Comparison between absorbed dose to water standards established by water calorimetry at the LNE-LNHB and by application of international air-kerma based protocols for kilovoltage medium energy x-rays

Nicolas Perichon, Benjamin Rapp, Marc Denozière, Josiane Daures, Aimé Ostrowsky, jean-marc bordy

Comparison between absorbed dose to water references established by water calorimetry at LNE-LNHB and by application of international protocols based on references in terms of air kerma for kilovoltage medium energy X-rays.

N. PERICHON, B.RAPP, M.DENOZIERE, J.DAURES, A.OSTROWSKY, J-M.BORDY
Laboratoire National Henri Becquerel,
Institut CEA LIST
CEA Saclay

Abstract

Until now, the only way to determine absorbed dose to water for medium energy X-ray beams was to calculate it from references in terms of air kerma by application of international dosimetric protocols. New standards in terms of absorbed dose to water had just been established at LNE-LNHB, the French primary standard laboratory for ionizing radiation, thanks to water calorimetry, for medium energy X-rays in the reference conditions described by protocols (at 2 cm depth in water). The aim of this study is to compare these new references in terms of absorbed dose to water measured by calorimetry in six medium energy X-ray beams to the dose values calculated from the application of four international protocols based on references in terms of air kerma: IAEA TRS-277, AAPM TG-61, IPEMB, NCS-10. The acceleration potentials of these beams are 80 kV; 120 kV; 150 kV; 180 kV; 250 kV and 300 kV with half value layers between 3.01 mm of aluminum and 3.40 mm of copper. A difference lower than 2.1 % was reported between the two methods. Standard uncertainty of water calorimetry being below 0.8 %, the one associated to the values from protocols being around 2.5 %, results are consistent considering the uncertainties. Calibration factors in terms of absorbed dose to water, established by application of calorimetry and air kerma dosimetric protocols were also compared. It appears that calibration factors established thanks to AAPM TG-61 protocol are in best agreement with the calibration factor established by water calorimetry.

1. Introduction

Medium energy X-rays, which tube high voltage is between 80 kV and 300 kV, are used in radiotherapy for low depth dose delivery (from millimeters to a few centimeters). These beams are used in some skin cancer treatments for lentigo maligna, kaposi's sarcoma for example [1-5]. They are also used for palliative care in the case of treatment of superficial rib metastases [5-7]. The other field of application of kilovoltage medium energy X-rays is imaging. Even if dose delivered by imaging are significantly lower than the ones delivered by radiotherapy, a current issue is how to take into account the dose received in the whole treatment process including kVCT imaging performed in order to plan the treatments or for the positioning of the patients.
The quantity of interest in radiotherapy is the absorbed dose to water. Currently, the only references available for medium energy X-ray beams are based on air kerma. The transfer dosimetric techniques described in international radiotherapy protocols and using air kerma have to be used in order to determine the absorbed dose to water. The reference conditions for these beams are described in protocols (IAEA TRS398 [8] for example) which recommend: a 2 cm reference depth in water, a 10 x 10 cm^2 irradiation field size at the reference depth and a distance source point of reference equals to the “usual treatment distance”. Moreover, in accordance with international protocols [8-12] , the limit between medium and high energy X-ray beams is arbitrarily defined by a tube high voltage of 300 kV. The limit between low and medium energy X-ray beams is not well

defined and varies with protocols.
In order to be able to apply dosimetric protocols using references in terms of absorbed dose to water, LNE-LNHB the French primary standard laboratory for ionizing radiation, had just set up new references in terms of absorbed dose to water for six medium energy X-ray beams in reference conditions of the protocols, using water calorimetry technique.
Calorimetric measurements were performed in six medium energy X ray beams: IEC61267 RQR6; IEC 61267 RQR9; IEC 61267 RQR10; CCRI 180; CCRI 250; ISO4037 selected among the norms and protocols ISO 4037 [13] ; IEC 61267 [14] and CCRI [15] (see Table 1).

Basic principle of water calorimetry is to determine absorbed dose to water by measurements of temperature rise under irradiation knowing the specific heat capacity of water [16-20]. Measurements are performed with a water calorimeter running at 4°C.
Experimentally, some correction factors have to be considered and the absorbed dose to water is given by equation 1:

$$D_w = C_p \Delta T (1-h)^{-1} k_c k_p k_\rho k_{prof}$$

with,

C_p the specific heat capacity of water for constant pressure at 4°C. Its value internationally adopted is 4204.8 $J.kg^{-1}.K^{-1}$ [21].

ΔT the temperature rise measured under irradiation. It is measured thanks to temperature probes inside a quartz vessel filled with ultrapure water.

h the water heat defect which takes into account the water radiolysis reactions under irradiation which can disturb the temperature rise measurements [22].

k_c the thermal conduction effect correction factor. This factor takes into account the disturbance of temperature rise induced by the different thermal conductivity of material surrounding the point of measurement (quartz of the vessel containing the water in which measurements are performed).

k_p the dosimetric perturbation correction factor. This factor takes into account the dosimetric perturbation induced by the calorimeter itself on measurements.

k_ρ calorimetric measurements being realized at 4°C and references being established at 20°C, this factor takes into account the difference of attenuation due to the difference of water density at these two temperatures.

k_{prof} the thermistor probes depth correction factor.

A new water calorimeter was set up at LNE-LNHB in order to perform measurements at a 2cm depth in water, which is the reference depth recommended by protocols for medium energy X-ray beams. A 10 x 10 cm^2 irradiation field was used at the reference depth at 50 cm from the source. A schematic drawing of the LNE-LNHB water calorimeter is given Figure 1.

This calorimeter is the first one among the primary standard laboratories to be able to realize measurements at 2 cm depth. Measurements at such a low depth were made possible by embedding the vessel, in which temperature rise measurements are performed, into the water phantom.

Results in terms of absorbed dose rate to water and their associated uncertainties are presented in Table 2.

This paper presents the determination of absorbed dose to water by application of four international protocols of dosimetry in radiotherapy: IAEA TRS-277 [10], AAPM TG-61 [9], IPEMB [12] and NCS-10 [11], for the same medium energy X-rays studied in calorimetry. A comparison between the new references in terms of absorbed dose to water at a 2 cm depth and their associated uncertainties established by water calorimetry at LNE-LNHB and the values determined by application of these protocols is made. Some correction factors had to be determined in order to be able to apply the protocols. Peixoto and Andreo [23] realized a theoretical intercomparison of the protocols applicable to medium energy X-ray beams and found a good agreement between the dosimetric data determined by protocols within 1-2 %. In the same way of this study, Munck [24] proposed a intercomparison of the protocols using a NE2571 ionization chamber and a cylindrical Scanditronix/Wellhofer type FC65-G chamber. The difference with the present study is that the calibration factor of the cylindrical Scanditronix/Wellhofer type FC65-G chamber traceable to PTB, was given at 5 cm depth in water whereas the protocol requires a 2 cm depth. So, because of a use at a 2 cm depth Munck underlined that strict adherence to protocol can't be done and conclude the study leaning in favor of calibrating medium kilovoltage x-ray beams at 2 cm depth. The comparison here presented respond to this attempt and can directly be performed in the conditions described by protocols (at 2 cm depth in water).

2. Materials

Tube high voltage

All irradiations were performed with the SEIFERT 320 kV ISOVOLT HS tube high voltage of LNE-LNHB. Maximum high voltage is 320 kV with a maximum power of 3 kW. Maximum intensity is 30 mA. The target of the tube is in tungsten and is angled to 20° relative to the beam axis. The only inherent filtration of this tube is 3 mm of beryllium. In order to obtain the quality (HVL) requested, additional removable filters in aluminum and/or copper (with high purity over 99.9 %) are used. A primary circular collimation (diameter 55 mm) is positioned at the exit of the tube at 21 cm from the target. A second squared collimation is used at 33 cm from the target (66 x 66 mm^2) in order to define the 10 x 10 cm^2 irradiation field size at 50 cm from the target. Measurements can be performed in terms of air kerma rate or absorbed dose rate to water because of the high stability of the power voltage of the tube.

Absolute measurements of air kerma

HVL measurements and references in terms of air kerma are determined thanks to the free air ionization chamber of the LNE-LNHB [25]. International comparisons were performed to assess this free air chamber and the good agreement with BIPM references (ratio of air kerma determined at BIPM by LNE-LNHB over the reference value of BIPM is 0.9999 (u = 0.0039) for CCRI180 beam and 0.9980 (u = 0.0039) for CCRI 250 beam [26]) allows us to be confident in the air kerma references and then into the calibration factor in terms of air kerma. Table 3 gives the characterization of the six beams here studied in terms of HVL.

References in terms of air kerma will be used to establish the air kerma calibration factors of the ionization chambers presented in the following section. These factors are necessary to apply the protocols based on references in terms of air kerma. The good knowledge of these references leads to reduce significantly the uncertainties.

Ionometric measurements

The ionization chambers used to perform ionometric measurements were chosen following the IAEA-TRS277 protocol which recommends cylindrical ionization chamber with a cavity volume between 0.1 and 1 cm^3. Two ionization chambers were selected: a NE2571 Farmer type (0.6 cm^3) and a PTW31010 Semiflex (0.125 cm^3).

In accordance with the AAPM TG-61 protocol, if the ionization chamber is not waterproof, waterproofing sleeve used should not leave an air space higher than 0.2 mm between the external wall of the chamber and the internal wall of the sleeve. Material of this sleeve should be in plastic. As the NE2571 ionization chamber is not waterproof, a waterproofing sleeve in PMMA was specially designed for this chamber in accordance with the recommendations above. The sleeve is also used for calibration in terms of air kerma.

NE2571 ionization chamber was chosen because of its stability and low energy dependence response in medium energy X-rays. Moreover, there is literature about the use of this type of ionization chamber in medium energy X-rays [9, 24, 27-28].

PTW31010 ionization chamber was used because it is a waterproof chamber which volume is in the range recommended by the protocol.

We can note that source to chamber distance and wall thickness of these chambers are sufficient to be in transient electronic equilibrium conditions in that way no build up cap needs to be used.

Phantom for ionometric measurements in water

A 30 x 30 x 30 cm^3 water phantom with wall in PMMA was used. The entrance window is a circular plate of quartz measuring 0.8 mm thickness and having a 12 cm diameter.

Monte Carlo simulations

Monte Carlo simulations of the device used for this study were realized at LNE-LNHB. Simulations of the tube high voltage, collimators and filtration were performed for the six beams studied with MCNPX code (using mcplib04 cross sections) [29].

3. Methods: Dose determination by application of international dosimetric protocols based on references in terms of air kerma

3.1 Theory of the protocols based on air kerma references

The methods followed in this study are the ones described in the four protocols: IAEA TRS-277 [10]; AAPM TG-61 [9] ; IPEMB [12] and NCS-10 [11]. Nevertheless, some correction factors needed to be determined or adapted to the conditions of this study. The theoretical approach is the same whatever the protocol considered. So, absorbed dose to water at a 2 cm depth is given by the general equation:

$$D_{w,2cm} = M_u N_K k_1 k_2 \left[\left(\frac{\bar{\mu}_{en}}{\rho} \right)_{w,air} \right]_{2cm}$$

with,

M_u The corrected reading of the chamber. It is performed in water at 50 cm from the source at a 2 cm depth in water with a 10 x 10 cm^2 irradiation field (in the same conditions as calorimetric measurements). For medium energy, the effective point of measurement of the chamber is the geometrical center of the cavity [10]. So, the chamber is positioned with the center of the cavity at a 2 cm depth in water. Values are corrected from atmospheric conditions: temperature, pressure and humidity; and for recombination. Specific ionometric measurements were realized to determine recombination correction factor value applying the following equation taken ?? extracted

from AAPM TG-61 protocol [9].

$$k_{rec} = \frac{1 - \left(\frac{V_H}{V_L}\right)^2}{\frac{M_H}{M_L} - \left(\frac{V_H}{V_L}\right)^2}$$

The results lead us to consider for the six beams studied a recombination correction factor equals to unity with an associated uncertainty of 0.05 % (k = 1).
Associated uncertainties of corrected readings in water are between 0.16 % and 0. 24% (k = 1) depending on the beam and the chamber considered.

N_K The calibration factor in terms of air kerma. It is given by the following equation:

$$N_K = \frac{K_{air}}{M_{air}}$$

It is determined thanks to the free air ionization chamber of the laboratory for each beam and ionization chamber studied. Associated uncertainties of air kerma calibration factor is between 0.34 % and 0.36 % (k = 1) depending on the beam and chamber considered.

$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$ The ratio of averaged mass energy absorption coefficient for water to air. The values used in this study are based on Hubbell and Seltzer's cross-sections [30-31] weighted by beams spectra determined by Monte-Carlo simulations of the device. The associated uncertainty is 2 % on this factor.

k_1 The factor which corrects for the difference of spectral distribution at the surface of the cavity between the calibration in air and the use at a 2 cm depth in water.

k_2 The factor which corrects for the non equivalent water of the ionization chamber when in the user's beam.

All of the four protocols applied in this study are based on this theoretical model. The difference lies in the name and the determination of the correction factors. The same corrected reading of the chambers in water, air kerma calibration factors and averaged mass energy absorption coefficient for water to air will be used to apply these different protocols. So, a description of the own factors of each protocols and their determination will be presented in the following sections.

3.2. The IAEA TRS 277 protocol

In this protocol, absorbed dose to water is given by the following equation

$$D_{w,Q} = M_{Q_0} N_{K,Q_0} k_{Q,Q_0} \left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm} R$$

$D_{w,2cm}$,M_u, N_K, $\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$ are the same as previously described.

k_u (equals to k_1 from theoretical approach) is the factor to account for variations in spectral distribution of X-ray beams used for the ionization chamber calibration free in air and that used by the user at a 2 cm depth in water. In accordance with the protocol, there are two components:
The first one takes into account the difference of beam quality between the beam used for calibration at standard laboratory and the one of the user. In this study the user and calibration beams are strictly the same so this first part of the factor equals to unity.
The second one corrects from the difference of the chamber response induced by the difference in spectral distribution when the chamber is calibrated in air and when used at a 2 cm depth in water (reference conditions). No values are proposed for this correction factor. The user has to check this variation not exceed 2.0 % and in this case is allowed to use a correction factor equals to unity with an associated uncertainty of 2.0 % (k = 1).
In order to determine the variation, Monte-Carlo simulations of the device were used. The spectral distribution of the six beams studied at a 2 cm depth in water (50 cm from the source with a 10 x 10 cm^2 irradiation field) were calculated. Then, Spekcalc and XCOMP5 programs [32-33] were used in order to generate spectral distribution in air whose characteristics (HVL, mean energy, general allure) match the ones of the distribution previously modeled. Spekcalc and XCOMP5 give us the filtration to use in order to generate the beams experimentally. So, we obtained an in air beam « equivalent » to the one at a 2 cm depth in water for each beams of interest (Table 4). Then we realized these equivalent beams experimentally and determined the calibration factor in terms of air kerma for the two ionization chambers used. The ratio of the calibration factors in terms of air kerma of the real beam to the equivalent one for each beam assessed is the factor wished. Results are given Table 5.

For each beam of interest and for the two ionization chambers the difference is below 2.0 % allowing us to choose a correction factor equals to unity with an associated uncertainty of 2.0 % according to the protocol (k = 1).

p_u is the correction factor which takes into account dosimetric perturbations.
Ma and Nahum [34] proposed a method to determine this correction factor. This is the one used in AAPM TG-61 protocol and called p_{disp} and which will be discussed in the following section.
A series of values is proposed by the IAEA TRS-277 protocol. They were applied. Nevertheless the exact definition of this factor and its mean of determination are not well described in the protocol. Users have to pay attention to consider the revised values of the coefficient and not the first ones. Associated uncertainties to these values is 2.0 % (k = 1).

3.3. The AAPM TG-61 protocol

In this protocol, absorbed dose to water is given by the following equation

$$D_{w,Q} = M_{corr} N_{D,w,Q_0} k_{Q,Q_0} \left[\left(\frac{\mu_{en}}{\rho}\right)_{w,air}\right]_{Q}$$

We decided to use the in-phantom method for all the beams in order to be consistent with the other protocols even if this method is not recommended below 100 kV in this protocol.

As usual, M_u, N_K, $\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$ are the same as previously described.

The global correction factor is defined as follows:

$$P_{Q,cham} = P_{E,\theta} P_{stem,water} P_{dis}$$

with,

$P_{E,\theta}$ the factor to take into account the change in the air kerma calibration factor due to the change of spectral energy and angular distribution of the beams.

$P_{stem,water}$ the factor to take into account stem influence on the ionization chamber readings (influence when ionization chambers is calibrated in air and when used in water).

P_{dis} the factor to take into account air kerma change at the point of measurement due to water displacement induced by the cavity volume, its wall and waterproofing sleeve if present.

Values of $P_{Q,cham}$ are given in the protocols for a NE2571 ionization chamber calibrated in terms of air kerma without proofing sleeve but used at a 2 cm depth in water with a proofing sleeve. In this study, the proofing sleeve was used both for air kerma calibration and measurements in water so the factor can't be directly applied. The factor which needs to be determined has to take into account the displacement of water induced by the presence or not of the sleeve. It is defined as the ratio of the displacement factor P_{dis} when the sleeve is present ($k_{dis,with\_sleeve}$) to the value when no sleeve is used ($k_{dis,without\_sleeve}$). It is given by the following equation:

$$\frac{k_{dis,with\_sleeve}}{k_{dis,without\_sleeve}}$$

These values were calculated thanks to Monte-Carlo simulations applying the method described by Ma and Nahum [34]. This factor is the ratio of the kerma in water at the reference depth in the medium none disturbed to the kerma in a low density water cavity (in fact density of air) in water. Volume considered is the one of the ionization chamber with its wall and the sleeve or not depending on the factor calculated. Uncertainties associated to the ratio of factors are 0.08 %.

Results of calculated factors are presented Figure 2. A good agreement is found between the values calculated without sleeve and the values determined by Seuntjens [35].
Thanks to Monte-Carlo simulations this factor was also adapted to application of the protocol for the PTW31010 ionization chamber.

The equation to determine absorbed dose to water by application of the TG-61 protocol is finally:

$$D_{w,z=2cm} = MN_k P_{Q,cham} \frac{k_{dis,avec\_capot}}{k_{dis,sans\_capot}} \left[\left(\overline{\frac{\mu_{en}}{\rho}} \right)_{w,air} \right]_{water}$$

3.4. The IPEMB and NCS-10 protocol

The general equation to determine absorbed dose to water is given by the following equation:

$$D_{w,Q} = M_{u,Q} N_{D,w,Q_0} k_{ch} \left[\left(\frac{\mu_{en}}{\rho} \right)_{w,air} \right]_{Q,Q_0}$$

In these two protocols a global correction factor is applied. In the IPEMB, a series of values is proposed. This one is based on studies from Rosser, Seuntjens, Ma and Nahum [27, 34, 36] . The uncertainties associated to this correction factor are also given and are 3.0 %. Whereas this factor was determined for NE2561 ionization chamber (waterproof), the protocol allows application to NE2571 ionization chamber without supplementary uncertainties. This approximation seems right because of the small ?? few difference in terms of volume and construction between these two chambers.

About the k_{ch} values by application of the NCS-10 protocol, these ones were determined and described in the studies of Seuntjens and Verhaegen. Standard uncertainty associated is 0.9 %.

4. Results and discussion

Figure 3 gives the comparison of absorbed dose rate to water determined by application of the four protocols: IAEA TRS-277; AAPM; TG-61; IPEMB and NCS-10 to the six beams of interest with the two ionization chambers (NE2571 and PTW31010). For each beams, results are normalized to the values obtained by application of the IAEA TRS-277 protocol to the NE2571 ionization chamber.
Uncertainty budgets for the application of the protocols to the six beams for the NE2571 ionization chamber and the PTW31010 ionization chamber are given in Table 6, Table 7, Table 8 and Table 9 respectively for the protocols IAEA TRS-277, AAPM TG-61, IPEMB and NCS-10. Uncertainties on corrected readings include uncertainty on position, current, atmospheric conditions and recombination factor. Additional uncertainties relative to the influence of the stem in air and in water and to the sleeve are taken into account. Choice was made to apply a correction factor equals to unity for the influence of stem and sleeve but to add uncertainties in the uncertainties budget. They were determined thanks to experimental measurements with an additional sleeve and stem.
First of all, we can say that variation of calibration factor in terms of air kerma with half value layer (HVL) is in good agreement with results obtained by Seuntjens [37]. Indeed calibration correction values decrease with HVL. We can also say that the use of a PMMA waterproofing sleeve don't need supplementary correction to apply, because the NE2571 ionization chamber is calibrated in air in terms of air kerma with this sleeve.
Results obtained by application of the four protocols: IAEA TRS 277; AAPM TG-61; IPEMB and NCS-10 to the two ionization chambers are in good agreement. Results obtained for the NE2571 are under uncertainties which are between and with a maximum deviation of. Results obtained for the PTW31010 are under uncertainties which are between and with a maximum deviation of. Standard uncertainties variation is due to the protocols and not to the ionization chambers. Indeed, the highest uncertainties are systematically obtained by application of the IAEA TRS 277 protocol. It's not surprising because of the associated uncertainties for the correction factors pu and ku. For each beam, no significant difference is observed between the two ionization chambers whatever the protocol used. Uncertainties around 3 % by application of the protocols were also found by Munck. They also concluded to compatibility of results from protocols concerning the “in-phantom method” which was applied here.
Nevertheless, several problems intrinsic to the application of these protocols can be underlined. Indeed, whatever the protocol used, the theoretical method being the same, absorbed dose to water determination is indirect and can lead to mistakes. Moreover, some uncertainties are not well known, difficult to define because of the lack of data and can be quite high (the mass absorption coefficient ratio for example). Some correction factors are not well defined: for example the k_u

factor from the IAEA TRS 277 protocol whose value was revised from 1.10 to 1.03 between the two version protocols. We can also say that some correction factors (k_u from the IAEA TRS-277 protocol for example) are not determinable in a laboratory or hospital which doesn't have primary standard detectors.

Figure 4 gives the comparison between all the results from application of the protocols with calorimetry values. Results are normalized to the calorimetrics absorbed dose rate values for each beam of interest. Results in terms of absorbed dose to water obtained by water calorimetry and by application of the protocols based on calibration factors in terms of air kerma were also found in good agreement. A maximum deviation of 1.2 % was registered with a water calorimetry associated uncertainty of 0.9 % and a protocol associated uncertainty around 2.5 %. But, we have to note that uncertainties associated to the application of the protocols are high.

Absorbed dose to water calibration factor can be determined thanks to the absorbed dose to water values. The general equation is:

$$N_{D,w} = \frac{D_w}{M_{u,w}}$$

The comparison realized about calibration factors in terms of absorbed dose to water is presented Figure 5 for the NE2571 ionization chamber and Figure 6 for the PTW31010 ionization chamber. Results are also in good agreement with values under uncertainties. Calibration factors determined from absorbed dose to water obtained by dosimetric protocols in terms of air kerma are in fact the air kerma calibration factor multiply by the different correction factors. So the difference of variation with energy of these $N_{D,w}$ is only due to the correction factors. For better reading of the figures, choice was made to not represent uncertainties associated to the $N_{D,w}$ determined by application of the protocols. Nevertheless, Table 10 and Table 11, sum up uncertainty values associated to the $N_{D,w}$, for the NE2571 ionization chamber and PTW31010 ionization chamber respectively. A better agreement with calorimetry is obtained for the NE2571 ionization chamber than for the PTW31010 ionization chamber. Moreover, for the two chambers, it appears that only the calibration factor established by application of AAPM TG-61 protocol seems to follow the variation of the calibration factor determined from calorimetric references.

5. Conclusion

New references in terms of absorbed dose to water for medium energy X-rays had just been established at LNE-LNHB thanks to water calorimetry at a 2 cm depth in the reference conditions described by protocols. Four protocols based on references in terms of air kerma were applied to two ionization chambers (NE2571 and PTW31010) to six medium energy X-rays beams chosen among norms and protocols in the range of interest (80 kV to 300 kV in accordance with international dosimetric protocols). The comparison performed between protocols shows a good agreement of them, whatever the beam or the chamber used. In the same way, the comparison between absorbed dose rates to water obtained by water calorimetry and by application of the protocols based on calibration factors in terms of air kerma were also found in good agreement. A maximum deviation, between these methods, of 2.1 % was registered with a water calorimetry associated uncertainty below 0.9 % (k = 1) and associated uncertainties around 2.5 % (k = 1) for the application of the protocols. So, despite of the good agreement, a significant reduction of uncertainties on absorbed dose rate to water is obtained using water calorimetry.
These new references in terms of absorbed dose to water will be useful for physicists who want to apply protocols requiring references in terms of absorbed dose to water like the IAEA TRS-398

protocol. Until now, it was not possible to strictly apply it because no absorbed dose to water references established at a 2 cm depth existed. Application of protocols using references in terms of absorbed dose to water will allow reducing significantly the uncertainties (factor of 2) and limiting the potential mistakes in the determination of the absorbed dose to water which is fastidious when applying international dosimetric protocols using references in terms of air kerma. Before being transferred to users, these references will be compared to the ones obtained by counterparts' laboratories. This comparison is planned to be realized in the framework of the HLT09 European project.

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Table 1 : Kilovoltage medium energy X-ray beams studied

Beam	High voltage (kV)	Additional filtration suggested by norms and protocols (mm)	HVL
IEC 61267 RQR6	80	2.50 Al	3.01 mm Al
IEC 61267 RQR9	120	2.50 Al	5.00 mm Al
IEC 61267 RQR10	150	2.50 Al	6.57 mm Al
CCRI 180	180	4.06 Al + 0.51 Cu	1.00 mm Cu
CCRI 250	250	4.02 Al + 1.72 Cu	2.50 mm Cu
ISO 4037 H300	300	4.00 Al + 2.50 Cu	3.40 mm Cu

Table 2 : Absorbed dose rate to water determined by water calorimetry for the six beams studied. Associated uncertainties are given at k =1.

Beam	Absorbed dose rate to water (at 2 cm depth ; DSC = 50 cm ; 10 x 10 cm^2 field size) determined by water calorimetry ($Gy.min^{-1}$)	u (%)
IEC 61267 RQR6	0.329	0.72
IEC 61267 RQR9	0.356	0.71
IEC 61267 RQR10	0.534	0.64
CCRI180	0.424	0.56
CCRI250	0.536	0.49
ISO4037 H300	0.405	0.55

Table 3 : Characterization of the six beams studied in terms of HVL

Beam	High voltage (kV)	1st HVL (norms)	Tolerance	1st HVL (exp.)	u (%)	Difference 1st HVL (%)
IEC 61267 RQR6	80	3.01 mm Al	± 0.1 mm	3.00 mm Al	± 1.0	- 0.3
IEC 61267 RQR9	120	5.00 mm Al	± 0.1 mm	4.99 mm Al	± 1.0	- 0.2
IEC 61267 RQR10	150	6.57 mm Al	± 0.1 mm	6.55 mm Al	± 1.0	- 0.3
CCRI 180	180	0.98 mm Cu	-	0.98 mm Cu	± 1.0	0.0
CCRI 250	250	2.48 mm Cu	-	2.48 mm Cu	± 1.0	0.0
ISO 4037 H300	300	3.40 mm Cu	± 5 %	3.40 mm Cu	± 1.0	0.0

Table 4 : Characteristics of the water equivalent beam in terms of tube high voltage and filtration

Beam	Water equivalent beam characteristics (high voltage; filtration)
IEC 61267 RQR6	70 kV; 4 mm Al
IEC 61267 RQR9	96 kV; 0.14 mm Cu
IEC 61267 RQR10	100 kV; 6.8 mm Al
CCRI 180	140 kV; 4 mm Al + 0.2 mm Cu
CCRI 250	250 kV; 4 mm Al + 0.4 mm Cu
ISO 4037 H300	300 kV; 4 mm Al + 0.4 mm Cu

Table 5 : k_u factors determined for each beam of interest for the two ionization chambers used

Beam	k_u	
	NE2571	PTW31010
IEC 61267 RQR6	0.994	1.020
IEC 61267 RQR9	1.014	1.012
IEC 61267 RQR10	0.990	0.988
CCRI180	1.005	1.010
CCRI250	1.010	0.999
ISO4037 H300	1.017	1.004

Table 6 : Uncertainties (in %) on the application of the IAEA TRS-277 protocol to the NE2571 ionization chamber (a) and to the PTW31010 (b).

	IEC 61267 RQR6		IEC 61267 RQR9		IEC 61267 RQR10		CCRI180		CCRI250		ISO4037 H300	
	a	b	a	b	a	b	a	b	a	b	a	b
Corrected reading	0.24	0.17	0.19	0.17	0.17	0.17	0.16	0.17	0.16	0.17	0.19	0.18
Air kerma calibration factor	0.34	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.34	0.34	0.35	0.35
k_u	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
p_u	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
stem	0.12	0.24	0.15	0.23	0.10	0.19	0.13	0.24	0.10	0.24	0.13	0.21
sleeve	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-
Total	**3.50**	**3.51**	**3.50**	**3.51**	**3.50**	**3.50**	**3.50**	**3.51**	**3.50**	**3.51**	**3.50**	**3.51**

Table 7 : Uncertainties (in %) on the application of the AAPM TG-61 protocol to the NE2571 ionization chamber (a) and to the PTW31010 (b).

	IEC 61267 RQR6		IEC 61267 RQR9		IEC 61267 RQR10		CCRI180		CCRI250		ISO4037 H300	
	a	b	a	b	a	b	a	b	a	b	a	b
Corrected reading	0.24	0.17	0.19	0.17	0.17	0.17	0.16	0.17	0.16	0.17	0.19	0.18
Air kerma calibration factor	0.34	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.34	0.34	0.35	0.35
$P_{Q,cham}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
$k_{\text{dis,total}}$	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
stem	0.12	0.24	0.15	0.23	0.10	0.19	0.13	0.24	0.10	0.24	0.13	0.21
sleeve	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-
Total	**2.19**	**2.17**	**2.19**	**2.17**	**2.18**	**2.17**	**2.18**	**2.17**	**2.18**	**2.17**	**2.18**	**2.17**

Table 8 : Uncertainties (in %) on the application of the IPEMB protocol to the NE2571 ionization chamber (a) and to the PTW31010 (b).

	IEC 61267 RQR6		IEC 61267 RQR9		IEC 61267 RQR10		CCRI180		CCRI250		ISO4037 H300	
	a	b	a	b	a	b	a	b	a	b	a	b
Corrected reading	0.24	0.17	0.19	0.17	0.17	0.17	0.16	0.17	0.16	0.17	0.19	0.18
Air kerma calibration factor	0.34	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.34	0.34	0.35	0.35
k_{ch}	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
stem	0.12	0.24	0.15	0.23	0.10	0.19	0.13	0.24	0.10	0.24	0.13	0.21
sleeve	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-
Total	**3.21**	**3.19**	**3.20**	**3.19**	**3.20**	**3.19**	**3.20**	**3.20**	**3.20**	**3.19**	**3.20**	**3.19**

Table 9 : Uncertainties (in %) on the application of the NCS-10 protocol to the NE2571 ionization chamber (a) and to the PTW31010 (b).

	IEC 61267 RQR6		IEC 61267 RQR9		IEC 61267 RQR10		CCRI180		CCRI250		ISO4037 H300	
	a	b	a	b	a	b	a	b	a	b	a	b
Corrected reading	0.24	0.17	0.19	0.17	0.17	0.17	0.16	0.17	0.16	0.17	0.19	0.18
Air kerma calibration factor	0.34	0.34	0.34	0.34	0.34	0.34	0.35	0.35	0.34	0.34	0.35	0.35
k_{ch}	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$\left[\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{w,air}\right]_{2cm}$	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
stem	0.12	0.24	0.15	0.23	0.10	0.19	0.13	0.24	0.10	0.24	0.13	0.21
sleeve	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-	0.30	-
Total	**1.83**	**1.81**	**1.82**	**1.81**	**1.82**	**1.80**	**1.82**	**1.81**	**1.82**	**1.81**	**1.82**	**1.81**

Table 10 : Uncertainties associated to calibration factors in terms of absorbed dose to water of the NE2571.

Beam	$uN_{D,w,TRS-277}$ (%)	$uN_{D,w,TG-61}$ (%)	$uN_{D,w,IPEMB}$ (%)	$uN_{D,w,NCS-10}$ (%)	$uN_{D,w,calorimetry}$ (%)
IEC 61267 RQR6	3.51	2.20	3.22	1.84	0.72
IEC 61267 RQR9	3.51	2.19	3.21	1.83	0.71
IEC 61267 RQR10	3.50	2.19	3.20	1.82	0.64
CCRI 180	3.50	2.19	3.21	1.83	0.56
CCRI 250	3.50	2.19	3.20	1.82	0.49
ISO 4037 H300	3.51	2.19	3.21	1.83	0.55

Table 11 : Uncertainties associated to calibration factors in terms of absorbed dose to water of the PTW31010.

Beam	$uN_{D,w,TRS-277}$ (%)	$uN_{D,w,TG-61}$ (%)	$uN_{D,w,IPEMB}$ (%)	$uN_{D,w,NCS-10}$ (%)	$uN_{D,w,calorimetry}$ (%)
IEC 61267 RQR6	3.51	2.18	3.20	1.81	0.74
IEC 61267 RQR9	3.51	2.18	3.20	1.81	0.73
IEC 61267 RQR10	3.51	2.17	3.20	1.81	0.66
CCRI 180	3.51	2.18	3.20	1.82	0.58
CCRI 250	3.51	2.18	3.20	1.81	0.52
ISO 4037 H300	3.51	2.18	3.20	1.81	0.58

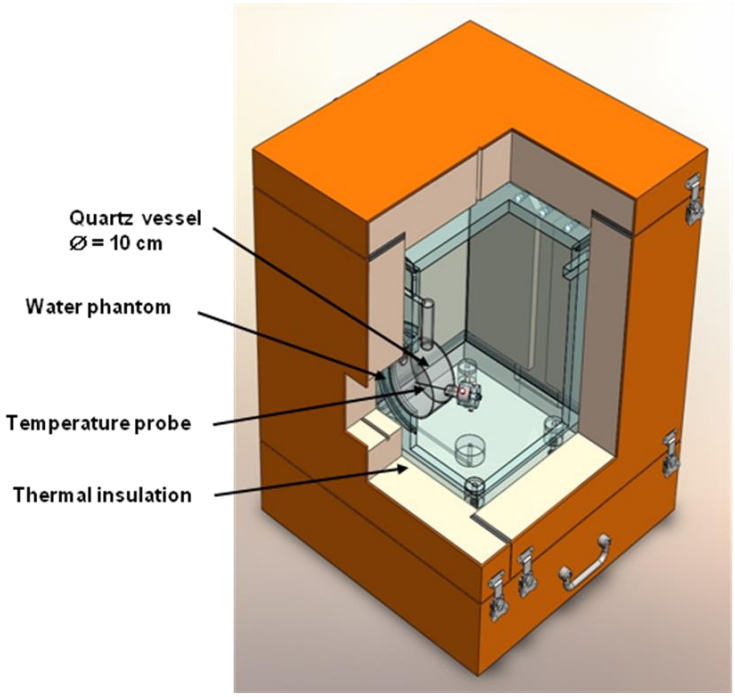

Figure 1 : Schematic drawing of the new LNE-LNHB water calorimeter designed for measurements at 2 cm depth (the reference depth of medium energy X-rays recommended by dosimetric protocols for radiotherapy)

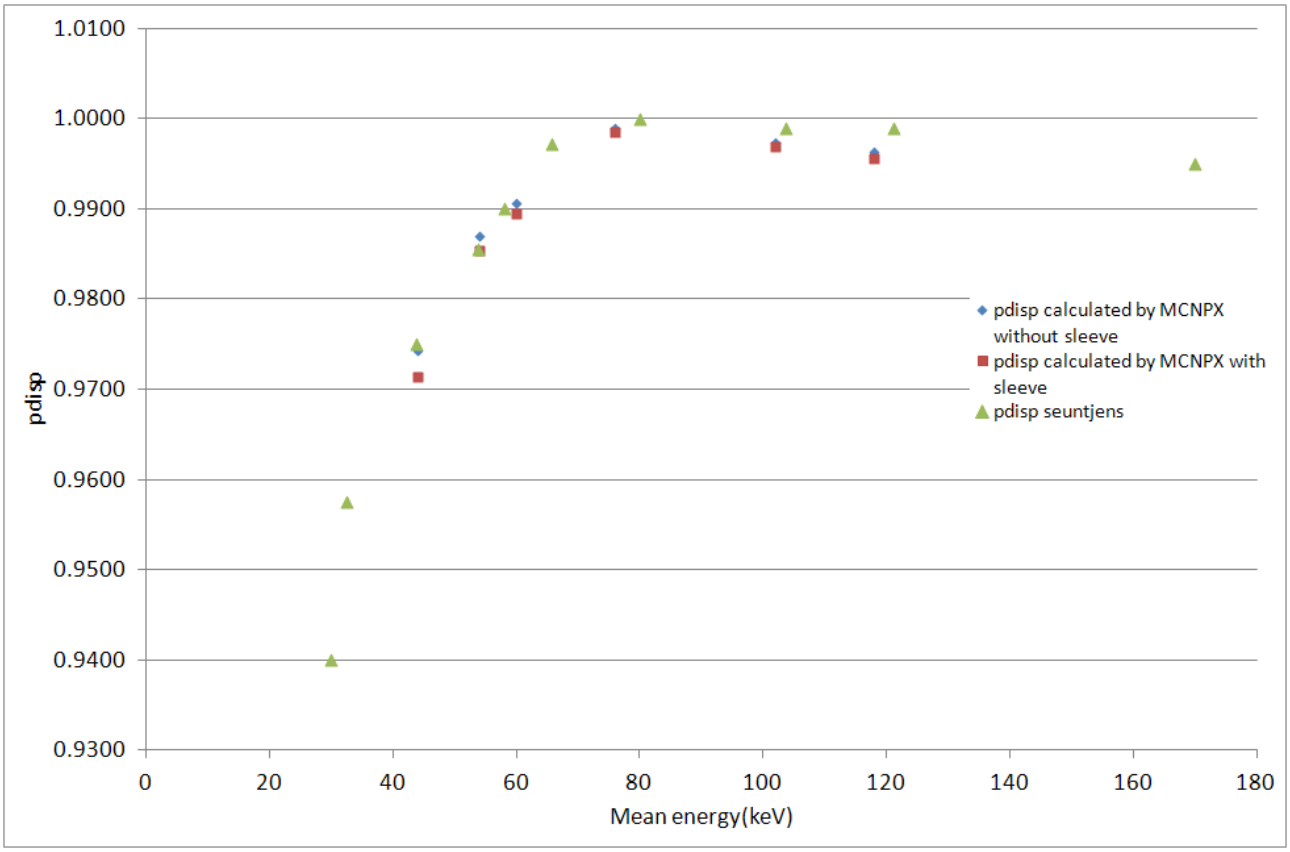

Figure 2 : Comparison of the displacement factors calculated by Monte-Carlo with and without proofing sleeve with Seuntjens data.

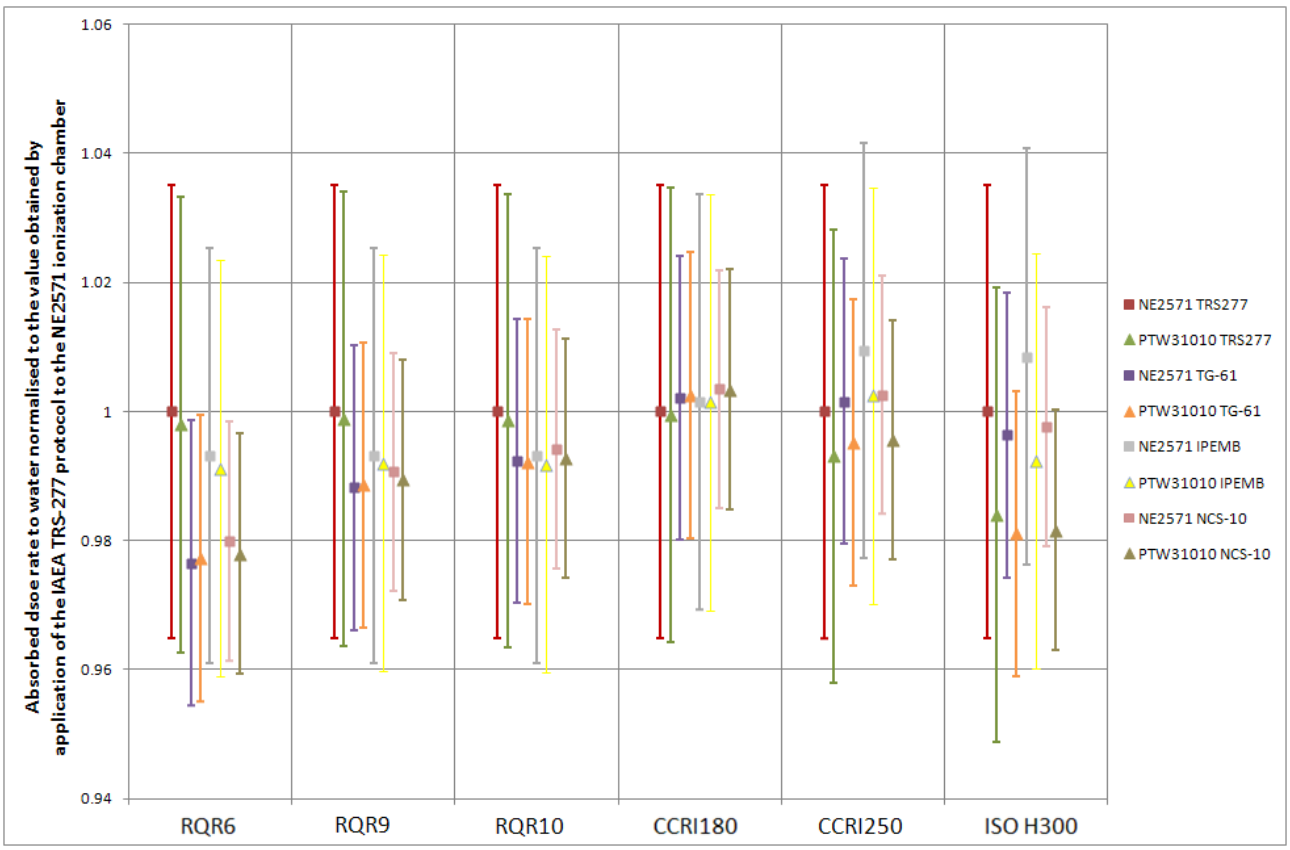

Figure 3 : Comparison in terms of absorbed dose rate to water determined by application of the four protocols studied to the two ionization chambers NE2571 and PTW31010 for the six beams. For each beam, results are normalized to the values obtained by application of the IAEA TRS-277 to the NE2571 ionization chamber.

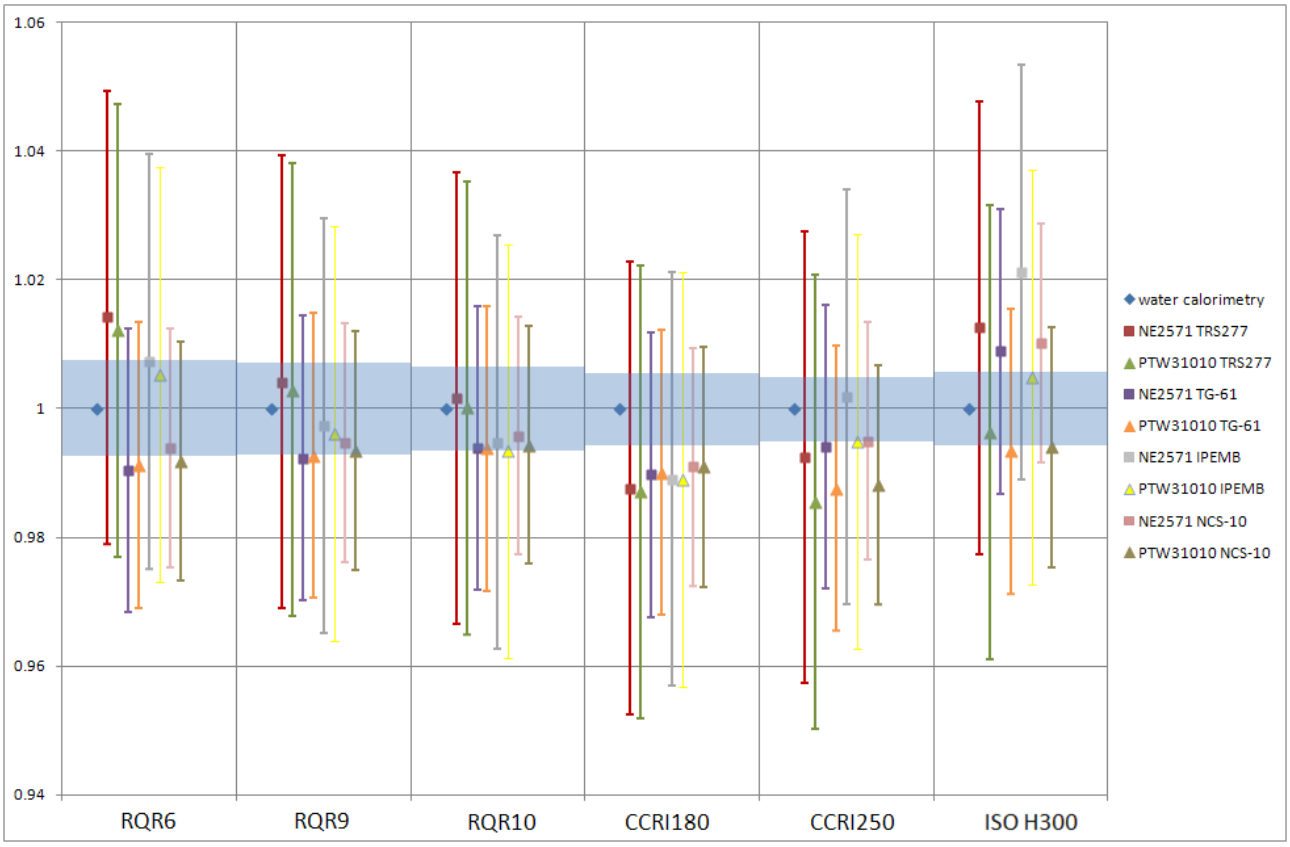

Figure 4 : Comparison in terms of absorbed dose rate to water of the four protocols studied apply to the two ionization chambers NE2571 and PTW31010 for the six beams of interest ; with the calorimetry references. For each beam, values are normalized to the ones obtained by water calorimetry.

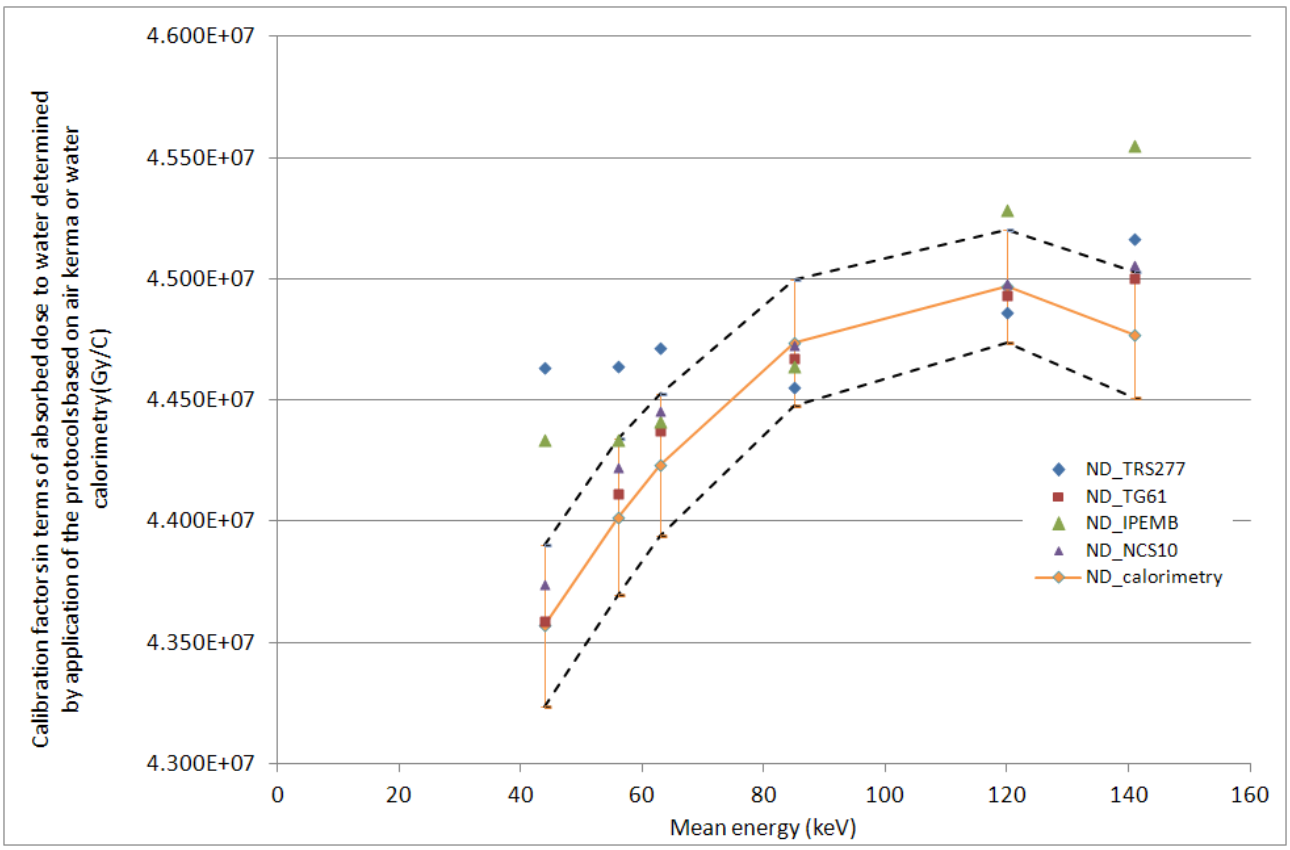

Figure 5: Comparison of calibration factors in terms of absorbed dose to water for the NE2571 ionization chamber. Dashed lines represent the uncertainties associated to the calibration factor determined thanks to calorimetric measurements.

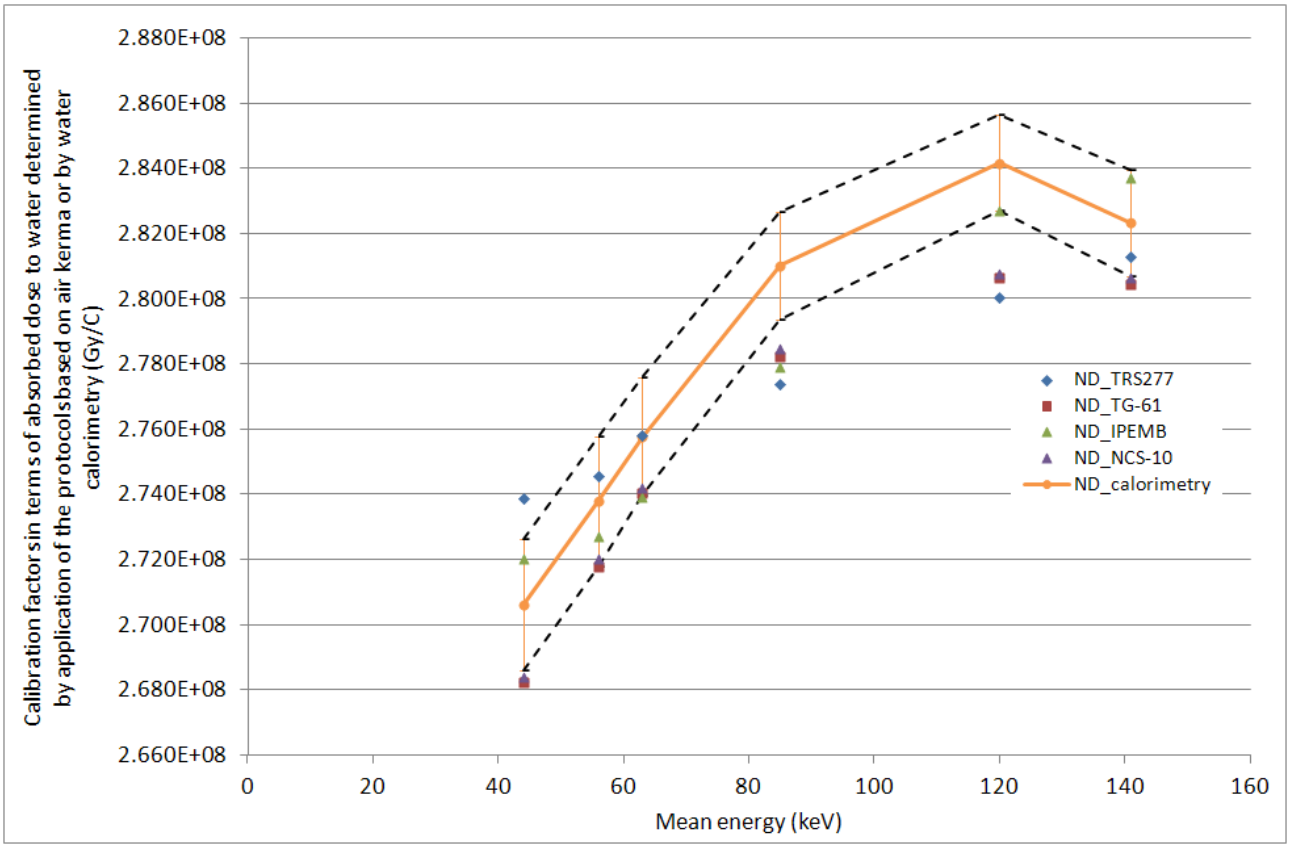

Figure 6 : Comparison of calibration factors in terms of absorbed dose to water for the PTW31010 ionization chamber. Dashed lines represent uncertainties associated to the calibration factor determined thanks to calorimetric measurements.