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A BELARUSIAN PROTOCOL FOR THE DOSIMETRY OF HIGH-ENERGY PHOTON BEAMS

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Since 1980 a number of national and international protocols and codes of practice for the dosimetry of photon and electron beams with energies above 1 MeV have been published in different countries. In 1987, the IAEA had published "An International Code of Practice" for such measurements. In all these protocols, the formalism is based on an exposure or air kerma calibration of user's ionization chambers in ^{60}Co beams. For the determination of the absorbed dose in water by dosimeters with ionization chambers it is necessary to apply some correction factors for dosimeter readings.

Great efforts have recently been spent in different countries for more accurate definition of the values for all factors that have to be taken into account during precision measurements. It should be noted that these corrections must be used during certification of clinical dosimeters in National certification or standardization centers in units of exposure or air kerma.

It is evident that National protocols must be very similar to International protocols, in particular, to the IAEA International Code of Practice, issued in 1987. Moreover, it is possible to use the recommended values for different correction and conversion factors and to be sure of their quality. Unification of the protocols allows us to conduct international intercomparisons of the results of dose measurements and treatment of patients.

The IAEA International Code of Practice, as well as national protocols of the USA and Scandinavian countries offer to users more free choice of different ionization chambers and the possibility of determining all the correction and conversion factors separately. On the other hand, in the English national protocol only a single conversion factor is used that is a combination of all the necessary corrections. Such a simple approach has been adopted in a number of Western Europe countries (the Netherlands, Italy, Switzerland, etc.). Moreover, in these protocols a limited number of ionization chambers are recommended as reference chambers. That is why it is possible to eliminate errors during correction of the results of measurements, involved with the necessity of the proper choice of the values from a number of data for a number of chambers.

Now we are developing Belarusian national protocols for the absorbed dose measurement for all kinds of radiation therapy with high energy photons and electrons. They are the four codes of practice for: photons with the energy generated above 1 MV, photons with the energy generated below 1 MV, electrons with the energy above 1 MeV, and photons used in brachytherapy.

From our point of view, a single conversion factor approach should be adopted in the Republic of Belarus. Under the existing economic conditions the limitation of the used ionization chambers will result in the reduction of expenses for dosimetric equipment and will make the task of more accurate dosimetry easier for users.

The application of new national dosimetric protocols in oncological clinics of the Republic of Belarus will allow us to reduce errors in dose delivered to patients and to improve the results of treatment.

As an example of the result of our work, one of the protocols for high energy photon beams is presented below.

BELARUSIAN PROTOCOL FOR THE DOSIMETRY OF HIGH-ENERGY PHOTON BEAMS

(Preliminary version)

Introduction.

This protocol is based on a Dutch protocol "Code of Practice for the Dosimetry of High-Energy Photon Beams", prepared by the Netherlands Commission on Radiation Dosimetry [Nederlande Comissie, Rep. NCS-2, NCS; 1986], (with permission from B.J. Mijnheer, the chairman of subcommission) and on an International Code of Practice "Absorbed Dose Determination in Photon and Electron Beams", published by IAEA in Technical Report Series No. 277 [IAEA, Rep. 277, Vienna; 1987]. Some data have been taken from new International Code of Practice for the Dosimetry "The Use of Plane Parallel Ionization Chambers in High Energy Electron and Photon Beams", published by IAEA in Technical Report Series No. 381 [IAEA, Rep. 381; 1997].

This protocol was prepared at the Medical Radiation Physics Department of the Belarusian Institute of Oncology and Medical Radiology and is intended for use in all hospitals of the Republic of Belarus providing radiation treatment for cancer patients.

Radiation Quantities and Units

For interaction of the ionizing radiation with matter the most important quantity is the absorbed dose, which is a measure of the amount of energy absorbed per unit mass of irradiated material:

$$D = \frac{d\bar{\varepsilon}}{dm}, \qquad (1)$$

where $d\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to mass *dm*. The mass *dm* can be taken to be very small but sufficiently large for the fluctuations to be negligible. Therefore, the absorbed dose is a point function and is continuous and differentiable and one may refer to its gradient and its rate (or time derivative). The absorbed dose may be specified in any medium for any type of ionizing radiation. The unit for the absorbed dose is $J \cdot kg^{-1}$ and there is special name for it, that is *gray* (Gy).

The formalism applied for the absorbed dose determination in a high-energy photon beam, using the ionization chamber method, is in principle very similar in all modern dosimetry protocols. They all recommend an air kerma or an exposure calibration of the user's ionization chamber. The *kerma* (kinetic energy released in material) is defined by the quotient:

$$K = \frac{dE_{tr}}{dm}, \qquad (2)$$

where dE_{tr} is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a material of mass *dm*.

The unit of the quantity kerma has the same dimension as that for absorbed dose, i. e. $J \cdot kg^{-1}$ with the special name gray (Gy). The quantity kerma, which may be applied to any material, is closely related to the quantity *exposure*, which applies only to photons interacting with air and is the quotient

$$X = \frac{dQ}{dm}, \qquad (3)$$

where *dQ* is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated by photons in air of mass *dm* are completely stopped in air. The unit for the exposure is $C \cdot kg^{-1}$. However, the special unit of exposure, röntgen (R) is still in fairly extensive use:

$1\ R = 2.58 \cdot 10^{-4}\ C \cdot kg^{-1}$

Exposure is the ionization equivalent of air kerma, except that the ionization arising from the absorption of bremsstrahlung emitted by the electrons is not to be included in *dQ*, i. e.

$$X = K_{air}(1-g)/(W/e), \qquad (4)$$

where K_{air} is air kerma, *g* is the fraction of the energy released that is dissipated as bremsstrahlung, *W* is the average energy required to create one ion pair in dry air and *e* is the electron charge.

The use of exposure will in due course be discontinued. It is mentioned in this protocol only because of its wide use in our country and because it facilitates the transition from exposure to the generally used quantity kerma.

Code of Practice

1. The national or local secondary standard shall be a cylindrical (thimble) ionization chamber having a graphite wall, some of the parameters for which are mentioned in Table 1.
2. The national (local) standard shall be calibrated in air in terms of air kerma at Belarusian Centre for Standardization, Metrology and Certification in a beam of ^{60}Co gamma rays. For this calibration the chamber shall be fitted with the build-up cap supplied with the chamber.
3. For certification measurements on a radiotherapy unit it is possible to use a Farmer type ionization chamber with PMMA wall, some of the parameters for which are mentioned in Table 1.
4. Certification measurements on a radiotherapy unit shall be made in a water phantom in terms of the absorbed dose at the reference point in the water phantom. The position of the reference point depends on the quality of the user's beam (Table 1). For such measurements, the chamber shall be fitted with a thin waterproofing sheath, e. g., made of PMMA, not thicker than 1 mm. If the PMMA sheath is thicker, then the reading has to be corrected using the factor given in Table 2.

Ionization chamber			PTW 30002	PTW 30001
Wall material			Graphite	PMMA
Build-up cap			PMMA	PMMA
Wall thickness g/cm^2			0.083	0.053
Inner radius r, mm			3.05	3.05
0.6 r, mm			1.8	1.8
$k_{att}k_m$.			0.982	0.972
TPR^{20}_{10}	D_{20}/D_{10}	d_{ref}, cm	$C_{w,u}$	$C_{w,u}$
0.50	0.44	5	***1.107***	***1.102***
0.53	0.47	5	***1.102***	***1.101***
0.56	0.49	5	***1.099***	***1.098***
0.59	0.52	5	***1.097***	***1.096***
0.62	0.54	5	***1.096***	***1.093***
0.65	0.56	5	***1.093***	***1.088***
0.68	0.58	5	***1.090***	***1.084***
0.70	0.60	5	***1.088***	***1.083***
0.72	0.61	10	***1.083***	***1.078***
0.74	0.63	10	***1.079***	***1.072***
0.76	0.65	10	***1.073***	***1.066***
0.78	0.66	10	***1.065***	***1.058***
0.80	0.68	10	***1.056***	***1.049***
0.82	0.69	10	***1.047***	***1.039***
0.84	0.71	10	***1.037***	***1.030***
Co-60		5	***1.098***	***1.099***

Table 1. Air kerma to absolute dose to water conversion factors, $C_{w,u}$, for the reference ionization chambers as function of the quality index; wall thickness according to PTW information, values for $k_{att}k_m$ are taken from [IAEA, Rep. 381, 1997].

Quality index, TPR^{20}_{10}	Thickness of sheath		
	5 mm	3 mm	1 mm
Cobalt-60	1.001	1.001	-
0.60	1.001	1.001	-
0.70	-	-	-
0.72	1.001	-	-
0.74	1.002	1.001	-
0.76	1.003	1.002	-
0.78	1.004	1.003	1.001
0.80	1.005	1.004	1.001
0.82	1.008	1.005	1.002

Table 2. Correction factors for measurements in a water phantom with an ionization chamber in a PMMA sheath as a function of the thicknessof the sheath, according to [Nederlandse Commissie, Rep.NCS-2, NCS; 1986].

Certification measurements on a ^{60}Co teletherapy unit is possible to do in terms of air kerma rate at the reference point, coincide with an isocentre, using appropriate build-up cap.

5. The radiation quality should be specified as the quality index, the ratio of absorbed dose measurements made at a constant source-detector distance, usually equal to SAD (Source-Axis Distance), at 20 cm and 10 cm depths in the water phantom, respectively, and a field size of 10 cm x 10 cm at the geometrical centre of the detector. The ratio of these absorbed doses is designated as TPR^{20}_{10} (TPR is short for "tissue-phantom ratio"). Furthermore, the radiation quality is often specified by another quantity obtained from depth dose data. It is the value D_{20}/D_{10}, i.e. the dose ratio for 20 cm and 10 cm depths, measured at SSD = 100 cm for a 10 cm x 10 cm field at the phantom surface.
6. For the absorbed dose determinations at the reference point in the water phantom by an ionization chamber a so-called effective point of measurement P_{eff} is used. The use of P_{eff} takes into account the spatial extent of the air cavity by locating the point of interest in front of the chamber centre to correct for the gradient of fluence within the chamber cavity. For a cylindrical ionization chamber P_{eff} (depth z_{Peff}) is displaced from the centre P (depth z_P) to the water surface. The value of displacement $z_{Peff} - z_P$ (an additional deepening of a chamber) is equal to 0.6r (according to [IAEA, Rep. 381, 1997.]) for all photon beams with qualities equal to or higher than ^{60}Co gamma rays, where r is an inner radius of ionization chamber.
7. The phantom surface shall be positioned at the standard for the unit source to surface distance normally used in clinical practice. A field size 10 cm x 10 cm at the phantom surface shall be used.
8. For a standard ionization chamber the absorbed dose to water will be given by:

$$D_{w,u} = M_u \, N_k \, C_{w,u} \, , \qquad (5)$$

where

$D_{w,u}$ is the absorbed dose to water in the user's beam at the position of the effective point of measurement of the chamber when the chamber is replaced by water,

M_u is the electrometer reading corrected for any difference between the ambient air conditions affecting the chamber at the time of measurement and the standard ambient air conditions for which the calibration factor applied (air temperature, pressure and humidity), for ion recombination and for polarity effects in the user's beam,

N_k is the air kerma calibration factor, given by Standard Dosimetry Laboratory or by Belarusian Centre for Standardization, Metrology and Certification, which converts the ionization chamber reading to air kerma for the calibration quality and geometry for standard ambient air conditions (usually 20°C, 101.3 kPa and 50% relative humidity),

$C_{w,u}$ is the air kerma to absorbed dose to water conversion factor, which depends on the chamber type and the radiation quality of the user's beam.

Subscripts w and u indicate water and user's beam, respectively.

9. Recommended $C_{w,u}$ values as a function of the quality index are given in Table 1.
10. The relative absorbed dose for other field sizes than 10 cm x 10 cm shall be obtained by direct measurement at the reference point.
11. Field instruments (e.g. used in a water phantom for depth dose and profile measurement, as well as for regular checking of an absorbed dose per monitor unit or an absorbed dose rate) shall be calibrated against the local standard at the radiation qualities at which they are to be used. This calibration shall be in terms of absorbed dose to water, and the field instrument and local standard shall be intercompared with their effective points of measurement at the reference point in the phantom. The absorbed dose to water calibration factors at the user's quality, $N_{w,u}$, is given by:

$$N_{w,u} = \frac{D_{w,u}}{M_{f,u}} = \frac{(M_u\, N_k\, C_{w,u})_{standard}}{M_{f,u}} \qquad (6)$$

where $M_{f,u}$ is the reading of the field instrument, corrected in a similar way as M_u.

12. The absorbed dose at other positions in the phantom shall be obtained by performing relative measurements with a field instrument and will be matched to the value determined at the reference point described in point 6. It should be taken into account that the field instrument readings are related to the effective point of measurement. The z_{Peff} - z_P values and the conversion factors for some field instruments are given in Table 3.

Ionization chamber			PTW 31002	PTW 31003
Wall material			PMMA	PMMA
Build-up cap			PMMA	PMMA
Wall thickness g/cm^2			0.083	0.089
Inner radius r, mm			2.75	2.75
0.6 r, mm			1.7	1.7
$k_{att}k_m$.			0.973	0.974
TPR^{20}_{10}	D_{20}/D_{10}	d_{ref}, cm	$C_{w,u}$	$C_{w,u}$
0.50	0.44	5	***1.103***	***1.104***
0.53	0.47	5	***1.102***	***1.105***
0.56	0.49	5	***1.100***	***1.103***
0.59	0.52	5	***1.097***	***1.101***
0.62	0.54	5	***1.094***	***1.098***
0.65	0.56	5	***1.090***	***1.092***
0.68	0.58	5	***1.087***	***1.088***
0.70	0.60	5	***1.084***	***1.085***
0.72	0.61	10	***1.079***	***1.080***
0.74	0.63	10	***1.074***	***1.075***
0.76	0.65	10	***1.068***	***1.069***
0.78	0.66	10	***1.060***	***1.061***
0.80	0.68	10	***1.051***	***1.052***
0.82	0.69	10	***1.041***	***1.042***
0.84	0.71	10	***1.032***	***1.034***
Co-60		5	***1.100***	***1.101***

Table 3. Air kerma to absolute dose to water conversion factors, $C_{w,u}$, for the ionization chambers using as field instruments, as function of the quality index; wall thickness according to PTW information, values for $k_{att}k_m$ are taken from [IAEA, Rep. 381; 1997].

Appendix A. General Equations.

According to the Bragg-Gray relation the absorbed dose to water at the position of the chamber's effective point of measurement in the absence of the chamber, $D_{w,u}$, can be given as:

$$D_{w,u} = M_u N_D (s_{w,air})_u (\Pi p_i)_u \,, \quad (7)$$

where

M_u is the corrected instrument reading: $M_u = M_{uncorr}\, p_t\, p_p\, p_{hum}\, p_{ion}\, p_{pol}$. M_{uncorr} is the uncorrected instrument reading; p_t, p_p, p_{hum} are the air temperature, pressure and humidity correction factors respectively; p_{ion} is the ion recombination correction factor and p_{pol} is the correction factor for polarity effects in the users beam;

N_D is the absorbed dose to air calibration factor, that is related with the air kerma calibration factor N_K and the exposure calibration factor N_X by the equations:

$$N_D = N_K\,(1-g)\,\Pi k_i = N_X\,W/e\,\Pi k_i, \quad (8)$$

where g is the fraction of energy of secondary charged particles that is converted to bremsstrahlung in air at the calibration quality, W/e is the quotient of the average energy expended to produce an ion pair in dry air and the electron charge, Πk_i is the product of a number of correction factors to be applied to the air kerma or exposure calibration factor;

$(s_{w,air})_u$ is the mass stopping power ratio water to air at the user's beam quality;

$(\Pi p_i)_u$ is the product of a number of correction factors to be applied to the measurements in the water phantom at the user's beam quality.

Equation (7) can be rewritten yielding equation (5):

$D_{w,u} = M_u\,N_k\,C_{w,u}$, with

$$C_{w,u} = (1-g)\,\Pi k_i\,(s_{w,air})_u\,(\Pi p_i)_u. \quad (9)$$

The product of the correction factors to be applied to the air kerma calibration factor is given by:

$\Pi k_i = k_{att}\,k_m\,k_{st}\,k_{ce}$, where

k_{att} is a correction for attenuation (absorption and scattering) in the wall and build-up cap of the ionization chamber;

k_m is a correction for the difference in composition between the wall plus build-up cap and air and can be calculated from:

$$k_m = \left[\alpha s_{wall,air}(\bar{\mu}_{en}/\rho)_{air,wall} + (1-\alpha)s_{cap,air}(\bar{\mu}_{en}/\rho)_{air,cap}\right]^{-1}, \quad (10)$$

where α is the fraction of ionization inside the air cavity due to electrons from the chamber wall; $(\bar{\mu}_{en}/\rho)_{air,wall}$ and $(\bar{\mu}_{en}/\rho)_{air,cap}$ are the ratios of the averaged mass energy absorption coefficients of air to wall material and air to build-up cap material, respectively; $s_{wall,air}$ and $s_{cap,air}$ are the mass stopping power ratios wall material to air and air to build-up cap material, respectively;

k_{st} is a correction for the stem effect for the employed field size;

k_{ce} is a correction for the effect of central electrode on the response of the chamber during the calibration.

The product of the correction factors to be applied to the measurements in the water phantom is given by:

$\Pi p_i = p_{wall}\,p_{ce}$,

where

p_{wall} corrects for the difference in composition between the ionization chamber wall and water and can be calculated from:

$$p_{wall} = \alpha\,s_{wall,w}\,(\bar{\mu}_{en}/\rho)_{w,wall} + (1-\alpha), \quad (11)$$

where α is the fraction of ionization inside the air cavity due to electrons from the chamber wall; $(\bar{\mu}_{en}/\rho)_{w,wall}$ is the ratio of the averaged mass energy absorption coefficients of water to wall material; $s_{wall,w}$ is the mass stopping power ratio wall material to water, respectively;

p_{ce} corrects for the effect of the central electrode on the response of the chamber during measurements in the water phantom.

Appendix B. Correction of Instrument Readings

- for the deviation of air temperature and pressure from the standard ambient air conditions:

$$p_{tp} = p_t p_p = \frac{p_0(273.2+t)}{p(273.2+t_0)}, \quad (12)$$

where p and t are the air pressure and temperature during measurements, p_0 and t_0 are the standard ambient air pressure and temperature pointed out in the calibration certificate for the chamber (usually 101.3 kPa and 20 °C);

- for the deviation of air humidity from the standard conditions:

The humidity of the ambient air has for the chambers mentioned in Tables 1 and 2 only a minor influence on the dosimeter readings. Thus, if the calibration coefficient is related to the relative humidity of 50% then in a range of 20% to 70% relative humidity no correction is needed for temperatures ranging between 15 °C and 25 °C.

- for the ion recombination:

The so called "two voltage" method is to be used. It is based on registration of two dosimeter readings, M_1 and M_2, received for two different voltages V_1 and V_2 for the same irradiation conditions. The ratio V_1/V_2 should be equal to or greater than 3. The recombination correction factor p_{ion} at the normal operating voltage V_1 can be obtained from a quadratic equation for pulsed and pulsed scanned radiation

$$p_{ion} = a_0 + a_1(M_1/M_2) + a_2(M_1/M_2)^2, \quad (13)$$

constants a_0, a_1 and a_2 are given in Table 4 according to [Weinhous and Meli, 1984] for pulsed radiation beams.

V_1/V_2	a_1	a_2	a_3
2.0	2.337	-3.636	2.299
2.5	1.474	-1.587	1.114
3.0	1.198	-0.875	0.677
3.5	1.080	-0.542	0.463
4.0	1.022	-0.363	0.341
5.0	0.975	-0.188	0.214

Table 4. The quadratic fit coefficients for the calculation of p_{ion} by the "two voltage" technique in pulsed radiation as a function of the voltage ratio V_1/V_2, according to [Weinhous and Meli; 1984].

- for the polarity effects

Two dosimeter readings, M_1 and M_2, are to be measured for two opposite voltage polarities. Then the correction factor for polarity effects can be calculated from:

$$p_{pol} = \left(\left|M_1\right| + \left|M_2\right|\right) / 2 \cdot \left|M_1\right| . \quad (14)$$

Appendix C Numerical Values

W/e: Now the generally accepted value of *W/e* for dry air is 33.97 ± 0.06 J/C.

g: The most recent calculations of the fraction of energy of secondary charged particles that is converted to bremsstrahlung in air amounts to 0.003 (for ^{60}Co gamma rays).

k_{att} k_m: Data for this product given in Tables 1 and 3 for different ionization chambers are taken from the new IAEA Code of Practice [IAEA, Rep. 381; 1997]. They have been determined by using a weighted mean from a survey of published experimental values and Monte Carlo calculations.

k_{st} : As in the most of dosimetric protocols, in this Code of Practice the stem effect correction factor is assumed to be equal to unity.

$s_{w,air}$: Mass stopping power ratios calculated by Andreo and Brahme [Andreo and Brahme, 1986] are given in Tables 5, 6 and 7 as a function of the quality index.

p_{wall}: Values for the correction factor taking into account the difference in composition between the ionization chamber wall and water have been determined applying equation (11). Initial data for calculation taken from [IAEA,Rep. 277, 1987; Andreo and Brahme, 1986; Lempert et. al., 1983] as well as the results are given in Tables 5, 6 and 7.

k_{ce} and p_{ce}: The product $k_{ce} \cdot p_{ce}$ is assumed to be unity at all photon beam qualities.

TPR^{20}_{10}	D_{20}/D_{10}	α	$s_{wall,air}$	$(\mu_{en}/\rho)_{w,wall}$	$s_{w,air}$	p_{wall}
0.50	0.44	0.68	1.008	1.120	1.135	0.996
0.53	0.47	0.64	1.007	1.114	1.134	0.993
0.56	0.49	0.56	1.003	1.113	1.132	0.992
0.59	0.52	0.50	1.000	1.113	1.130	0.992
0.62	0.54	0.44	0.996	1.113	1.127	0.993
0.65	0.56	0.36	0.992	1.114	1.123	0.994
0.68	0.58	0.30	0.987	1.115	1.119	0.995
0.70	0.60	0.26	0.984	1.115	1.116	0.996
0.72	0.61	0.24	0.979	1.117	1.111	0.996
0.74	0.63	0.22	0.973	1.119	1.105	0.997
0.76	0.65	0.20	0.967	1.121	1.099	0.997
0.78	0.66	0.18	0.959	1.125	1.090	0.998
0.80	0.68	0.17	0.950	1.130	1.080	0.999
0.82	0.69	0.16	0.941	1.134	1.069	1.000
0.84	0.71	0.16	0.932	1.139	1.059	1.000
Co-60		0.63	1.002	1.113	1.133	0.990

Table 5. Fraction of ionization α due to electrons arising in the chamber wall, taken from [Lempert et. al. 1983], mass stopping power ratios from [Andreo and Brahme 1986] for wall material to air $s_{wall,air}$, for water to air, $s_{w,air}$, ratios of averaged mass energy absorption coefficients for water to wall material $(\mu_{en}/\rho)_{w,wall}$ from [IAEA, Rep. 277, 1987], and calculated factor p_{wall}, that corrects for the difference in composition between the ionization chamber wall and water, for the ionization chamber PTW 30002 with graphite walls (wall thickness 0.083 g/cm^2) as function of the quality index.

TPR^{20}_{10}	D_{20}/D_{10}	α	$s_{wall,air}$	$(\mu_{en}/\rho)_{w,wall}$	$s_{w,air}$	p_{wall}
0.50	0.44	0.56	1.105	1.031	1.135	1.002
0.53	0.47	0.48	1.104	1.031	1.134	1.002
0.56	0.49	0.40	1.102	1.030	1.132	1.001
0.59	0.52	0.32	1.099	1.030	1.130	1.001
0.62	0.54	0.27	1.096	1.031	1.127	1.001
0.65	0.56	0.22	1.091	1.031	1.123	1.000
0.68	0.58	0.18	1.087	1.032	1.119	1.000
0.70	0.60	0.16	1.084	1.033	1.116	1.001
0.72	0.61	0.15	1.079	1.035	1.111	1.001
0.74	0.63	0.14	1.073	1.038	1.105	1.001
0.76	0.65	0.13	1.066	1.041	1.099	1.001
0.78	0.66	0.12	1.057	1.045	1.090	1.002
0.80	0.68	0.12	1.047	1.051	1.080	1.002
0.82	0.69	0.12	1.037	1.056	1.069	1.003
0.84	0.71	0.12	1.027	1.062	1.059	1.004
Co-60		0.47	1.102	1.030	1.133	1.001

Table 6. Fraction of ionization α due to electrons arising in the chamber wall, taken from [Lempert et. al.; 1983], mass stopping power ratios from [Andreo and Brahme, 1986]

for wall material to air $s_{wall,air}$, for water to air, $s_{w,air}$, ratios of averaged mass energy absorption coefficients for water to wall material $(\mu_{en}/\rho)_{w,wall}$ from [IAEA, Rep. 277, 1987], and calculated factor p_{wall}, that corrects for the difference in composition between the ionization chamber wall and water, for the ionization chamber PTW 30001 with PMMA walls (thickness 0.053 g/cm^2) as function of the quality index.

TPR^{20}_{10}	D_{20}/D_{10}	α	$s_{wall,air}$	$(\mu_{en}/\rho)_{w,wall}$	$s_{w,air}$	p_{wall}
0.50	0.44	0.68	1.105	1.031	1.135	1.003
0.53	0.47	0.64	1.104	1.031	1.134	1.002
0.56	0.49	0.56	1.102	1.030	1.132	1.002
0.59	0.52	0.50	1.099	1.030	1.130	1.001
0.62	0.54	0.44	1.096	1.031	1.127	1.001
0.65	0.56	0.36	1.091	1.031	1.123	1.001
0.68	0.58	0.30	1.087	1.032	1.119	1.001
0.70	0.60	0.26	1.084	1.033	1.116	1.001
0.72	0.61	0.24	1.079	1.035	1.111	1.001
0.74	0.63	0.22	1.073	1.038	1.105	1.002
0.76	0.65	0.20	1.066	1.041	1.099	1.002
0.78	0.66	0.18	1.057	1.045	1.090	1.002
0.80	0.68	0.17	1.047	1.051	1.080	1.003
0.82	0.69	0.16	1.037	1.056	1.069	1.004
0.84	0.71	0.16	1.027	1.062	1.059	1.005
Co-60		0.63	1.102	1.030	1.133	1.001

Table 7. Fraction of ionization α due to electrons arising in the chamber wall, taken from [Lempert et. al., 1983], mass stopping power ratios from [Andreo and Brahme, 1986] for wall material to air $s_{wall,air}$, for water to air, $s_{w,air}$, ratios of averaged mass energy absorption coefficients for water to wall material $(\mu_{en}/\rho)_{w,wall}$ from [IAEA, Rep. 277, 1987], and calculated factor p_{wall}, that corrects for the difference in composition between the ionization chamber wall and water, for the ionization chambers PTW 31002 and 31003 with PMMA walls (thickness 0.083 and 0.089 g/cm^2 respectively) as function of the quality index.

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