Absorbed-dose beam quality conversion factors for cylindrical chambers in high energy photon beams

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Recent working groups of the AAPM [Almond *et al.*, Med. Phys. **26**, 1847 (1999)] and the IAEA (Andreo *et al.*, Draft V.7 of ''An International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water,'' IAEA, 2000) have described guidelines to base reference dosimetry of high energy photon beams on absorbed dose to water standards. In these protocols use is made of the absorbed-dose beam quality conversion factor, k_Q which scales an absorbed-dose calibration factor at the reference quality ^{60}Co to a quality Q, and which is calculated based on state-of-the-art ion chamber theory and data. In this paper we present the measurement and analysis of beam quality conversion factors k_Q for cylindrical chambers in high-energy photon beams. At least three chambers of six different types were calibrated against the Canadian primary standard for absorbed dose based on a sealed water calorimeter at ^{60}Co [$\mathrm{TPR}_{10}^{20}=0.572$, $\%\mathrm{dd}(10)_x=58.4$], 10 MV [$\mathrm{TPR}_{10}^{20}=0.682$, $\%\mathrm{dd}(10)_x=69.6$), 20 MV ($\mathrm{TPR}_{10}^{20}=0.758$, $\%\mathrm{dd}(10)_x=80.5$] and 30 MV [$\mathrm{TPR}_{10}^{20}=0.794$, $\%\mathrm{dd}(10)_x=88.4$]. The uncertainty on the calorimetric determination of k_Q for a single chamber is typically 0.36% and the overall 1σ uncertainty on a set of chambers of the same type is typically 0.45%. The maximum deviation between a measured k_Q and the TG-51 protocol value is 0.8%. The overall rms deviation between measurement and the TG-51 values, based on 20 chambers at the three energies, is 0.41%. When the effect of a 1 mm PMMA waterproofing sleeve is taken into account in the calculations, the maximum deviation is 1.1% and the overall rms deviation between measurement and calculation 0.48%. When the beam is specified using TPR_{10}^{20}, and measurements are compared with k_Q values calculated using the version of TG-21 with corrected formalism and data, differences are up to 1.6% when no sleeve corrections are taken into account. For the NE2571 and the NE2611A chamber types, for which the most literature data are available, using $\%\mathrm{dd}(10)_x$, all published data show a spread of 0.4% and 0.6%, respectively, over the entire measurement range, compared to spreads of up to 1.1% for both chambers when the k_Q values are expressed as a function of TPR_{10}^{20}. For the PR06-C chamber no clear preference of beam quality specifier could be identified. When comparing the differences of our k_Q measurements and calculations with an analysis in terms of air-kerma protocols with the same underlying calculations but expressed in terms of a compound conversion factor C_Q, we observe that a system making use of absorbed-dose calibrations and calculated k_Q values, is more accurate than a system based on air-kerma calibrations in combination with calculated C_Q (rms deviation of 0.48% versus 0.67%, respectively). © *2000 American Association of Physicists in Medicine.* [S0094-2405(00)01512-1]

I. INTRODUCTION

Prior to 1999, reference dosimetry of clinical high energy photon beams was largely performed using chambers calibrated free-in-air in terms of air kerma at the reference radiation quality ^{60}Co. The clinical reference quantity of interest, on which patient dosimetry is based, is absorbed dose to water. To make the transfer between the calibration situation and the end-user's beam, use was made of a chamber dependent formalism such as presented in the IAEA TRS-277[1] or the AAPM TG-21.[2] A variety of uncertainty estimates of air-kerma based protocols have been made leading to different final uncertainties in the absorbed dose to water.[1,3]

In the last two decades, standards labs around the world have been involved with the development and commissioning of absorbed-dose-to-water standards and the provision of calibration services directly in terms of absorbed dose to water. In parallel with these developments, two major international protocol committees, the AAPM TG-51 and the IAEA have drawn up guidelines to allow dissemination of the absorbed-dose-to-water standards.[4,5] Both protocols make use of chamber dependent absorbed-dose beam quality conversion factors, k_Q, defined as the multiplicative factor used in conjunction with an absorbed dose calibration factor at a reference quality, usually ^{60}Co, to arrive at the absorbed dose calibration factor in a linac beam of quality Q. The TG-21 protocol already presented expressions which could be used to calculate absorbed dose calibration factors, $N_{D,w}^{Q}$, for a quality Q, starting from either a ^{60}Co exposure or absorbed dose calibration factor.[2] The German DIN 6800 standard[6] presented the concept of absorbed-dose beam quality conversion factor, k_Q and, based on the relation between exposure calibration factor at ^{60}Co and absorbed-dose calibration factor at quality Q, it expressed and calculated k_Q factors in terms of air-kerma protocol related quantities. A summary in

English of DIN-6800[6] was presented by Hohlfeld.[7]

The procedure of using a single absorbed-dose ^{60}Co calibration factor in conjunction with a k_Q factor is not used in the United Kingdom. Instead, secondary standard NE2561 or NE2611A chambers are calibrated directly in terms of absorbed dose to water at a range of high energy photon beam qualities at the National Physical Laboratory (NPL).[8,9] Various other national laboratories are in the process of establishing high-energy calibration capabilities based on calorimetry.[10]

The ultimate goal is to make use of measured beam quality correction factors and the IAEA protocol[5] recommends the use of measured k_Q factors if possible. In general, however, there is a lack of accurate systematic measurements of absorbed-dose calibration factors $N_{D,w}$ or, alternatively, k_Q factors. This is one of the reasons why the protocol committees of the AAPM[4] and IAEA[5] adopted calculated values of k_Q. Calculated values of k_Q require accurate knowledge of the variation of stopping power ratios water-to-air, perturbation corrections and W_{air} with energy. Various estimates of the total uncertainty on calculated k_Q values have been reported: 1.2% to 1.5%[11] and later on, 1.0%.[5] It is expected that, because of the increasing availability of primary standards of absorbed dose to water, more experimental data on k_Q are going to be available in the future.

Selection of the parameter to specify the radiation quality of clinical photon beams also plays an essential role in the final accuracy of any procedure for the dissemination of absorbed dose, whether by direct calibration, through k_Q factors, or using an air-kerma based system. Because of the difficult nature of accurate absorbed-dose measurements, k_Q measurements are usually performed at standards laboratories in dedicated setups and the linac beams used are mostly ''nonclinical,'' stressing the need for an adequate beam quality specifier to allow meaningful comparisons and to make experimental data useful for interpolation. The AAPM TG-51 protocol makes use of the photon component of the percentage depth dose at 10 cm (SSD 100 cm), $\%\text{dd}(10)_x$,[4] whereas the IAEA code of practice uses the more conventional TPR^{20}_{10}.[5] The latter is independent of SSD and electron contamination of the primary beam (except at high energies). However, obtaining $\%\text{dd}(10)_x$ depends on SSD, and, for higher energies, requires correction for electron contamination.[4] The issue of beam quality specification has been the subject of recent controversy.[12–15]

As well as the specifiers chosen in each of the protocols, another difference is that the forthcoming IAEA[5] protocol includes corrections for the effect of a 0.5 mm PMMA waterproofing sleeve, whereas the TG-51[4] protocol inherently assumes waterproof chambers.

Careful measurements of k_Q using Fricke dosimetry for a limited set of chamber types have been reported previously.[16–19] Recent work using calorimetry and theoretical techniques, has demonstrated that the radiation chemical yield of the Fricke dosimeter increases by $0.7\% \pm 0.3\%$ between ^{60}Co and 20 MV,[20] and the results of previously reported measurements need to be corrected to account for this change. Direct, graphite-calorimetry-based measurements of absorbed-dose calibration factors in high-energy photon beams have been performed at the NPL as part of their absorbed-dose calibration service.[8] A limited number of k_Q measurements have been based on water calorimeters.[21,22]

In this paper we present values of k_Q measured against the Canadian primary standard for absorbed dose. This standard is a sealed water calorimeter operated at 4 °C. Six ionization chamber types with three or more chambers of each type for three high-energy photon beam qualities are involved in this study. We compare our data to a selection of high quality data from the literature as well as to the AAPM[4] recommendations and study the adequacy of two parameters, i.e., $\%\text{dd}(10)_x$ and TPR^{20}_{10} in specifying the beam quality, based on our data as well as the high quality k_Q data reported by others.

We also analyze our results in the framework of the air-kerma based TG-21 protocol. Shortt *et al.*[23,24] compared absorbed-dose calibration factors at ^{60}Co and two linac energies for a subset of the chambers used in this work with those measured at two European standards laboratories. Comparisons at ^{60}Co have also been carried out with the National Institute of Standards and Technology (NIST)[25] and the Bureau International des Poids et Mesures (BIPM)[26] all showing that the NRC absorbed-dose standard is consistent with dose standards worldwide. The underlying work on the establishment of absorbed dose to water using the sealed water calorimeter is described elsewhere.[27] Since the results reported in this work depend on the establishment of the NRC sealed water calorimeter the essential features of the system are described briefly.

Finally, all accuracies mentioned here should be put into perspective by remembering the other uncertainties in the calibration of the output of a clinical linac which are dominated by (i) the measurement with the field instrument in a clinical beam, and (ii) the stability of the monitor. These latter elements introduce a combined uncertainty of around 1.3% in high-energy photon beams.[3] Beyond this are the many more uncertainties associated with determining the dose to the tumour. However, the purpose of the present and related work is to produce a reference dosimetry system whose uncertainty does not make a significant contribution to the overall uncertainty in the dose delivered to the tumor.

II. MATERIALS AND METHODS

A. Definitions

The absorbed-dose beam quality conversion factor, k_Q, is defined as the ratio of the absorbed-dose-to-water calibration factor, $N^Q_{D,w}$ at quality Q to the same quantity at a reference quality, usually ^{60}Co,

$$k_Q = \frac{N^Q_{D,w}}{N^{\text{Co}}_{D,w}}. \tag{1}$$

In contrast to the tradition with N_K, $N^Q_{D,w}$ is corrected for saturation so that it applies to 100% collection efficiency. A direct measurement of k_Q involves determining the absorbed-dose calibration factor $N_{D,w}$ both at quality Q and

at ^{60}Co. The air-kerma to absorbed-dose conversion factor C_Q, is measured as the ratio of $N_{D,w}$ at quality Q to N_K, i.e.,

$$C_Q = \frac{N^Q_{D,w}}{N_K}, \tag{2}$$

where, in this case, N_K is for 100% collection efficiency. [In other papers[17,25] we have defined a similar ratio for ^{60}Co beams that is labeled C_K. The latter is 0.15% greater than C_Q mainly because gradient effects in the reference plane were ignored.] Both k_Q and C_Q are obviously chamber dependent. Whereas k_Q becomes unity at ^{60}Co, C_Q is not unity at ^{60}Co and depends also on the build-up cap.

B. The NRC primary standard for absorbed dose to water

A stagnant water calorimeter of the Domen type was constructed and is described in detail elsewhere.[27] Briefly, the calorimeter consists of a $30\times30\times30$ cm^3 water tank, and the measurement of temperature rise, ΔT_w, is performed using 0.4–0.5 mm thermistor probes located on the axis of a cylindrical vessel of 60 mm diameter. By operating at 4 °C we eliminate convection, and the effects of heat transfer due to conduction are accounted for by numerical modelling of the heat transport in the calorimeter. The absorbed dose to water, D_w, is obtained by multiplication of ΔT_w with the specific heat capacity of water at constant pressure, c_w, as well as a number of correction factors k_i, some of which are slightly energy dependent and need to be studied in detail before trustworthy measurements of k_Q can be performed. The full dose equation is

$$D_w = \Delta T_w \cdot c_w \cdot k_c \cdot k_p \cdot k_{dd} \cdot k_\rho \cdot \frac{1}{1-k_{\mathrm{HD}}}. \tag{3}$$

The correction factors have the following meaning.

k_c, a correction for heat loss. Its value is derived from numerical calculations of heat transport, including the nonwater materials (glass vessel, thermistor probes) and a separate heat transport calculation involving the nonuniformity of the dose profile both laterally and in depth. The energy dependence of this correction is brought about by (1) absorption of radiation in the vessel and probes relative to water (stopping power ratio) and (2) differences in depth-dose profiles leading to differences in heat loss at the different energies. Correction factors are of the order of 0.1%–0.2%. The energy dependence of this factor is approximately 0.09% between ^{60}Co and 30 MV x rays.

k_p, a correction for the field perturbation due to scattering properties of calorimeter construction materials differing from water. The correction varies from 1.002 to 0.999 between ^{60}Co and 30 MV for our vessel system.

k_{dd}, a correction for the nonuniformity of the lateral dose profile in the measuring plane. It is usually within 0.05% of unity, except at 10 MV where it is larger (0.12%) due to the way the beam is flattened and for ^{60}Co where it is 0.10%.

k_ρ, a correction for the fact that the water density is different at 4 °C than at the reference temperature to which the ion chamber calibrations are referred (i.e., 22 °C). The energy dependence of this correction factor is determined by the measuring depth (5 g/cm^2 at ^{60}Co) and 10 g/cm^2 for the linac beams) and the dose gradient, and varies by about 0.04% between 10 MV and 30 MV.

k_{HD}, the heat defect due to radiation induced chemical reactions. For the pure water system the heat defect is zero regardless of energy (see Sec. II E 1).

Further details on the performance of the sealed water calorimeter and the determination of the correction factors are found in another paper and reports.[27,28] In Sec. III A we summarize the uncertainties of the calorimeter system and how they contribute to the uncertainty of k_Q.

C. Ionization chamber types and performance verification

Absorbed-dose calibrations were performed for 17 Farmer ionization chambers of five different types and for three NE2611A ionization chambers, a chamber type used as secondary standard chambers in the United Kingdom. In addition to the chambers provided to us on loan, the in-house NRC Farmer-type chambers NE2571 with serial numbers 667 and 1527 were used. The types and characteristics of the chambers are listed in Table I. Except for the NE2571 type, where five chambers were used, we used three chambers of each type. One of the predicates of clinical dosimetry protocols based on ^{60}Co calibration factors is that correction factors for all chambers of the same type are the same. In order to find out whether there would be a correlation in the performance at low photon energies and values of k_Q for a particular chamber, irregularities in wall thickness uniformity and/or dust inside the chamber were studied. We measured the axial uniformity of the chamber response in 50 kV (HVL: 1.1 mm Al; $E_{\mathrm{eff}}=22$ keV) x rays. The maximal response variation as a function of angle for the plastic chambers amounts to around 1.5% (Exradin A12: 1.3%, PTW 30001: 1.6%; PR06-C: 1.6%) except for the NE2581 types in which case it was up to 4%. Response variations for the graphite chambers (NE2571, NE2611A) were usually limited to $0.17\%\pm0.06\%$.

D. Photon beams and beam quality specifiers

Table II shows the radiation qualities used for the ion chamber measurements. The ^{60}Co beam was provided by an Eldorado 6 unit. For the linac beams, we made use of an electron beam, swept along the surface of an imaginary cone, with the apex of the cone being fixed at a point on the surface of a plane x-ray target. The target was a water cooled, fully stopping Al block. At higher energies, as pointed out before,[29] this procedure generally leads to reasonably flat profiles without any further flattening. At 10 MV, however, an additional Al cone was required to further flatten the field. The uncertainty on the electron energy is typically 1%. A collimator setup of a clinical accelerator was used for field size definition. More detailed information on the collimator arrangement can be found elsewhere.[30]

The nominal source-surface distance was 100 cm for all measurements and the calibration depth was 10.00 g/cm^2 and

TABLE I. Chamber types, serial numbers, and composition of ion chambers used in this study. The cavity diameters were between 6.1 and 6.4 mm except for the NE2611 which has a diameter of 7.4 mm.

Chamber type	Serial number	Wall material and thickness	Central electrode, diameter	Stem	Cap	A_{wall}
NE2571	667,1527,2572 2587,2595	C 0.065 g/cm^2	Al 1 mm	Al	Delrin	0.990
NE2611A	136,137,138	C 0.090 g/cm^2	Al 1 mm	Al	Delrin	0.984
NE2581	1047,1067, 1078	A150 0.040 g/cm^2	A150 3 mm	Al	Lucentine	0.990
PTW N30001	358,359,360	PMMA/C 0.045 g/cm^2	Al 1 mm	Al	PMMA	0.991
Capintec PR06-C	68907,68910 68927	C552 0.050 g/cm^2	C552 1 mm	C552	Polystyrene	0.991
Exradin A12	101,149,150	C552 0.088 g/cm^2	C552 1 mm	C552 (hollow)	C552	0.991

5.36 g/cm^2 for the linac beams and ^{60}Co, respectively. These depths include the PMMA window thickness of 3 mm which was scaled to effective depth in water using the nominal mass density of 1.19 g/cm^3 of PMMA. For the measurements in the linac beams, two sheets of Styrofoam, each of 5 cm thickness, (ρ=0.028 g/cm^3) located directly and at 15 cm upstream of the calorimeter tank, respectively, were also present during chamber as well as calorimeter work.

The field size for both the linac beams and the ^{60}Co beam was 10×10 cm^2 at the measuring depth. Beam output of the linac was monitored at two positions, using a pair of cylindrical chambers just upstream of the collimators and a four quadrant transmission monitor downstream of the collimators. The consistency of these monitors for normalization of the chamber signal within a day of measurements was typically better than 0.1%. In addition, to follow the day-to-day variation of the monitors, we used a graphite thimble ionization chamber mounted in an Al miniphantom. This system, further referred to as the ''phantom-monitor,'' was positioned at a reference distance upstream from the calorimeter box every morning before in-phantom chamber or calorimeter work started. In the case of the ^{60}Co beam accurate timing was based on a constant-frequency signal provided by the time and frequency group of our Institute. Table II also summarizes the dose rates used for all reported chamber calibrations and calorimetry at the linac and for the chamber calibrations at ^{60}Co.

For all linac beams central-axis depth-ionization curves and lateral profiles at the reference depth were measured in the calorimeter tank using a PTW 233642 (0.125 cm^3) chamber mounted on a scanning system. For each linac radiation quality we experimentally determined TPR_{10}^{20} and the photon component of the percentage depth-dose at 10 cm, $\%dd(10)_x$. TPR_{10}^{20} was measured according to its definition, i.e., by keeping the source-detector distance constant and moving the phantom. For the purpose of determining $\%dd(10)_x$, the central-axis depth-dose was measured with a 1 mm lead filter in the primary beam positioned at 44 cm upstream from the surface of the calorimeter phantom. A correction for ion chamber replacement was applied by shifting the depth-dose curve upstream over a distance of 0.6 times the chamber inner radius. The photon component at 10 cm was extracted according to the fit presented in the AAPM TG-51 protocol[4] and interpolated to match the distance (44 cm) between lead filter and phantom surface in our setup. Since the field size was 10×10 cm^2 at the measuring depth, a Monte Carlo calculated correction was applied to obtain $\%dd(10)_x$ for a field size of 10×10 cm^2 at the phantom

TABLE II. Summary of the calibration conditions, photon beams, and measured beam quality specifiers. The repetition rate of the pulsed beams was 240 Hz and the pulse width was about 2 μs. The uncertainties on the beam quality specifiers are 1σ.

Beam designation	^{60}Co	10 MV	20 MV	30 MV
Source-surface distance	100 cm	100 cm	100 cm	100 cm
Calibration depth (g/cm^2)	5.36	10.00[a]	10.00[a]	10.00[a]
Field size at measuring point	10×10 cm^2	10×10 cm^2	10×10 cm^2	10×10 cm^2
Electron energy		10 MeV	20 MeV	30 MeV
Target thickness (Al)		2.5 cm	4.5 cm	6.0 cm
Sweep angle		4.2°	4.2°	2.8°
Flattening filter		Al-cone	none	none
TPR_{10}^{20}	0.572(±0.001)	0.682(±0.001)	0.758(±0.001)	0.794(±0.001)
$\%dd(10)_x$	58.4(±0.1)	69.6(±0.2)	80.5(±0.2)	88.4(±0.2)
Dose rate (Gy/min)	1.5	1.5	1.8	2.5

[a]Note: This depth excludes 10 cm of Styrofoam upstream from the calorimeter tank (ρ=0.028 g/cm^3).

surface. These corrections amounted to an increase in absolute $\%dd(10)_x$ of 0.50% at 10 MV, 0.32% at 20 MV, and 0.25% at 30 MV. Since the two insulating layers of Styrofoam were in place during the profile measurements, a further Monte Carlo calculated correction was applied to account for the effect of the difference in effective depth to the measurement of the beam quality specifier $\%dd(10)_x$ (increases in absolute $\%dd(10)_x$ of 0.84%, 0.84%, and 0.97% at 10 MV, 20 MV, and 30 MV, respectively). Direct determinations of $\%dd(10)_x$ for a field size of 10×10 cm^2 at the phantom surface without Styrofoam were within 0.1% of the corrected measurements described above. The 10 and 20 MV beams were also simulated using the Monte Carlo system EGS4/BEAM, and profiles and depth-dose curves were calculated and were shown to agree with the measured profiles to within 1% of maximum ionization within 1 cm inside the geometrical edges of the field.[30] The ^{60}Co beam (Table II) is horizontal and the window thickness of the tank is 3 mm PMMA, making measurement of $\%dd(10)_x$ impossible. Therefore a Monte Carlo calculated value of $\%dd(10)_x = 58.4$, taken from Yang *et al.*[31] was used. The measured value of TPR_{10}^{20} was 0.576 compared to the calculated 0.572. The uncertainties on the beam quality specifiers as quoted in Table II are 1σ. For the linac beams these were calculated based on positioning accuracy and measurement reproducibility and the applied corrections. For ^{60}Co, the statistical uncertainties on the Monte Carlo calculations have been used.

The beams used in this work are similar to, but not exactly the same, as the soft NRC beams described in the paper of Ross *et al.*[29] In the earlier work the SSD and measuring depth were 125 cm and 7 cm, respectively, and the monitor used was a plane parallel chamber mounted inside the water tank directly upstream from the calibration point. In Sec. III C the present data are plotted in conjunction with the former Fricke based data for NRC's hard and soft beams and with data from other groups.

E. Determination of $N_{D,w}$, k_Q, and C_Q

1. D_w based on water calorimetry

The calorimeter was used to measure absorbed dose to water per monitor unit, normalized on the phantom-monitor value. Briefly, establishing the absorbed dose to water in the calorimeter phantom for each radiation quality involved at least 1 month of calorimetry before and after the chamber measurements (between 150 and 200 runs per energy), assuming no setbacks due to failing thermistor probes or water purity issues. It was essential to monitor water purity to ensure proper behavior of the calorimeter response for each fill and energy. Therefore we used three water systems: a pure-water system (saturated with Ar or N_2), a hydrogen saturated system and a 43/57 mixture of hydrogen and oxygen. The calorimeter response was verified so that the relative difference between the pure-water system or the hydrogen system, and the hydrogen/oxygen mixture agreed with model calculations of the relative heat defect at 4 °C. The relative differences between the 43/57 mixture[32] of H_2/O_2 and the pure water system amounted to 2.3%, 2.3%, and 2.1% at 10 MV, 20 MV, and 30 MV, respectively. The model calculations at 4 °C predict a difference of 2.2% at 1.5 Gy/min and 2.1% at 3 Gy/min. The H_2 system, was 0.1% higher and 0.2% lower than the pure-water system at 10 MV and 20 MV, respectively, whereas theory predicts a steady state with zero heat defect for this system as well as the pure-water system. Unlike in Seuntjens *et al.*[27] we have decided to base the absorbed dose determination on the pure-water system only. Our experience over the years of the maximal discrepancy of the three mentioned systems (0.3%) is used as an uncertainty estimate on the heat defect in the steady state pure-water system.

2. Ion chamber measurements

In the linac beams, all individual chamber calibrations were performed directly in the water calorimeter with the detection vessel removed, and after the water temperature had been increased to room temperature. The wooden insulating calorimeter box was removed and replaced with a frame holding a 0.1 mm resolution scanning system. The chamber mounted on the scanner was moved close to the reference position. Fine-tuning of the chamber position at the reference depth was performed using a telescope and a mechanical standoff.

At ^{60}Co, the absorbed-dose calibrations of the chambers were performed against the NRC absorbed-dose standard as declared on 1 July 1998, which is based on extensive measurements using the same sealed water calorimeter as used in the linac experiments, but for dissemination purposes, the dose value at ^{60}Co has been transferred from the calorimeter phantom to a $50\times50\times50$ cm^3 water phantom using ionization chambers and Fricke dosimeters. It has been demonstrated that water-to-air stopping-power ratios and hence calibration factors are virtually phantom size independent,[33] justifying a transfer procedure based on ionization chambers. All the chambers involved in this work were therefore individually calibrated in the $50\times50\times50$ cm^3 water phantom for which the beam data have been provided in Table II.

All the ion chamber measurements in the linac beams were normalized on the phantom-monitor and were corrected for temperature and pressure to the standard conditions (22 °C, 101.325 kPa). It is also known that, especially for plastic walled chambers, their volume is somewhat dependent on the temperature at which the calibrations are performed. For the Exradin A12 chamber we established that the volumetric expansion increases the volume, and therefore decreases the calibration factor by 0.04%/°C. For the graphite chambers (NE2571, NE2611A) this effect is an order of magnitude smaller. To avoid concerns about volumetric expansion for the plastic chambers, we performed the chamber calibrations in the calorimeter tank at a temperature of 22 °C $\pm$1 °C.

Chamber irradiations were performed with polarizing voltages of 300 V, 150 V, and -300 V. Ion recombination corrections P_{ion} were determined using the linear two-voltage technique as implemented in TG-51[4] for linac beams.

TABLE III. Saturation and polarity correction factors at 20 MV. The dose rate amounted to 1.8 Gy/min; the pulse repetition frequency was 240 Hz.

			P_{ion}	
Chamber type	Serial No.	P_{pol}	this work	Formula of Derikum and Roos (Ref. 34)
NE2571	667	0.9991	1.0024	
	2572	0.9990	1.0028	
	2587	0.9997	1.0012	
	2595	0.9993	1.0023	
	1527	0.9998	1.0022	
	Average		1.0022	1.0021
NE2611A	136	0.9996	1.0029	
	137	0.9997	1.0021	
	138	0.9997	1.0020	
	Average		1.0023	1.0022
NE2581	1047	1.0002	1.0034	
	1067	1.0001	1.0035	
	1078	1.0008	1.0029	
	Average		1.0033	1.0014
PTW N30001	358	0.9995	1.0013	
	359	0.9993	1.0010	
	360	0.9994	1.0019	
	Average		1.0011	1.0020
PR06-C	68 907	0.9993	1.0019	
	68 910	1.0007	1.0013	
	68 927	1.0001	1.0013	
	Average		1.0015	1.0018
Exradin A12	101	0.9993	1.0020	
	149	1.0000	1.0021	
	150	0.9996	1.0016	
	Average		1.0019	1.0020

Derikum and Roos[34] studied saturation correction factors of some thimble-type ionization chambers in pulsed beams. They showed that only for the NE2561 and the PTW M233641 chambers the saturation curves were linear when plotted as $1/M$ vs $1/V$, where V is the chamber potential. For other chambers they found $1/M$ drops more quickly at higher voltages than expected. This excess charge was attributed to charge multiplication and the points at high voltages were eliminated so that correction factors for recombination could be derived. With the exception of the PTW M23332 chamber, their results were expressed as $P_{ion}=1.001+(0.15\,d^2r/V)$ where d represents the equivalent electrode spacing in mm, r the pulse charge density in $10^{-5}\,\mathrm{C\,m^{-3}}$ and V the polarizing voltage in V. The first term is for initial recombination and the second term represents the dose-per-pulse dependent volume recombination. Table III lists ion chamber recombination correction factors at 20 MV using the linear two-voltage technique, compared with Derikum and Roos' empirical fit. The agreement between measured and expected values is within 0.01% for the graphite chambers and within 0.1% for the plastic chambers. The NE2581 chamber is the single chamber for which the two-voltage recombination correction is *larger* than expected based on the equivalent electrode spacing.

In continuous beams, Zankowski and Podgorsak[35] showed that standard recombination theory does not work due to what they interpret as charge multiplication effects at high voltages. In a recent extensive study using a subset of the ionization chambers used in this work, Yang *et al.*[36] showed that a correction based on the full saturation curve differs by less than 0.16% from the correction based on the quadratic form, (i.e., $1/M$ vs $1/V^2$) of the two-voltage technique, and differs by less than $\pm 0.12\%$ from unity for all cylindrical chamber types studied here. From the Yang *et al.*[36] study, it is not clear what the exact mechanism is leading to a nonlinear $(1/V^2,1/M)$ saturation curve. For these reasons, in this work, we have chosen to measure the saturation correction in the linac beams using the linear two-voltage approach in the form outlined in TG-51,[4] and ignore the saturation correction at ^{60}Co, where the rms deviation between a full analysis of the saturation curve and unity was 0.074%.[36] In the linac beams, we assign uncertainties to our measured values of P_{ion} based on the difference between the expected value from the Derikum and Roos[34] analysis, and our measurements using the two-voltage technique.

The polarity correction, P_{pol}, corrects a reading at positive polarity to the average of the readings at positive and negative polarity. As an example, measured polarity corrections at 20 MV are listed in Table III. The polarity correction factor was found to have no significant energy dependence.

The factor P_{dd} corrects for the dose profile over the region occupied by the chamber. It is derived from measuring the dose profile in two dimensions at the depth of interest. The correction arises from the integration of the profile and comparing with the dose at the reference position. The correction amounts to about 1.001 at all linac energies for a Farmer-type chamber.

Since different electrometers have been used in the linac beams and the ^{60}Co beam, corrections for the electrometer calibration in terms of absolute charge, P_{elec}, have been applied. This amounted to $<0.15\%$ correction.

For waterproofing, all but the waterproof Exradin A12 chambers were inserted in a 1 mm PMMA sleeve. At ^{60}Co, a sleeve of this material and this thickness has been proven to increase the response of an NE2571 chamber by $0.06\%\pm0.03\%$.[37] In a 20 MV beam, the same sleeve *decreases* the response by $0.19\%\pm0.10\%$.[37] In the TG-51 report, it is recommended to use a waterproofing sleeve of $\leqslant 1$ mm thick for nonwaterproof chambers, the effect of which has not been included in the calculations underlying the k_Q data in that report.[38] With the exception of the Exradin A12 chamber, the k_Q data presented in this work apply to the chambers inserted in a 1 mm PMMA sleeve, i.e., no sleeve correction was applied to the data.

Once the corrections have been derived, the fully corrected chamber reading is calculated as

$$M_{corr}=M_{P,T}P_{ion}P_{pol}P_{dd}P_{elec}, \tag{4}$$

where $M_{P,T}$ represents the temperature and pressure corrected chamber reading. The absorbed dose to water calibration factors $N_{D,w}$ were calculated as the ratio of the calorimeter dose per unit phantom-monitor to the corrected chamber reading per unit phantom-monitor. k_Q factors were then derived by applying Eq. (1).

At ^{60}Co, in addition, the chambers were also calibrated free-in-air against the Canadian standard for air kerma, and the air-kerma to absorbed-dose conversion factor C_{Co} was derived. The experimental values of C_Q, the air-kerma to absorbed-dose conversion factor at linac beam quality Q, were calculated as $C_Q = C_{\mathrm{Co}} k_Q$.

F. Calculations of k_Q and C_Q

We compare our experimental values of k_Q with the currently recommended values of the AAPM TG-51.[4] The calculations were done with the PROT program[39,40] that calculates the quantities needed to calculate k_Q. Elements of the PROT program have been used to generate the data in the TG-51 protocol. Whereas TG-51 only lists k_Q factors as a function of the beam quality specifier $\%\mathrm{dd}(10)_x$, PROT also calculates the data as a function of TPR_{10}^{20}. Many modifications and corrections to the formalism and data have been published since the publication of the AAPM TG-21 protocol in 1983.[41–43] PROT calculates values of C_Q using both the original TG-21[2] and a fully corrected version of TG-21 [TG-21 (corr)].[40,43] The fully corrected version of TG-21 uses the corrected formalism combined with stopping power data based on ICRU Report 37[44] (taken from the IAEA TRS-277 Code of Practice[1]), the TG-21 values for the replacement correction factor[38] and the P_{cel} correction for an aluminum electrode.[38]

None of the protocols mentioned above has the correction for the waterproofing sleeve incorporated into the equation for P_{wall}. However, to compare state-of-the-art theory (as opposed to protocol values) with experimental values of k_Q or C_Q, corrections for the waterproofing sleeve have been applied when appropriate using a three-component extension of the standard equation for P_{wall}.[43,45] When this is the case, it will be specifically stated. Ross and Shortt[37] studied sleeve correction factors for the NE2571 and the PR06-C chambers. For PMMA sleeves the behavior of the response was in good agreement with the three-component calculation although some uncertainty was involved in extrapolating their result to zero sleeve thickness. We have compared calculated sleeve corrections with measured sleeve corrections for the waterproof Exradin A12 chamber, where such an extrapolation is not needed, and the agreement was within 0.1% for all beams. Inclusion of the sleeve component for a 1 mm PMMA sleeve into the model for P_{wall} increases calculated k_Q values by 0.07%, 0.22%, and 0.36% at 10 MV, 20 MV, and 30 MV, respectively. The forthcoming IAEA Code of Practice includes a similar correction but for the effects of a 0.5 mm PMMA waterproofing sleeve.[5]

Based on using $C_Q = C_{\mathrm{Co}} k_Q$, with the C_{Co} values obtained using the fully corrected version of TG-21, and the TG-51 values of k_Q corrected for the effect of the waterproofing sleeve (if present), we have also derived values of C_Q as a function of $\%\mathrm{dd}(10)_x$. This approach has been labeled as an ''optimal air-kerma'' protocol, and is, except for the conversion of air-kerma to absorbed-dose at ^{60}Co and the incorporation of a sleeve correction, exactly equivalent to TG-51.

III. RESULTS AND DISCUSSION

A. Uncertainties on measured absorbed dose calibration factors, $N_{D,w}$, and on beam quality conversion factors k_Q and C_Q

A credible uncertainty analysis of measured absorbed dose beam quality conversion factors is very important in view of the recent protocol recommendations of the AAPM[4] and the IAEA[5] which utilize calculated beam quality conversion factors. Table IV presents the components contributing to the combined standard uncertainty on a water calorimetric measurement of k_Q for a single chamber. All the sources of uncertainties in the calorimetric experiment are mentioned. By combining these with the uncertainty from the ion chamber measurements, uncertainty estimates on the absorbed-dose calibration factor, $N_{D,w}$ are obtained. The uncertainty on the long term reproducibility of the linac monitors arises from our daily phantom-monitor measurements over the course of several months of measurements at each quality. For the uncertainty on P_{ion} in the linac beams, we have used the maximum difference between the two-voltage result and the fit provided by Derikum and Roos.[34] At ^{60}Co, where no correction for recombination was implemented, we used 0.074%, which is the rms deviation between unity and the full saturation curve investigation[36] for a subset of the chambers of the present work. Uncertainty estimates for the other, more straightforward chamber correction factors have been itemized in Table IV (items 12, 15, 16).

Table IV also shows the uncertainty on C_Q. It is larger because systematic components in a calorimetric determination of absorbed dose to water, as well as the uncertainty on an air-kerma calibration (0.32%[46]) cannot be removed from the determination of C_Q. However, if measured values of C_Q or k_Q are used, the uncertainty on the dose value assigned in an arbitrary accelerator beam is the same for the k_Q or the C_Q systems since in the end, the measured values of $N_{D,w}^{60\mathrm{Co}}$ or N_K cancel out as long as the same ^{60}Co standards are used to measure k_Q or C_Q and the calibration factors. Type B uncertainties related to the air-kerma or dose calibration at ^{60}Co do not propagate into the final dose determination at linac energies, which is only determined by the calorimetric dose measurement[39] and an ion chamber measurement in these beams.

In order to arrive at the combined standard uncertainty on the absorbed dose beam quality conversion factors k_Q and C_Q, the combined standard uncertainty on a determination of k_Q or C_Q for a single chamber (Table IV) was combined with the 1σ sample standard deviations on k_Q and C_Q so as to incorporate the chamber-to-chamber variation of the conversion factors within a type. This is likely to be a conservative estimate of the uncertainty because some of the chamber-to-chamber variation may be statistical in nature (due to monitor variations) and therefore may have been counted already in the type A uncertainty given in Table IV. The combined standard uncertainty on the measured k_Q values, including the sample standard deviation on chamber-to-chamber variations, amounts typically to 0.45%. From the 1σ sample standard deviations on k_Q and C_Q (data not

TABLE IV. Type A and type B percent uncertainties on the water calorimetric determination of k_Q and C_Q for a single chamber. Uncertainties which are common to both the reference quality ^{60}Co, and the high energy photon beam quality of interest in the determination of k_Q have been bracketed, and are removed from the total uncertainty calculation on k_Q. However, they are included in the uncertainty estimates on C_Q, as is the uncertainty resulting from the air-kerma calibration factor. The number of degrees of freedom in the type A uncertainties are indicated in square brackets.

Source and type of uncertainty (in %)		^{60}Co	10 MV	20 MV	30 MV
Type A					
1	Reproducibility $\Delta T/MU$	0.06[190]	0.15[93]	0.10[165]	0.14[55]
2	Short term reproducibility M_{corr}/MU	0.02[32]	0.03[23]	0.06[22]	0.08[26]
3	Long term reproducibility linac monitors		0.10[17]	0.12[18]	0.15[24]
Type B					
Calorimeter related quantities					
4	$c_{w,p}$ (specific heat capacity)	(<0.005)	(<0.005)	(<0.005)	(<0.005)
5	Thermistor sensitivity $\overline{S}$	(0.20)	(0.20)	(0.20)	(0.20)
6	k_c (heat loss)	0.15	0.15	0.15	0.15
7	k_p (vessel perturbation)	0.05	0.02	0.02	0.02
8	k_{HD} (three systems)	(0.3)	(0.3)	(0.3)	(0.3)
9	k_ρ (density of water)	0.02	0.02	0.02	0.02
10	k_{dd} (profile nonuniformity)	0.02	0.02	0.02	0.02
11	Positioning calorimeter, probes, and vessel	0.10	0.10	0.09	0.08
Chamber related quantities					
12	P_{dd}	0.02	0.02	0.02	0.02
13	P_{ion}	0.07	0.16	0.16	0.11
14	P_{pol}	0.01	0.01	0.01	0.01
15	P_{elec}	0.02	0.01	0.01	0.01
16	Positioning chamber	0.05	0.05	0.04	0.04
Overall					
	$N_{D,w}$	0.42	0.48	0.47	0.47
	k_Q		0.38	0.37	0.38
	C_Q	0.54	0.58	0.57	0.58

shown) it was concluded that the chamber-to-chamber variation in C_Q is mainly due to the variability in chamber response at linac energies (as is the case with the k_Q system) and not due to the variability at ^{60}Co as a result of differences in build-up caps, which have a much more minor effect. So, based on the data, there was no obvious difference in chamber intervariability between the k_Q system versus the C_Q system.

The overall standard uncertainty on the measurement of k_Q for a single chamber (0.38%) is consistent with the uncertainty quoted by Ross *et al.*[29] (0.35%) although the energy dependence of ϵG of the Fricke dosimeter (and its uncertainty) was ignored in that paper. Guerra *et al.*[18] estimate the uncertainty on their measurements to be about 0.65% (excluding the uncertainty on the energy dependence of ϵG). Our combined standard uncertainty of 0.45% is consistent with the value of 0.5% quoted by Palmans *et al.*[22] which is also based on sealed water calorimetry. Vatnitsky *et al.*[21] also used water calorimetry to study k_Q values for the PR06-C and the PTW-W30001 (sic) chambers.[21] However the quoted 1σ uncertainty on their k_Q values is no better than about 1%. We have therefore not considered their data further in this work.

B. Air-kerma to absorbed-dose conversion factor at ^{60}Co, C_{Co}

A major conceptual difference between air-kerma-based protocols and absorbed-dose-based protocols is the use of build-up caps in calibrations based on air-kerma standards. Table V shows ^{60}Co air-kerma and absorbed-dose calibration factors and their ratios. Calculations of C_{Co} based on the best available data, including a correction for the 1 mm PMMA sleeve when present, are compared to the measured values. The sample standard deviations on the measured values of C_{Co} are less than 0.2% for all chamber types and the graphite walled chambers showed generally a lower sample standard deviation on the measured C_{Co} values than for the plastic walled chambers, an observation consistent with their superior measured rotational response (see Sec. II C).

Second, when comparing the C_{Co} values for different chamber types relative to each other, we find agreement to better than 0.1% between our experimental results and the data presented by Boutillon and Perroche[47] for a subset of the chamber types (NE2571, NE2561, and PR06-C). Note that such a comparison is independent of the standards of air kerma or absorbed dose used. Equally good agreement is obtained between our measurements and similar data traceable to the BIPM for the NE2571, NE2561, NE2581, and PTW N30001 chambers in the recent draft (V.7) of the upcoming IAEA protocol.[5] Based on the Canadian standards for air kerma and absorbed dose, the agreement between the calculated value of C_{Co} and the measured value is within 0.47% for all chamber types, with the measured C_{Co} generally being lower than the calculated value except for the PR06-C and the NE2581 chambers.

Although the experimental uncertainty on C_{Co} is of the

TABLE V. Summary of ^{60}Co calibration factors and C_{Co} conversion factors based on the Canadian absorbed-dose and air-kerma standards. The calculated C_{Co} values are based on the code PROT (Ref. 40) using the fully corrected equations (Ref. 49) and stopping power ratios based on ICRU Report 37 (Ref. 44) and include the effect of the 1 mm PMMA sleeve used for the in-phantom measurement. The column Δ^{calc}_{meas} summarizes the differences between calculation and the average of the measurements. The reproducibility of the measurements of chamber response with different caps is estimated to be 0.05%. Uncertainties shown in brackets are 1σ estimates of the sample standard deviations.

Chamber type	Serial number	N_K [cGy/nC]	N_D [cGy/nC]	C_{Co} Individual	C_{Co} Average	Calculated	$\%\Delta^{calc}_{meas}$
NE2571	2572	4.1494	4.5274	1.0911			
(graphite)	2595	4.1182	4.4944	1.0914			
	2587	4.1288	4.5073	1.0917	1.0915	1.0948	+0.30%
	1527	4.1745	4.5545	1.0910	(0.04%)		
	667	4.0739	4.4496	1.0922			
NE2611	136	9.4457	10.233	1.0833			
(graphite)	137	9.4579	10.254	1.0841	1.0838	1.0857	+0.18%
	138	9.5779	10.381	1.0838	(0.04%)		
NE2581	1047	5.3047	5.7681	1.0874			
(A150)	1067	5.2227	5.6811	1.0878	1.0878	1.0827	−0.47%
	1078	5.3256	5.7949	1.0881	(0.03%)		
PTW	358	4.8191	5.2508	1.0896			
N30001	359	4.8143	5.2411	1.0887	1.0883	1.0916	+0.30%
(PMMA)	360	4.8015	5.2177	1.0867	(0.14%)		
Capintec	68907	4.3412	4.7106	1.0851			
PR06-C	68910	4.3276	4.6949	1.0849	1.0861	1.0841	−0.18%
(C552)	68927	4.3061	4.6866	1.0883	(0.18%)		
Exradin	149	4.5672	5.0101	1.0970			
A12	101	4.5070	4.9330	1.0945	1.0955	1.0991	+0.33%
(C552)	150	4.4847	4.9110	1.0951	(0.12%)		

	Cap material	C_{Co} Measured	C_{Co} Calculated	$\%\Delta^{calc}_{meas}$
	Polystyrene	1.0861	1.0841	−0.18%
	C552	1.0964	1.1063	+0.90%
PR06-G	PMMA	1.0869	1.0909	+0.36%
(C552)	Lucentine[a]	1.0833	1.0841[a]	+0.07%
	Delrin	1.0900	1.0954	+0.50%

[a]The composition of lucentine was considered the same as that of polystyrene.

order of 0.6%, the trends of the individual C_{Co} factors relative to the value for another chamber type are significant, again because common uncertainties due to the standards cancel out. In this respect, the NE2581 and the PR06-C chambers behave differently than the other chambers: their calculated C_{Co} factors are *lower* than the measured values, whereas the calculated values are systematically higher by 0.2% to 0.3% for all other types. The NE2581 and the PR06-C chamber have build-up caps of lucentine and polystyrene, respectively, where lucentine is described as a polystyrene-based plastic. In order to find out whether polystyrene, used as a cap material, is responsible for this effect, we compared C_{Co} factors using a PR06-G chamber (a fully guarded version of the PR06-C chamber) with build-up caps of polystyrene, C552, PMMA, lucentine, and delrin taken from the other chambers used in this study. The lower part of Table V shows the measured C_{Co} factors compared with calculated C_{Co} for the same chamber/different cap combinations. Based on measurements with a specific chamber and using different caps of the same material, the reproducibility of measuring response for a given cap type, was found to be of the order of 0.05%. Again we observed that a polystyrene cap on the PR06-G chamber causes the measured C_{Co} to be higher than calculated, whereas for C552, PMMA, and delrin caps, C_{Co} is lower than calculated by 0.4%–0.9%. The observation that polystyrene used as cap or sheath material shows deviations from the two-component model, was also made by Hanson and Tinoco,[45] and this might mean that the electron or photon cross sections for polystyrene used in the model are wrong. Similar observations were made when comparing measured and calculated response of plane-parallel chambers where the agreement was worst for polystyrene chambers.[48]

Another observation can be made when comparing the two chambers of the same wall material, i.e., the PR06-G (or C) and the Exradin A12. The use of a C552 cap on a PR06-G

TABLE VI. Implied change in clinical reference dosimetry at ^{60}Co in Canada and the USA as a result of going from an air-kerma to absorbed-dose-based calibration system. ''TG-21:'' the dose according to TG-21 as published (Ref. 2), ''TG-21 (corr):'' the dose according to TG-21 with corrected equations and data. The anticipated results for the USA were derived from our measurements and on the recent intercomparisons of air-kerma and absorbed-dose standards between NRC and NIST (Ref. 25). See text about apparent discrepancy with data in Shortt *et al.* (Ref. 25). In all TG-21 protocol calculations, no sleeve corrections were applied.

	$\Delta^{D_w}_{D_w(\text{TG-21})}$		$\Delta^{D_w}_{D_w(\text{TG-21(corr)})}$	
	Canada	USA	Canada	USA
NE2571	0.2%	1.4%	−0.2%	0.9%
NE2611A or NE2561	0.2%	1.4%	−0.1%	1.0%
NE2581	0.7%	1.8%	0.6%	1.7%
PTW N30001	0.1%	1.2%	−0.2%	0.9%
Capintec PR06-C	0.8%	1.9%	0.3%	1.4%
Exradin A12	0.2%	1.3%	−0.4%	0.8%

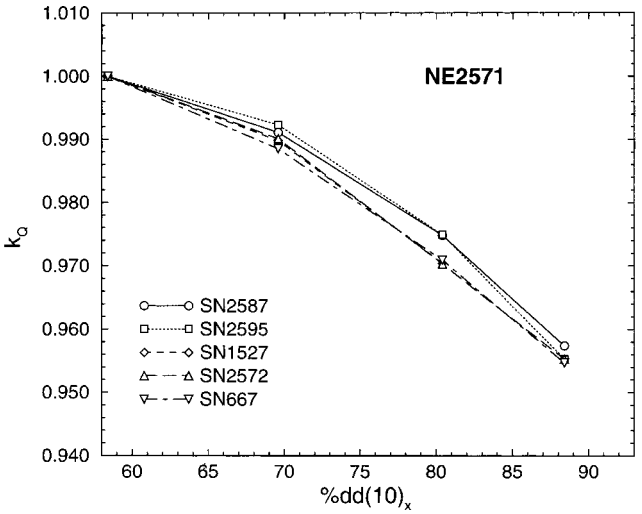

FIG. 1. Absorbed dose beam quality conversion factor k_Q for five chambers of the NE2571 type as a function of %dd(10)$_x$.

chamber brings the measured C_{Co} very close to the experimental and calculated value of C_{Co} for the Exradin A12 chamber. However, the calculated C_{Co} value for the PR06-G chamber with C552 cap is higher by 0.9% than the measurement and higher by 0.6% compared to the calculated C_{Co} value for the Exradin A12 chamber. The 0.6% difference between the calculated C_{Co} values for the PR06-G chamber with C552 build-up cap and the Exradin A12 with its own C552 build-up cap, is brought about by the difference in wall thickness between both chambers and the fact that the P_{wall} correction is larger for C552 than for all the other chamber wall materials, so that the deficiencies in the model for P_{wall} stand out more distinctly.

The above observations related to build-up caps influence the final dose assigned in the user beam when based on air-kerma calibrations. In an absorbed-dose-based calibration system, this uncertainty is no longer involved.

If any of the chambers of this study are used the implied change in dose resulting from the transfer from an air-kerma based system to absorbed-dose-based system can be derived from our measurements. This change depends on the implementation of the protocol as well as on the air-kerma and absorbed-dose standards, respectively. Recent comparisons of the air-kerma and absorbed-dose standards at ^{60}Co between the National Research Council Canada (NRC), and the National Institute for Standards and Technology (NIST)[25] have shown that the NIST air-kerma standard is 0.61% lower than the NRC standard, and the NIST dose-standard is 0.50% higher than the NRC dose-standard. Using this information, the C_{Co} from our measurements were translated into what they would have been if they were based on the USA standards. Table VI summarizes the implied changes in absorbed dose at ^{60}Co for Canada and the USA when changing from an air-kerma-based system (''TG-21 as published''[2] or ''TG-21 corrected''[43,49]) to absorbed dose. The table makes two points: (i) the change is less in Canada than the USA by about the 1.1% difference in the standards; and (ii) using the corrected version of TG-21 would generally have reduced the changes. The data in Table VI for the NE2571 are 0.1% to 0.2% lower than in the corresponding table of Shortt *et al.*[25] because gradient effects have been taken into account here.

C. Experimentally determined absorbed-dose beam quality conversion factors k_Q

Figure 1 presents water calorimetry based k_Q factors for five NE2571 chambers as a function of %dd(10)$_x$. The spread on the k_Q factors is determined by individual chamber characteristics as well as measurement reproducibility determined by short and long term monitor stability. For the chambers of this type the maximum differences in k_Q factors amount to 0.23%, 0.45%, and 0.28% for 10 MV, 20 MV, and 30 MV, respectively. For the other chamber types those chamber-to-chamber differences are similar though somewhat smaller, but only three chambers of each type were investigated in those cases. In what follows we have combined the sample standard deviation of all investigated chambers of a given type with the combined standard uncertainty on a k_Q determination for a single chamber as presented in Table IV in order to determine the overall uncertainty for each chamber type.

Table VII summarizes our measured type average k_Q values for the six chamber types and compares the results to the data of the TG-51[4] protocol as well as the TG-51 data corrected for the effect of the 1 mm PMMA sleeve when used. These comparisons are discussed below in Sec. III E 2.

D. Beam quality specification of high-energy photon beams

Figures 2 and 3 show our measured data for the type average k_Q factors for the NE2571 chamber in comparison with recent high-quality data from the literature for the same chamber type as a function of TPR^{20}_{10} and %dd(10)$_x$, respectively. The data from Guerra *et al.*,[18] from Shortt *et al.*,[17] and from Ross *et al.*[29] have been corrected for the increase in ϵG as reported in Klassen *et al.*,[20] supplemented with calorimeter based ϵG data at 10 MV. The correction used was

TABLE VII. Water-calorimetry-based beam quality conversion factors, k_Q. The second and the third line for each chamber type represent the percentage differences between the TG-51 (Ref. 4) protocol values (both as published and as corrected for the effect of a 1 mm PMMA sleeve) and the values of this work defined as $100\times(k_{Q,\mathrm{prot}}-k_Q)/k_Q$. The beam quality specifiers given are NAP, $\%\mathrm{dd}(10)_x$ and TPR_{10}^{20}. The uncertainty on the type average k_Q value is of the order of 0.4%–0.5%. The rms deviations between measured and calculated k_Q values are calculated for every chamber at 10 MV, 20 MV, and 30 MV (''rms deviation,'' $n-1\geqslant 8$). The overall rms deviation is the average taken for all chamber types ($n-1=59$).

		Beam quality				
	NAP	10 MV	20 MV	30 MV	rms deviation between meas. and TG-51	
	$\%\mathrm{dd}(10)_x$	69.6	80.5	88.4		
Chamber type	TPR_{10}^{20}	0.682	0.758	0.794	As publ.	Corr. sleeve
NE2571	k_Q	0.9904	0.9723	0.9557		
	$\%\Delta^{\mathrm{TG-51}}$	−0.04%	+0.05%	+0.35%	0.25%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$	+0.04%	+0.27%	+0.71%		0.45%
NE2611A	k_Q	0.9944	0.9724	0.9560		
	$\%\Delta^{\mathrm{TG-51}}$	−0.37%	+0.24%	+0.53%	0.41%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$	−0.29%	+0.46%	+0.89%		0.61%
NE2581	k_Q	0.9888	0.9609	0.9458		
	$\%\Delta^{\mathrm{TG-51}}$	−0.71%	+0.00%	+0.00%	0.41%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$	−0.63%	+0.22%	+0.36%		0.44%
PTW-N30001	k_Q	0.9883	0.9660	0.9469		
	$\%\Delta^{\mathrm{TG-51}}$	−0.20%	+0.18%	+0.69%	0.45%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$	−0.13%	+0.41%	+1.06%		0.67%
Capintec PR06-C	k_Q	0.9961	0.9761	0.9606		
	$\%\Delta^{\mathrm{TG-51}}$	−0.72%	−0.74%	−0.78%	0.74%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$	−0.64%	−0.52%	−0.41%		0.53%
Exradin A12	k_Q	0.9941	0.9728	0.9572		
	$\%\Delta^{\mathrm{TG-51}}$	−0.24%	+0.00%	+0.00%	0.17%	
	$\%\Delta^{\mathrm{Sl.Corr.}}$					0.17%
Overall rms deviation between measurement and TG-51					0.41%	
Same for TG-51 data corrected for the effect of a 1 mm PMMA sleeve						0.48%

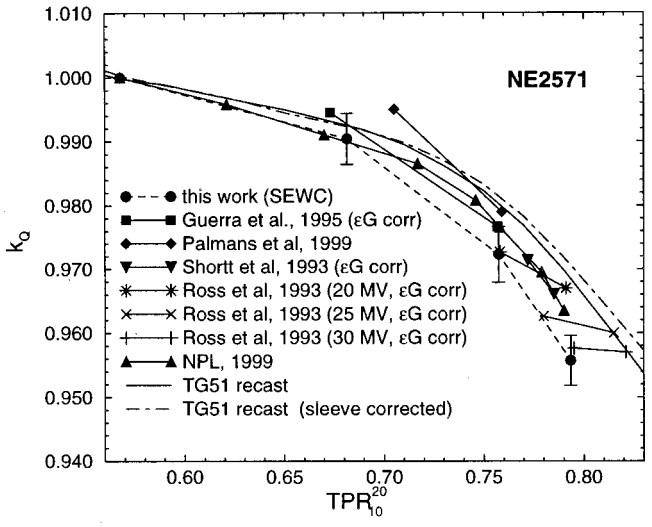

FIG. 2. Comparison between absorbed-dose beam quality conversion factors, k_Q, for the NE2571 chamber as a function of TPR_{10}^{20}, with experimental data from the literature. The data from Guerra *et al.* (Ref. 18), from Shortt *et al.* (Ref. 17), and from Ross *et al.* (Ref. 29) have been corrected for the energy dependence of the radiation chemical yield of the Fricke dosimeter as discussed in the text. The light and heavily filtered Ross *et al.* (Ref. 29) data that belong to the same accelerating potential are connected by full lines. The Palmans *et al.* (Ref. 22) data are water calorimetry based. The NPL data are based on graphite calorimetry (Ref. 50). The full line shows the data from TG-51 [recast as a function of TPR_{10}^{20} (Ref. 38)] and the dashed–dotted line the same data corrected for the effect of a 1 mm PMMA sleeve. SEWC stands for sealed water calorimeter.

$$k_E=1-0.033\,37(\mathrm{TPR}_{10}^{20}-0.572)\quad \text{for } 0.572\leqslant \mathrm{TPR}_{10}^{20}\leqslant 0.800. \tag{5}$$

The data from NPL for the NE2571 chamber are from the NPL CCRI(I) contribution.[50] To present the NPL data as a

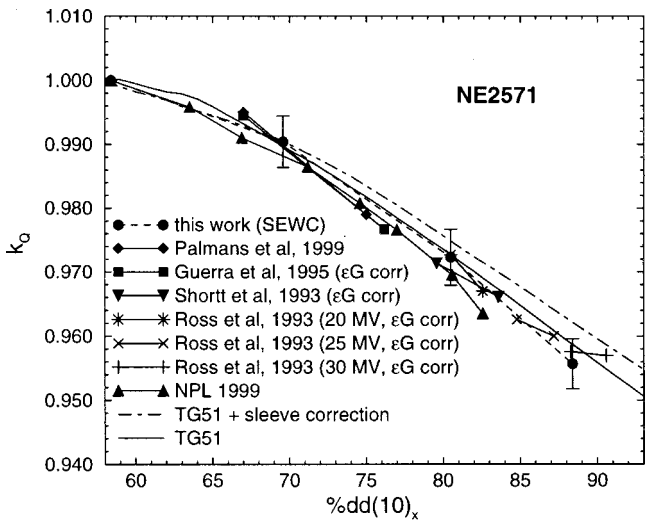

FIG. 3. Same as Fig. 2 but as a function of $\%\mathrm{dd}(10)_x$. The full line and the dashed–dotted line show the data from the TG-51 protocol (Ref. 4) and the data from the TG-51 protocol with correction for a 1 mm PMMA sleeve, respectively. SEWC stands for sealed water calorimeter.

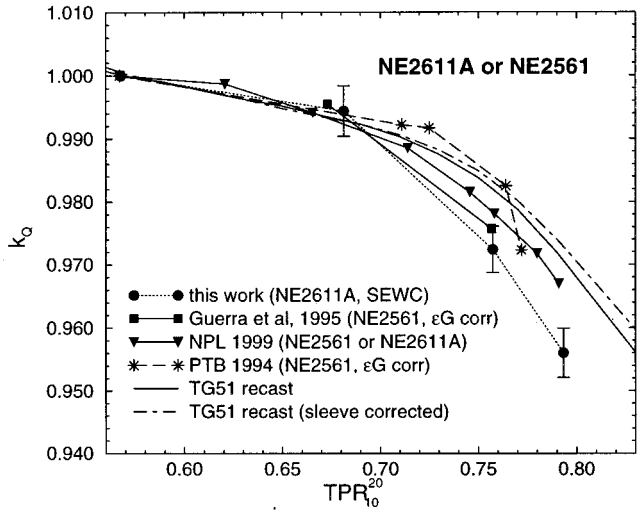

FIG. 4. Comparison between absorbed-dose beam quality conversion factors k_Q for the NE2611A chamber as a function of TPR_{10}^{20}, with experimental data from the literature. The data from Guerra *et al.* (Ref. 18) and the PTB data [adapted from Boutillon *et al.* (Ref. 16)] have been corrected for the energy dependence of the radiation chemical yield of the Fricke dosimeter as discussed in the text. The NPL data are based on graphite calorimetry (Ref. 50). The full line shows the data from TG-51 [recast as a function of TPR_{10}^{20} (Ref. 38)] and the dashed–dotted line the same data corrected for the effect of a 1 mm PMMA sleeve. SEWC stands for sealed water calorimeter.

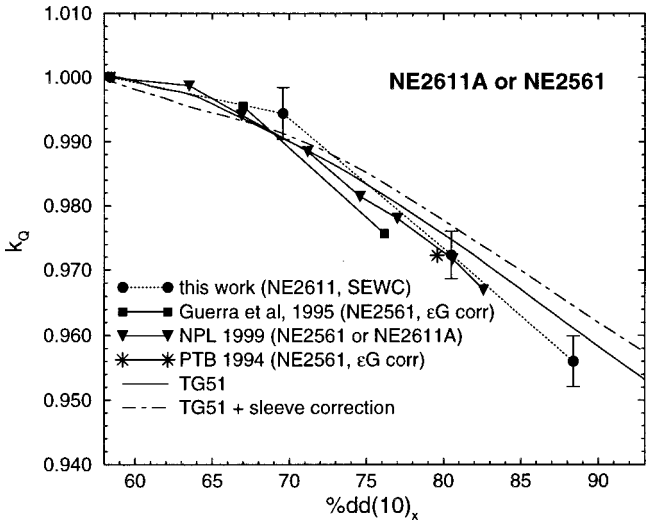

FIG. 5. Same as Fig. 4 but as a function of $\%dd(10)_x$. The full line and the dashed–dotted line show the data from the TG-51 protocol (Ref. 4) and the data from the TG-51 protocol with correction for a 1 mm PMMA sleeve, respectively. SEWC stands for sealed water calorimeter. Values of $\%dd(10)_x$ for other PTB beams in Fig. 4 were not available to us (see text).

function of $\%dd(10)_x$, use was made of an NRC EGS4/BEAM Monte Carlo study of the NPL setup.[51] In this study, $\%dd(10)_x$ values at a SSD 100 cm were derived from measured values of %dd(10) at SSD of 120 cm and 118 cm provided by NPL. The uncertainty on the correction of the measured NPL %dd(10) values amounts to 0.5%. Similarly, the %dd(10) values in the work of Ross *et al.*,[29] which were calculated for an SSD of 125 cm, were recalculated to specify $\%dd(10)_x$ at 100 cm SSD and a field size of 10×10 cm^2 at the phantom surface. Unlike the soft 20 MV beam used for this work and the soft beams in the work of Ross *et al.*,[29] the Shortt *et al.*[17] data were measured at NRC using a 20 MV beam where field flatness was obtained by using a flattening filter. Shortt *et al.*[17] also performed measurements at the 18 MV ($TPR_{10}^{20}=0.772$) beam of the Physikalisch Technische Bundesanstallt (PTB).[17] In this case we derived a $\%dd(10)_x$ of 79.6 from the measurement of a percentage depth-dose curve and corrected for electron contamination using the open beam formula of TG-51.[4] The k_Q values of Palmans *et al.*[22] were measured using a sealed water calorimeter operated at 4 °C as in this work.

The variety of linac beams presented in these graphs allows the performance of various beam quality specifiers to be examined. Measured k_Q values show a spread of up to 1.1% in Fig. 2 when plotted as a function of TPR_{10}^{20} whereas this spread becomes 0.4% when $\%dd(10)_x$ is used as beam quality specifier. When using TPR_{10}^{20} as a specifier, the Palmans *et al.* measured value of k_Q at $TPR_{10}^{20}=0.705$ is 0.84% higher than an interpolation of our values whereas using $\%dd(10)_x$ as a specifier implies the measurements agree within 0.17%.

Figures 4 and 5 show the k_Q data for the NE2611A chamber. Literature data for the NE2561 chamber have been plotted on the same graph since both chambers are usually considered to be equivalent. The data from Guerra *et al.*[18] and from the PTB as reported by Boutillon *et al.*[16] have been corrected for the energy dependence of ϵG in the same fashion as described above. The Boutillon *et al.*[16] paper only presents the PTB data as a function of TPR_{10}^{20} and $\%dd(10)_x$ values for all PTB beams were not available to us except for the 18 MV beam which was the same as the one used in the Shortt *et al.* work [$TPR_{10}^{20}=0.772$; $\%dd(10)_x=79.6$]. For the NE2611A the measured data exhibit a spread of up to 1.1% using TPR_{10}^{20} as beam quality specifier and only 0.5% using $\%dd(10)_x$. When using TPR_{10}^{20} as a specifier, the NPL measured value of k_Q at TPR_{10}^{20} of 0.79 is 1.1% greater than the NRC value for a beam with the same value of TPR_{10}^{20}. When $\%dd(10)_x$ is used as a specifier, the NPL value agrees to within 0.1% of the interpolated NRC values.

It should also be pointed out that, for the NE2571 and the NE2611A chambers, if the soft NRC beams were to be excluded from the comparison, using TPR_{10}^{20} all k_Q values generally lie within a band of $\pm0.4\%$ with the exception of the Guerra *et al.* NE2561 point at $TPR_{10}^{20}=0.75$ which is lower by 1% than the interpolated PTB data (Fig. 4).

Figures 6 and 7 show k_Q data for the PR06-C chamber. In this case, our data are compared with the data from Shortt *et al.*,[17] Ross *et al.*,[29] and Guerra *et al.*[18] For the lower energies [$TPR_{10}^{20}\leqslant0.75$, $\%dd(10)_x\leqslant79$] the agreement of our k_Q data and the Guerra *et al.*[18] data is better (within $\pm0.2\%$) when using TPR_{10}^{20} compared to a spread of 0.6% using $\%dd(10)_x$. However, at high energies [$TPR_{10}^{20}>0.75$; $\%dd(10)_x>79$] the data spread is 1.1% when expressed as a function of TPR_{10}^{20} and only 0.3% when expressed as a function of $\%dd(10)_x$.

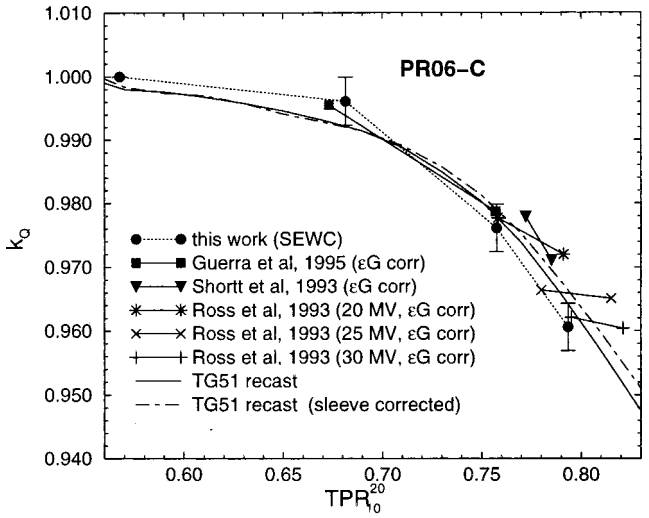

FIG. 6. Comparison between absorbed-dose beam quality conversion factors k_Q for the PR06-C chamber as a function of TPR_{10}^{20}, with experimental data from the literature. The data from Guerra *et al.* (Ref. 18) and from Ross *et al.* (Ref. 29) have been corrected for the energy dependence of the radiation chemical yield of the Fricke dosimeter as discussed in the text. The light and heavily filtered Ross *et al.* (Ref. 29) data that belong to the same accelerating potential are connected by full lines. The full line shows the data from TG-51 [recast as a function of TPR_{10}^{20} (Ref. 38)] and the dashed–dotted line the same data corrected for the effect of a 1 mm PMMA sleeve. SEWC stands for sealed water calorimeter.

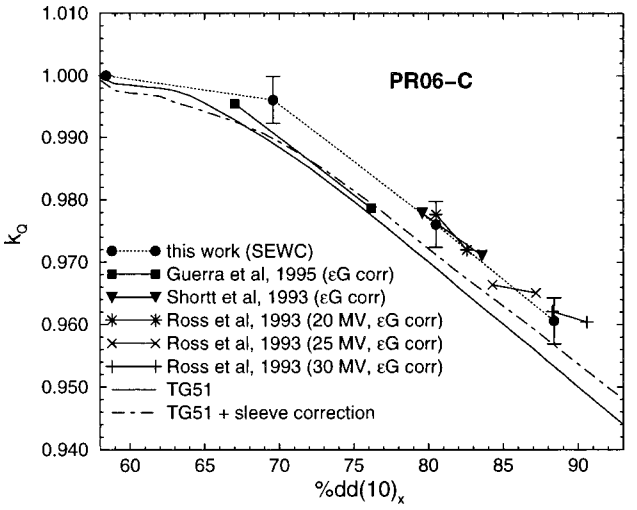

FIG. 7. Same as Fig. 6 but as a function of $\%dd(10)_x$. The full line and the dashed–dotted line show the data from the TG-51 protocol (Ref. 4) and the data from the TG-51 protocol with correction for a 1 mm PMMA sleeve, respectively. SEWC stands for sealed water calorimeter.

Figures 8 and 9 show k_Q data for the PTW-N30001 and the Exradin A12 chambers, respectively. To our knowledge, no other high-quality experimental data are available for the PTW N30001 and the Exradin A12 chambers.

In the above we have emphasized the spread in the k_Q values with different beam quality specifiers, both because this is the most relevant criterion when talking of the overall quality of a specifier and also because, as we will see below, the calculated values of k_Q tend to be larger than the measured values, and thus any spread in values shows up as a larger discrepancy with the theory. However, if one were to base a protocol completely on measured k_Q values specified by TPR_{10}^{20}, then a more relevant criterion is to ask, how wide is the band about a mean value. In this case the spreads of up to 1.1% are reduced to bands about the ''accepted value'' of $\pm 0.6\%$ or less, and this is clearly acceptable for clinical dosimetry, as long as the accepted value is based on a wide variety of measured data from different machine types.

E. Comparisons with theory

1. TG-51

In Figs. 3–8, the TG-51 protocol's values of k_Q are shown by the solid lines. Table VII presents a detailed comparison to TG-51's values as a function of TG-51's beam quality specifier $\%dd(10)_x$, including the rms deviations between measured and calculated k_Q factors for all chambers used, and averaged over all linac energies. All measured data are in a band of -0.78% to $+0.69\%$ from the TG-51 values. The overall average rms deviation between measurement and TG-51 for all chambers and energies (60 data points) amounts to 0.41% which is comparable to the 0.45% overall uncertainty on the measured values (Sec. III A).

In Figs. 2, 4, and 6 the TG-51 values of k_Q expressed as a function of TPR_{10}^{20} are compared to the measured data. For the NE2571 and NE2561 chambers the agreement between measured and calculated values is much worse (up to 1.5% discrepancies for the chambers shown in the figures; up to 1.61% for all chambers studied) at high energies using this beam quality specifier since the calculated values are typically higher than all measured values. For the PR06-C chamber the agreement with the measured values is improved using this specifier although the worst case with the $\%dd(10)_x$ specifier is 0.78%.

2. State-of-the-art chamber theory

Because most of the chambers used in our measurements are not waterproof and the calculations behind the TG-51 report do not incorporate a sleeve correction, a fair comparison with state-of-the-art calculations should account for sleeve corrections. In Figs. 3–8, the TG-51 data, corrected using the three-component sleeve correction[43,45,52] instead of the two-component wall correction,[53,54] are shown by the dashed–dotted line and detailed comparisons are given in Table VII. The inclusion of the sleeve correction generally increases the differences with the measurements for either beam quality specifier at higher energies for all chambers except the PR06-C. The overall rms deviation between TG-51 values corrected for sleeve effect and measurement for all chambers is 0.48%. The range of differences increases to -0.64% to $+1.06\%$ when the sleeve effect is taken into account.

Considering the sleeve corrected k_Q values, at 10 MV, the measured k_Q factors are equal (0.04% different for the NE2571, Table VII) or slightly (up to 0.64%) higher than the TG-51 values, at high energies the situation is generally re-

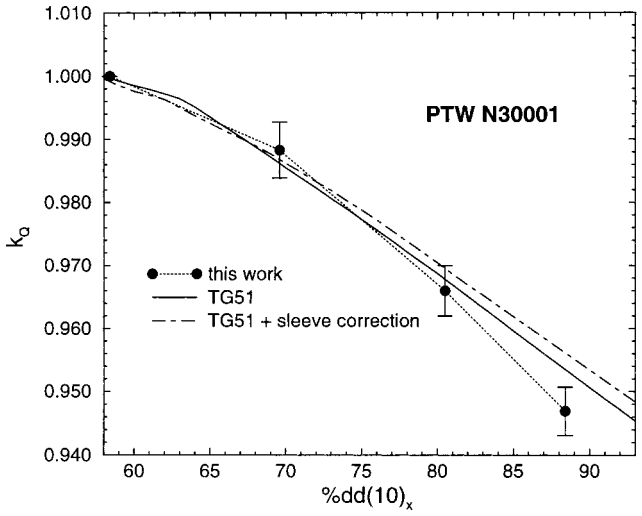

FIG. 8. Measured beam quality correction factors k_Q for the PTW-N30001 chamber as a function of %dd(10)$_x$. The full line and the dashed–dotted line show the data from the TG-51 protocol (Ref. 4) and the data from the TG-51 protocol with correction for a 1 mm PMMA sleeve, respectively.

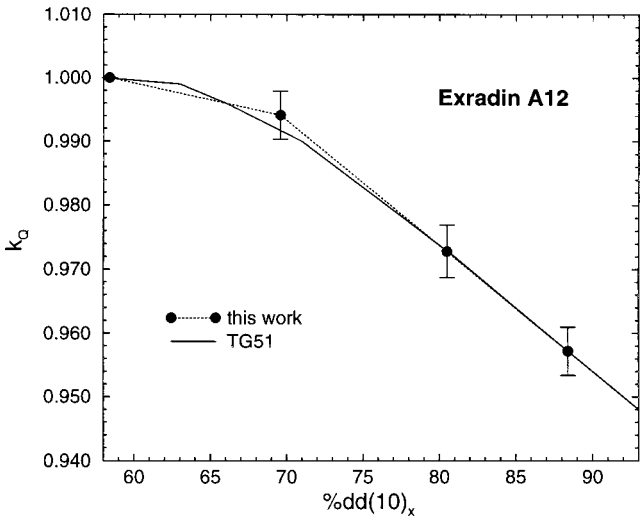

FIG. 9. Measured beam quality correction factors k_Q for the Exradin A12 chamber as a function of %dd(10)$_x$. The full line is the TG-51 values.

versed. This observation holds for all chamber types, except for the PR06-C chamber where the measured k_Q is always higher than the protocol values.

The Exradin A12 chamber and the PR06-C chamber are both chambers with C552 wall but the Exradin A12 has a thicker wall (0.088 g/cm^2 vs 0.050 g/cm^2). If one corrects the measured k_Q values for the PR06-C chamber to account for the 1 mm PMMA sleeve by using calculated corrections, the resulting k_Q values are within 0.1%. However, the calculated k_Q factor for the PR06-C chamber differs by up to 0.64% from the measurements, whereas it agrees to within 0.24% in the case of the Exradin A12 chamber. This observation is in agreement with the observations made regarding Table V, if, for consistency, a cap of C552 is used in the in-air calibration: the difference between calculated C_{Co} and measured C_{Co} is 0.90% for the PR06-G chamber whereas it is only 0.33% for the Exradin A12 (Table V). When calculating the ratio of the k_Q of the PR06-C chamber and the graphite walled NE2571 chamber, the measured ratio is 0.7%, 0.8%, and 0.9% higher than the calculated ratio for 10 MV, 20 MV, and 30 MV, respectively. Since a measured ratio of k_Q values is independent of the dose standard, and a calculated ratio for Farmer-type chambers is only determined by wall and central electrode correction factors, these observations confirm the problems with the two-component model for P_{wall}.[29]

3. Comparison of experimental C_Q factors with TG-21-based values

Table VIII presents the calorimeter-based values of C_Q in comparison with the AAPM TG-21 protocol values of this quantity. Two versions of the TG-21 protocol have been used: the originally published version (data and equations),[2] and the fully corrected version of the protocol[43] which uses data and equations exactly compatible with the calculations behind TG-51 except for the use of the beam quality specifier (which is TPR_{10}^{20} in this case). The differences between the original version of TG-21 and our measurements are up to 3.0% at the highest energies, and are composed of two effects (1) problems with beam quality specification using TPR_{10}^{20} and (2) the use of old data and the errors in the formalism. The situation is improved upon going to the corrected version of TG-21 where differences are less than 1.4% in all cases. We also compare our measured C_Q values with optimal air-kerma calculations defined as the product of C_{Co} values using the fully corrected version of TG-21, and the TG-51 values of k_Q corrected for the effect of the waterproofing sleeve (if present). The only difference between these values and the corrected version of TG-21 is in the beam quality specification and the sleeve correction. The differences from measurements using this approach are at most 1.3%. In columns 6–8 of Table VIII we also present the rms deviations between measured and calculated C_Q values using the three approaches. Overall a progressive improvement of the agreement between measurement and calculation can be observed.

4. Accuracy of a k_Q system compared to a C_Q system

The ''optimal air-kerma'' C_Q values (Table VIII) actually correspond to using exactly equivalent physics (data, equations, and beam quality specification) as TG-51 but corrected for the effect of waterproofing sleeve and extended to convert from air kerma to absorbed dose in ^{60}Co. Comparing the rms deviations in Tables VII and VIII, the values are lower for all chamber types for the k_Q system than for the C_Q system: the overall average rms deviation in the C_Q system is 0.67% compared to 0.48% for the k_Q system. This means that for the chamber types investigated in this study, the accuracy of an absorbed-dose-based protocol making use of calculated k_Q values is superior to an air-kerma-based system making use of calculated C_Q values based on the same physics. This improved accuracy is a combination of two

TABLE VIII. Water calorimetry based air-kerma to absorbed dose conversion factors, C_Q. The second and third line for each chamber type represent the percentage differences between the original AAPM TG-21 protocol (as published) and the AAPM TG-21, fully corrected protocol (corr) respectively, and the experimental values of this work defined as $100\times(C_{Q,\mathrm{prot}}-C_Q)/C_Q$. For those comparisons TPR_{10}^{20} has been used as the beam quality specifier. The term ''optimal air-kerma'' refers to state-of-the-art ion chamber theory including correction for the effect of a 1 mm PMMA waterproofing sleeve and combined with $\%\mathrm{dd}(10)_x$ as beam quality specifier. The C_Q data in this case are the state-of-the-art calculation of C_{Co} including sleeve correction (Table V) multiplied with k_Q from TG-51 with sleeve correction. The rms deviations between measured and calculated C_Q are shown for each chamber type combined for 10 MV, 20 MV, and 30 MV ($n-1\geqslant 8$).

		Beam quality			rms deviation		
Chamber type	NAP $\%\mathrm{dd}(10)_x$ TPR_{10}^{20}	10 MV 69.6 0.682	20 MV 80.5 0.758	30 MV 88.4 0.794	TG-21 (orig)	TG-21 (corr)	Optimal air-kerma
NE2571	C_Q	1.0810	1.0613	1.0431			
	$\%\Delta^{\text{TG-21(orig)}}$	+0.95%	+1.66%	+2.10%	1.61%		
	$\%\Delta^{\text{TG-21(corr)}}$	+0.26%	+0.75%	+1.18%		0.81%	
	$\%\Delta^{\text{optimal air-kerma}}$	+0.31%	+0.56%	+0.98%			0.69%
NE2611A	C_Q	1.0777	1.0539	1.0361			
	$\%\Delta^{\text{TG-21(orig)}}$	+0.52%	+1.71%	+2.18%	1.64%		
	$\%\Delta^{\text{TG-21(corr)}}$	−0.22%	+0.79%	+1.24%		0.87%	
	$\%\Delta^{\text{optimal air-kerma}}$	−0.14%	+0.64%	+1.07%			0.74%
NE2581	C_Q	1.0756	1.0453	1.0288			
	$\%\Delta^{\text{TG-21(orig)}}$	+0.25%	+1.74%	+1.92%	1.51%		
	$\%\Delta^{\text{TG-21(corr)}}$	−0.94%	+0.26%	+0.49%		0.63%	
	$\%\Delta^{\text{optimal air-kerma}}$	−1.15%	−0.23%	−0.10%			0.65%
PTW N30001	C_Q	1.0756	1.0513	1.0305			
	$\%\Delta^{\text{TG-21(orig)}}$	+1.21%	+2.31%	+2.96%	2.28%		
	$\%\Delta^{\text{TG-21(corr)}}$	+0.20%	+0.96%	+1.61%		1.09%	
	$\%\Delta^{\text{optimal air-kerma}}$	+0.16%	+0.66%	+1.28%			0.92%
Capintec PR06-C	C_Q	1.0819	1.0601	1.0433			
	$\%\Delta^{\text{TG-21(orig)}}$	+0.20%	+1.17%	+1.31%	1.04%		
	$\%\Delta^{\text{TG-21(corr)}}$	−0.73%	−0.17%	+0.02%		0.47%	
	$\%\Delta^{\text{optimal air-kerma}}$	−0.81%	−0.69%	−0.59%			0.74%
Exradin A12	C_Q	1.0890	1.0657	1.0486			
	$\%\Delta^{\text{TG-21(orig)}}$	+1.09%	+2.38%	+2.55%	2.11%		
	$\%\Delta^{\text{TG-21(corr)}}$	+0.29%	+1.16%	+1.40%		1.06%	
	$\%\Delta^{\text{optimal air-kerma}}$	+0.08%	+0.35%	+0.30%			0.29%
Overall average rms deviation between measurement and protocol;							
			TG-21(orig)		1.70%		
			TG-21(corr)			0.82%	
			optimal air-kerma				0.67%

effects: (1) the absence of the build-up cap in the calibration at ^{60}Co in the k_Q system, and the extent to which a protocol calculation must be able to predict its effect for a particular chamber; (2) the distribution of the measured C_Q conversion factors around the calculated curve, and how a normalization at ^{60}Co affects this distribution. In particular, comparing the differences in calculated and measured C_{Co} (Table V) with the differences in C_Q between the ''optimal air-kerma'' approach and the measurements (Table VIII) shows that the majority of the differences at the high energies have the same sign as the differences at ^{60}Co. Therefore, normalization at ^{60}Co improves the overall consistency and the overall rms deviation for all chambers in the k_Q system compared to the C_Q system. It should be remembered though that if measured rather than calculated values of k_Q and C_Q factors are used, both systems are equally accurate.

IV. CONCLUSIONS

In this paper we presented measured beam quality conversion factors k_Q, and C_Q as a function of photon energy between ^{60}Co and 30 MV [$58<\%\mathrm{dd}(10)_x<89$; $0.57<\mathrm{TPR}_{10}^{20}<0.80$] for six types of cylindrical chambers. We used the Canadian primary standard for absorbed-dose to water based on a sealed water calorimeter to calibrate the chambers in terms of absorbed dose to water. The uncertainty on the measurement of k_Q for a single chamber amounted typically to 0.36%, the uncertainty on C_Q was 0.60%. Within a set of five NE2571 chambers, a maximum difference between k_Q factors of 0.45% was observed. The differences between measured and TG-51 based k_Q values were no more than 0.8%. If sleeve corrections are accounted for, the maximum difference between measurement and calculation amounts to 1.1%. The rms deviation based on 20

chambers at three energies between our measured type average k_Q values and the k_Q values of the AAPM TG-51 protocol for all investigated chamber types amounted to 0.41% which is the same as our estimated uncertainties on the measurement. When sleeve corrections are accounted for in the calculated k_Q value, the rms deviation increases to 0.48%.

The measured k_Q values were up to 1.6% different compared with TG-51 values recast as a function of TPR_{10}^{20} (k_Q values calculated using a corrected formalism and ICRU Report 37[44] stopping powers but using TPR_{10}^{20} as a beam quality specifier). We have demonstrated that this is due to the inadequacy of TPR_{10}^{20} to specify the soft NRC beams, since the former NRC data[29] for heavily filtered beams based on Fricke dosimetry, corrected for the energy dependence of ϵG, agreed with calculated k_Q values to within 0.4% when the beam quality was specified by TPR_{10}^{20}.

By combining our data with calorimeter or corrected Fricke-based literature data we showed that k_Q values for the NE2571 were specified by $\%dd(10)_x$ with a spread of 0.4% compared to TPR_{10}^{20} where the data spread was 1.1%. For the NE2611 chamber, k_Q values were specified by $\%dd(10)_x$ with a spread of 0.6% compared to a spread of 1.1% when expressed as a function of TPR_{10}^{20}. For the PR06-C chamber TPR_{10}^{20} is a slightly better specifier at low energies but at high energies $\%dd(10)_x$ is preferable. We noted anomalies with this chamber type when compared to its calculated response. For the remaining chambers investigated (NE2581, PTW-N30001, Exradin A12) insufficient high-quality data prevent definitive conclusions as to the performance of each of the specifiers. Nonetheless, just by examining the internal consistency of the measured data from a variety of accelerator beams it has been demonstrated that $\%dd(10)_x$ is a better beam quality specifier for radiotherapy photon beams in the sense that it properly specifies the soft NRC beams whereas TPR_{10}^{20} does not do as well. This result was predicted by calculations.[55] We found that not only critical evaluation of the techniques (i.e., Fricke versus calorimetry) that have been used to measure k_Q values reported in the literature, but also the details of the measurement of $\%dd(10)_x$ were essential to arrive at this result. On the other hand, absorbed-dose determination using experimental k_Q factors specified as a function of TPR_{10}^{20} remains accurate to within $\pm 0.6\%$ if a wide variety of accelerator beams are used. This is, in clinical terms, perfectly acceptable.

Our work also shows that protocols making use of ^{60}Co absorbed-dose calibration factors in combination with calculated k_Q values, are more accurate than a state-of-the-art protocol based on air-kerma calibrations and using calculated C_Q values based on exactly the same formalism and data but needing an in-air to in-water conversion. The rms deviation between the measured k_Q values and those calculated using sleeve corrections is 0.48% compared to 0.67% for the corresponding C_Q values.

Overall, our work has provided numerical data to back up the theoretical k_Q data adopted in the current absorbed dose based protocols for high energy photon beams and can thereby help to assess their accuracy.

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[1] IAEA, *Absorbed Dose Determination in Photon and Electron Beams; An International Code of Practice*, Vol. 277 of Technical Report Series (IAEA, Vienna, 1987).

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

[3] D. I. Thwaites, ''Uncertainties at the end point of the basic dosimetry chain,'' *IAEA-SM-330/18, Proceedings of Symposium on Measurement Assurance in Dosimetry* (IAEA, *Vienna, 1994)*, pp 239–255.

[4] P. R. Almond, P. J. Biggs, B. M. Coursey, W. F. Hanson, M. S. Huq, R. Nath, and D. W. O. Rogers, ''AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams,'' Med. Phys. **26**, 1847–1870 (1999).

[5] 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 based on Absorbed-Dose-to-Water Standards: An International Code of Practice for Dosimetry*, Draft V.7 (IAEA, Vienna, 2000).

[6] DIN 6800, *Dosismessverfahren in der Radiologischen Technik—Ionisationsdosimetrie*, Vol. Teil 2 (Beuth Verlag GmbH, Berlin and Cologne, 1980).

[7] K. Hohlfeld, ''The standard DIN 6800: Procedures for absorbed dose determination in radiology by the ionization method,'' *Proceeding of 1987 Symposium on Dosimetry in Radiotherapy* (IAEA, Vienna 1988), Vol. 1, pp. 13–24.

[8] K. E. Rosser, B. Owen, A. R. DuSautoy, D. H. Pritchard, I. Stoker, and C. J. Brend, ''The NPL absorbed dose to water calibration service for high energy photons,'' IAEA-SM-330/35, *Proceedings of Symposium on Measurement Assurance in Dosimetry (IAEA, Vienna, 1994)*, pp. 73–81.

[9] IPSM, ''Code of Practice for high-energy photon therapy dosimetry based on the NPL absorbed dose calibration service,'' Phys. Med. Biol. **35**, 1355–1360 (1990).

[10] J. Medin, J. Seuntjens, N. Klassen, C. Ross, and G. Stucki, ''The OFMET sealed water calorimeter,'' Proceedings of the NPL workshop on calorimetry, pp. 66–74 (National Physical Laboratory, UK, 2000).

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

[12] P. Andreo, ''On the beam quality specification of high-energy photons for radiotherapy dosimetry,'' Med. Phys. **27**, 434–440 (2000).

[13] D. W. O. Rogers, ''Comment on 'On the beam quality specification of high-energy photons for radiotherapy dosimetry [Med. Phys. **27**, 434–440 (2000)]','' Med. Phys. **27**, 441–444 (2000).

[14] D. W. O. Rogers and J. P. Seuntjens, *Photon Beam Quality Specification for Comparisons of Absorbed Dose to Water*, BIPM document CCRI(1)99-25 (BIPM, Sèvres, France, 1999).

[15] P. Andreo, ''Reply to Comment on 'On the beam quality specification of high-energy photons for radiotherapy dosimetry [Med. Phys. **27**, 441–444 (2000)]','' Med. Phys. **27**, 1693–1695 (2000).

[16] M. Boutillon, B. M. Coursey, K. Hohlfeld, B. Owen, and D. W. O.

Rogers, ''Comparison of primary water absorbed dose standards,'' IAEA-SM-330/48, *Proceedings of Symposium on Measurement Assurance in Dosimetry* (IAEA, Vienna, 1994), pp. 95–111.
[17] K. R. Shortt, C. K. Ross, M. Schneider, K. Hohlfeld, M. Roos, and A. M. Perroche, ''A comparison of absorbed dose standards for high energy x-rays,'' Phys. Med. Biol. **38**, 1937–1955 (1993).
[18] A. S. Guerra, R. F. Laitano, and M. Pimpinella, ''Experimental determination of the beam quality dependence factors, k_Q, for ionization chambers used in photon and electron dosimetry,'' Phys. Med. Biol. **40**, 1177–1190 (1995).
[19] J. P. Seuntjens, K. R. Shortt, C. K. Ross, C. M. Ma, and D. W. O. Rogers, ''Measurement of beam quality factors k_Q for cylindrical ionization chambers in high energy photon beams,'' Med. Phys. **23**, 1071, abstract (1996).
[20] N. V. Klassen, K. R. Shortt, J. P. Seuntjens, and C. K. Ross, ''Fricke dosimetry: the difference between G(Fe^{3+}) for ^{60}Co γ-rays and high-energy x-rays,'' Phys. Med. Biol. **44**, 1609–1624 (1999).
[21] S. M. Vatnitsky, J. V. Siebers, and D. W. Miller, ''Calorimetric determination of the absorbed dose-to-water beam quality correction factor k_Q for high-energy photon beams,'' Med. Phys. **22**, 1749–1752 (1995).
[22] H. Palmans, W. Mondelaers, and H. Thierens, ''Absorbed dose beam quality correction factors k_Q for the NE2571 chamber in a 5 MV and 10 MV photon beam,'' Phys. Med. Biol. **44**, 647–663 (1999).
[23] K. R. Shortt, C. K. Ross, J. P. Seuntjens, F. Delaunay, P. Gross, E. Leroy, and A Ostrowsky, ''Comparison of dose standards for linac photon beams at NRC Canada and LPRI France,'' Med. Phys. **23**, 1103, abstract (1999).
[24] K. R. Shortt, ''Five dosimetric comparisons at Cobalt-60 energy involving NRC in 1998,'' *Proceedings of the 1999 COMP Annual Meeting* (Canadian Organization of Medical Physicists, Edmonton, Alberto, 1999), pp. 135–137.
[25] K. Shortt, J. Shobe, and S. Domen, ''Comparison of dosimetry calibration services at the NRCC and the NIST,'' Med. Phys. **27**, 1644–1654 (2000).
[26] P. J. Allisy-Roberts, D. T. Burns, K. R. Shortt, C. K. Ross, and J. P. Seuntjens, Comparison of the standards of absorbed dose to water of the NRC, Canada and the BIPM for ^{60}Co γ rays, Rapport BIPM-99/13 (BIPM, Sévres, France, 2000).
[27] J. P. Seuntjens, C. K. Ross, N. V. Klassen, and K. R. Shortt, A status report on the NRC sealed water calorimeter, Technical Report PIRS-584, NRC Canada, Ottawa, K1A OR6, 1999.
[28] J. Seuntjens and H. Palmans, ''Correction factors and performance of a 4 °C sealed water calorimeter,'' Phys. Med. Biol. **44**, 627–646 (1999).
[29] C. K. Ross, K. R. Shortt, D. W. O. Rogers, and F. Delaunay, ''A Test of TPR_{10}^{20} as a Beam Quality Specifier for High-Energy Photon Beams,'' IAEA-SM-330/10, *Proceedings of Symposium on Measurement Assurance in Dosimetry* (IAEA, Vienna, 1994), pp. 309–321.
[30] D. Sheikh-Bagheri, D. W. O. Rogers, C. K. Ross, and J. P. Seuntjens, ''Comparison of measured and Monte Carlo calculated dose distributions from the NRC linac,'' Med. Phys. **27**, 2256–2266 (2000).
[31] C. L. Yang, D. W. O. Rogers, and J. P. Seuntjens, ''Calculation of photon beam quality specifiers,'' *Proceedings of the 1998 COMP Annual Meeting* (Canadian Organization of Medical Physicists, Edmonton, Alberta, 1998), pp. 186–188.
[32] N. V. Klassen and C. K. Ross, ''Water calorimetry: the heat defect,'' J. Res. Natl. Inst. Stand. Technol. **102**, 63–74 (1997).
[33] A. Booth and D. W. O. Rogers, Monte Carlo study of effects of phantom size, radial position, and depth on photon beam calibration, NRC Report PIRS-507, NRC Canada, Ottawa, K1A OR6, 1995.
[34] K. Derikum and M. Roos, ''Measurement of saturation correction factors of thimble-type ionization chambers in pulsed photon beams,'' Phys. Med. Biol. **38**, 755–763 (1993).
[35] C. Zankowski and E. B. Podgorsak, ''Determination of saturation charge and collection efficiency for ionization chambers in continuous beams,'' Med. Phys. **25**, 908–915 (1998).
[36] C. L. Yang, D. W. O. Rogers, K. R. Shortt, and L. Van der Zwan, ''Ion recombination in ion chambers in continuous radiation,'' *Proceedings of the 1999 COMP Annual Meeting* (Canadian Organization of Medical Physicists, Edmonton, Alberta, 1999), pp. 23–25.
[37] C. K. Ross and K. R. Shortt, ''The effect of waterproofing sleeves on ionization chamber response,'' Phys. Med. Biol. **37**, 1403–1411 (1992).
[38] 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, DC, 1996), pp. 319–356.
[39] D. W. O. Rogers, ''The advantages of absorbed-dose calibration factors,'' Med. Phys. **19**, 1227–1239 (1992).
[40] D. W. O. Rogers and A. Booth, PROT: A general purpose utility for calculating quantities related to dosimetry protocols, Technical Report PIRS-529, NRC Canada, Ottawa, K1A 0R6, 1996.
[41] C. K. Ross and D. W. O. Rogers, ''Comments on 'The effects of air humidity on ionization chamber response','' Radiat. Prot. Dosim. **22**, 127–128 (1988).
[42] R. J. Schulz, P. R. Almond, G. Kutcher, R. Loevinger, R. Nath, D. W. O. Rogers, N. Suntharalingham, K. A. Wright, and F. Khan, ''Clarification of the AAPM Task Group 21 Protocol,'' Med. Phys. **13**, 775–759 (1986).
[43] D. W. O. Rogers, ''Fundamentals of high energy x-ray and electron dosimetry protocols,'' in *Advances in Radiation Oncology Physics, Medical Physics Monograph 19*, edited by J. Purdy (AAPM, New York, 1992), pp. 181–223.
[44] ICRU, Stopping powers for electrons and positrons, ICRU Report 37, ICRU, Washington, DC, 1984.
[45] W. F. Hanson and J. A. D Tinoco, ''Effects of plastic protective caps on the calibration of therapy beams in water,'' Med. Phys. **12**, 243–248 (1985).
[46] P. J. Allisy-Roberts, D. T. Burns, K. R. Shortt, and C. K. Ross, Comparison of the air kerma standards of the NRC and the BIPM for ^{60}Co γ rays, Rapport BIPM-99/12, 2000.
[47] M. Boutillon and A.-M. Perroche, ''Comparisons and Calibrations at the Bureau International des Poids et Mesures in the field of x and γ rays,'' IAEA-SM-330/22, *Proceedings of Symposium on Measurement Assurance in Dosimetry* (IAEA, Vienna, 1994), pp. 15–23.
[48] D. W. O. Rogers, ''Calibration of parallel-plate ion chambers: Resolution of several problems by using Monte Carlo calculations,'' Med. Phys. **19**, 889–899 (1992).
[49] D. W. O. Rogers and C. K. Ross, ''The role of humidity and other correction factors in the AAPM TG-21 dosimetry protocol,'' Med. Phys. **15**, 40–48 (1988).
[50] P. Sharpe, Progress report on radiation dosimetry at NPL, BIPM Report CCRI(I)/99-20, 1999.
[51] B. R. B. Walters and D. W. O. Rogers, Monte Carlo estimates of $\%dd(10)_X$ for the NPL photon beams, NRC Report PIRS-659, NRC, Ottawa, 1999.
[52] M. T. Gillin, R. W. Kline, A. Niroomand-Rad, and D. F. Grimm, ''The effect of thickness of the waterproofing sheath on the calibration of photon and electron beams,'' Med. Phys. **12**, 234–236 (1985).
[53] A. Shiragai, ''A proposal concerning the absorbed dose conversion factor,'' Phys. Med. Biol. **23**, 245–252 (1978).
[54] A. Shiragai, ''Effective mass stopping power ratio in photon dosimetry,'' Phys. Med. Biol. **24**, 452–454 (1979).
[55] A. Kosunen and D. W. O. Rogers, ''Beam quality specification for photon beam dosimetry,'' Med. Phys. **20**, 1181–1188 (1993).