Reference dosimetry in clinical high-energy photon beams: Comparison of the AAPM TG-51 and AAPM TG-21 dosimetry protocols

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Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) has recently developed a new protocol for the calibration of high-energy photon and electron beams used in radiation therapy. The formalism and the dosimetry procedures recommended in this protocol are based on the use of an ionization chamber calibrated in terms of absorbed dose-to-water in a standards laboratory's ^{60}Co gamma ray beam. This is different from the recommendations given in the AAPM TG-21 protocol, which are based on an exposure calibration factor of an ionization chamber in a ^{60}Co beam. The purpose of this work is to compare the determination of absorbed dose-to-water in reference conditions in high-energy photon beams following the recommendations given in the two dosimetry protocols. This is realized by performing calibrations of photon beams with nominal accelerating potential of 6, 18 and 25 MV, generated by an Elekta MLCi and SL25 series linear accelerator. Two widely used Farmer-type ionization chambers having different composition, PTW 30001 (PMMA wall) and NE 2571 (graphite wall), were used for this study. Ratios of AAPM TG-51 to AAPM TG-21 doses to water are found to be 1.008, 1.007 and 1.009 at 6, 18 and 25 MV, respectively when the PTW chamber is used. The corresponding results for the NE chamber are 1.009, 1.010 and 1.013. The uncertainties for the ratios of the absorbed dose determined by the two protocols are estimated to be about 1.5%. A detailed analysis of the reasons for the discrepancies is made which includes comparing the formalisms, correction factors and quantities in the two protocols, as well as the influence of the implementation of the different standards for chamber calibration. The latter has been found to have a considerable influence on the differences in clinical dosimetry, even larger than the adoption of the new data and recommended procedures, as most intrinsic differences cancel out due to the adoption of the new formalism.
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Key words: AAPM TG-51 protocol, AAPM TG-21 protocol, standards of absorbed dose to water, photon beam dosimetry

I. INTRODUCTION

During the last three decades the American Association of Physicists in Medicine (AAPM),[1–3] the International Atomic Energy Agency (IAEA),[4] and organizations from various countries[5–8] have published several dosimetry protocols and Codes of Practice for the calibration of high-energy photon and electron beams. They are based on the exposure or air-kerma calibration factor of an ionization chamber in a ^{60}Co gamma ray beam and a formalism for the determination of the absorbed dose-to-water in reference conditions. These protocols incorporated the advances in radiation dosimetry that existed at the time of writing them to improve the accuracy of photon and electron beam calibrations.

In recent years, the major emphasis in primary standards laboratories around the world has shifted from standards for exposure or air kerma to those for absorbed dose-to-water. The rationale is to establish a better basis for dosimetry that relates directly to the quantity of interest in the clinic, absorbed dose-to-water. Andreo[9] and Rogers[10] have given the advantages of basing clinical reference dosimetry on the standards of absorbed dose-to-water.

Task Group 51 of the Radiation Therapy Committee of the AAPM has developed a new external beam dosimetry protocol based on the use of an ionization chamber calibrated in terms of absorbed dose-to-water in a ^{60}Co beam.[11] The IAEA,[12] in collaboration with other international organizations (WHO, PAHO, and ESTRO), has also developed a new Code of Practice that as well is based on the same chamber calibration procedure. These two new protocols follow those by the German Standard DIN,[13] the British IPSM[14] and the IAEA Code of Practice for plane-parallel chambers,[15] that have discussed and implemented the procedures for the determination of absorbed dose-to-water based on standards of absorbed dose-to-water.

The recommendations of the AAPM TG-51[11] protocol differ significantly from those of the AAPM TG-21[2] protocol. These differences need to be clearly stated and appreciated. Furthermore, the consequences of these differences may be important in the dosimetric evaluation of various collaborative clinical trials around the world. Thus it is important to perform a comparison between the AAPM TG-51 and the AAPM TG-21 protocols and provide an insight into the origin of the differences between them. Similar comparisons in the past[16–23] have provided valuable information about similarities, discrepancies, and inconsistencies that existed among other protocols. This paper reports the results of a series of dosimetric measurements of absorbed dose-to-water in photon beams performed following the recommendations of the AAPM TG-51[11] and the AAPM TG-21[2] protocols. Measurements are made with two widely used Farmer type ionization chambers in 6, 18 and 25 MV photon beams. Critical comparisons between the two protocols are performed and the sources of similarities and discrepancies are identified.

II. METHODS

A strict comparison of the determination of absorbed dose-to-water in reference conditions using the recommended procedures given in the AAPM TG-51 and AAPM TG-21 protocols requires that both the $N_{D,w}^{^{60}\mathrm{Co}}$ and N_X calibration factors be available for the chambers used in the comparison. To identify the reasons for discrepancies due exclusively to the procedures and data recommended by the two protocols, the assumption that the two types of calibration factors are exactly correlated will be made and the $N_{D,w}^{^{60}\mathrm{Co}}$ calibration factor will be derived theoretically from N_X. Departure from this correlation will be discussed later. To enable comparison of data in the two protocols, beam quality conversion factors (denoted by k_Q, see below) will be derived from TG-21 data and the various contributing factors analyzed. It will then be possible to identify the small changes due mainly to better data and new recommendations that are given in the AAPM TG-51[11] protocol.

Comparison of the two protocols thus involves the following three steps:

(i) Determination of the absorbed dose-to-water using the equations in AAPM TG-21 and a N_X calibration factor.

(ii) Determination of the absorbed dose-to-water using the equations in AAPM TG-51 and an $N_{D,w}^{^{60}\mathrm{Co}}$ calibration factor.

(iii) Determination of the absorbed dose-to-water using the equations in AAPM TG-51 but calculating k_Q using the AAPM TG-21 data; further, the calibration factor $N_{D,w}^{^{60}\mathrm{Co}}$ is derived theoretically from the N_X calibration factor.

In what follows a brief description of the formalisms given in the AAPM TG-21[2] and AAPM TG-51[11] protocols will be given, followed by a derivation of the relation between $N_{D,w}^{^{60}\mathrm{Co}}$ and N_X, and an expression for k_Q.

According to the AAPM TG-21 protocol, the absorbed dose-to-water, D_w^Q, at the reference depth in water in a photon beam of quality Q, and in the absence of the chamber, is given by

$$D_w^Q = M N_{\mathrm{gas}} (\overline{L}/\rho)_{\mathrm{gas}}^{w} P_{\mathrm{ion}} P_{\mathrm{repl}} P_{\mathrm{wall}}. \tag{1}$$

The meanings of the various parameters that appear in Eq. (1) can be found in the TG-21 protocol.[2]

According to the AAPM TG-51 protocol, the absorbed dose-to-water, D_w^Q, at the reference depth in water, in a photon beam of quality Q, and in the absence of the chamber, is given by

$$D_w^Q = M^* k_Q N_{D,w}^{^{60}\mathrm{Co}}, \tag{2}$$

where M^* is the reading of the dosimeter with the *point of measurement* of the chamber positioned at the reference depth, corrected for ion recombination, polarity effect, electrometer calibration factor and the standard environmental conditions of temperature, pressure, and relative humidity of the air in the ion chamber. k_Q is a chamber-specific factor which corrects for the effects of the difference between the calibration quality ^{60}Co and the actual user quality Q. Note that at the calibration quality ^{60}Co, the value of k_Q is unity. $N_{D,w}^{^{60}\mathrm{Co}}$ is the absorbed dose-to-water calibration factor of the user ionization chamber in a reference quality ^{60}Co beam.

The TG-51 protocol provides calculated values of k_Q for various cylindrical chamber types. The main advantage of using an experimentally determined value of $N_{D,w}^{^{60}\mathrm{Co}}$ for a given ionization chamber together with directly measured values of beam quality correction factors k_Q for that particular chamber at other beam qualities is that individual chamber responses at various beam qualities are intrinsically taken into account. In contrast, the calculated values of k_Q ignore chamber-to-chamber variations in response with energy within a given chamber type.[12]

Calculation of k_Q requires precise specification of beam quality Q. For photon beams, the AAPM TG-51[11] protocol recommends that $\%\mathrm{dd}(10)_x$, the percentage depth dose at 10 cm depth excluding electron contamination, be used as the beam quality specifier. The protocol provides calculated values of k_Q as a function of $\%\mathrm{dd}(10)_x$ for various cylindrical ionization chamber types. Details on these calculations of k_Q have been given by Rogers.[24] Similar calculations of k_Q as a function of the photon beam quality $\mathrm{TPR}_{20,10}$ were reported previously by Andreo[9] and Rogers[10] and recently by the new IAEA Code of Practice.[12]

At the calibration quality of ^{60}Co, Eqs. (1) and (2) can be rewritten as

$$D_w^{^{60}\mathrm{Co}} = M^{^{60}\mathrm{Co}} [P_{\mathrm{ion}}]_{^{60}\mathrm{Co}} N_{\mathrm{gas}} [(\overline{L}/\rho)_{\mathrm{gas}}^{w} P_{\mathrm{repl}} P_{\mathrm{wall}}]_{^{60}\mathrm{Co}}, \tag{3}$$

and

$$D_w^{^{60}\mathrm{Co}} = M^{^{60}\mathrm{Co}} N_{D,w}^{^{60}\mathrm{Co}} \tag{4}$$

from which the following relation between $N_{D,w}^{^{60}\mathrm{Co}}$ and N_{gas} can be derived:

$$N_{D,w}^{^{60}\mathrm{Co}} = N_{\mathrm{gas}}[(\overline{L}/\rho)_{\mathrm{gas}}^{w} P_{\mathrm{repl}} P_{\mathrm{wall}}]_{^{60}\mathrm{Co}}. \quad (5)$$

Note that $M^{^{60}\mathrm{Co}}$ in Eq. (4) has been corrected for the effect of P_{ion} and thus has the same meaning as that of $M^{^{60}\mathrm{Co}}[P_{\mathrm{ion}}]_{^{60}\mathrm{Co}}$ of Eq. (3). An equation analogous to Eq. (5) could be written for any beam quality Q simply replacing ^{60}Co by Q. This is not done here to emphasize that the calibration quality recommended by TG-51 is ^{60}Co gamma rays; thus only calibration factors $N_{D,w}^{^{60}\mathrm{Co}}$ are considered.

Values of $N_{D,w}^{^{60}\mathrm{Co}}$, calculated by using Eq. (5), can be used to verify that the beam calibrations based on the absorbed dose and exposure based formalisms yield approximately the same absorbed dose-to-water under reference conditions. This serves as a good consistency check for the entire calibration procedure. It should be emphasized that $N_{D,w}^{^{60}\mathrm{Co}}$ ''calibration'' factors calculated by using Eq. (5) are not traceable to primary standards of absorbed dose-to-water.

A. Expression for k_Q

The beam quality conversion factor k_Q is defined as

$$k_Q = \frac{N_{D,w}^{Q}}{N_{D,w}^{^{60}\mathrm{Co}}} = \frac{D_w^Q/M^Q}{D_w^{^{60}\mathrm{Co}}/M^{^{60}\mathrm{Co}}}. \quad (6)$$

Substituting the values of D_w^Q and $D_w^{^{60}\mathrm{Co}}$ by their corresponding equations according to TG-21 [Eq. (1)], an expression for k_Q is obtained as[9]

$$k_Q = \frac{[(\overline{L}/\rho)_{\mathrm{air}}^{w} P_{\mathrm{repl}} P_{\mathrm{wall}}]_Q}{[(\overline{L}/\rho)_{\mathrm{air}}^{w} P_{\mathrm{repl}} P_{\mathrm{wall}}]_{^{60}\mathrm{Co}}} \frac{(W_{\mathrm{air}})_Q}{(W_{\mathrm{air}})_{^{60}\mathrm{Co}}}, \quad (7)$$

where the quality dependence of W is explicitly included. For high-energy photon beams one makes the assumptions that $(W_{\mathrm{air}})_Q = (W_{\mathrm{air}})_{^{60}\mathrm{Co}}$. Writing $P_{\mathrm{repl}} = P_{gr} P_{fl}$ and incorporating the perturbation effect due to the lack of air equivalence of the central electrode, P_{cel}, in Eq. (7) one gets

$$k_Q \approx \frac{[(\overline{L}/\rho)_{\mathrm{air}}^{w} P_{gr} P_{fl} P_{\mathrm{wall}} P_{\mathrm{cel}}]_Q}{[(\overline{L}/\rho)_{\mathrm{air}}^{w} P_{gr} P_{fl} P_{\mathrm{wall}} P_{\mathrm{cel}}]_{^{60}\mathrm{Co}}}, \quad (8)$$

where the approximate symbol ($\approx$) is used in Eq. (8) to indicate the possible energy dependence of W. It is emphasized that when experimental and theoretical values of k_Q are compared it is the full Eq. (7) that is relevant, rather than the approximate Eq. (8).[12] Equation (8) has been used for the calculation of k_Q for various cylindrical chamber types and the data have been given in the AAPM TG-51 protocol. These values of k_Q are different from those given by Rogers[24] because the data set used for the calculations of k_Q given in the AAPM TG-51 protocol are slightly different from those used in Ref. 24.

B. Experimental method

Two 0.6 cm^3 Farmer-type ionization chambers having the same central electrode but different wall and buildup cap materials were used in this study. Specifically, (i) a PTW 30001 Serial No. 1340 chamber with a PMMA wall and buildup cap and aluminum central electrode, and (ii) a NE 2571 Serial No. 2415 chamber with graphite wall and Delrin buildup cap and aluminum central electrode are used for intercomparison. A description of the various dimensions (i.e., radius, length, thickness, etc.) of these chambers can be found in Ref. 11. The absorbed dose-to-water and exposure calibration factors for the two chambers were provided by an Accredited Dosimetry Calibration Laboratory (K & S Associates, Inc., Nashville, TN). For the PTW chamber the values of the calibration factors $N_{D,w}^{^{60}\mathrm{Co}}$ and N_X are $N_{D,w}^{^{60}\mathrm{Co}} = 5.288 \times 10^7$ Gy/C and $N_X = 5.470 \times 10^9$ R/C. The corresponding values for the NE chamber are $N_{D,w}^{^{60}\mathrm{Co}} = 4.536 \times 10^7$ Gy/C and $N_X = 4.679 \times 10^9$ R/C, respectively.

The photon beams were generated by an Elekta MLCi and SL25 series linear accelerator. All measurements were made in a water phantom. Prior to taking all measurements, the ion chambers and the phantom were allowed to equilibrate with ambient air at room temperature for more than 24 h.

The AAPM TG-21 recommended depths of calibration are different from those recommended in the AAPM TG-51 protocol. Since the present work is a comparison between two protocols, the measurement depth should be the same in both cases. For the present intercomparison, the calibration conditions given in the AAPM TG-51 protocol were chosen. For all photon beams, measurements were taken with a source–surface distance (SSD) of 100 cm, a depth of 10 cm in the water phantom and a field size of 10 cm $\times$ 10 cm at the phantom surface.

The beam quality in the AAPM TG-51[11] protocol is specified by the percent depth dose at 10 cm depth, $\%\mathrm{dd}(10)_x$, excluding electron contamination. On the other hand, AAPM TG-21[2] recommends that the so-called tissue-phantom ratio, $\mathrm{TPR}_{20,10}$ be used for beam quality specification. The recommendations of the AAPM TG-51 protocol were followed strictly to measure $\%\mathrm{dd}(10)_x$ for all photon beams. Depth ionization measurements along the central axis were made by using a Wellhofer WP700 computerized beam scanner. The values of $\mathrm{TPR}_{20,10}$ were measured in a water phantom using the PTW 30001 chamber. Measurements were made by keeping the source-to-chamber distance fixed at 100 cm and adjusting the water level such that the central axis of the chamber was placed at 10 and 20 cm depths in the water phantom. The field size at the plane of the central axis of the chamber was 10 cm $\times$ 10 cm.

Comparison of the two protocols, as presented in this study, requires the measured data for $\%\mathrm{dd}(10)_x$ and $\mathrm{TPR}_{20,10}$ only. The $\mathrm{TPR}_{20,10}$ data presented here correspond to the average of at least six readings, more typically eight readings per point. Half of the readings were taken with positive polarity and half with negative polarity. All ionization measurements were referenced to that of a 0.3 cm^3 PTW chamber mounted on the head of the machine. This circumvents the problems associated with instabilities in machine output and monitor response. When referenced to the 0.3 cm^3 PTW monitor chamber, the measurements were repeatable to within $\pm 0.2\%$.

TABLE I. Comparison of absorbed dose-to-water determined by following the recommendations of the AAPM TG-51 and the AAPM TG-21 protocols. The chamber readings, corrected for temperature, pressure, electrometer calibration factor and ion collection efficiency, cancel out in the ratio of comparison. The uncertainties for the different beam qualities are 0.4% for $\%\mathrm{dd}(10)_x$ and 0.2% for $\mathrm{TPR}_{20,10}$.

Chamber	Beam energy (MV)	Beam quality AAPM TG-51 $\%\mathrm{dd}(10)_x$	Beam quality AAPM TG-21 $\mathrm{TPR}_{20,10}$	$\frac{(k_Q)_{\text{TG-51}}}{(k_Q)_{\text{TG-21}}}$	$\frac{(N_{D,w}^{60\mathrm{Co}})_{\text{measured}}}{(N_{D,w}^{60\mathrm{Co}})_{\text{calculated}}}$	$\frac{(D_w^Q)_{\text{TG-51}}}{(D_w^Q)_{\text{TG-21}}}$	AAPM TG-51 $\frac{D_w^Q(\mathrm{NE})}{D_w^Q(\mathrm{PTW})}$	AAPM TG-21 $\frac{D_w^Q(\mathrm{NE})}{D_w^Q(\mathrm{PTW})}$
PTW 30001	6	67.7	0.683	0.996	1.012	1.008	0.999	0.999
NE 2571	6	67.7	0.683	0.995	1.014	1.009		
PTW 30001	18	80.1	0.776	0.995	1.012	1.007	1.009	1.006
NE2571	18	80.1	0.776	0.996	1.014	1.010		
PTW 30001	25	83.3	0.798	0.997	1.012	1.009	1.005	1.002
NE 2571	25	83.3	0.798	0.999	1.014	1.013		

III. RESULTS

Equations (1) and (2) have been used for the calculations of absorbed dose-to-water for the AAPM TG-21 and AAPM TG-51 protocols respectively. Equation (8) has been used for the calculation of k_Q and Eq. (5) for the calculation of $N_{D,w}^{60\mathrm{Co}}$ from N_X. The notations used in both protocols to denote various factors and coefficients have been retained the same in the present manuscript. In the analysis of the data the influences of the contribution from beam quality specification and various correction factors as well as that from the calibration factors of ionization chambers based on different standards are considered separately. Table I gives the measured values of $\%\mathrm{dd}(10)_x$ and $\mathrm{TPR}_{20,10}$ for the photon beams investigated in this study. Also, given in the table are comparisons of the results of the absorbed doses to water determined according to the recommendations the AAPM TG-51 and the AAPM TG-21 protocols. For both chambers, the absorbed doses to water determined according to AAPM TG-51, $(D_w^Q)_{\mathrm{TG}-51}$, are found to be higher than the absorbed doses to water, $(D_w^Q)_{\mathrm{TG}-21}$, determined according to AAPM TG-21, by 0.8% for the PTW chamber and by 0.9% for the NE chamber at 6 MV. At 18 MV, $(D_w^Q)_{\mathrm{TG}-51}$ is found to be higher than $(D_w^Q)_{\mathrm{TG}-21}$ by 0.7% for the PTW chamber and by 1.0% for the NE chamber. These ratios change to 0.9% and 1.3%, respectively, for the PTW and NE chambers at 25 MV. Table I also shows that the ratios of $(D_w^Q)_{\mathrm{TG}-51}$ for the NE and PTW chamber are 0.999, 1.009 and 1.005 at 6, 18 and 25 MV, respectively. The corresponding results for $(D_w^Q)_{\mathrm{TG}-21}$ are 0.999, 1.006 and 1.002.

IV. DISCUSSION

A. Influence of beam quality specification and various correction factors

To enable a comparison of the absorbed dose-to-water using the two protocols and to provide a convenient means of identifying the relative contributions of each factor to the absorbed dose, calculations were performed by following the method described in step (iii) in Sec. II. This involves the calculation of k_Q values determined using data from TG-21 and the use of a theoretically derived $N_{D,w}^{60\mathrm{Co}}$. As mentioned in Sec. II, it is assumed that the calibration factors $N_{D,w}^{60\mathrm{Co}}$ and N_X are exactly correlated. A theoretically derived $N_{D,w}^{60\mathrm{Co}}$ is used in the dose calculation to illustrate the differences that arise exclusively due to protocols and not due to the type of standards used. These results are compared to the corresponding factors in TG-51 in Table I, where parameters from both protocols, which are similar in meaning, have been grouped together. It can be seen from the table that the two components that contribute to the observed difference in absorbed dose between the two protocols are (i) the values of k_Q (as already stated, in the case of TG-21, these are calculated using the data given in the TG-21 protocol), and (ii) the differences between the measured and calculated values of the absorbed dose-to-water calibration factor, $N_{D,w}^{60\mathrm{Co}}$, of the ionization chamber. The two components are discussed in detail below.

The beam quality conversion factor k_Q is given by the ratios, at the user quality Q and $^{60}\mathrm{Co}$, of water/air stopping-power ratios and of the perturbation factors P_{gr}, P_{fl}, P_{wall} and P_{cel}, as well as of the mean energy expended in air per ion pair formed. The stopping power ratios depend only on the beam quality, whereas the perturbation correction factors P_{cel}, P_{gr}, P_{fl} and P_{wall} are chamber specific factors, which also depend on the beam quality. It can be seen from Table I that the AAPM TG-51 calculated values of k_Q are slightly lower than those obtained using the AAPM TG-21 data, the maximum difference being 0.5%. Earlier calculations by Rogers[24] show similar results at the energies of interest in the present study although differences of about 1% were found by him at 10 MV. To analyze the details of this difference, the ratios of each perturbation correction factor and the stopping power ratios at qualities Q and $^{60}\mathrm{Co}$ are given in Table II for the chambers and energies investigated in this study.

The largest contribution to the observed discrepancy in k_Q is the quotient of water-to-air stopping power ratios, $[(\overline{L}/\rho)_{\text{air}}^{w}]_{60\mathrm{Co}}^{Q}$. At 6, 18, and 25 MV, this quotient is responsible for a decrease of 0.7%, 1.1%, 0.9%, respectively, between the two k_Q values. The stopping power ratios used in

TABLE II. Comparison of ratios of water-to-air stopping power ratios and various perturbation correction factors at various beam qualities Q and ^{60}Co according to the AAPM TG-51 and the AAPM TG-21 protocols. The uncertainties for the different beam qualities are 0.4% for %dd(10)$_x$ and 0.2% for TPR$_{20,10}$.

Chamber	Beam energy (MV)	Beam quality AAPM TG-51 %dd(10)$_x$	Beam quality AAPM TG-21 TPR$_{20,10}$	Protocol	$\left[\left(\frac{\bar{L}}{\rho}\right)^w_{air}\right]^Q_{^{60}Co}$	$(P_{cel})^Q_{^{60}Co}$	$(P_{repl})^Q_{^{60}Co}$	$(P_{wall})^Q_{^{60}Co}$	$\frac{(k_Q)_{TG-51}}{(k_Q)_{TG-21}}$
PTW	6	67.7	0.683	AAPM TG-51	0.987	1.001	1.001	1.000	
30001				AAPM TG-21	0.994	1.000	1.001	0.999	0.996
				Ratio	0.993	1.001	1.000	1.002	
NE 2571	6	67.7	0.683	AAPM TG-51	0.987	1.001	1.001	1.004	
				AAPM TG-21	0.994	1.000	1.001	1.003	0.995
				Ratio	0.993	1.001	1.000	1.001	
PTW	18	80.1	0.776	AAPM TG-51	0.962	1.003	1.002	1.002	
30001				AAPM TG-21	0.973	1.000	1.002	0.999	0.995
				Ratio	0.989	1.003	1.000	1.003	
NE 2571	18	80.1	0.776	AAPM TG-51	0.962	1.003	1.002	1.007	
				AAPM TG-21	0.973	1.000	1.002	1.003	0.996
				Ratio	0.989	1.003	1.000	1.004	
PTW	25	83.3	0.798	AAPM TG-51	0.955	1.003	1.003	1.003	
30001				AAPM TG-21	0.964	1.000	1.003	0.999	0.997
				Ratio	0.991	1.003	1.000	1.003	
NE 2571	25	83.3	0.798	AAPM TG-51	0.955	1.003	1.004	1.008	
				AAPM TG-21	0.964	1.000	1.004	1.003	0.999
				Ratio	0.991	1.003	1.000	1.005	

the AAPM TG-51 protocol have been taken from the calculations of Rogers and Yang,[25] which is an update of the calculation by Kosunen and Rogers.[26] These data are based on electron stopping power data recommended in the ICRU Report 37[27] and are consistent with the data used in the primary standards laboratories. In contrast, the stopping power ratios used in the AAPM TG-21 protocol are based on the Berger and Seltzer 1980 electron stopping powers (data included in the ICRU Report 35[28]) in which the density effect correction is calculated according to the Sternheimer and Pearls (1971) approximation.[29] The use of improved data set for the calculation of stopping power ratios causes the values of $(\bar{L}/\rho)^w_{air}$ in the AAPM TG-51 protocol to be lower than those of the AAPM TG-21 protocol. Earlier work by Huq and Nath,[17] comparing the recommendations of the AAPM TG-21 protocol and the IAEA Code of Practice TRS 277,[4] showed similar differences in the stopping power ratios between the two. It should be noted that the stopping power ratios used in the IAEA Code of Practice TRS 277 are based on the electron stopping power data recommended in the ICRU Report 37.[27]

Several groups have investigated the effect of the central electrode on the response of an ionization chamber. For cylindrical chamber types, P_{cel} corrects for the lack of air equivalence of the central electrode. A correction factor for this effect was introduced, for example, in IAEA TRS-277[4] that was proven to be excessive and modified in the second edition of that Code of Practice. Monte Carlo calculations of Ma and Nahum[30] and the experimental determination of Palm and Mattsson[31] have shown that for Farmer-type chambers with an aluminum electrode of diameter 1 mm, the chamber response increases by about 0.7% at the reference depth in a ^{60}Co beam. These values are in good agreement with the previous work of Mattsson[32] and Rogers *et al.*[33] Furthermore, the work of Ma and Nahum[30] and Palm and Mattsson[31] also showed that the response of such chambers also increase by 0.43% to 0.75% for photon beam qualities TPR$_{20,10}$ of 0.80 and 0.58 [approximately, %dd(10) of 86% and 62% where %dd(10) excludes electron contamination], respectively. It is assumed that these results vary linearly with beam quality. These values of P_{cel} have been incorporated in the AAPM TG-51 protocol. The AAPM TG-21 protocol does not incorporate any such correction in its formalism. For the chambers and x-ray energies employed in this study, the effect of the central electrode is to increase the AAPM TG-51 value of k_Q by up to about 0.3% at 18 and 25 MV.

The replacement correction factor $P_{repl}(=P_{gr}P_{fl})$ accounts for the change in photon and electron fluence that occurs because of replacement of phantom material by chamber cavity. Two effects arise from the chamber cavity: (i) the perturbation by the cavity of the electron fluence due to scattering differences between the air cavity and the medium, and (ii) a displacement correction which accounts for the fact that a cylindrical chamber cavity with its center at the reference depth samples the electron fluence at a point which is closer to the radiation source than the reference depth. This correction depends on the inner radius of the cavity. The former effect is corrected by P_{fl} and the second effect by P_{gr}. Since transient electronic equilibrium is assumed to exist at the reference depth, the value of P_{fl} is taken to be unity. The values of P_{gr} used in the AAPM TG-51 protocol have been taken from the data given in the AAPM TG-21 protocol. Consequently, this factor does not contribute any differences in the absorbed dose determination between the two protocols.

Both protocols use the expression developed by Almond and Svensson[34] for the calculation of P_{wall}, which includes stopping power ratios and mass energy absorption coefficient ratios. In the AAPM TG-51 calculations of P_{wall} the stopping power ratios have been taken from Rogers and Yang[25] whereas $(\overline{\mu_{en}/\rho})$-ratios have been taken from the IAEA Code of Practice TRS 277[4] [these were given as a function of $\mathrm{TPR}_{20,10}$ and have been recasted to $\%\mathrm{dd}(10)_x$]. Quantitative differences in $(\overline{\mu_{en}/\rho})$-ratios between the protocols range from 0% at 6 MV to 0.8% at 25 MV photon beam. The values of the parameter α required for the calculations of P_{wall} have been taken from Lempert *et al.*[35] by both protocols. When the AAPM TG51 values of $(P_{\mathrm{wall}})^{Q}_{^{60}\mathrm{Co}}$ are compared with the corresponding values obtained from the AAPM TG-21 protocol, a discrepancy of up to 0.5% is observed which results from the use of different data sets in the two protocols.

The beam quality in the AAPM TG-51 protocol is specified by the percentage depth dose at 10 cm depth excluding electron contamination, i.e., $\%\mathrm{dd}(10)_x$. The protocol gives values of k_Q as a function of $\%\mathrm{dd}(10)_x$ for various cylindrical chamber types. On the other hand, the AAPM TG-21 protocol recommends that $\mathrm{TPR}_{20,10}$ be used as a beam quality specifier for photon beams and gives the stopping power ratios as a function of $\mathrm{TPR}_{20,10}$. In a recent study Huq *et al.*[36] have shown that the use of $\%\mathrm{dd}(10)_x$ or $\mathrm{TPR}_{20,10}$ to determine the values of k_Q leads to a maximum difference of about 0.15% in the value of k_Q. The influence of this contributing factor is, therefore, minimal.

It is important to emphasize that in spite of the relatively large contribution of the quotient of stopping power ratios (decrease), its combination with the contribution of the quotients of perturbation factors (increase) results in a net decrease which in no case is larger than 0.5%. This is the difference that can be solely attributed to the data and procedures recommended in TG-51 compared with TG-21.

The use of the electrometer calibration factor deserves some attention. According to the AAPM TG-51 protocol, if an electrometer is calibrated separately from the ionization chamber then a calibration factor, P_{elec}, supplied by the calibration laboratory, needs to be applied to correct the electrometer reading to true Coulombs. On the other hand, if the chamber and electrometer are calibrated together as a unit, then the combined calibration factor for $N_{D,w}^{^{60}\mathrm{Co}}$ will typically be given in units of Gy/rdg or Gy/nC (depending on the electrometer readout) and no separate electrometer calibration factor is required, i.e., P_{elec} has a value of unity. The AAPM TG-21 protocol does not provide any explicit recommendation with regard to the use of electrometer calibration factor. However, since it has become a standard of practice to use the electrometer calibration factor when using the AAPM TG-21 protocol, the factor P_{elec} is not considered as a difference between the two protocols in the present study.

Ding *et al.*[37] has recently performed a comparison of absorbed doses determined in reference conditions following the recommendations of the AAPM TG-51 and TG-21 protocols for high-energy photon (^{60}Co, 6 and 18 MV) and electron (6–20 MeV) beams. Their results show that the estimated dose changes in reference dosimetry between TG-51 and TG-21 are between 1.4% and 2.2% for a ^{60}Co beam and 0.8% and 1.5% for photon beams with energies of 6 and 18 MV respectively when chamber calibration is traceable to NIST. At 6 and 18 MV, the present results agree well with those of Ding *et al.*[37]

B. Influence of the calibration factor based on different standards

As shown in Table I, the difference between the measured and calculated values of $N_{D,w}^{^{60}\mathrm{Co}}$ has the largest effect on the observed differences in the absorbed dose-to-water between the two protocols. The measured value of $N_{D,w}^{^{60}\mathrm{Co}}$ is found to be higher than the calculated value by 1.2% for the PTW chamber and 1.4% for the NE chamber.

It is known that calibrations of ^{60}Co beams based on standards of air kerma, K_{air}, and standards of absorbed dose-to-water, D_w, differ by typically 1% for most ionization chambers although there are two exceptions that will be discussed below. A detailed discussion on this discrepancy has been given in the new IAEA Code of Practice.[12] Measurements at the IAEA Dosimetry Laboratory using various ionization chambers with calibrations traceable to the BIPM have shown that at ^{60}Co, the absorbed dose-to-water determined by using measured values of $N_{D,w}^{^{60}\mathrm{Co}}$ is about 1% higher than that determined by using the air kerma calibration factor N_K together with the IAEA Code of Practice TRS 277.[4] The observed differences are in most cases within the combined standard uncertainty of the two Codes of Practice based on standards of absorbed dose-to-water and air kerma, but they provide a clear indication of the influence of adopting different calibration factor types even when they are both traceable to the standards of a given laboratory. The difference at ^{60}Co is transported into the comparisons at high-energy photons, establishing a systematic difference between $N_{D,w}$ and K_{air} or X-based dosimetry protocols. Depending on the ratio of calibration factors $N_{D,w}/N_K$ supplied by a given primary standards laboratory, the observed change at ^{60}Co may become[12] the most significant contributing factor to any differences that are observed in high-energy photon beam calibration based on standards of absorbed dose-to-water.

It is important to emphasize that international comparisons of standards of absorbed dose-to-water at ^{60}Co at the BIPM show agreement of the standards within 0.7% of each other. The relative standard deviation of these results is about 0.5%.[12] These differences are slightly higher than those of air kerma primary standards for ^{60}Co beam. Discrepancies of the order of 1% between measured and calculated values of $N_{D,w}^{^{60}\mathrm{Co}}$ are therefore expected when $N_{D,w}^{^{60}\mathrm{Co}}$ and N_K calibrations, traceable to BIPM, NIST and other national standards laboratories, are used in the hospitals. Exceptions to these discrepancies, where the two factors almost agree, are for calibrations traceable to the German (PTB) and Canadian (NRCC) standard laboratories. In the first case, the agreement occurs because the Fricke-based PTB absorbed dose-to-water standard is approximately 0.7% lower than the rest of laboratories[12] (although a new standard is under de-

TABLE III. Estimated relative standard uncertainty (%) in the determination of absorbed dose to water at the reference depth in high energy photon beams using the TG-21 N_X-N_{gas} and TG-51 $N_{D,w}$ formalisms.

	TG-21	TG-51
Step 1: User chamber calibration factor	N_{gas}	$N_{D,w}^{60CO}$
Combined uncertainty	0.8	0.6
Step 2: User beam measurements		
Combined uncertainty in dosimeter reading[a]	0.9	
Step 3a: Quantities and perturbation factors for the user beam		
Combined uncertainty in stopping power ratios, perturbation factors and their assignment to beam quality	0.9	
Step 3b: Beam quality correction k_Q (calculated) (Ref. 12)		1.0
Combined uncertainty in D_w^Q	1.5	1.4

[a]Includes long-term stability of the dosimeter, establishment of reference conditions, measurement of beam quality, and dosimeter reading relative to timer or beam monitor.

velopment). In the second case the agreement follows the new water calorimeter standard adopted by NRCC and readers are referred to the work of Shortt *et al.*[38] for a detailed comparison between the NRCC and NIST standards.

It can thus be concluded that the sources of the observed discrepancies between the two types of protocols are most likely the inaccuracies in the numerical values of the various factors and expressions (i.e., P_{wall}, etc.) that enter into the air kerma or exposure based formalism, as well as the possibility of systematic effects in the air kerma primary standards.[39] As already indicated, there is a strong evidence to support that absorbed dose-to-water standards are to be preferred, also due to the robustness of the realization of these standards.

V. DETERMINATION OF UNCERTAINTIES

It should be noted that neither the AAPM TG-21 protocol nor the TG-51 protocol provides an estimation of the uncertainties involved in the process of determination of the absorbed dose-to-water in reference conditions. In order to determine the uncertainties for the ratio of the absorbed doses determined by the two protocols, a brief analysis of the uncertainties using the $N_X - N_{gas}$ and $N_{D,w}$ formalisms is presented first. The values estimated are given in Table III, and are based on the ISO guide for the expression of uncertainties;[40] they refer to relative standard uncertainties (u_c). It will be assumed that calibrations are made at an ADCL with a typical average uncertainty for the relevant calibrations.

For the TG-21 $N_X - N_{gas}$ formalism, the first step made by the user is the determination of the chamber factor N_{gas}. The estimated u_c is 0.8%, which approximately duplicates the uncertainty of the starting N_X calibration factor supplied by the ADCL. The second step consists of the measurements carried out by the user at the photon beam; u_c varies with the type of beam and ionization chamber, and is typically around 0.9% for a Farmer-type chamber. The following step corresponds to the values of quantities and perturbation correction factors selected by the user for the beam-chamber combination; using recent estimates given in the IAEA Code of Practice[12] results in a u_c of about 1% for a Farmer-type chamber. When the three steps are combined, the estimated relative standard uncertainty in the determination of the absorbed dose-to-water using the TG-21 $N_X - N_{gas}$ formalism becomes 1.5%.

For the first step in the TG-51 $N_{D,w}$ formalism, typical ADCL uncertainties for the $N_{D,w}$ calibration factor are around 0.6% for Farmer-type chambers. Uncertainties associated with the measurements in the user beam are identical to those quoted above for the $N_X - N_{gas}$ formalism. The remaining step 3 is the beam quality correction factor k_Q for which the IAEA Code of Practice[12] gives u_c of approximately 1%. When the three steps are combined, the estimated relative standard uncertainty in the determination of the absorbed dose-to-water using the TG-51 $N_{D,w}$ formalism becomes approximately 1.4%. If k_Q factors are directly measured for the user chamber in a high-energy photon beam at primary standards laboratories, typical uncertainties in k_Q are of the order of 0.5%–0.7%; this results in a combined uncertainty of the absorbed dose-to-water determination of 1.2%–1.3%.

Even if the estimated standard uncertainties of the two formalisms appear to be almost identical, the present analysis does not take into account chamber-to-chamber differences in N_{gas} for a given chamber-type (other than those included in N_X), which are intrinsically included in $N_{D,w}$ calibrations. The same occurs with the chamber-dependent perturbation factors in calculated k_Q factors, which are intrinsically included in measured k_Q values. The unresolved difference between dose determinations in ^{60}Co using the two formalisms, which are most likely related to the primary standards, are also beyond the scope of the present work. These issues would undoubtedly increase the uncertainty of the absorbed dose determination for the $N_X - N_{gas}$ formalism but in a manner difficult to estimate at present, favoring the use of a $N_{D,w}$-based protocol, preferably in conjunction with experimental k_Q values measured for the user chamber.

When independent beam calibrations are made using TG-21 and TG-51, a conservative estimate of the relative standard uncertainty of the dose ratios would simply combine in quadrature the two final uncertainties given in Table III, that is, 1.5% for TG-21 and 1.4% for TG-51 using calculated k_Q values. This procedure yields a combined uncertainty of 2%. However, cancellations must be taken into account as, with the exception of the beam quality determination, the same experimental results are used in both cases. This in practice reduces the estimation to the combination of the uncertainties of steps 1 and 3 in the two cases, yielding approximately 1.5%.

VI. SUMMARY

This paper presents the results of a set of dosimetric measurements made with a PTW and NE Farmer chamber in a water phantom and exposed to 6, 18, and 25 MV photon beams. Using the results of these measurements a comparison between the AAPM TG-51 and the AAPM TG-21 protocols is performed. Depending upon the choice of ionization chamber and beam quality, the discrepancy in absorbed dose-to-water between the two protocols is found to range between 0.7% and 1.3%. The AAPM TG-51 doses-to-water are found to be higher than the AAPM TG-21 doses by up to 0.9% at 6 MV and up to 1.0 % at 18 MV. The largest discrepancy of 1.3% is observed when a NE chamber is used at 25 MV.

The reason for the discrepancies has been analyzed, with the finding that the data and procedures recommended in the AAPM TG-51 protocol are responsible for a maximum contribution of about 0.5%. The rest of the difference is presumably caused by the change in the primary standard used for chamber calibrations.

When the recommendations of the AAPM TG-51 protocol are followed the ratios of NE to PTW chamber doses are found to be 0.999, 1.009 and 1.005 at 6, 18 and 25 MV, respectively. The corresponding results for the AAPM TG-21 protocol are 0.999, 1.006 and 1.002. This apparent inconsistency is presumably attributed to deficiencies in our present knowledge of perturbation factors and quantities used to calculate k_Q values, which are expected to be reduced when direct calibrations in terms of absorbed dose-to-water become feasible at high-energy photon qualities.

There are substantial differences between the two protocols of which the most important ones are summarized as follows:

(i) The formalism in the AAPM TG-51 protocol is based on the calibration factor of an ionization chamber in terms of absorbed dose-to-water. The AAPM TG-21 protocol, on the other hand, is based on the exposure calibration factor of an ionization chamber. This change of standards between the two protocols leads to a difference of up to 1.4% between the measured values of $N_{D,w}^{^{60}\mathrm{Co}}$ and values of $N_{D,w}^{^{60}\mathrm{Co}}$ calculated from N_X.

(ii) The beam quality in the AAPM TG-51 protocol is specified by percent depth dose at 10 cm depth, $\%\mathrm{dd}(10)_x$, excluding electron contamination. The AAPM TG-21 protocol, on the other hand, recommends that $\mathrm{TPR}_{20,10}$ be used as a beam quality specifier; the contribution of this difference is practically negligible, being of the order of 0.15%.

(iii) In contrast to the AAPM TG-21 protocol, the stopping power ratios used in the AAPM TG-51 protocol are based on the electron stopping power data recommended in the ICRU Report 37. This results in corrections of up to 1.1% in the determination of k_Q which is compensated by the changes introduced in perturbation factors, the net result being a maximum difference of about 0.5%;

(iv) The effect of aluminum central electrode of diameter 1 mm on the response of a Farmer type ionization chamber is included in the AAPM TG-51 protocol. The AAPM TG-21 protocol does not include any such correction factor in its formalism;

(v) The AAPM TG-51 protocol includes explicitly the use of an electrometer correction factor that converts the electrometer reading to true Coulombs. The AAPM TG-21 protocol does not incorporate explicitly such factor in its formalism; and

(vi) The AAPM TG-51 protocol recommends that all reference dosimetry measurements be performed in a water phantom. The AAPM TG-21 protocol recommends that any of water, PMMA or clear polystyrene phantom can be used for reference dosimetry measurements. The effect of this recommendation remains to be analyzed.

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[1] The AAPM Subcommittee on Radiation Dosimetry, ''Protocol for the dosimetry of x- and gamma-ray beams with maximum energies between 0.6 and 50 MeV,'' Phys. Med. Biol. **16**, 379–396 (1971).

[2] AAPM American Association of Physicists in Medicine, Task Group 21, ''A protocol for the determination of absorbed dose from high-energy photon and electron beams,'' Med. Phys. **10**, 741–771 (1983).

[3] R.J. Schulz, P.R. Almond, G. Kutcher, R. Loevinger, R. Nath, D.W.O. Rogers, N. Suntharalingam, K.A. Wright, and F. Khan, ''Clarification of the AAPM Task Group 21 protocol,'' Med. Phys. **13**, 755–759 (1986).

[4] IAEA International Atomic Energy Agency, ''Absorbed dose determination in photon and electron beams: An International Code of Practice,'' Technical Report Series No. 277 (2nd ed. in 1997), IAEA, Vienna (1987).

[5] NACP Nordic Association of Clinical Physics, ''Procedures in external radiation therapy dosimetry with electron and photon beams with maximum energies between 1 and 50 MeV,'' Acta Radiol.: Oncol., Radiat., Phys., Biol. **19**, 55–79 (1980).

[6] NCS NEDERLANDSE COMMISSIE VOOR STRALINGSDOSIMETRIE, ''Code of Practice for the dosimetry of high-energy photon beams,'' Report NCS-2, Delft: NCS (1986).

[7] HPA Hospital Physicist's Association, ''Revised Code of Practice for the dosimetry of 2 to 25 MV X-ray and of Caesium-137 and Cobalt-60 gamma-ray beams,'' Phys. Med. Biol. **28**, 1097–1104 (1983).

[8] HPA Hospital Physicist's Association, ''Code of Practice for electron beam dosimetry in radiotherapy,'' Phys. Med. Biol. **30**, 1169–1194 (1985).

[9] P. Andreo, ''Absorbed dose beam quality factors for the dosimetry of high-energy photon beams,'' Phys. Med. Biol. **37**, 2189–2211 (1992).

[10] D.W.O. Rogers, ''The advantages of absorbed-dose calibration factors,'' Med. Phys. **19**, 1227–1239 (1992).

[11] AAPM American Association of Physicists in Medicine, Task Group 51, ''AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams,'' Med. Phys. **26**, 1847–1870 (1999).

[12] P. Andreo, D.T. Burns, K. Hohlfeld, M. Saiful Huq, T. Kanai, F.Laitano. V.G. Smyth, and S. Vynckier, ''Absorbed dose determination in external beam radiotherapy: An international Code of Practice for dosimetry based on standards of absorbed dose-to-water,'' Technical Report Series, in press, IAEA, Vienna (2000).

[13] DIN DEUTSCHES INSTITUT FUR NORMUNG, Dosismessverfahren nach der sondenmethode fur photonen- und elektronenstrahlung, teil 2: Ionisationsdosimetrie, Deutsche Norm DIN 6800-2, Deutsches Institut fur Normung, Berlin (1997).

[14] IPSM Institute of Physical Sciences in Medicine, ''Code of Practice for high-energy photon therapy dosimetry based on NPL absorbed dose calibration service,'' Phys. Med. Biol. **35**, 1355–1360 (1990).
[15] IAEA International Atomic Energy Agency, ''The use of planeparallel ionization chambers in high-energy electron and photon beams. An international Code of Practice for dosimetry,'' Technical Report Series No, 381, IAEA, Vienna (1997).
[16] M.A. Hunt, S. Malik, C. Thomason, and M.E. Masterson, ''A comparison of the AAPM 'protocol for the determination of absorbed dose from high energy photon and electron beams' with currently used protocols,'' Med. Phys. **11**, 806–813 (1984).
[17] M. Saiful Huq and R. Nath, ''Comparison of IAEA 1987 and AAPM 1983 protocols for dosimetry calibration of radiotherapy beams,'' Med. Phys. **18**, 26–35 (1991).
[18] M. Saiful Huq, A.G. Agostinelli, and R. Nath, ''Calibration of high-energy photon and electron beams for radiotherapy using AAPM 1983 and IAEA 1987 dosimetry protocols,'' Med. Phys. **20**, 293–298 (1993).
[19] J.M. Paul, R.F. Koch, and P.C. Philip, ''AAPM Task Group 21 protocol: Dosimetric evaluation,'' Med. Phys. **12**, 424–430 (1985).
[20] P.R. Almond, ''A comparison of x-ray dose calibration using different phantom materials,'' Radiother. Oncol. **4**, 319–323 (1985).
[21] H. Kubo and P. Cheng, ''Absorbed dose comparison among commercial ionization chambers in polystyrene and acrylic phantoms,'' Med. Phys. **15**, 269–272 (1988).
[22] B.J. Mijnheer and L.M. Chin, ''The effect of differences in data base on the determination of absorbed dose in high-energy photon beams using the American Association of Physicists in Medicine Protocol,'' Med. Phys. **16**, 119–122 (1989).
[23] O. Mattsson, ''Comparison of different protocols for the dosimetry of high-energy photon and electron beams,'' Radiother. Oncol. **4**, 313–318 (1985).
[24] D.W.O. Rogers, ''Fundamentals of dosimetry based on absorbed-dose standards,'' in *Teletherapy Physics, Present and Future*, edited by J.R. Palta and T.R. Mackie (AAPM, Washington D.C., 1996), pp. 319–356.
[25] D.W.O. Rogers and C.L. Yang, ''Corrected relationship between $\%dd(10)_x$ and stopping power ratios,'' Med. Phys. **26**, 538–540 (1999).
[26] A. Kosunen and D.W.O. Rogers, ''Beam quality specification for photon beam dosimetry,'' Med. Phys. **20**, 1181–1188 (1993).
[27] ICRU International Commission on Radiation Units and Measurements, ''Stopping powers for electrons and positrons,'' ICRU Report No. 37, Bethesda, MD, 1984.
[28] ICRU International Commission on Radiation Units and Measurements, ''Radiation dosimetry: Electron beams with energies between 1 and 50 MeV,'' ICRU Report No. 35, Bethesda, MD, 1984.
[29] R.M. Sternheimer and R.F. Peierls, ''General expression for the density effect for the ionization loss of charged particles,'' Phys. Rev. B **3**, 3681 (1973).
[30] C.M. Ma and A.E. Nahum, ''Effect of size and composition of central electrode on the response of cylindrical ionization chambers in high-energy photon and electron beam,'' Phys. Med. Biol. **38**, 267–290 (1993).
[31] A. Palm and O. Mattsson, ''Experimental study on the influence of the central electrode in Farmer type ionization chambers,'' Phys. Med. Biol. **44**, 1299–1308 (1999).
[32] L.O. Mattsson, ''Application of the water calorimeter, Fricke dosimeter and ionization chamber in clinical dosimetry: An evaluation of correction factors and interaction coefficients,'' thesis, University Gothenburg, Sweden, 1984.
[33] D.W.O. Rogers, A.F. Bielajew, and A.E. Nahum, ''Ion chamber response and A_{wall} correction factors in a ^{60}Co beam by Monte Carlo simulation,'' Phys. Med. Biol. **30**, 429–443 (1985).
[34] P.R. Almond and H. Svensson, ''Ionization chamber dosimetry for photon and electron beams: Theoretical considerations,'' Acta Radiol.: Ther., Phys., Biol. **16**, 177 (1977).
[35] G.D. Lempert, R. Nath, and R.J. Schulz, ''Fraction of ionization from electrons arising in the wall of an ionization chamber,'' Med. Phys. **10**, 1–3 (1983).
[36] M. Saiful Huq, M. Hossain, and P. Andreo, ''A comparison of the AAPM TG-51 protocol and the IAEA absorbed-dose-to-water based Code of Practice for dosimetry calibration of high energy photon beams,'' Med. Phys. **26**, 1153 (1999).
[37] G.X. Ding, J.E. Cygler, and C.B. Kwok, ''Clinical reference dosimetry: Comparison between AAPM TG-21 and TG-51 protocols,'' Med. Phys. **27**, 1217–1225 (2000).
[38] K.R. Shortt, J. Shobe, and S. Domen, ''Comparison of dosimetry calibration factors at the NRCC and the NIST,'' Med. Phys. **27**, 1644–1654 (2000).
[39] A.F. Bielajew and D.W.O. Rogers, ''Implication of new correction factors on primary air kerma standards in Co-60 beams,'' Phys. Med. Biol. **37**, 1283–1291 (1992).
[40] ISO International Organization for Standardization 1995 *Guide to the expression of uncertainty in measurement*, 2nd ed. [Published by ISO in the name of BIPM, IEC, IFCC, IUPAC, IUPAP and OIML] (Geneva: ISO).