the electric field distribution at the edge of the air volume, as shown in Figure 3. It has been suggested that such an effect could be part of the explanation for the response of the PTW/Markus chamber [25].

All of the measurements reported in the literature have shown that the NACP and Holt/Memorial designs of chamber have a p_u equal to unity within a few tenths of one

TABLE II. EXPERIMENTAL DETERMINATION BY KUCHNIR AND REFT [28] OF PERTURBATION FACTORS FOR SEVERAL PLANE-PARALLEL CHAMBER TYPES. *$P_{repl,E}$ as a function of $\bar{E}_0$, the mean energy at the surface, and $\bar{E}_z$, the mean energy at the depth of measurement. The values were determined by comparison with a Farmer chamber using $P_{repl,cyl,E}$ from [11] and were normalised to 1.000 at the highest electron energy.*

$\bar{E}_0$ (MeV)	$\bar{E}_z$	NACP	Markus	Holt	Capintec	Exradin
4.7	2.5	0.993	0.966	1.002	0.969	0.985
5.2	3.1	0.997	0.976	1.004	0.964	0.984
8.0	4.7	0.994	0.993	1.003	0.985	0.992
11.0	6.4	0.990	0.994	0.995	0.976	0.992
14.0	7.6	0.996	0.998	0.997	0.986	0.994
17.0	12.3	0.993	0.991	0.994	0.991	0.989
20.6	18.4	1.000	1.000	1.000	1.000	1.000

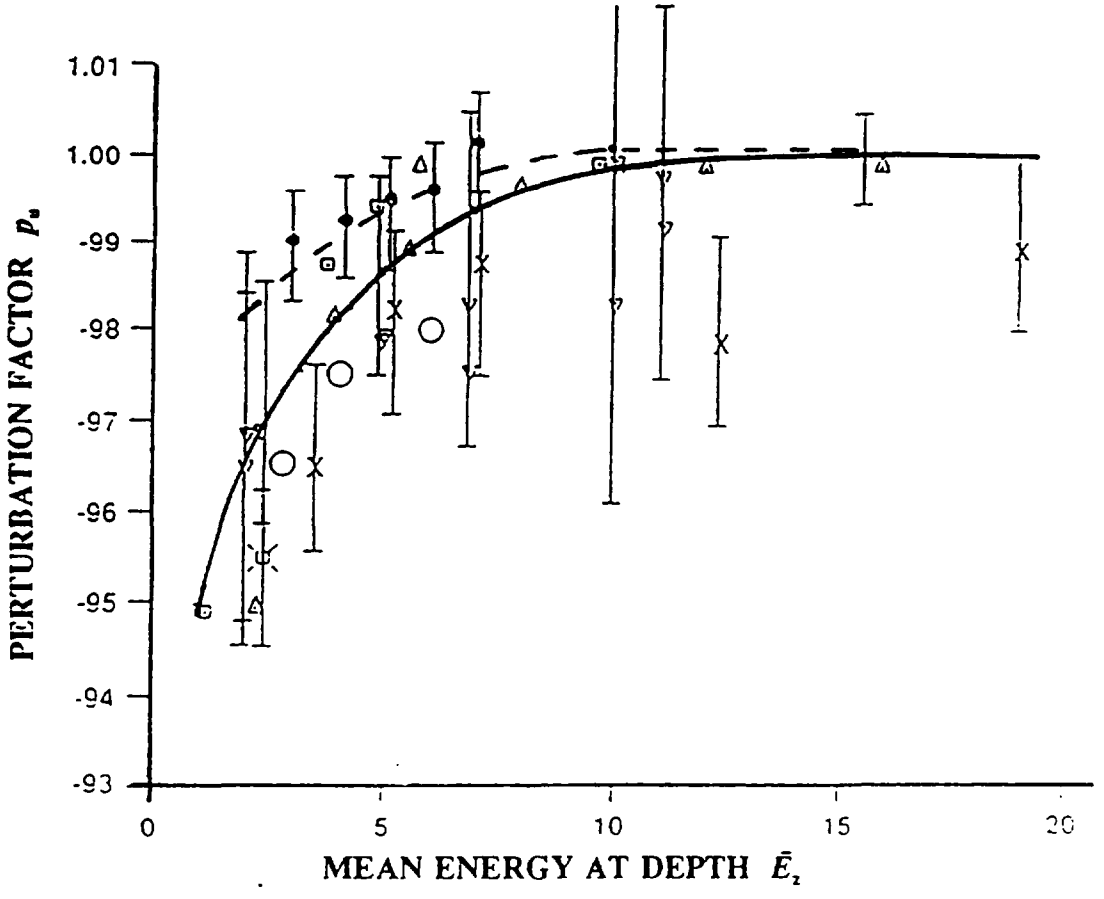

FIGURE 4. *Experimental determinations of the perturbation factor p_u, at d_{max}, as a function of $\bar{E}_z$ for the PTW/Markus chamber. Data points: □ [27]; ▽ [28]; × [29]; ○ [30]; ● [9]; △ [31]. The full curve is the least-squares fit to the data in [26]: $p_u = 1 - 0.072\exp(-.336\bar{E}_z)$. and the dashed curve is the adopted in [14] (adapted from [26]).*

percent, even at the lowest energies investigated. Other chambers exhibit p_u values which can be significantly different from unity. By way of a summary of the work to date, Figure 4, adapted from [9] and [26], is a compilation of measurements by many different authors for the PTW/Markus chamber.

Table II presents some recent results for a number of chambers investigated by Kuchnir and Reft [29]; their *reference* chamber was a cylindrical one, however (see above).

4. THEORETICAL WORK ON PERTURBATION IN ELECTRON BEAMS

The explanation for perturbation effects in low-density i.e. gas cavities was put forward by Harder [32]. He realised that the angular distribution of primary electrons changed with depth in electron beams and that this could lead to irregular patterns of (primary) electron fluence in and just behind gas cavities. He coined the term *in-scattering* for the phenomenon of an increased fluence in an ionization chamber, and suggested that a perturbation factor less than unity was needed to correct for the effect. It must be emphasised, however, that all discussion of perturbation effects is meaningless unless they are referred to a particular depth in the *undisturbed medium*. This is expressed in the following definition of a perturbation factor p_{cav} which corrects solely for the effect of the air cavity:

$$\Phi_{med}(P_{eff}) = \overline{\Phi}_{cav}\, p_{cav} \qquad (2)$$

where $\Phi_{med}(P_{eff})$ and Φ_{cav} refer to the primary electron fluence in the undisturbed medium (at $z = P_{eff}$) and in the cavity (averaged over the volume) respectively. Further one should note that this definition of the perturbation correction factor is only consistent with Equ. 1 if at the same time any "distortions" in the **energy** spectrum of this fluence caused by *in-scattering* etc. are negligible. Otherwise it would not be possible to use the standard computations of the stopping-power ratio, which are based on the Bragg-Gray requirements of **identical** fluences, differential in energy, in the medium and in the detector material.

Harder [32] used multiple-scattering theory, as developed by Rossi (see [20]) to derive an expression for the increase in fluence in a gas cavity. However, his derivation was strictly only valid for an initially plane-parallel beam on a very *thin* cavity [20,33]. Morris and Owen [3] applied the Harder theory to the geometry of their chamber design, modifying it to take account of the all-important guard ring. They obtained a value of $p_{cav} = 0.995$ for $\bar{E}_z = 0.5$ MeV, compared to 0.96 when the guard ring was not taken into account. They conducted experiments using an extrapolation chamber and showed that when varying the plate separation between 1 and 3 mm at $\bar{E}_z = 2$ MeV there was no evidence for any perturbation effect.

Olofsson and Nahum [33] made measurements with a specially constructed chamber with a *thick* cavity designed to show a large perturbation. They compared their measurements with the predictions of the Harder theory [32] and also with a refined version of the multiple-scattering approach given in [20] and in [21]. None of the theories predicted the measured values accurately, but the Svensson-Brahme expression [21] performed well at depths less than the dose maximum. It is important to realise that neither of the above theories took into account the **decrease** in planar electron fluence with depth, which sets in just before the depth of maximum dose. One should not expect predictions to agree, therefore, except at small depths. A theoretical approach that takes account, in approximate fashion, of the effect of *electron loss* has been developed [34]; the fluence in the air cavity was modelled by a fine mesh of straight electron tracks, with their angular distribution given by Fermi-Eyges theory [20]. This model predicted that the perturbation correction factor should eventually become

greater than unity at depths beyond the dose maximum. Gajewski and Izewska [35] applied the Fermi-Eyges form of multiple-scattering theory to the geometry of the PTW/Markus chamber. They also modelled electron loss in a similar manner to [34]. Their theory yielded $p_{cav} = 0.973$ at $\bar{E}_z = 2.2$ MeV, which is consistent with experiment.

The assumption behind the position of P_{eff} is that the chamber *samples* the electron fluence incident through the front window, with all electrons entering through the side walls prevented from reaching the sensitive air volume due to the geometry of the guard ring. This in turn assumes that there are relatively few electrons travelling at large angles; it is obvious that electrons incident at right angles to the beam direction will be able to contribute to the measured signal, irrespective of the width of the guard ring. However, at depth close to or beyond that of maximum dose such *perpendicular* electrons must be present. In fact, an appreciable fraction of the chamber signal at large depths arises from backscattered electrons. Consequently the choice of the inside of the front window for P_{eff} irrespective of depth cannot be justified.

Bjärngard and Kase [36] contains a very interesting discussion on the nature of the perturbation caused by differences in density between the air cavity and the surrounding chamber wall. In particular, they questioned the approach employed in [11] where the electron fluence correction factor, i.e. p_{cav}, and a gradient correction factor (instead of P_{eff}) are treated as two independent perturbations. They argued that this implied that the electron fluence could be perturbed even when no field gradient was present, which they contended was unphysical. They pointed out that the assumption in [11] that the gradient correction was unity at d_{max} was unjustified as both the directional distribution and the energy spectrum are changing rapidly at this depth.

Direct Monte-Carlo simulations of the dose in an air cavity at a depth in low-energy electron beams are currently underway [Ma, private communication]. Such simulations make very heavy demands on computer time to achieve the desired sub 0.5% precision even when the technique of correlated sampling is exploited [24]. Thus it is only just now possible to carry out such simulations. *It would be prudent to wait for the results of these calculations before finalising any new recommendations on plane-parallel chambers.*

5. BACKSCATTER EFFECTS IN ELECTRON BEAMS

Hunt et al [37] drew attention to the possibility of backscatter corrections for parallel-plate chambers irradiated in electron beams. They investigated the change in chamber response for different electron energies (in the range 5 - 14 MeV) for varying thicknesses and diameters of backscattering material and for varying backscatter material type. Electron backscatter was found to be proportional to atomic number of the scatterer and inversely proportional to the electron energy. Using PMMA as the scatterer backing the air volume of a chamber it was shown in [35] that the backscatter effects saturated at 4 mm thickness, independent of electron energy. However scattering effects did not saturate with diameter of the scatterer until diameters of several cm were reached, increasing with electron energy. Comparative measurements with different parallel-plate chambers showed differences in dose up to around 2% at lower energies, which were interpreted as a deficiency of electron backscatter into the air volume from the material backing the volume, as compared with water. This data has been linked by Klevenhagen [38] to his previous work on higher atomic-number scatterers [39]. Klevenhagen [38] has provided correction factors to allow for electron backscatter deficiency relative to water for a range of materials likely to back the air volume in practical chambers. Very recently, theoretical calculations of the effect of electron backscatter on the signal in an air cavity have been performed with a semi-empirical electron

transport code [40]. The results show a similar energy dependence as the Klevenhagen experimental data [39]

In summary, the above work strongly suggests that backscatter plays a role in the response of certain plane-parallel chambers. It should be part of any theoretical treatment of the variation of p_u with electron energy and with chamber material, but has so far not been taken into account (see section 4). Note that in the AAPM notation, this effect would be included in the factor P_{wall} as P_{repl} only concerns the effect of the air cavity. It is suggested, therefore, that *in future* p_u should be written as the product of two factors:

$$(p_u)^e = (p_{cav})^e \, (p_{wall})^e \qquad (3)$$

where the superscript *e* may be used to distinguish the factors from those applying in a ^{60}Co beam at calibration.

Recent Monte-Carlo work [17,41] on the response of plane-parallel chambers in ^{60}Co beams (see next section) shows that here too **electron** backscattering has a significant effect on chamber response. This serves to emphasise the near impossibility of designing a chamber which is *perturbation*-free in both electron and photon radiation.

6. RESPONSE IN COBALT-60

6.1. Introduction and Experimental findings

Plane-parallel chambers are not intended for absolute dose determination in megavoltage photon beams. However, many of the current calibrations of such chambers (see next section) are performed in a ^{60}Co beam, against a cylindrical, Farmer-type chamber which has been supplied with an N_X or N_K calibration factor. Thus it is essential to know how a flat chamber behaves in a Cobalt beam i.e. one wishes to know what the perturbation factor is.

Almond and Svensson [42] proposed a simple 2-component theory for the response of non-thick-walled cylindrical chambers in megavoltage photon beams. It was shown experimentally [22] that this theory worked reasonably well for the common designs of thimble chamber and values of p_{wall} based on this expression have been incorporated into many of the current national dosimetry protocols e.g. [11] as well as adopted by the IAEA [16].

Mattsson [8,43] investigated the effect of different wall materials in plane-parallel chambers on their response at a range of photon qualities. The response of different chambers was always normalized in a high-energy electron beam, it being assumed that any wall effects were negligible in such a beam. A subsequent theoretical treatment of the wall effect [44] has supported this assumption. It was found that the Almond-Svensson expression failed to predict the measured behaviour. Mattsson [43] ascribed the difficulties to the non-homogenous nature of the materials surrounding the air cavity in the NACP chambers he investigated. Since then several other investigations have confirmed these findings, e.g. [10,45]. Thus it has been difficult to obtain reliable values of the wall perturbation for use at the Cobalt calibration, e.g. [46].

6.2. Monte-Carlo Work

Rogers [17] has investigated the response of parallel-plate chambers in ^{60}Co radiation using the EGS4 Monte-Carlo system; the "new code" CAVRZ was employed. The PRESTA algorithm for optimising the electron transport steps was used together with a value of 1%

for ESTEPE; the choice of the parameters in the electron transport algorithm when simulating the dose in small air cavities is discussed in [47].

Rogers has introduced the factor K_{comp} which effectively describes the difference in chamber response, at Co-60, between that of a chamber with a completely homogeneous wall material, i.e. which acts as a *thick-walled* chamber in a ^{60}Co beam, and that of the actual chamber under investigation. In ICRU terminology [20] we can write

$$k_m = \left[s_{wall,air} \; (\bar{\mu}_{en}/\rho)^{air}_{wall} \; K_{comp} \right]^{-1} \qquad (4)$$

where we identify k_m as the correction for non-air equivalence of the (cylindrical) chamber wall in the expression [16,20]:

$$N_D = N_K \; (1-g) \; k_m \; k_{att} \qquad (5)$$

It is argued in [17] that K_{comp} is essentially the same quantity as P_{wall}, the correction for non-medium equivalence of the chamber wall, when the chamber is irradiated in phantom. The only difference between them is due to the effect of scattered photons from the rest of the phantom, which would not be present in the in-air calibration situation.

The geometry of the calculation was intended to correspond to the in-air ^{60}Co calibration. Thus 0.5 gcm^{-2} of buildup material was added to the front face of the chambers; this material was chosen to match that of the chamber's *predominant* material.

These Monte-Carlo simulations confirmed the *surprising* behaviour of certain plane-parallel chambers in ^{60}Co radiation that had been found in experiments, e.g. [43,45]. The energy deposition in the air cavity, i.e. the chamber response, was shown to depend very strongly on the material *behind* the cavity. This was ascribed to changes in electron backscattering (cf section 5). The results supported the conclusions of others [43,45,48] that when more than one medium is involved, "naive" models of ion chamber response are not valid, e.g. the 2-component expression [42] referred to earlier. Such models did not even predict the correct *direction* of the change in response when different materials were used for buildup caps (with the materials elsewhere unchanged). Reasonable agreement between the Monte-Carlo results and the various experimental ones was obtained. It was concluded that the Markus, Holt/Memorial and Exradin chambers could be treated as if they were "homogeneous" chambers i.e. K_{comp} and P_{wall} were both unity for build-up caps and phantom materials matching the composition of the chambers. The Capintec PS-033 and NACP chambers were, by contrast, definitely non-homogeneous in their behaviour. Thus for these chambers one simply cannot trust any simple theoretical model, which is consistent with the original findings of Mattsson [41]. This emphasized the need for very careful experimental determinations of ^{60}Co correction factors for plane-parallel chambers. One can also conclude from [17] that a reasonable degree of confidence can now be placed in the Monte-Carlo simulation of chamber response [24,49].

7. CALIBRATION METHODS

Plane-parallel chambers are not generally provided with buildup caps unlike cylindrical chambers. They are not built to be irradiated free in air in a ^{60}Co beam. Nevertheless, some means of calibrating them must be found. Mattsson et al. [8] reviewed the various possibilities. These included comparisons against a cylindrical chamber in a ^{60}Co beam *in-air* and *in-phantom* and in a high-energy electron beam *in-phantom*. In all cases the aim is to derive an N_D ($\equiv N_{gas}$) factor for the chamber such that the Bragg-Gray expression can be applied as in Equ. 1.

The NACP code [7] considered this question in detail. Its primary recommendation was that the calibration should be carried out by the user in a high-energy electron beam. $N_{D,pp}$ is then given by

$$N_{D,pp} = \frac{M_{cyl}\, N_{D,cyl}\, p_{u,cyl}}{M_{pp}\, p_{u,pp}} \qquad (6)$$

where $p_{u,cyl}$ is the perturbation factor for the cylindrical chamber in the electron beam, $p_{u,pp}$ for the plane-parallel chamber. The chambers are placed with their P_{eff}s at the same depth and $\bar{E}_0$ should be at least 18 MeV in order to minimise the uncertainty on $p_{u,cyl}$; it is assumed that $p_{u,pp}$ is unity at this energy for any chamber. The subsequent realisation that charge-storage effects could affect ion chamber readings means that the use of solid insulating plastic phantoms as specified in [7] should be avoided (see next section).

The alternative NACP recommendation, for those clinics which did not have access to a high-energy electron beam, was to perform the calibration in a ^{60}Co beam where the air kerma rate was known at a particular position. The chamber must have build-up material placed in front of the entrance window. Material is also placed behind the chamber to provide backscatter i.e. the chamber is irradiated *in-phantom* at the depth of the dose maximum. This measurement yields a value for $(N_{K,pp})_B$, where it should be emphasised that the effect of backscatter from the phantom is included (denoted by subscript B). Then $N_{D,pp}$ is given by

$$N_{D,pp} = (N_{K,pp})_B\, (1-g)\, (k_{pp})_B \qquad (7)$$

where $(k_{pp})_B$ is equivalent to $k_m k_{an}$ for cylindrical chambers [16,19,48] but now includes a correction for backscatter from the phantom. The value of (k_{pp})B for the NACP chamber had been determined experimentally [8] as 0.996±0.006 for this particular geometry. It was noted in [7] that the theoretical prediction of $(k_{pp})_B$, based on the 2-component theory [42] evaluated for the material in the front window of the chamber, did not agree with experiment. This is exactly what subsequent investigators have found [10,18,45]. It was stated in [7] that this second calibration method should be performed at the National Standards Laboratory in order to reduce the uncertainties.

A different approach was taken in the UK codes [4,13] and has also been more recently discussed by Attix [51]. Here the calibration is carried out by the user in a ^{60}Co beam. The Vinten model 631 flat chamber (see above) is compared against the NE2561 secondary standard chamber in a PMMA phantom with their centres at 5 cm depth in a ^{60}Co beam. Once again the wall effect of the plane-parallel chamber must be known in ^{60}Co radiation and, as for the NACP chamber, theoretical predictions did not agree with experiment [13].

This *in-phantom* method yields the $N_{D,pp}$ value directly through

$$(N_D)_{pp} = \frac{M_{cyl}\, N_{D,cyl}\, (p_{wall,cyl})_{Co}}{M_{pp}\, (p_{wall,pp})_{Co}} \qquad (8)$$

which is essentially the same as Equ. 6. except that now the comparison is done in a ^{60}Co beam rather than in a high-energy electron beam: the subscript *Co* has been added to the p_{wall} factors to emphasise this. In fact, the UK code [13] was not based on the N_D formalism, giving instead C_e values for the 631 chamber. Other protocols have recommended one or both of the methods mentioned so far. The IAEA protocol [16] merely referred to NACP[7].

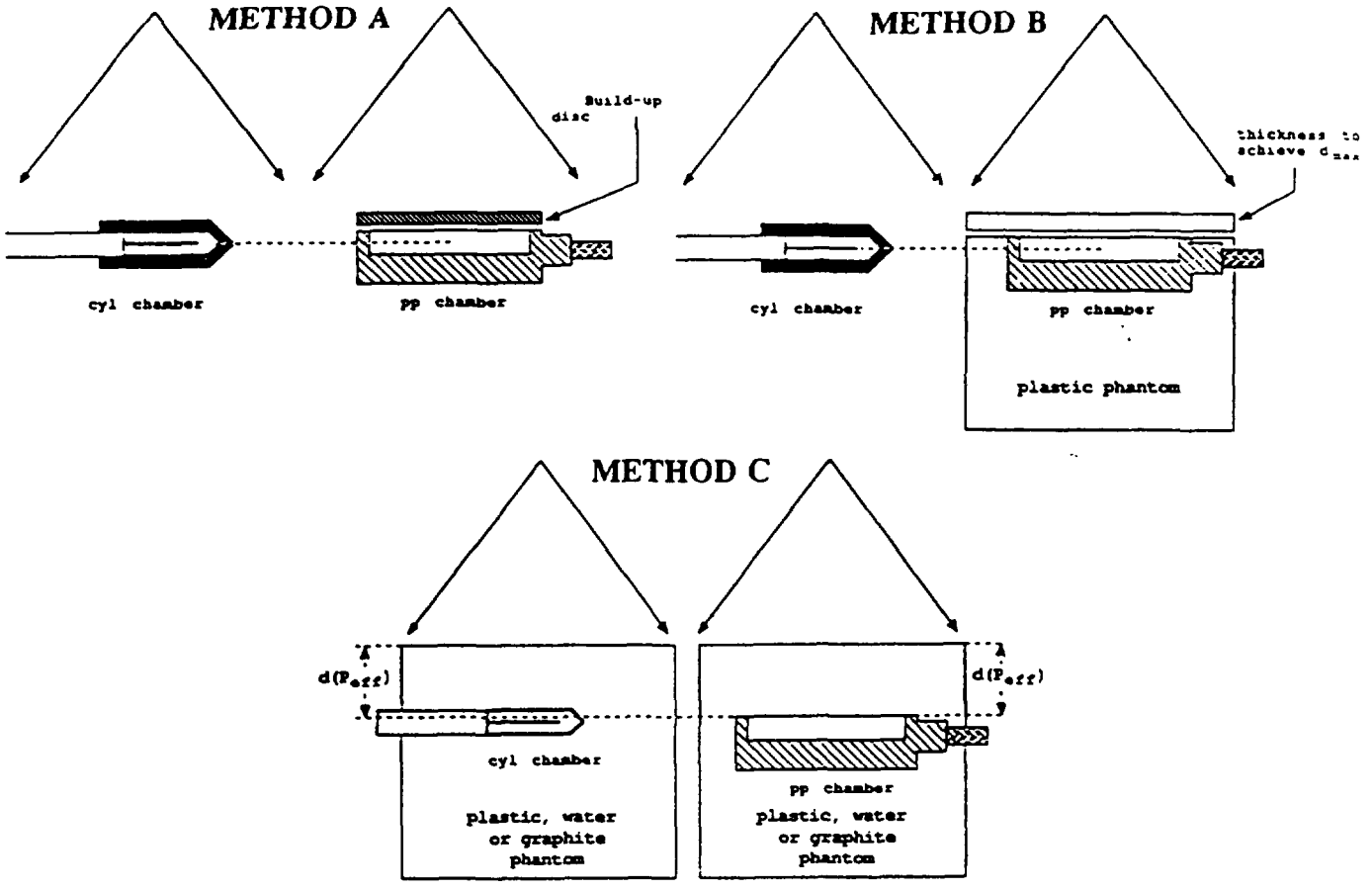

FIGURE 5. *The three alternative methods for calibrating a plane-parallel chamber in a ^{60}Co beam: A - determining $N_{K,pp}$ by intercomparison with a cylindrical chamber with a known $N_{K,cyl}$; B - as for A but with the plane-parallel chamber placed in a plastic phantom; C - determining $N_{D,pp}$ directly by an intercomparison with a cylindrical chamber with a known $N_{D,cyl}$ at a reference depth in a phantom, with P_{eff} at the same depth for the two chambers (adapted from [18]).*

The issue of calibration has been reconsidered in two recent reports [18,25]. The three possible calibration methods in a ^{60}Co beam are shown in Figure 5, taken from [18]. Method B is the same as that in [7] and Method C is equivalent to that in [13,51], both of which have been described above. Method A is a variation on method B but without the phantom; thus minimal backscatter is involved. It is recommended in [14].

Laitano et al [18] have determined experimentally the correction factors (i.e. k_{pp}, $p_{wall,pp}$ etc.) for the three alternative methods in Figure 5 for the various commercially available chambers. The plane-parallel chamber under study was always compared to the *reference* cylindrical chamber in a high-energy electron beam. The expression they and other authors used to derive the $(p_{wall,pp})_{Co}$ factors required to derive $N_{D,pp}$ from Equ. 8 was

$$(p_{wall,\,pp})_{Co} = \left(\frac{M_{cyl}}{M_{pp}}\right)_{Co} \left(\frac{M_{pp}}{M_{cyl}}\right)_{e} \left(\frac{p_{u,\,pp}}{p_{u,\,cyl}}\right)_{e} (p_{wall,\,cyl})_{Co} \qquad (9)$$

This expression follows from combining Equs. 6 and 8 and then requiring that the N_Ds be the same irrespective of radiation quality; the factor $(p_{u,pp})_e$ is assumed to be unity as in Equ. 6. Their results provide writers of future protocols with a very useful compilation data, which is reproduced here in Table III:

TABLE III. CORRECTION FACTORS FOR THE CALIBRATION OF PLANE-PARALLEL CHAMBERS IN A COBALT-60 BEAM. *Experimental determinations by Laitano et al [18] corresponding to the geometries A, B and C in Figure 5. The factors were derived by comparing the plane-parallel chamber with a reference cylindrical chamber made out of pure graphite including the central electrode in both a ^{60}Co and a 20-MeV electron beam. The statistical uncertainties (1 σ) are ±0.5% on the average.*

Experimental condition	In-air A2	A1	In-air B1	B2	In-phantom C1	C2	C3	C4
Build-up material	PMMA	Graphite						
Phantom material			PMMA	Polystyrene	PMMA	Poly-styrene	Water	Graphite
Correction factor	$(k_{pp})_{A2}$	$(k_{pp})_{A1}$	$(k_{pp})_{B1}$	$(k_{pp})_{B2}$	$(p_{wall})_{C1}$	$(p_{wall})_{C2}$	$(p_{wall})_{C3}$	$(p_{wall})_{C4}$
Chamber type								
PTW M23343 (Markus)	0.988	0.997	1.030	1.039	1.001	0.982	1.004	1.011
Capintec PS-033	1.002	1.015[a]	1.047	1.057	0.985	0.968	0.985	0.996
PTW M23346 (Schulz)	0.993	0.996	1.039	1.040	0.997	0.988	0.997	1.009
Holt/ Memorial[b]				1.018		1.006		
NACP 02	0.971	0.978	1.018	1.014	1.016	1.006	1.026	1.020

[a] Polystyrene build-up
[b] The Holt chamber is specifically designed to be used only in a polystyrene phantom

TABLE IV. A COMPARISON BETWEEN THE CORRECTION FACTORS OBTAINED IN [18] AND THOSE OF OTHER AUTHORS. *Data refers to the calibration of plane-parallel chambers in a cobalt-60 beam. See Table IV for the meaning of A1, C2 etc. Data from "other authors" modified by applying p_{cel} = 1.008 where necessary.*

Chamber type	Experimental condition	Correction factors		Ratio Other/This
		This work	Other authors	
PTW M23343	A1	0.997±0.4%	0.993±0.4%[a]	0.996
(Markus)	C1	1.001±0.4%	1.004±1.1%[b]	1.003
Capintec	B1[g]	1.047±0.5%	1.044±0.6%[c]	0.997
PS-033	C2	0.968±0.4%	0.951±1.3%[b]	0.982
Holt/	C2	1.006±0.5%	0.985[d,f]	0.979
Memorial			1.011±0.2%[e]	1.005
NACP 02	A1	0.978±1.0%	0.982±0.5%[c]	1.004
			0.980±0.4%[a]	1.002
	B1[g]	1.018±1.0%	1.015±0.6%[c]	0.997
	C1	1.016±1.0%	1.006±0.3%[c]	0.990
	C4	1.021±1.0%	1.027[c,f]	1.006

[a] Wittkämper et al [45]; [b] Kubo et al [31]; [c] Mattsson et al [8]; [d] Krithivas and Rao [53]; [e] Kubo [54]
[f] Uncertainty not reported by authors; [g] Data normalized to a 10.5×10.5 field

Laitano et al [18] also made a compilation of the correction factors determined by other workers and corrected these, where necessary, for the effect of the graphite central electrode of the Farmer cylindrical chamber, taking p_{cel} = 1.008 at ^{60}Co. It should be noted, however, that Andreo et al [52] have recently questioned this value. These comparisons are given in Table IV.

To summarize, there are a number of alternative calibration methods, some of which are in use in the various national protocols. The user must be given clear guidance as to which method is preferable in a given situation. There are strong arguments in favour of the intercomparison in a high-energy electron beam as it avoids any factors concerned with the response of the plane-parallel chamber in a ^{60}Co beam. The new AAPM recommendations [26] endorse this conclusion.

There will be some clinics which do not have access to either high-energy electron beams or to ^{60}Co. In such cases factors must be determined for use at other photon qualities, e.g. 4 MV; the new UK electron code, currently in preparation, will contain such data. Our own measurements (unpublished) and those by Wittkämper et al [45] for qualities up to 8 MV indicate only very small changes from the ^{60}Co values given above.

8. NON-WATER PHANTOMS

Water is the preferred phantom material for absolute determinations of the absorbed dose. However, for low-energy electrons and plane-parallel chambers the positional uncertainties can become significant and some of these chambers may be difficult to waterproof. Thus all protocols make separate recommendations which recognise the need for solid phantoms for use with plane-parallel chambers.

Typically some standard industrial plastics have been used, mainly PMMA and polystyrene. In older protocols, essentially pre-1981, no major differences were recognised between these and water, except for electron density differences. However, it is now accepted that four types of problems may be associated with their use:

i) depths must be scaled to the equivalent depth in water. A number of approaches have been used, scaling by electron density, by stopping power or range, by 50% depth, etc. A discussion of some of these can be found in [55].

ii) because of different scattering properties, electron fluence build-up changes with material [7,56,57]. This can give up to about 3% corrections to measurements in polystyrene at about 5 MeV effective energy at the measurement point [58,59]. PMMA is often taken to exhibit negligible differences to water due to this. However there is evidence to support corrections of up to about 1% at lower energies [60].

iii) for insulating phantoms, *charge-storage* effects, arising from electrons stopped in the material and unable to disperse, can modify the measured ionisation in a cylindrical cavity during subsequent irradiation [61,62]. These effects can be large, depending on the material, the accumulated dose and the dose-time history of the phantom. Charge storage effects are minimised by using phantoms made up of a series of sheets, each as thin as possible and no more than 2 cm, rather than using solid block phantoms [63]. They do not appear to affect measurements with plane-parallel chambers. The principal calibration method recommended in [7] can be influenced by this effect as it involves an intercomparison between a plane-parallel chamber and a cylindrical one in a plastic phantom in a high-energy electron beam.

iv) sample variations can occur between different manufacturers, mixes or batches of the same nominal plastic. For example, there are well-documented differences for electron beam measurements carried out in clear or white polystyrene [57].

Some protocols recommend alternative materials specifically formulated for dosimetric purposes and available commercially. For example, A-150 plastic is included in [12,16]; it is conducting and therefore eliminates charge-storage problems. Epoxy-based water-substitutes are included in [55] and are likely to be increasingly mentioned in new protocols for low-energy electrons. They exhibit negligible charge-storage effects and can show only small effects of types (i) and (ii) above, depending on formulation. However, there may be different formulations available under similar generic names; thus sample variability cannot be ruled out.

9. SUMMARY AND CONCLUSIONS

This report has covered most of the aspects of the use of parallel-plate chambers. Its main points are:

- Sufficient data now exists on the commonly used plane-parallel chambers to recommend overall p_u factors in low-energy electron beams; these depart significantly from unity for certain chambers

- Plane-parallel chamber response in ^{60}Co radiation is now much better understood but it is still not possible to predict correction factors theoretically; measurements must be performed. A large body of such data is now available

- The method of choice for calibrating plane-parallel chambers (i.e. deriving N_D) is an intercomparison with a cylindrical chamber in a high-energy ($\bar{E}_0$> 20 MeV) electron beam. The main issue is the reduction of uncertainties involved in the determination of N_D. A second issue is whether the user or the Standards Laboratory carries out the calibration.

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TESTING OF THE IAEA CODE: ABSORBED DOSE DETERMINATION AT Co 60 GAMMA RADIATION

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Abstract

At several Primary Standard Dosimetry Laboratories measurements of absorbed dose to water have been performed with ionization chambers of different types. These ionization chambers are calibrated against both, primary standards of air kerma and water absorbed dose. Using the formalism of the IAEA Code of Practice the absorbed dose to water in Co 60 gamma beams was derived and compared with direct measurements of water absorbed dose. This yields a very valid test of the IAEA Code.

1. INTRODUCTION

The method of absorbed dose determination on which the IAEA International Code of Practice (TRS 277, 1987) [1] is based involves the use of ionization chambers calibrated free in air in terms of air kerma K_a at Co 60 gamma radiation. The formalism is given to derive the absorbed dose D_w in high-energy photon and electron beams. In testing the IAEA Code it is essential that at Co 60 gamma radiation the absorbed dose values measured according to the IAEA Code are in agreement with the measurements based on an absorbed dose primary standard.

National Primary Standard Dosimetry Laboratories and the BIPM (PSDL) have developed fundamental methods of water absorbed dose determination. It is at this level where the first step in testing of the IAEA Code must be carried out, as here the uncertainties in the air kerma and the absorbed dose measurements are at their minimum values achievable .

At the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, Germany the calibration of about 15 different ionization chambers in terms of air kerma and water absorbed dose at Co 60 gamma radiation has been performed. These measurements add to the information available from investigations [2], [3] and calibrations performed in the past. Similar work was carried out at the BIPM [4] and the Bundesamt für Eich- und Vermessungswesen, Vienna, Austria (BEV) [5]. Their results are shown here, too.

2. METHOD

Following the IAEA formalism the absorbed dose is determined from equation (9) of the IAEA Code

$$D_w (P_{eff}) = M_u N_D (s_{w,air})_u p_u$$

which for Co 60 gamma radiation and inserting the equation (7) of the IAEA Code

$$N_{D,c} = N_K (1-g) k_{att} k_m$$

results in

$$D_w (P_{eff}) = M N_K (1-g) k_{att} k_m (s_{w,air})_{Co} p_{Co}$$

In the results of this investigation the absorbed dose values derived from this equation will be denoted by $D_w (N_K)$. The calculated conversion factor C_{calc} following the IAEA Code is the product of $(1-g) k_{att} k_m (s_{w,air})_{Co} p_{Co}$ and the correction factor k_r (see below).

Using an ionization chamber calibrated directly in terms of water absorbed dose (calibration factor N_w), where the reference point of the ionization chamber coincides with the center of the chamber volume on the chamber axis the corresponding equation is given as

$$D_w (P) = M N_w$$

At PSDLs the calibration of thimble-type ionization chambers in a Co 60 gamma beam in the water phantom is usually performed with the reference point of the ionization chamber on the axis at the center of the ionization volume. This reference point is placed at the reference depth of 5 cm. The absorbed dose values derived following this procedure will be denoted $D_w (N_w)$.

As P_{eff} is shifted by r/2 towards the radiation source in relation to the point P, in comparing both procedures a correction factor k_r is applied to relate both methods to the same depth in the phantom [6]. k_r is given by $k_r = 1 + \delta\, r/2$ with

$$\delta = 1/M(P)\ \left|dM(P)/dz\right|$$

where M(P) is the reading in the reference depth of 5 cm and $\left|dM(P)/dz\right|$ is the absolute amount of the gradient of the reading (representing the depth dose curve) at that depth.

The calibration factors N_K and N_w are determined by comparison against the primary standards of air kerma and water absorbed dose, respectively. The measured ratio N_w/N_K is denoted C_{exp}.

3. RESULTS

In table I the results of 13 different ionization chambers are shown, where the calibration measurements in the PTB Co 60 reference radiation field were carried out in December 1992 and January 1993. The overall uncertainty of the measured ratio N_w/N_K is estimated to be roughly 1% on the one standard deviation level including the uncertainties of the primary standards. In comparing the ratios of the absorbed doses $D_w(N_K)/D_w(N_w)$ for different ionization chambers the uncertainty (excluding those of the standards) may be half the value stated.

More than ten years ago Kuszpet et al. [2] at the PTB have determined C_λ and C_E conversion factors and stopping power ratios using calibrated ferrous sulphate dosemeters. Their measurements performed very similarily as those carried out now have been re-evaluated taking into account the change in the primary standard of exposure [9] from 01.01.1986 on according to the CCEMRI recommendation [10]. The results are close to those measured nowadays.

In 1989 an indirect comparison of the water absorbed dose standards of the PTB and the National Research Council (NRC), Ottawa, Canada was carried out for 18 and 20 MV X-rays using five ionization chambers of different types as transfer instruments. The comparison was linked to

Table I. Results of PTB measurements (December 1992 - January 1993)

Ionization chamber type	Serial No.	Build-up cap diameter mm	material	N_w/N_K measured ratio	Conversion-factor C_{calc}	$\frac{D_w(N_K)}{D_w(N_w)}$
NE 2561	# 240	17.0	Delrin	1.0829	1.087	1.004
NE 2561	# 244	17.0	Delrin	1.0838①		1.003
NE 2561	# 274	17.0	Delrin	1.0848		1.002
NE 2561	# 275	17.0	Delrin	1.0836		1.003
PR 06	# 65838	18.2	PMMA	1.0893①	1.092	1.002
PR 06	# 66223 A	18.2	PMMA	1.0897		1.002
M 23331	# 412	15.0	PMMA	1.0940①	1.090	0.996
M 23332	# 272	12.0	PMMA	1.0924①	1.095	1.003
NE 2571	# 977	15.0	Delrin	1.0956①②	1.096	1.000
NE 2571	# 1748	15.0	Delrin	1.0803②		1.015
NE 2505/3,3A	# 519	16.6	PMMA	1.0830	1.092	1.005
NE 2505/3,3A	# 521	16.6	PMMA	1.0667		1.020
NE 2505/3,3B	# 1706	16.6	PMMA	1.0764	1.088	1.015

① This chamber has been calibrated regularly since two years, the calibration factor being constant within 0.15 %

② Measurement were repeated, the results are within 0.1 %

Table II. Results of $D_w(N_K)/D_w(N_w)$ obtained for ionization chambers used as transfer instruments at a comparison between NRC and PTB. The C_{calc} values used are 1.096 and 1.083, respectively.

Ionization chamber	Serial No.	N_w/N_K at PTB	N_w/N_K at NRC	$D_w(N_K)/D_w(N_w)$ at PTB	$D_w(N_K)/D_w(N_w)$ at NRC
NE 2571	# 667	1.092	1.092	1.004	1.004
	# 1527	1.087	1.093	1.008	1.003
PR 06	# 64037	1.084	1.085	0.999	0.998
	# 65838	1.080	1.084	1.003	0.999
	# 66564	1.087	1.084	0.996	0.999

existing Co 60 gamma radiation absorbed dose standards and to air kerma standards by comparing the measurements of those quantities at the BIPM, NRC and PTB [3].

The PTB air kerma primary standard is described in detail in [7]. The primary standard of absorbed dose is based upon a chemical method, where the total absorption of 5.6 MeV electrons produced by a microtron is used to calibrate the radiation response of the Fricke solution [8]. The resulting uncertainty in the absorbed dose to water is about 0.7 % (one standard deviation). As primary standard of water absorbed dose the NRC uses Fricke solution whose calibration is based on measurements with a water calorimeter and a calculation of the heat defect (11). Using the data given in [3] the ratio of $D_w(N_K)/D_w(N_w)$ was calculated and the results are presented in table II.

Any calibration at a PSDL which is in terms of both water absorbed dose and air kerma can be referred to the generation of a $D_w\ (N_K)/D_w\ (N_w)$ value. As an example the calibration of the NE 2571 Serial No. 377 of the University of Umea yielded a ratio of 1.080 for N_w/N_K which converted to the ratio of the absorbed doses is 1.012 for the conditions of the measurement differing from those of table I.

4. RESULTS FROM OTHER PSDLs

At the BIPM N_w and N_K was measured directly for 11 commercial ionization chambers. (NE 2561, NE 2571, Capintec C, Capintec G, T1 Exradin and T2 Exradin). It has been found that for chambers of the same type the ratio of the calibration factors is constant to better than 0.5 %. It is interesting also to note that measurements made with two different ionization chambers at a depth of 17 cm in water show that the ratio of N_w and N_K does not vary by more than 0.1 % from 5 cm to 17 cm [4]. With the kind permission of the author results to be published [12], [13] are given in table III. The absorbed dose to water primary standard at the BIPM is based upon the ionometric method using a graphite-walled ionization chamber embedded in a waterproof PMMA sleeve at the reference depth of 5 cm in the water phantom [14].

As a result of the co-ordinated research programme on testing the IAEA Code of Practice by the BEV [5] ten ionization chambers (with build-up caps) have been calibrated in terms of air

Table III. Information from the BIPM on $D_w(N_K)/D_w(N_w)$ determined from calibrations for different countries to whom the chamber belong.

		C_{exp}	C_{calc}	ratio	$\frac{D_w(N_K)}{D_w(N_w)}$
uncertainty		0.4 %	1.0 %		
chamber	country				
NEL 2561	Denmark	1.088	1.083	1.005	0.995
	IAEA	1.084		1.001	0.999
	Norway	1.091		1.008	0.992
	Netherland	1.091		1.007	0.993
NEL 2571	Canada	1.099	1.094	1.005	0.995
	Czechoslovakia	1.098		1.004	0.996
Capintec	Canada	1.093	1.083	1.010	0.990
	Canada	1.095		1.012	0.988
	Norway	1.093		1.010	0.990
Exradin T2	BIPM	1.092	1.072	1.020	0.980
		1.092		1.020	0.980
Exradin T1		1.103	1.089	1.014	0.986

C_{exp}: conversion factor determined experimentally
C_{calc}: conversion factor determined with the protocol of calculation of IAEA

kerma free in air at the BEV/OeFSZ Co 60 gamma beam. The ionization chambers were then placed (without build-up caps) in the water phantom with the effective point of measurement in the reference depth (5 cm) of the phantom, where the absorbed dose to water is derived from the BEV primary standard of absorbed dose, the graphite calorimeter [15]. The results can be seen in table IV.

Table IV. Data of $D_w(N_K)/D_w(N_w)$ obtained at the BEV [5].

Chamber	Internal radius mm	Material wall	cap	$D_w(N_K)/D_w(N_w)$
NE 2561 (NPL)	3.7	GRAPHITE	DELRIN	1.001
NE 2571	3.15	GRAPHITE	DELRIN	1.003
NE 2581	3.15	A-150	PMMA	1.005
PTW M 233641	2.75	PMMA	PMMA	1.001
ÖFZS TK 01	3.5	DELRIN	DELRIN	1.000
ÖFZS CC1	5.5	GRAPHITE	(4 mm)	1.001
PTW M 233642	2.75	PMMA	PMMA	1.003
PTW M 23332	2.5	PMMA	PMMA	1.003
CAPINTEC PR-06	3.2	C-552	PMMA	1.003
IC 10 (WELLH.)	3.0	C-552	PMMA	1.002

5. COMPARISON AND DISCUSSION OF RESULTS

The results can be discussed under different aspects:

a) with regard to the deviation of the mean value from one

b) with regard to the laboratories, where the measurements have been carried out,

c) with regard to the results for a given ionization chamber type

In total, data for 13 different ionization chamber types are presented here. As the serial number of the ionization chambers was not identified in every presentation of the results, the number of specimens of one type investigated can not be stated unequivocally. In the tables V, VI and VII results for specified ionization chamber types are given.

Looking at the data for the NE 2571 ionization chamber type for which data from four different laboratories are available (see table V) a good agreement is obvious. The mean value is very close to one. This means that absorbed determinations using the NE 2571 and the formalism of the IAEA Code give the same results as measurements based on a direct water absorbed dose calibration from a PSDL. The variation coefficient of half a per cent hints to a very good agreement between the PSDLs. Similar conclusions can be drawn from tables VI and VII.

However, it should be noted that the level of these investigations does not always correspond to that of an international comparison between PSDLs including the BIPM.

The comparison of dosimetry procedures based on a N_K calibration with those based on a N_W calibration should be carried out at the level of the PSDLs. This avoids increased uncertainties

Table V. Data for the NE 2571 ionization chamber from different sources.

Serial No.	Laboratory	Data from Table	$\frac{D_w(N_K)}{D_w(N_w)}$
# 667	PTB	II	1.004
# 1527	PTB	II	1.008
667	NRC	II	1.004
1527	NRC	II	1.003
unknown	BIPM	III	0.995
unknown	BIPM	III	0.996
unknown	BEV	IV	1.003
977	PTB	I	1.000
1748	PTB	I	1.015
377	PTB/Umea		1.012
		Mean	1.004
			±0.006

Table VI. Data for the NE 2561 ionization chamber from different sources.

Serial No.	Laboratory	Table	$\frac{D_w(N_K)}{D_w(N_w)}$	
# 240	PTB	I	1.004)	
# 244	PTB	I	1.003)	1.003
# 274	PTB	I	1.002)	
# 275	PTB	I	1.003)	
unknown	BIPM	III	0.995)	
unknown	BIPM	III	0.999)	0.995
unknown	BIPM	III	0.992)	
unknown	BIPM	III	0.993)	
unknown	BEV	IV	1.001	
		Mean	0.999	
			±0.005	

Table VII. Data for the Capintec PR 06 ionization chamber from different sources.

Serial No.	Laboratory	Table	$\frac{D_w(N_K)}{D_w(N_w)}$
# 65838	PTB	I	1.003
# 66223A	PTB	I	1.003
# 64037	PTB	II	0.999
# 65838	PTB	II	1.003
# 66564	PTB	II	0.996
# 64037	NRC	II	0.998
# 65838	NRC	II	0.999
# 66564	NRC	II	0.999
unknown	BIPM	III	0.990
unknown	BIPM	III	0.988
unknown	BIPM	III	0.990
unknown	BEV	IV	1.003
		Mean	0.998
			±0.006

by additional transfers of the calibration factors in the calibration chain from the PSDL to the users. Discrepancies at this level reported between protocols based on air kerma calibration factors and procedures using absorbed dose to water calibration factors [16] in Co 60 gamma beams are in contradiction with the findings given here.

Similar comparisons in high-energy photon beams show very good agreement, too [3], [17].

On the other hand, looking at the lower part of tables I and III the ratio of $D_w(N_K)/D_w(N_w)$ for other ionization chamber types differs up to 2 % from one. In table I the value for the NE 2571 in the fourth last line is obviously rather high. An explanation for this behaviour is not at hand. The ionization chamber presented in the last row of table I has undergone repair which may have caused a different behaviour of the chamber compared to other chambers of that type. For the Farmer type ionization chambers NE 2505 the information on the chamber wall and cap materials and dimensions used to calculate the data of the Code may be not as reliable as the experimental values of N_w/N_K. The component materials of these ionization chambers have changed over the years [18]. In table III the values for the Exradin ionization chambers deviate from one by an extent which is far above the experimental uncertainty for these data. This indicates the need for improvement in the calculation of the conversion factor C_{cal} (see table III).

6. CONCLUSION

The IAEA Code of practice has been tested in Co 60 gamma beams. For most ionization chamber types very good agreement was found between the absorbed dose values derived according to the IAEA Code and the results of measurements using ionization chambers calibrated in terms of water absorbed dose at PSDLs.

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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 %.

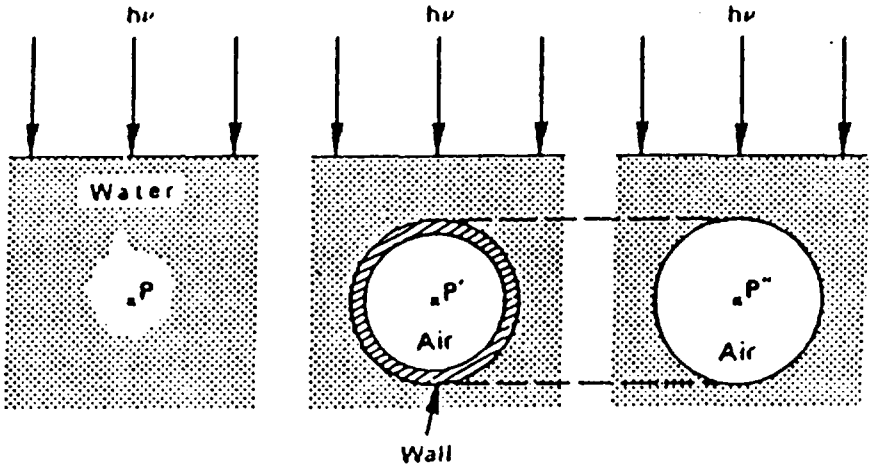


Fig.1. The absorbed dose at a point P in an undisturbed medium (water phantom) is to be determined. An exposure or air kerma calibrated chamber is placed with its centre P at that point. The chamber has been calibrated free in air. Included in the calibration factor are any disturbances due to the chamber 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

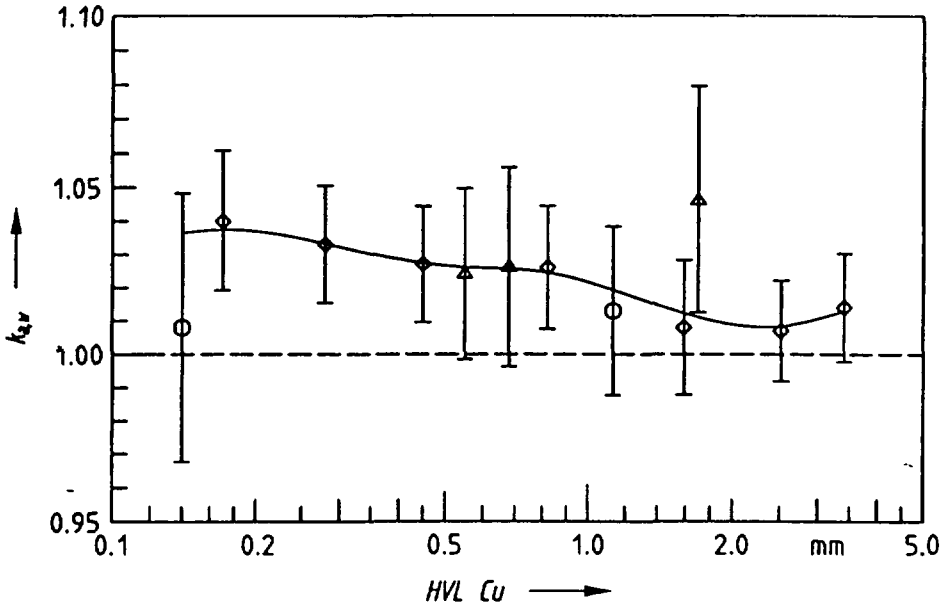


Fig.2. Energy dependence of the correction factor $k_{a,w}$ derived from the comparison of water absorbed dose calorimetry and air kerma measurement with a Farmer-type ionization chamber. The squares indicate the results of Seuntjens et al., the circles those of Mattsson and the triangles the results 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 %.

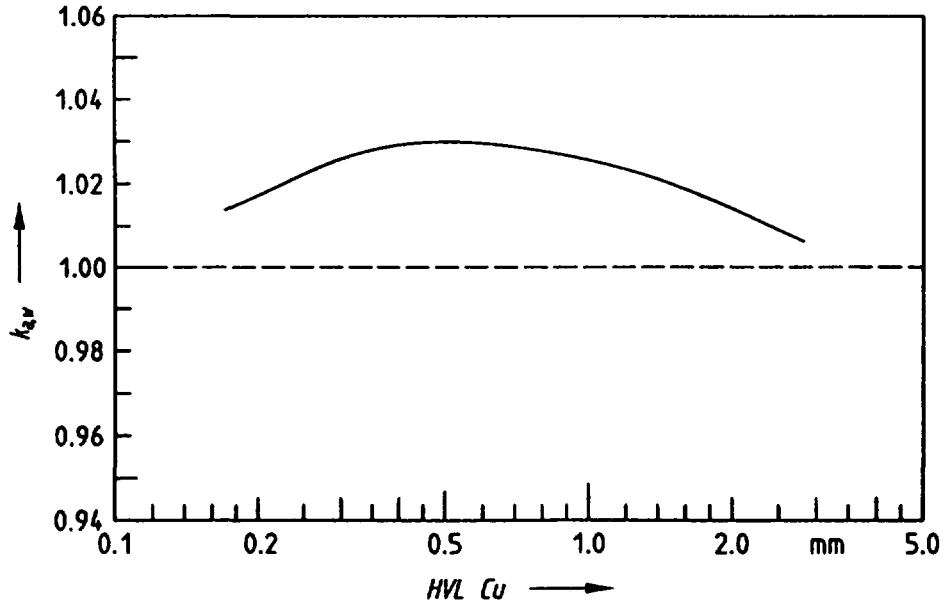


Fig.3. Correction factor $k_{a,w}$ for the PTW 23331 ionization chamber dependent on the radiation quality characterized by the HVL in Cu. The curve results from smoothed date taken from [3].

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 FACTOR $k_{a,w}$

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

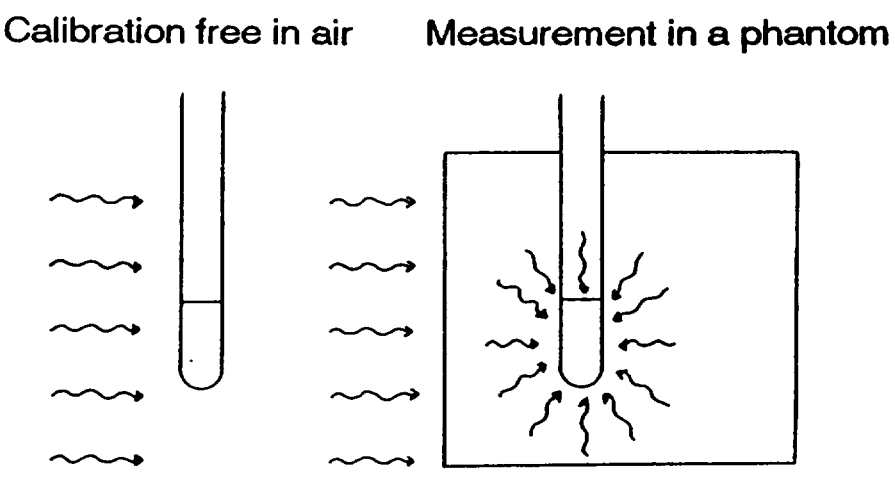


Fig.4. At the calibration of the ionization chamber in terms of air kerma free in air the chamber is exposed to an unidirectional radiation field of a given radiation quality. During the measurement at the depth in the water phantom the radiation field is modified with respect to its spectral and angular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

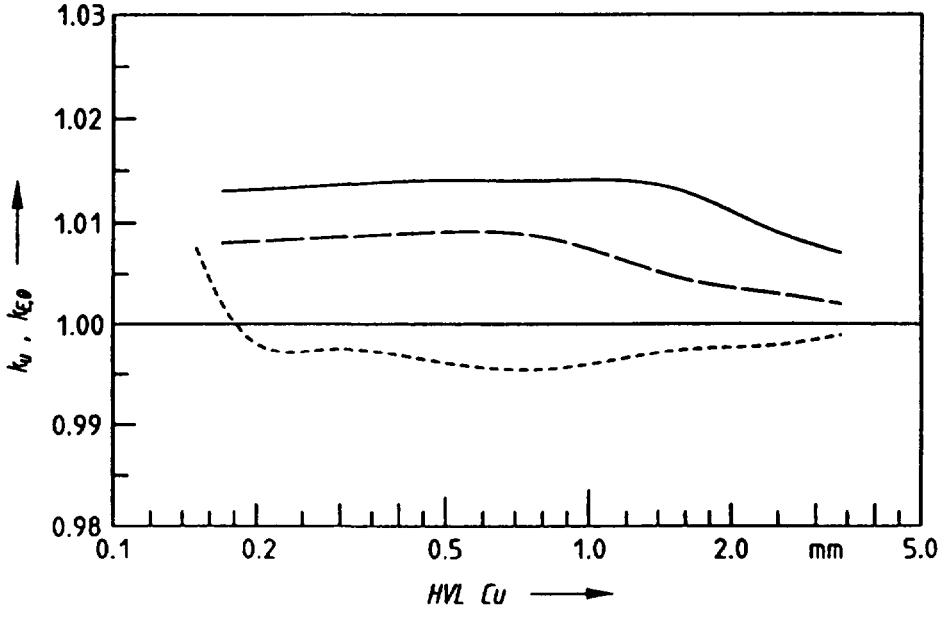


Fig.5. The component correction factor $k_{E,\theta}$ for the energy and angular dependence of response is shown for two ionization chamber types. For the NE 2571 (solid line) the curve is taken from Seuntjens at al. [13] and for the PTW M23331 the reference is Schneider and Kramer [29]. Seuntjens et 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

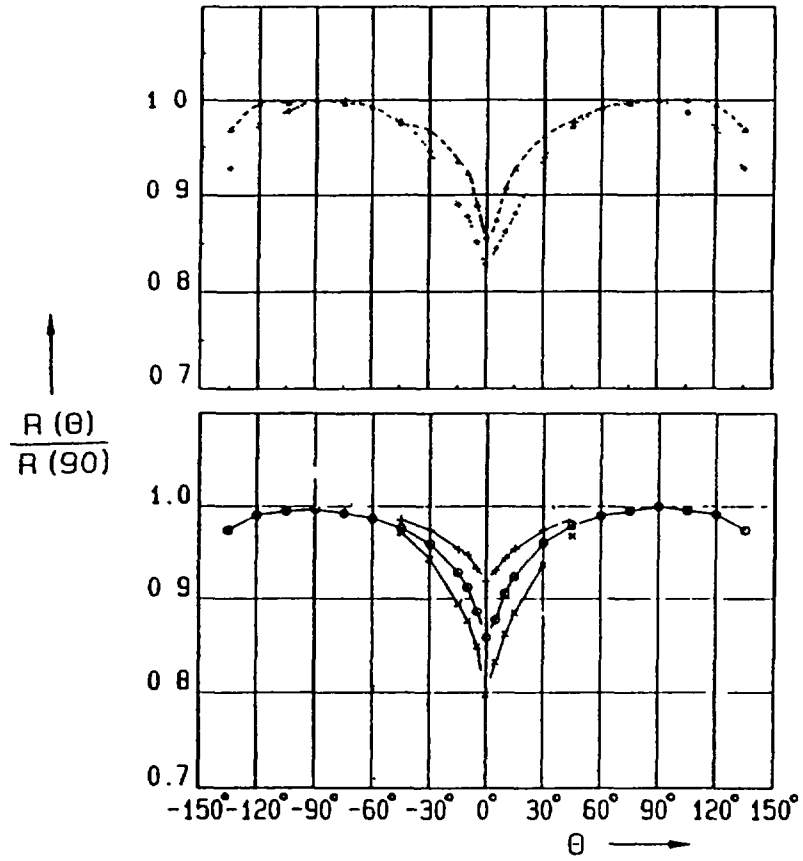


Fig.6. Illustration of the experimental data in the determination of $k_{E,\theta}$. As $k_{E,\theta}$ depends on two variables E and θ, only the angular dependence of response R (θ) of two ionization chamber types (NE 2571) and PTW M23331) is presented with the radiation quality as parameter. The curves 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

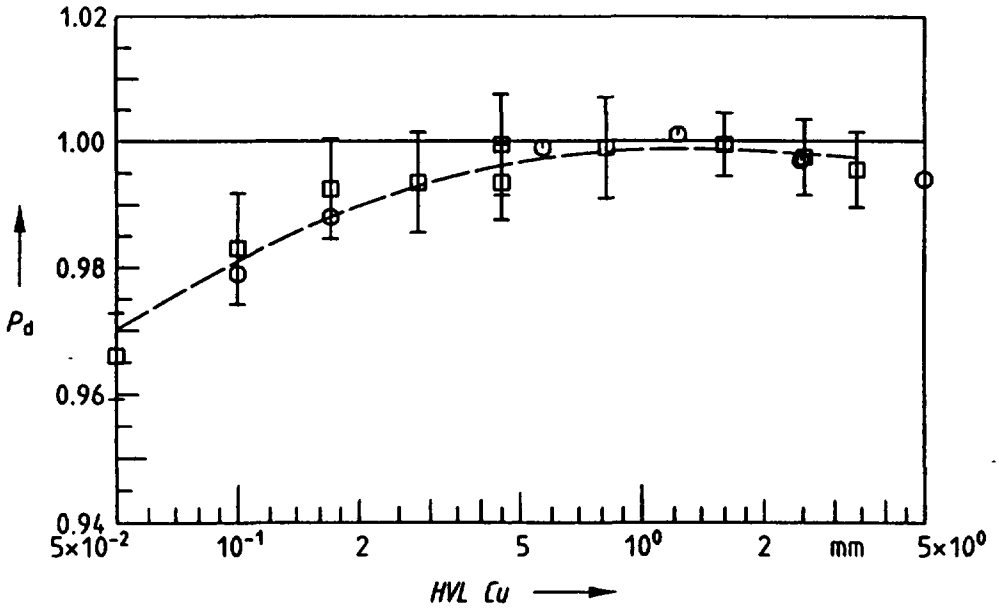


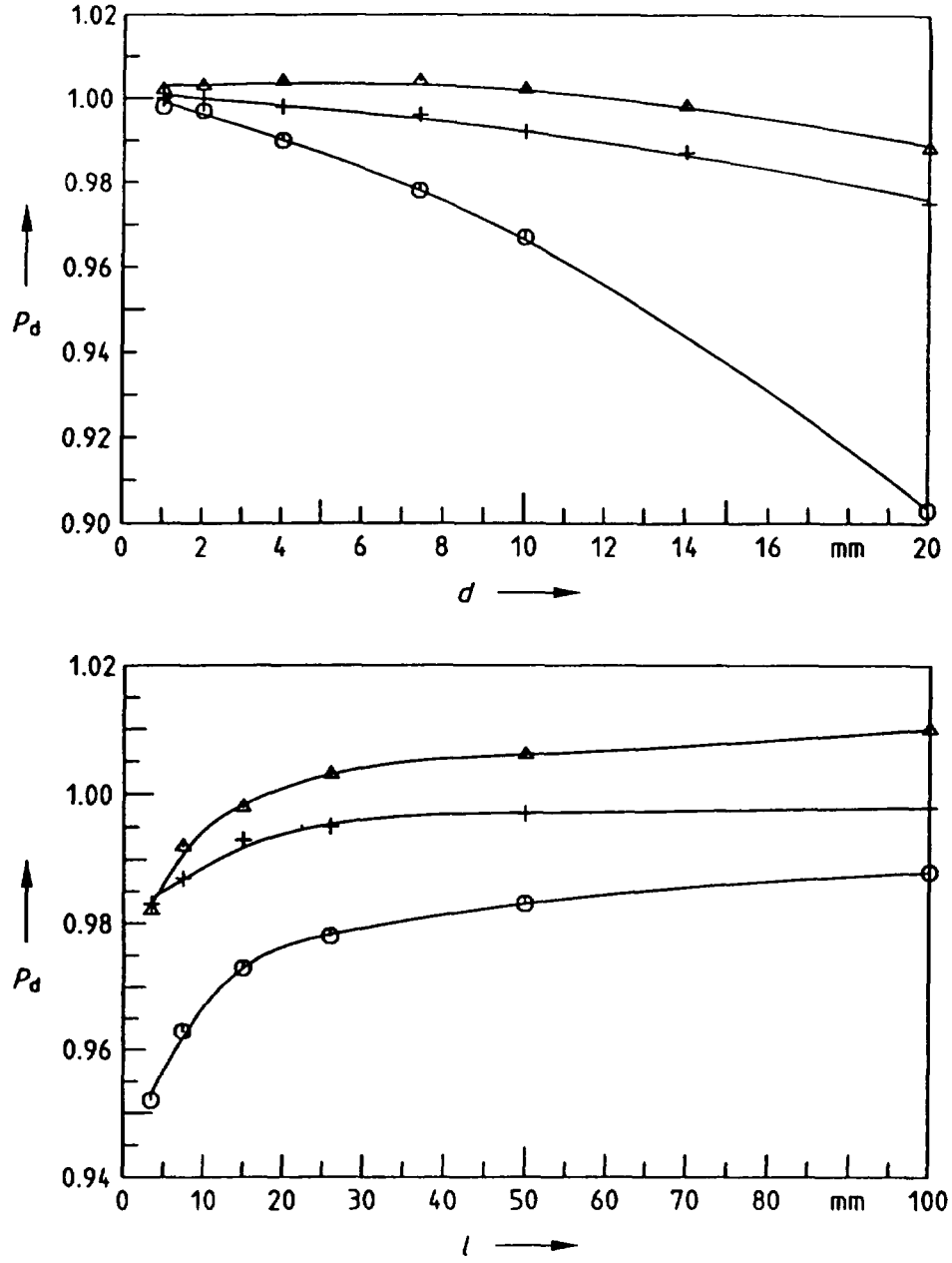
Fig. 7. The component correction factor p_d for the displacement of phantom material by the ionization chamber. Two Monte Carlo calculations (circles: Ma and Nahum [26]; squares. Seuntjens et al. [13] were carried out for the NE 2571 ionization chamber with statistical uncertainties of 0.2% and 0.5%,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

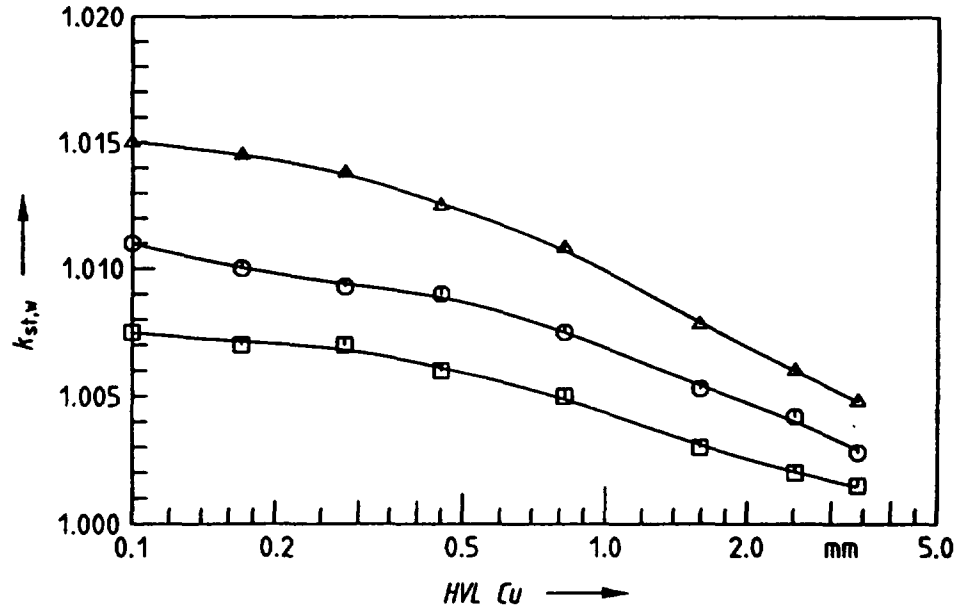


Fig.9. The energy dependence of the factor $k_{st,w}$ describing the influence of the stem in the water phantom was measured in different phantom materials (squares: SR6, circles: PMMA, triangles: graphite) for the PTW M23331 ionization chamber [29]. The measured values fall on a smooth curve indicating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

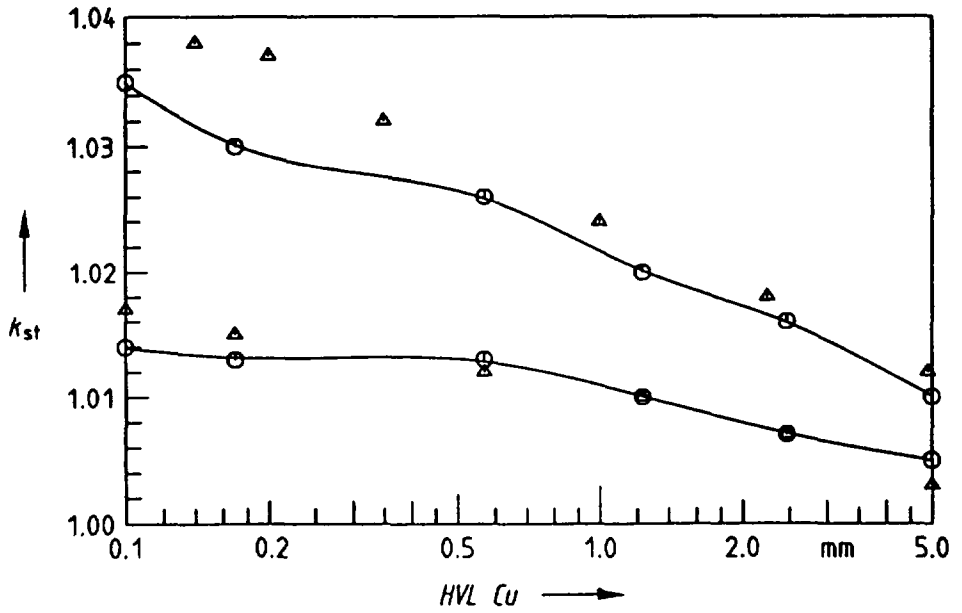


Fig.10. The stem effect correction factor k_{st} for the NE 2571 (upper curve) and NE 2561 (lower curve) ionization chamber calculated by Ma and Nahum [30] agree very well with measured values for the NE 2561 ionization chamber from Rosser [6] and for the NE 2571 ionization chamber determined experimentally 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

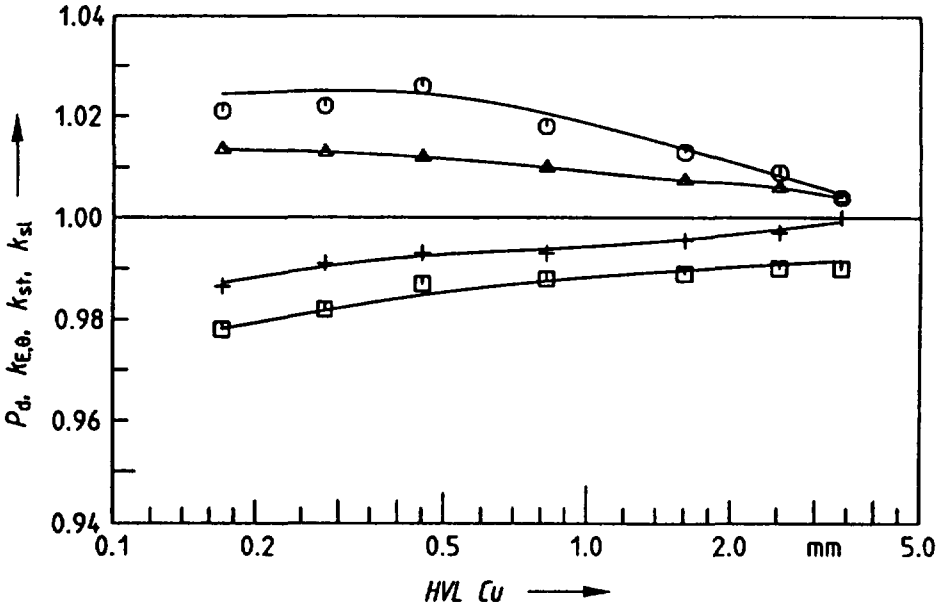


Fig.11. The component correction factor p_d, (squares) $k_{E,\theta}$, (circles) k_{st} (triangles) and k_{sl} (crosses) for the PTW M23331 ionization chamber determined by Schneider and Kramer [29].

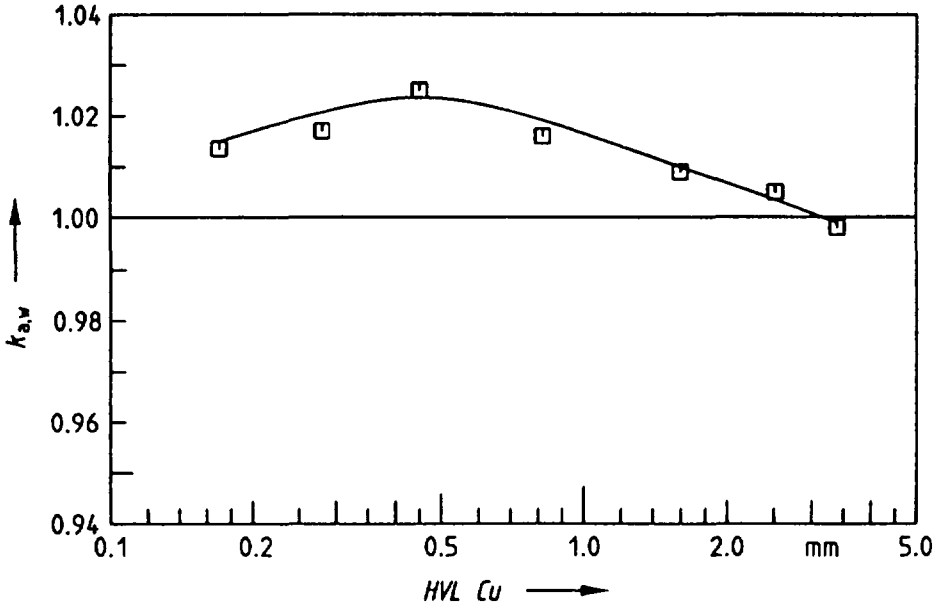


Fig.12. The correction factor $k_{a,w}$ for the PTW M23331 ionization chamber resulting from the multiplication of the curves given in figure 11. k_{sl} has not been taken into account, as the sleeve normally used with this chamber will have a much smaller wall thickness than that for which the curve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

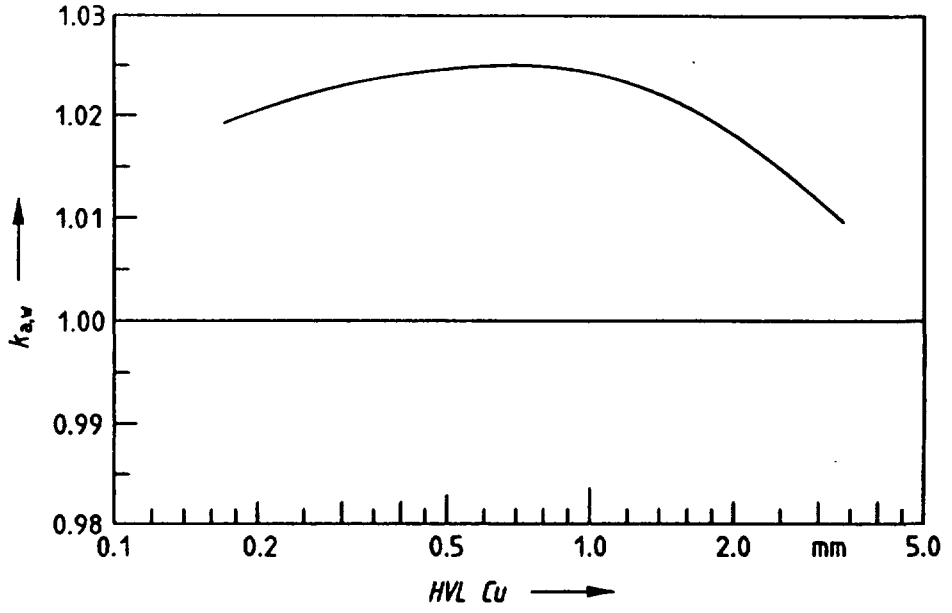


Fig.13. The correction factor $k_{a,w}$ for the NE 2571 ionization chamber as the product of p_d, $k_{E,\theta}$, and k_{st} from figures 5,7, and 10 respectively.

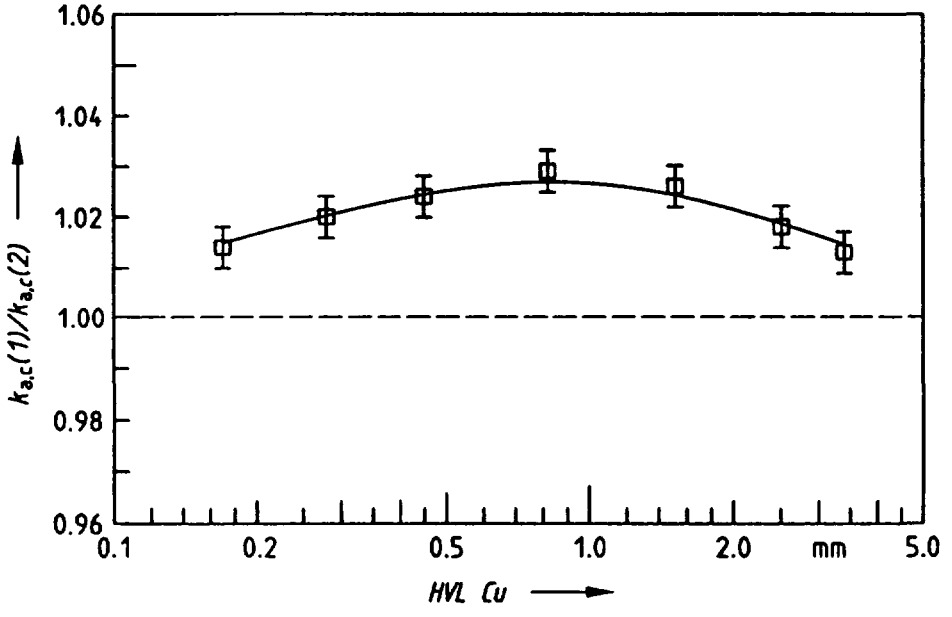


Fig.14. The ration of $k_{a,c}(1)/k_{a,c}(2)$ for two different ionization chambers (1:PTW M23331; 2: PTW M23332) as a function of radiation quality.

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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