Physica Medica 57 (2019) 221–230

Contents lists available at ScienceDirect

Physica Medica

journal homepage: www.elsevier.com/locate/ejmp

Original paper

Calculation of k_Q factors for Farmer-type ionization chambers following the recent recommendations on new key dosimetry data

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ARTICLE INFO

Keywords:
Beam quality correction factor
k_Q
ICRU 90
Monte-Carlo calculated k_Q
Radiotherapy dosimetry

ABSTRACT

Purpose: To calculate by Monte Carlo simulations k_Q factors for Farmer-type ionization chambers in megavoltage photon beams using the new key dosimetry data recommended by the International Commission on Radiation Units and Measurements (ICRU) Report 90.

Methods: Monte Carlo calculations were performed with the EGSnrc code system using both the ICRU 90 and the ICRU 37 data. Farmer-type ionization chambers with graphite and plastic walls and with graphite wall and a plastic waterproofing sleeve were considered (Nuclear Enterprise NE 2571, IBA FC65-G and FC65-P). k_Q factors were calculated for photon beams in the range 6–25 MV using phase-space files as input radiation sources. The photon beam qualities in terms of $TPR_{20,10}$ and $\%dd(10)_x$ were established by simulating the depth-dose curves in water. Absorbed doses to the air cavity and to water were calculated using the *egs_chamber* user code with a target statistical uncertainty below 0.1%.

Results: The update of key dosimetry data according to the ICRU report 90 had an impact of −0.2% in the absorbed dose to water and up to 0.5% in the absorbed dose to the air cavity. Nevertheless, changes partially offset each other when entering in k_Q as ratio, and the final impact on the k_Q values was below 0.3%.

Conclusions: The calculated values of k_Q tend to be lower than the current values in the IAEA TRS-398 protocol with differences up to about 0.5%. A slightly better agreement (within 0.3%) is observed with the Monte-Carlo calculated values provided by the addendum to the AAPM's TG-51 protocol.

1. Introduction

The International Code of Practice IAEA TRS-398 for dosimetry in radiotherapy [1] proposed a coherent system of clinical dosimetry that simplified the procedures to obtain the quantity absorbed dose to water (D_w) in dosimetry on a clinical beam. The strength of the TRS-398 approach lies in the fact that a calibration coefficient for a therapy level dosimeter is directly provided in terms of the quantity of interest in radiotherapy dosimetry, D_w, thus avoiding the application of a relatively complex formalism that derived from the formerly common dosimetric approach based on measurements of the quantity air kerma, K_{air}. Such former approach required the application of correction factors that were partly based on complex experimental measurements and calculations based on theoretical models, which inevitably introduced uncertainties that have become increasingly unacceptable. Additionally, the benefit of a simplified dosimetric approach, such as that introduced by the IAEA TRS-398, is in the reduced risk of errors in the determination of absorbed dose to water in the radiation beam.

A limitation still exists, however, in that the radiation beams available at the clinical centre may be different from the beams available at either the Secondary Standards Dosimetry Laboratories (SSDL) or at the Primary Standards Dosimetry Laboratories (PSDL). To overcome this limitation, when a dosimeter is used in a beam of quality Q that is different from the one used in its calibration, Q_0, the absorbed dose to water can be determined through the application of the relationship:

$$D_{w,Q} = M_Q N_{D,w,Q_0} k_{Q,Q_0} \tag{1}$$

where $D_{w,Q}$ is the absorbed dose to water at the user quality Q, M_Q is the ionization chamber signal in the same beam corrected for influence parameters at reference conditions, $N_{D,w,Q0}$ is the calibration coefficient of the ionization chamber determined at the PSDL or SSDL at the quality Q_0 (commonly the ^{60}Co quality), and k_{Q,Q_0} (denoted k_Q when Q_0 is ^{60}Co) is a factor that corrects for the difference between the ionization chamber response at the reference beam quality Q_0 and at the actual user quality Q. k_{Q,Q_0} factors could not easily be determined at the beginning, due to limited availability of primary standards of the quantity D_w. These factors were therefore estimated by applying the

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https://doi.org/10.1016/j.ejmp.2018.12.006
Received 31 July 2018; Received in revised form 8 November 2018; Accepted 10 December 2018
Available online 17 January 2019

Bragg-Gray cavity theory, where possible, with the notable introduction of chamber type-specific perturbation factors known as p_Q. Over the past few years, several limitations have emerged from the use of the TRS-398 Code of Practice, that were inherent in the type of experimental data available when publishing the TRS-398 and the assumptions that were made in the models [2–7]. These items could later become re-addressed thanks to the more widespread availability of primary standards of D_w, and also, notably, with the advancement in Monte Carlo computer codes of particle transport for radiation dosimetry. The advancements in Monte Carlo codes have lent the opportunity to calculate the k_{Q,Q_0} more directly, by relatively simple calculations that involve the determination of absorbed dose to water at the reference point and the absorbed dose averaged over the sensitive volume of the ionization chamber. The approach based on several multiplicative correction factors that had been developed earlier on could therefore be abandoned [8]. Coupled with the necessity of estimating k_{Q,Q_0}factors for chamber models that were not available at the time of the first publication of the TRS-398, and with the advent of new technologies for cancer radiotherapy, for which k_{Q,Q_0} factors could not exist earlier, the International Atomic Energy Agency (IAEA) has piloted an update of the TRS-398, to be published (soon). This update involves the active participation of worldwide laboratories who are contributing via the submission to the IAEA of revised or newly determined k_{Q,Q_0} factors, either experimentally or via Monte Carlo computation.

Recently, the International Commission on Radiological Units has published a revised set of key data that have a significant influence on fundamental radiation dosimetry (ICRU 90) [9]. The key physical data pertain to revised values of mean excitation energies in some materials of common use in radiation dosimetry (notably graphite and liquid water), on the effects of the re-expressed density of these materials, and on the re-normalization of the photoelectric cross-sections for low energy x-rays. In turn, these new data have an impact in the determination, be this with primary standards or via Monte Carlo computation, of factors that underlie the determination of D_w and K_{air}, including stopping power ratios. For example, the increase in the mean excitation energy and the change in the density used to evaluate the density-effect correction both result in a decrease in the electronic stopping power. Depending on the design and the realization of the existing national primary standards, several revisions may be necessary to account for the new key data of ICRU 90 (see for example Burns and Kessler 2018 [10]). It is expected that to some extent the new key data have an impact on the k_Q factors as well. Effects of adopting the ICRU 90 key data in Monte Carlo calculations of k_Q were recently evaluated, in photon beams, by Czarnecki et al. [11] for the NE 2571 chamber and by Mainegra-Hing and Muir [12] for the NE 2571, the PTW 30013 and the Exradin A19 ionization chambers. Both investigations showed a small impact of the new key dosimetric data on k_Q values, reporting changes below 0.35% for the NE 2571 and even smaller for the other two chamber types. Nevertheless, up-to-date $k_Q$values should be compliant with the ICRU Report 90 and therefore new determinations of k_Q for other models of reference ionization chambers are advisable.

This work is part of the EMPIR RTNORM project "k_Q factors in modern external beam radiotherapy applications to update IAEA TRS 398" whose goal is to provide measured and calculated up-to-date values of k_Q factors for a series of ionization chambers and a range of radiation beam modalities, which will contribute to the on-going revision of the TRS-398. k_Q factors for three models of Farmer-type ionization chambers with different wall materials (IBA dosimetry: FC65-G and FC65-P, Nuclear Enterprise: NE 2571) were determined in high energy photon beams by Monte Carlo calculations using the EGSnrc code system that has recently been updated to adopt the new key data published in the ICRU Report 90 [13].

2. Materials and methods

According to the IAEA TRS-398 [1] the beam quality correction factor k_Q is defined as the ratio of the ionization chamber calibration coefficients at the beam quality Q and at the reference ^{60}Co gamma beam. This can be expressed as

$$k_Q = \frac{N_{D,w,Q}}{N_{D,w}} = \frac{D_{w,Q}/M_Q}{D_{w,^{60}Co}/M_{w,^{60}Co}} \tag{2}$$

where $D_{w,Q}$ and $D_{w,Co}^{60}$ are the absorbed dose to water at the calibration point at beam quality Q and ^{60}Co, respectively, and M is the chamber signal (i.e. the collected charge) at quality Q or ^{60}Co in the calibration reference conditions, corrected for the influence quantities (temperature, pressure, ion recombination etc). Assuming that the conversion of the energy deposited by radiation in the chamber sensitive volume into collected charge is independent of energy, Eq. (2) can be rewritten in a format which lends it well to Monte Carlo calculations:

$$k_Q = \frac{D_{w,Q}/D_{ch,Q}}{D_{w,^{60}Co}/D_{ch,^{60}Co}} \tag{3}$$

where D_{ch} is the average absorbed dose in the chamber active volume placed at the measurement point in water, for either radiation quality Q or ^{60}Co.

In this work, all the quantities in Eq. (3) were obtained by Monte Carlo calculations using the EGSnrc code system [13]. D_{ch} was obtained simulating the irradiation of an ionization chamber in reference conditions in a water phantom and D_w simulating the radiation beam transport in the homogeneous water phantom. Monte Carlo simulations were made following the recommendations of the ICRU report 90 [9] on *i)* the mean excitation energy (I) of water and graphite; *ii)* the data to be used for calculating the density effect correction for graphite; *iii)* the renormalized photoelectric cross sections. In order to estimate the impact of the new ICRU 90 recommendations on k_Q calculation, simulations were also run in compliance with the old ICRU 37 [14] recommendations without any change in other inputs.

Calculations were made for radiotherapy photon beams in the energy range from 6 MV to 25 MV. Three models of Farmer-type ionization chambers (Nuclear Enterprises: NE 2571, IBA Dosimetry: FC65-G and FC65-P) with the same nominal active volume, but with different wall materials, were considered. The main characteristics of the ionization chambers are reported in Table 1. The ionization chambers were modelled in detail according to the manufacturers' specifications, using the egs++ geometry package [15]. The chamber models included a 2 cm long stem and, for the NE 2571 chamber, a 1 mm thick waterproofing PMMA envelope. Sketches of the chamber models are shown in Fig. 1.

2.1. Monte Carlo calculation of k_Q

The *egs_chamber* user code [16] was used for calculating the two pairs of D_{ch} and D_w in Eq. (3). D_{ch} was obtained by scoring the energy deposited in the air cavity of the ionization chamber placed with its reference point at the reference depth (5 g cm^{-2} for ^{60}Co and 10 g cm^{-2} for accelerator beams) in a cube of water with side 30 cm. D_w at the reference point in water was approximated by the absorbed dose to water scored in a small volume of water. To investigate the influence of the scoring volume dimensions on the computed D_w values, calculations were made for different scoring volume sizes and shapes. In particular, the following scoring volumes were considered: *i)* a disk-shaped volume with radius 1 cm in the plane perpendicular to the beam axis and thickness 0.025 cm in the beam direction, as commonly used for k_Q calculation [3,17–19]; *ii)* a cylindrical voxel with radius and height 0.25 cm; *iii)* a cylindrical volume with length 2.4 cm and radius 0.31 cm, mimicking the air cavity shape of a Farmer-type ionization chamber.

Photons and electrons were followed down to a kinetic energy of 1 keV (PCUT = 0.001 MeV and ECUT = 0.512 MeV electron mass included) and transport parameters were set to the values allowing the

Table 1
Characteristic of the ionization chambers modelled for Monte Carlo calculation of k_Q factors in high energy photon beams.

	NE 2571	FC65-G	FC65-P
air cavity length	2.405 cm	2.360 cm	2.360 cm
air cavity radius	0.314 cm	0.310 cm	0.310 cm
wall thickness	0.036 cm	0.04 cm	0.04 cm
wall material	graphite (1.8 g cm^{-3})	graphite (1.82 g cm^{-3})	Delrin (1.425 g cm^{-3})
central electrode radius	0.05 cm	0.05 cm	0.05 cm
central electrode length	2.057 cm	2.100 cm	2.100 cm
central electrode material	Al (2.6989 g cm^{-3})	Al (2.6989 g cm^{-3})	Al (2.6989 g cm^{-3})
sleeve material	PMMA (1.19 g cm^{-3})	–	–
sleeve thickness	0.1 cm	–	–
air cavity volume	0.688 cm^3	0.650 cm^3	0.650 cm^3
stem materials	Al, graphite, PCTFE (2.1 g cm^{-3})	Al, graphite, insulators (1.42 and 1.12 g cm^{-3})	Al, insulators (1.42 and 1.12 g cm^{-3})

most accurate interaction models (the adopted settings are listed in Table 2).

Materials data were generated using the EGSnrc/PEGS4 program with input data for the density effect corrections from the material-density files supplied with the EGSnrc package. If the density file was not available for a given material, the density effect corrections were generated using the Sternheimer and Peierls general formula implemented in PEGS4 [13]. For the ICRU 90 compliant simulations, *i)* the *I* value was 81 eV and 78 eV for graphite and water, respectively; *ii)* for graphite the crystalline density of 2.265 g/cm^3 was used when determining the density effect correction while using the bulk density in the radiation transport simulation; *iii)* the renormalized photon cross sections were used (option *'mcdf-xcom'* in EGSnrc). For the ICRU 37 simulations the *I* values for graphite and water were 78 eV and 75 eV, respectively, the bulk density of graphite was used for both the density effect corrections and the actual simulations and the XCOM photon cross sections were used (option *'xcom'* in EGSnrc). In radiotherapy dosimetry, as well as in related Monte Carlo calculations, water density is currently set to 1 g cm^{-3}, neglecting its temperature dependence. However, since the updated PEGS4 water-density file distributed with the EGSnrc package uses the water density at the reference temperature of 20 °C, the ICRU 90 simulations in this work were run with water density of 0.9982 g cm^{-3}.

Among the variance reduction techniques (VRTs) implemented in EGSnrc, the range-based Russian Roulette (RR) and the photon cross section enhancement (XCSE) were applied to improve the calculation efficiency [16]. The RR allows to terminate the trajectory of electrons that are not directly contributing to the dose in the scoring regions, without neglecting contributions from potential bremsstrahlung photons. When applying the XCSE technique, the photon cross sections are increased by a given factor in a region surrounding the scoring cavity so to conveniently increase the number of electrons set in motion by the incident photons while keeping the number of transported photons constant. For the XCSE a region extending about 2 cm beyond the D_w and D_{ch} scoring regions was included in the simulation geometry. The enhancement factor was 128 for ^{60}Co and 6 MV beams and 64 for 10 MV to 25 MV beams. Preliminary tests showed that these values allowed to conveniently improve the simulation efficiency.

Table 2
Monte Carlo transport parameters and cross section options used for k_Q calculation in this work.

Parameter	Adopted value
Boundary crossing algorithm	EXACT
Electron-step algorithm	PRESTA-II
Spin effects	On
Brems cross sections	NIST
Brems angular sampling	KM
Pair cross sections	BH
Pair angular sampling	NRC
Triplet production	On
Electron Impact Ionization	ik
Bound Compton scattering	On
Radiative Compton corrections	On
Rayleigh scattering	On
Photoelectron angular sampling	On
Atomic relaxations	On
Photonuclear attenuation	On
Photonuclear cross sections	default
Photon cross sections	mcdf-xcom (xcom for ICRU 37)
Compton cross sections	default

Phase-space files describing accelerator photon beams with 10 cm × 10 cm field size at a source distance of 100 cm were used as input sources for the *egs_chamber* simulations. Phase-space files for a

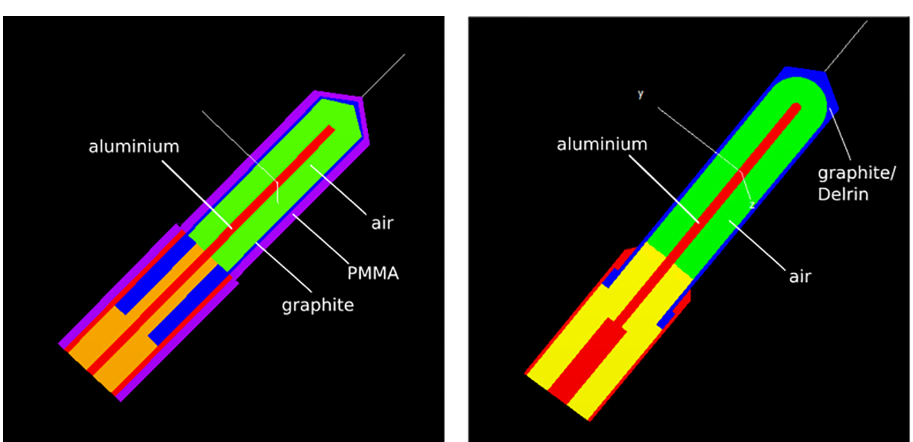

Fig. 1. Sketches of the NE 2571 (left) and the IBA FC65 (right) ionization chamber models used for Monte Carlo calculations of k_Q factors. Details on the stem geometries and materials are not shown for the FC65 chamber. Both chambers have an air cavity with length 2.4 cm and radius 0.31 cm, an aluminium central electrode with 0.1 cm diameter and wall thickness of 0.04 cm. A PMMA waterproofing envelope 0.1 cm thick was included in the NE 2571 model.

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Table 3
Phase-space files available for k_Q calculation in this work. The reference 10 cm × 10 cm field size is defined at 80.5 cm for the Eldorado 6 ^{60}Co unit and at the source-to-surface distance (SSD) of 100 cm for the accelerators. Phase-space files that were provided at an SSD of 90 cm were converted into files at 100 cm source distance by simulating the transport in 10 cm of air.

Beam code	Facility	SSD cm	Particles number	File size	Reference
^{60}Co	Eldorado 6	80.5	3.0E+07	1.4 GB	[20,24]
6 MV_a	Varian Clinac iX	100	1.8E+08	4.9 GB	[20]
6 MV_b	Saturne 43	90	2.5E+07	0.7 GB	[21]
6 MV_c	Elekta Precise	90	1.3E+08	3.7 GB	[22]
10 MV	Elekta Precise	90	2.4E+08	7.0 GB	[22]
12 MV	Saturne 43	90	2.5E+07	0.7 GB	[21]
20 MV	Saturne 43	90	2.5E+07	0.7 GB	[21]
25 MV	Elekta Precise	90	1.0E+08	3.2 GB	[22]

6 MV beam produced by a Varian Clinic iX accelerator were downloaded from the IAEA phase-space database for external beam radiotherapy (https://www-nds.iaea.org/phsp/photon/Varian_Clinac_iX_6MV/) [20]. Phase-space files for 6 MV, 12 MV and 20 MV beams produced by a Saturne 43 General Electric accelerator were supplied by the Laboratoire National de Métrologie et d'Essais – Laboratoire National Henri Becquerel (LNE-LNHB) [21]. Phase-space files for 6 MV, 10 MV and 25 MV beams produced by an Elekta Precise accelerator were provided by the National Research Council of Canada (NRC) [22]. Photon beams from three different accelerators were considered so that k_Q factors could be calculated for a larger number of beam qualities. In this regard it is worth mentioning that the three 6 MV beams mentioned above have different quality indices. The phase-space file for the reference ^{60}Co gamma beam was generated with the BEAMnrc user code [23] using the input file for modelling the ELDORADO 6 ^{60}Co radiotherapy unit available from the IAEA phase-space database (https://www-nds.iaea.org/phsp/Co60/) [24]. The beam with field size 10 cm × 10 cm at source distance of 80.5 cm was simulated. Some details on the above phase-space files are given in Table 3.

Calculations of k_Q factors were also made by modelling the radiation source as a photon point source collimated to a field size of 10 cm × 10 cm at the source distance of 100 cm. For the accelerator beams, the photon energy distribution at the water surface was derived from the above phase-space files, using the BEAMDP utility [25]. For the ^{60}Co gamma beam, the Mora et al. [26] spectrum distributed with the EGSnrc package was used.

Determination of k_Q factors with a type A standard uncertainty (i.e. summation in quadrature of Monte Carlo statistical uncertainties) around 0.1% requires calculation of D_w and D_{ch} with standard uncertainties below 0.7%. With these goals, the number of histories to be simulated was around 10^9, or larger when the smallest D_w scoring volume was used. Considering the number of particles in the available phase-space files, in some cases particles were recycled even more than 100 times.

2.2. Beam quality index

The beam quality for each phase-space file was established in terms of both $TPR_{20,10}$ and $\%dd(10)_x$ [1,27] by simulating the depth-dose curve in water by means of the *EGSnrc/dosxyznrc* user code [28]. To evaluate the impact of the ICRU 90 recommendations on the calculated beam quality values, simulations were run using both the ICRU 90 and the ICRU 37 key data. The phase-space files for the beam field size 10 cm × 10 cm and the source distance of 100 cm were used as input sources. The absorbed dose was scored in voxels centred on the beam axis with 2 mm thickness in the beam direction and 1 cm^2 section. The photon and electron cut-off energies were set to 10 keV (PCUT = 0.01 MeV and ECUT = 0.521 MeV electron mass included). The simulation parameters were the same as in Table 2, except for the radiative Compton corrections, the photonuclear attenuation and the bremsstrahlung cross sections that were set to the default values (Off, Off and BH, respectively). The photon splitting and the range rejection techniques were used to improve the calculation efficiency without recycling of particles from the phase-space file. The range rejection was applied to electrons with energy larger than 1 MeV and the splitting factor was set to values allowing calculation of absorbed doses with statistical uncertainty in the range from 0.1% to 0.4%. Splitting factors between 20 and 200 were applied according to the number of particles in the input phase-space file.

The $TPR_{20,10}$ was determined as [1]

$$TPR_{20,10} = 1.2661\frac{D_{20}}{D_{10}} - 0.0595 \quad (4)$$

where D_{10} and D_{20} are the absorbed doses to water at 10 cm and 20 cm depths in water. Accurate estimates of D_{10} and D_{20} were obtained by exponential fits of the calculated doses around the 10 cm and 20 cm depths.

The $\%dd(10)_x$ was obtained as absorbed dose to water at 10 cm depth relative to the maximum dose of the depth dose curve. According to the $\%dd(10)_x$ definition in the AAPM's TG-51 protocol [27], for photon beams from 10 MV to 25 MV absorbed dose values entering the $\%dd(10)_x$ expression were determined for pure photon beams (i.e. electrons in the phase-space files were not transported in the water phantom).

Aiming at the evaluation of possible effects of the simulation parameters and techniques on the calculated beam quality index, the $TPR_{20,10}$ was also determined from Monte Carlo calculations made with the *egs_chamber* user code using the ICRU 90 key data. Values of transport parameters and VRTs were the same as for the k_Q calculation and absorbed doses at 10 cm and 20 cm were scored in cubic water voxels with side 0.25 cm. In addition, the *egs_chamber* user code was used to calculate the absorbed dose in the cavity of a Farmer-type ionization chamber placed at 10 cm and 20 cm in water to simulate the experimental determination of $TPR_{20,10}$ by means of the ratio of ionization chamber signals.

3. Results

3.1. Beam quality

Table 4 shows the $TPR_{20,10}$ values obtained from the depth dose curves simulated using the *dosxyznrc* user code with the ICRU 37 and ICRU 90 key dosimetry data. Variations in $TPR_{20,10}$ values due to the different sets of key data are within ± 0.2%, that is within the type A uncertainty with coverage factor k = 2 (2σ). Similar variations were obtained for the $\%dd(10)_{x.}$ It should be noted that in the ICRU 90 simulations the density of water at 20 °C (ρ = 0.9982 g cm^{-3}) was used while the value 1 g cm^{-3} was used in the ICRU 37 simulations. Data in Table 4 were determined using in Eq. (4) values of D_{10} and D_{20} pertaining to 10 g cm^{-2} and 20 g cm^{-2}, respectively. If values of D_{10} and

Table 4
Values of $TPR_{20,10}$ calculated by Monte Carlo simulations using the ICRU 37 and ICRU 90 key data for photon beams from 6 MV to 25 MV. Absorbed doses at 10 cm and 20 cm were scored in 1 cm × 1 cm × 0.2 cm voxels centered on the beam axis.

Beam	$TPR_{20,10}^{ICRU\_37}$	$TPR_{20,10}^{ICRU\_90}$	$TPR_{20,10}^{ICRU\_90}/TPR_{20,10}^{ICRU\_37}$
6 MV_a	0.6631	0.6632	1.0002
6 MV_b	0.6688	0.6678	0.9985
6 MV_c	0.6721	0.6735	1.0021
10 MV	0.7305	0.7311	1.0008
12 MV	0.7450	0.7449	0.9998
20 MV	0.7773	0.7770	0.9996
25 MV	0.7995	0.7994	0.9999

D_{20} at the linear depths 10 cm and 20 cm are used, the ICRU 90 $TPR_{20,10}$ values in Table 4 tend to increase, but variations are within 0.1%. Concerning the $\%dd(10)_x$ values, effects of using the linear or the mass thickness of water were always below 0.1%.

The $TPR_{20,10}$ values obtained from the *egs_chamber* simulations using the scoring voxel with side 0.25 cm agreed with the *dosxyznrc* results within ± 0.4%. It is worth noting that the photon and electron cut-off energies were 10 keV for the *dosxyznrc* simulations and 1 keV for the *egs_chamber* simulations. Differences with $TPR_{20,10}$ values obtained simulating the ratio of ionization signals at 10 cm and 20 cm for the NE 2571 ionization chamber were within the type A uncertainties (1σ). Statistical uncertainties of absorbed doses calculated with *egs_chamber* were below 0.08%.

3.2. k_Q factors

The impact of the ICRU 90 recommendations on k_Q calculation for the NE 2571 ionization chamber was evaluated in two steps. Firstly, simulations were run using the updated density effect correction for graphite and the updated I values for graphite and water. Then the renormalized photoelectric cross sections were adopted in the simulations. With reference to the ICRU 37 compliant simulations, in the first step an increase in k_Q values around 0.2% was obtained. In the second step variations were always within the statistical uncertainties indicating that, as expected, the renormalized photoelectric cross sections have minimal impact on simulations in the megavoltage range. Nevertheless, a systematic decrease in k_Q was observed that partially compensated the increase in the first step. Then the final increase of k_Q was in the range from 0.06% to 0.14%.

The whole effect on calculated k_Q values due to the ICRU 90 recommendations was evaluated also for the IBA FC65-G and FC65-P chambers with cavity wall of graphite and Delrin, respectively. Variations in the k_Q values were in the range −0.1% to 0.27% for the IBA FC65-G and in the range −0.12% to 0.14% for the IBA FC65-P. Fig. 2 shows the ICRU 90 effects separately on D_{ch} for the three ionization chambers and on D_w. Variations in D_w values are around −0.2% with no evidence of energy dependence, while variations in D_{ch} are positive (up to 0.5%) with a tendency to decrease with photon beam energy. As expected, D_{ch} variations are larger for the two chambers with graphite walls. The small differences between these two chambers can be mainly ascribed to the PMMA waterproofing envelope included in the NE 2571 chamber model.

Concerning the impact of the size of the scoring volume on the calculated D_w values, no significant effects were observed when the input source was modelled as a collimated point source. D_w values obtained using different scoring volumes were in agreement with each other within 0.1%, that is consistent with the type A uncertainties (2σ). Using phase-space files as input sources, differences between D_w values scored in the disk-shaped volume with radius 1 cm and in the cavity-shaped volume were also around 0.1%. However, these D_w values deviated up to 0.8% from the values relevant to the scoring volume with radius 0.25 cm. The ICRU 90 k_Q values obtained for the NE 2571 chamber using small and large scoring volumes are shown in Fig. 3 for the two types of input radiation sources.

The k_Q factors calculated for the NE 2571, the FC65-G and FC65-P ionization chambers, and their type A standard uncertainties are reported in Table 5 as a function of the Monte Carlo $TPR_{20,10}$ and $\%dd(10)_x$ obtained using the ICRU 90 key data. k_Q data refer to simulations with phase-space file input sources and disk-shaped scoring volume with radius 1 cm for D_w determination.

4. Discussion

Monte Carlo simulations were used for calculating k_Q factors for Farmer-type ionization chambers in high energy photon beams. The impact of the new ICRU 90 recommendations as well as of other simulation parameters on k_Q calculation were investigated. Two waterproof chambers with graphite and Delrin walls and one non-waterproof chamber with graphite wall were considered. Calculations were made for radiotherapy photon beams from three different types of accelerators for which phase-space files were available. To provide a consistent k_Q dataset, the photon beam qualities were also established by means of Monte Carlo simulations.

Concerning the influence of the simulation modalities on the calculation of the quality index, varying the radius of the water scoring region in the plane perpendicular to the beam axis from 2.4 cm to 0.25 cm results indicate no significant effects. Furthermore, estimates of the $TPR_{20,10}$ parameter obtained using two user codes, with different transport parameters and variance reduction techniques, differed from each other up to 0.4%. Assuming for such a difference a rectangular distribution, and considering that the contribution of type A standard uncertainty was 0.15%, a type B standard uncertainty of 0.2% can be associated to the simulation modality. Effects of adopting the ICRU 90 key data on the calculated beam quality indices $TPR_{20,10}$ and $\%dd(10)_x$ were within ± 0.2% in the energy range from 6 MV to 25 MV. These results agree with findings of Czarnecki et al. [11] who reported variations within 0.24% for the $TPR_{20,10}$ quality index. Considering that both figures are within the statistical uncertainties (2σ) of Monte Carlo calculations, it can be concluded, as in [12], that the update of the ICRU key data has negligible effects on the calculated beam quality index. Finally, for absorbed dose calculations, setting the actual water density to establish the water depth yielded a variation in both the $TPR_{20,10}$ and

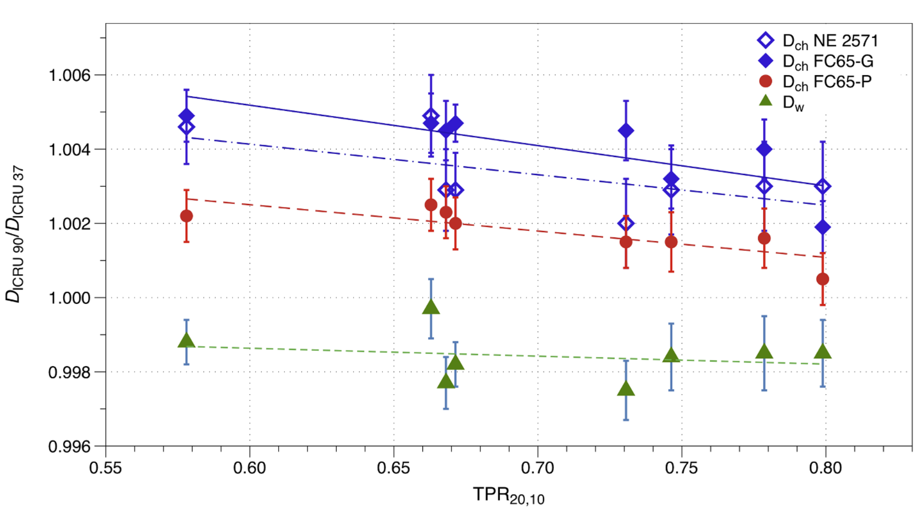

Fig. 2. Ratios of absorbed doses calculated using the ICRU 90 and the ICRU 37 key data. D_w is the absorbed dose to water and D_{ch} is the absorbed dose to air in the ionization chamber cavity. Data relevant to D_{ch} are shown for chambers with plastic wall (circles) and with graphite wall (diamonds). Open diamonds refer to the chamber with a PMMA waterproofing sleeve. Linear fit of data are shown in order to improve the data visualization.

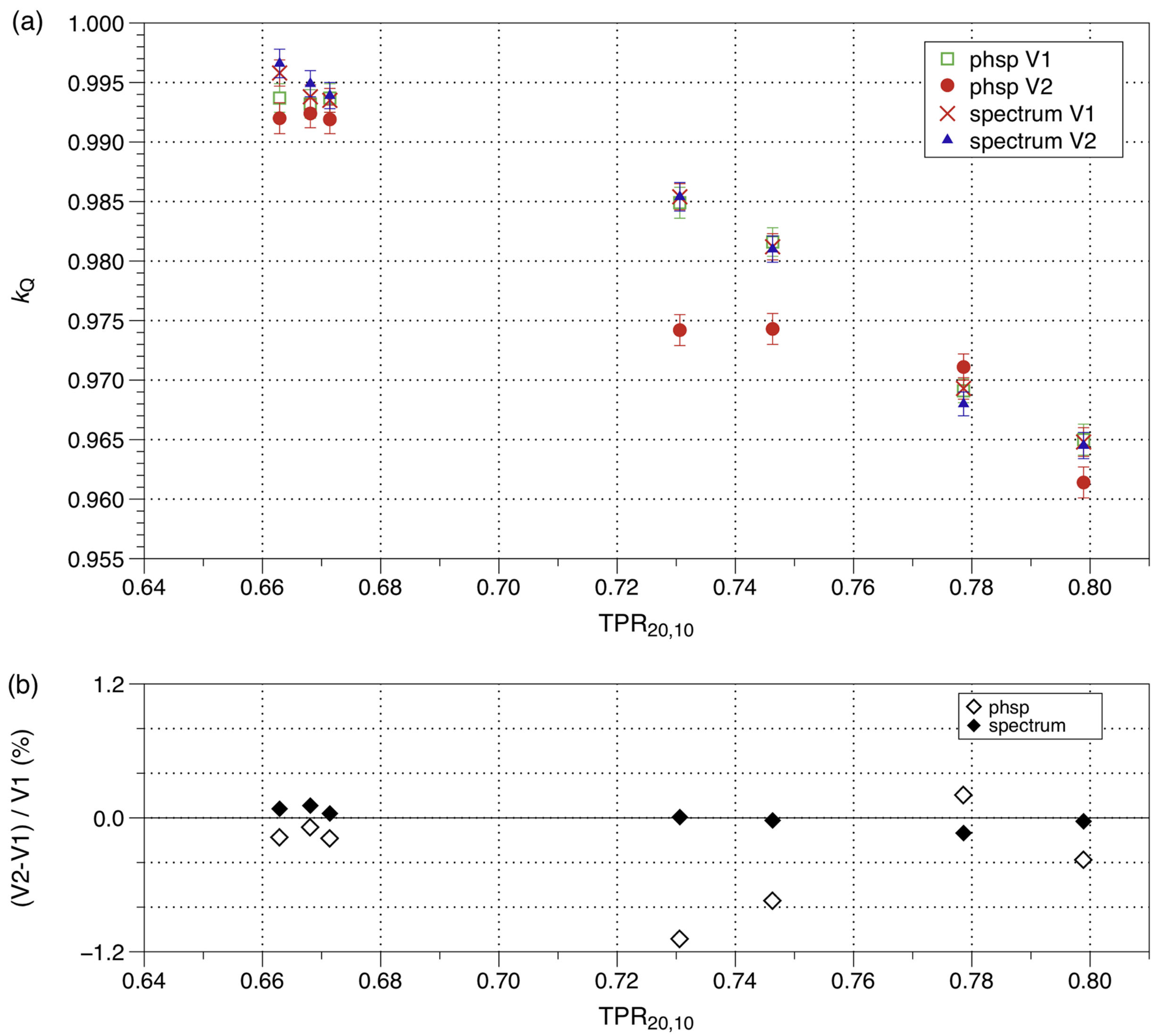

Fig. 3. (a) k_Q factors calculated for the NE 2571 ionization chamber using absorbed dose to water values scored in a disk-shaped volume with radius 1 cm (V1) and 0.25 cm (V2). The input photon source in the Monte Carlo simulations was a phase-space file (phsp) or a collimated point source with spectrum derived from the same phase-space file (spectrum). (b) Percentage differences between k_Q values obtained with scoring volumes V1 and V2.

Table 5
Monte Carlo k_Q factors calculated using the ICRU 90 key dosimetry data for three models of Farmer-type ionization chambers. Relative uncertainties represent the type A standard uncertainty.

$TPR_{20,10}$	$\%dd(10)_x$	k_Q					
		NE 2571		FC65-G		FC65-P	
		value	u (%)	value	u (%)	value	u (%)
0.663	66.0	0.9937	0.12%	0.9931	0.10%	0.9917	0.09%
0.668	66.7	0.9932	0.12%	0.9935	0.10%	0.9916	0.09%
0.671	66.5	0.9937	0.12%	0.9925	0.09%	0.9906	0.09%
0.731	73.5	0.9849	0.13%	0.9847	0.10%	0.9821	0.10%
0.746	75.1	0.9816	0.12%	0.9822	0.10%	0.9789	0.10%
0.779	81.6	0.9691	0.10%	0.9677	0.10%	0.9643	0.10%
0.799	83.9	0.9650	0.14%	0.9644	0.10%	0.9605	0.10%

$\%dd(10)_x$ values below 0.1%. On the basis of these results, considering a standard uncertainty associated to Eq. (4) of 0.1% for the $TPR_{20,10}$ [29], and a 0.2% typical standard deviation of the calculated maximum dose value for the $\%dd(10)_x$, a combined standard uncertainty of 0.3% is associated to the $TPR_{20,10}$ and $\%dd(10)_x$ values in Table 5.

k_Q values were determined by Monte Carlo calculation of D_w and D_{ch} for the beam quality Q and for the reference ^{60}Co quality (according to Eq. (3)). Calculations made in this work using different simulation modalities highlighted that the choice of the scoring volume for calculating D_w at the reference point can significantly affect the k_Q values. In principle, the scoring volume should be as small as possible to well approximate the absorbed dose to a point. However, the smaller the scoring volume, the more critical the Monte Carlo calculation becomes. One critical aspect is that an increasing number of simulation histories are required to reach the same level of statistical uncertainty. This has two tangible effects: the simulation times become exceedingly long, and the particles available in the phase space stack are used over and over again which could yield underestimated uncertainties [28]. The smallest scoring volume used in this work was a voxel with radius 0.25 cm and the resulting k_Q values are compared in Fig. 3 to those obtained with disk-shaped volume with radius 1 cm. Results in Fig. 3 show a very good agreement between k_Q factors obtained with either voxel size and using collimated point sources, while large differences are evident for the data obtained using the phase-space files as input sources. For some beams, differences are much larger than the type A uncertainties, even if a coverage factor of 3 is considered. These discrepancies could be explained in terms of the different beam uniformity obtained with the two types of radiation sources over the scoring volumes. Focusing on the values of D_w, from which the k_Q factors are derived, the collimated point source ensures a good beam uniformity over both the D_w scoring volumes, and the corresponding D_w values agree within 0.14%. On the contrary, the phase-space file mimics the actual beam profile, so that a volume averaging effect could be introduced in the determination of D_w as a function of the lateral extension of the voxel. A deep analysis of the k_Q factors plotted in Fig. 3 that originate from the phase-space files points out that, when decreasing the scoring radius from 1 cm to 0.25 cm, the D_w value varied by about +0.3% for the reference ^{60}Co beam. For the accelerator beams the variations were between −0.1% and +0.2% except for the 10 MV, 12 MV and 20 MV beams, for which the variation was −0.8%, −0.4% and +0.5%, respectively. The variation was positive or negative depending on the shape of the beam profile. When evaluating the corresponding effects on the calculated k_Q factor, the +0.3% variation of D_w in ^{60}Co was fairly well compensated in photon beams where the D_w variation was also positive, overall resulting in a k_Q variation of up to 0.2%. Conversely, for those photon beams where the D_w variation was negative, the positive D_w variation in ^{60}Co is not compensated and the resulting values of k_Q deviate up to about −1% for the 10 MV and the 12 MV beams. The negative variation in D_w with decreasing scoring radius in these two latter beams is consistent with the experimental beam non-uniformity reported elsewhere [21,22], however Monte Carlo variations reported here appear comparatively larger. Still, these variations are compatible with a best-scenario agreement between simulated and measured beam profiles of the order of a few tenths of a percent, since this agreement does not exclude larger fluctuations at level of the single small voxel. These results show that using a very small voxel might not be the most convenient choice when using a phase space file as the radiation source. In every comparison of k_Q values from both Monte Carlo and experimental determinations, attention should be paid to possible influences of volume averaging effects. When choosing for the calculation of D_w and D_{ch} scoring volumes with similar lateral extension, any problems that may be emerging from the simulated beam non-uniformity would be compensated for. This is the case of k_Q data in Table 5 also shown in Fig. 3, which were obtained using the phase-space files as input sources and a D_w scoring radius of 1 cm. Those k_Q values agreed within 0.2% with the corresponding values obtained by simulations with collimated point sources and spectra, thus confirming the correct choice of D_w scoring

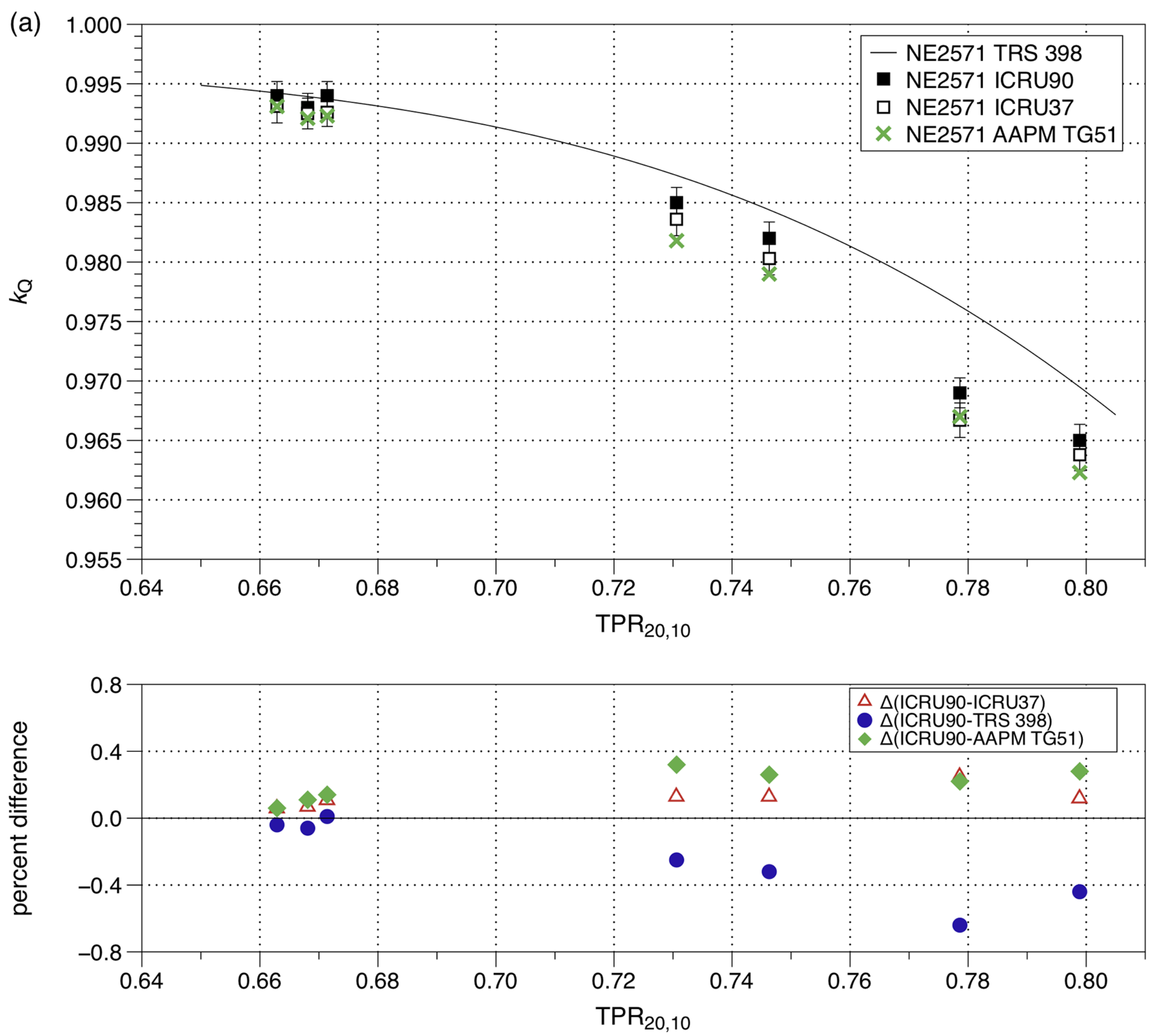

Fig. 4. The top panels show k_Q values obtained in the present work for the NE 2571 ((a), squares), the FC65-G ((b), diamonds), and the FC65-P ((c), circles) ionization chambers, calculated using key dosimetry data from the ICRU 90 (full symbols) and the ICRU 37 (open symbols). Uncertainty bars represent the type A standard uncertainties. The continuous lines represent the IAEA TRS-398 k_Q factors. Crosses refer to the Monte-Carlo calculated k_Q factors recommended by the addendum to the AAPM's TG-51 protocol. The bottom panels show the percentage differences between ICRU 90 k_Q values and the corresponding ICRU 37, TRS-398 and AAPM TG-51 values.

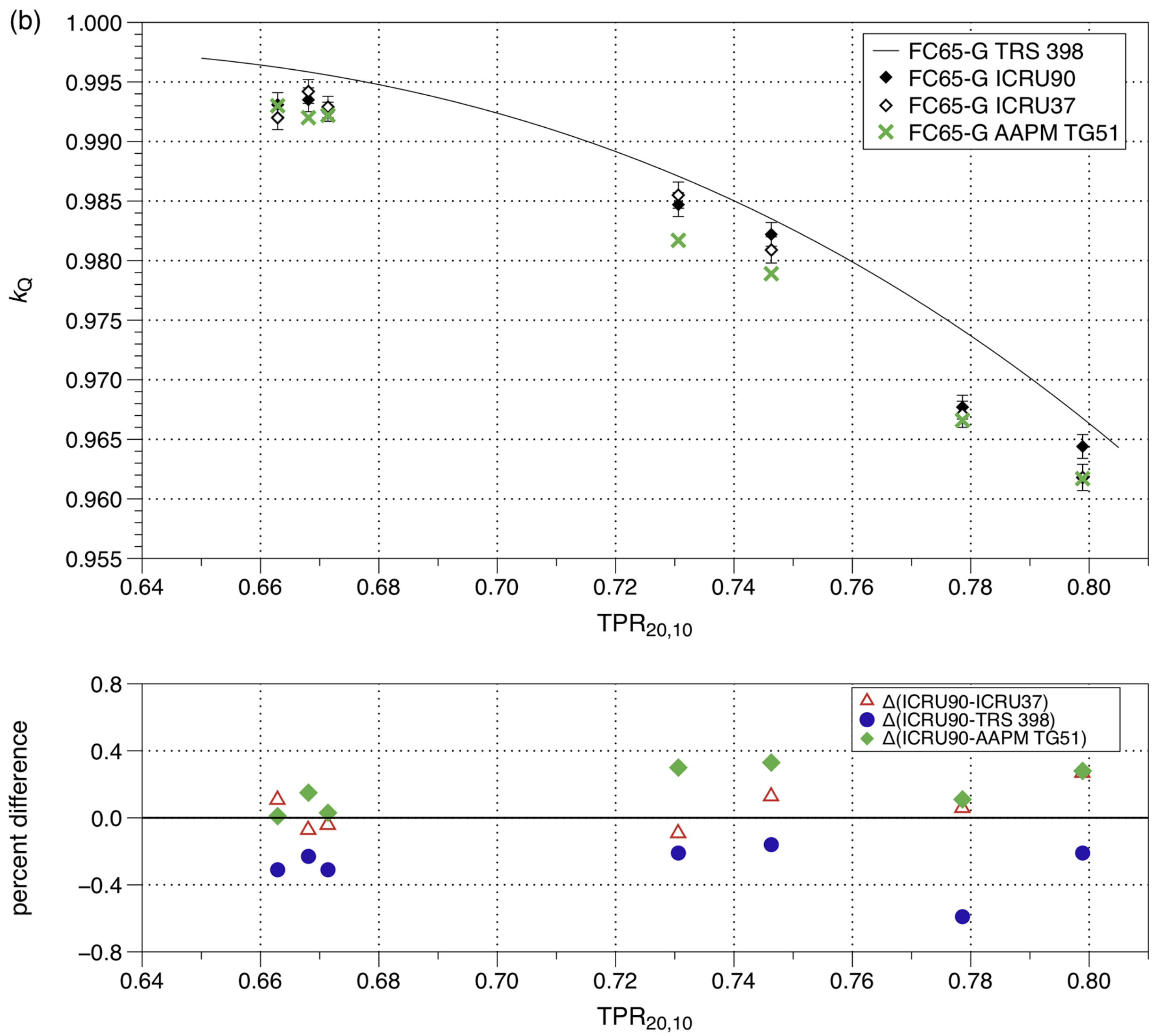

Fig. 4. (*continued*)

conditions. Other investigators have reported the same level of agreement between data obtained from phase-space files and spectra using a scoring radius of 1 cm as in this work [3,17,30].

Compared to simulations based on the ICRU 37 data, the adoption of the key data recommended by the ICRU report 90 resulted in 0.2% decrease of D_w values for all the beam qualities and in an increase up to 0.5% of D_{ch} (see Fig. 2). Changes partially offset each other in the dose ratios entering Eq. (3) and the overall effect on k_Q values was between +0.06% and +0.14% for the NE 2571 chamber, and in the range −0.1% to +0.3% for the FC65-G chamber, both having graphite cavity walls. An even smaller overall effect (within ± 0.1%) was observed for the FC65-P chamber with a Delrin cavity wall. Results for the NE 2571 chamber are consistent with results in [11,12], where increases in k_Q values within 0.35% and 0.14%, respectively, were shown. The k_Q factors calculated using both the ICRU 90 and the ICRU 37 key data are shown in Fig. 4 for the NE 2571 (a), the FC65-G (b) and FC65-P (c) chambers, respectively, in comparison with the corresponding values provided by the IAEA TRS-398 [1]. The k_Q factors recommended by the addendum to the AAPM's TG-51 protocol [31] are also shown in Fig. 4a–c. Since the k_Q values in both dosimetry protocols do not include any volume averaging effect, k_Q values obtained here using D_w values scored in the larger voxel were considered. For the ICRU 90 compliant k_Q values, deviations from the TRS-398 values are the smallest (typically within 0.3%,) for the FC65-P chamber, between 0.2% and 0.6% for the FC65-G chamber and up to 0.64% for the NE 2571 chamber. Actually, for the latter ionization chamber, the calculated k_Q values agree very well with the IAEA TRS-398 values at lower energies, but deviations tend to increase at higher energies. For all the three chambers, the k_Q values here reported tend to be lower than the TRS-398 values. If the comparison is made with the k_Q values provided by the addendum to the AAPM's TG-51 protocol [31] the data of this work tend to be higher, but closer, with deviations not exceeding 0.3%. In particular, k_Q factors were in excellent agreement (deviations within ± 0.2%) for the FC65-P chamber, and, limited to the ICRU 37 values, for the NE 2571 chamber. An explanation for such better agreement follows. The k_Q factors provided by the IAEA TRS-398 were calculated according to the cavity theory using, for the perturbation factors, theoretical models and data available at the time of its first publication (2000). On the basis of more recent literature, some of those models and data need to be revised [2–7]. On the contrary, the addendum to the AAPM's TG-51 protocol [31] provides ICRU 37 complaint k_Q factors calculated by Muir and Rogers [17] using the Monte-Carlo EGSnrc code, that was the same approach used in this work.

Concerning the NE 2571 chamber, results of this work agree with Monte Carlo data obtained with the EGSnrc code in [3,11,17] all showing that the calculated k_Q values are lower than the values recommended in the TRS-398. As in the present work, differences

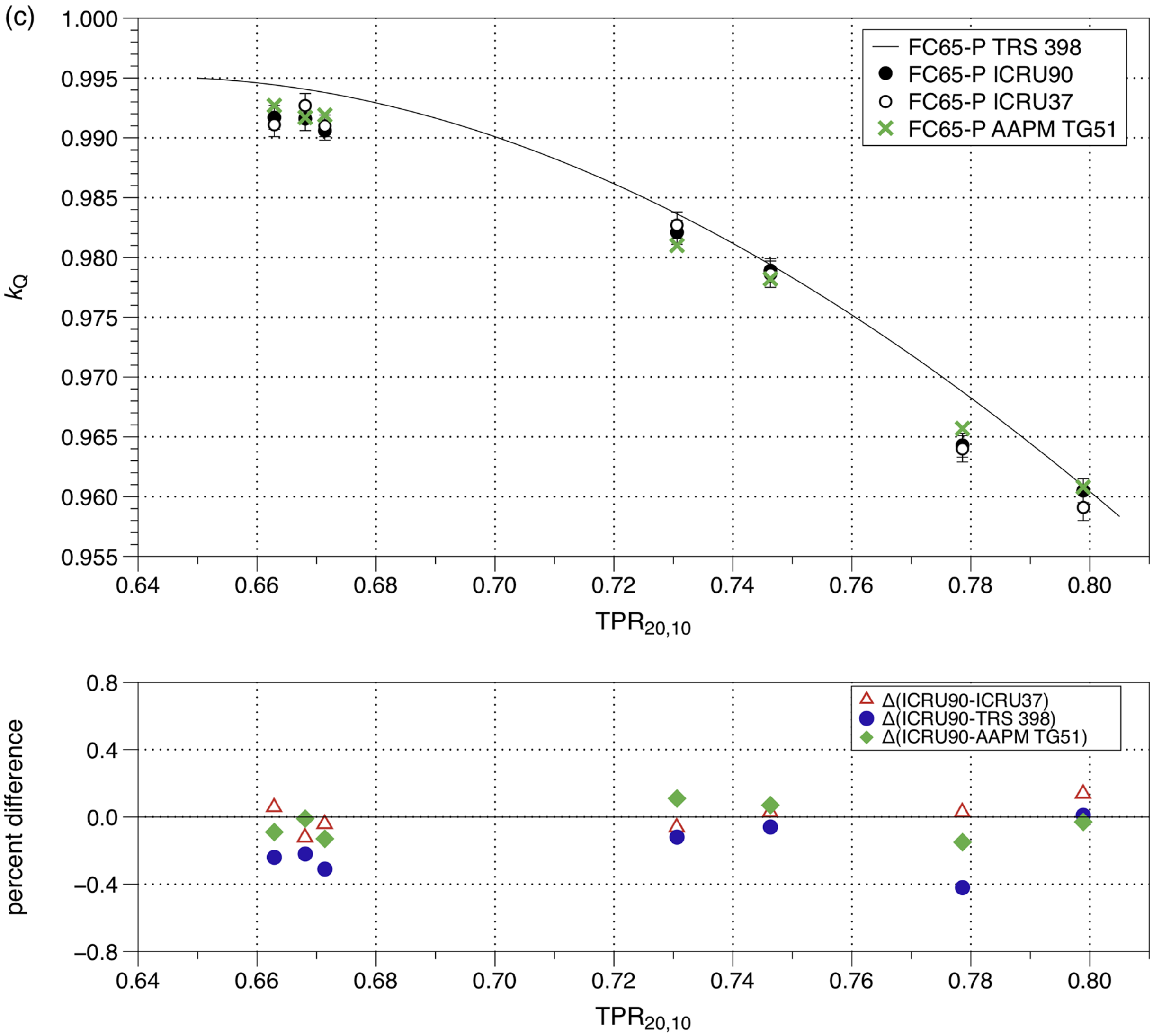

Fig. 4. (*continued*)

increase with beam energy and deviations are up to about 0.9%, using the ICRU 37 key data. Literature results based on the Monte Carlo code PENELOPE substantially agree with the EGSnrc results. Erazo and Lallena [18] reported slightly larger deviations from the TRS-398 values, while results from Reis and Nicolucci [19] agree within 0.2% with those of this work. When comparing to measured k_Q values, it is recommended to refer to compiled data from various sources, to reduce the risk of erroneous interpretations due to the use of individual chambers [7]. In this context, the ICRU 90 k_Q data from this study agree very well with measured data compiled by the Netherlands Commission on Radiation Dosimetry [32] and by Andreo [7], with differences below ± 0.2% and ± 0.1% , respectively.

5. Conclusions

Beam quality correction factors k_Q were determined in megavoltage photon beams by Monte Carlo calculation using the ICRU 90 key dosimetry data. Sets of calculated k_Q values were produced for the NE 2571, the FC65-G and FC65-P Farmer-type ionization chambers for $TPR_{20,10}$ values ranging from 0.663 to 0.80 and $\%dd(10)_x$ values ranging from 66 to 84. For the NE 2571 ionization chamber, a 1 mm-thick PMMA waterproofing sleeve was included in the chamber model that was used in the Monte Carlo calculations.

Deviations of the ICRU 90 compliant k_Q factors from the corresponding values calculated using the ICRU 37 data were typically within 0.2% for the ionization chambers with graphite walls (NE 2571 and FC65-G) and within ± 0.1% for the ionization chamber with Delrin wall (FC65-P). This relatively small impact of the ICRU 90 recommendations on the k_Q values can be explained by the partial compensation, of larger effects that the ICRU 90 recommendations yield, on the individual quantities entering in the calculation of k_Q factors as a ratio.

Compared to the k_Q factors given in the IAEA TRS-398, the Monte Carlo values obtained in this work tend to be lower, with differences typically within 0.5%. Deviations from the Monte-Carlo calculated k_Q values recommended by the AAPM's TG-51 protocol were always lower than 0.3%. In particular, deviations of ± 0.2% were found for the FC65-P as well as, limited to the ICRU 37 results, for the NE 2571 chamber. Considering that the AAPM's TG-51 k_Q values were obtained using the ICRU 37 dosimetry data, the slightly larger deviations found for the chambers with graphite walls are consistent with the impact of the ICRU 90 recommendations. Finally, the ICRU 90 k_Q data from this study agree very well with compilations of published measured data.

Acknowledgments

The authors wish to thank the NRC and the LNHB for providing the phase space files used as input sources in the Monte Carlo calculations of this work. The authors also thank IBA Dosimetry for providing the blueprints of the FC65 chambers.

This work is part of the RTNORM research project which has received funding from the EMPIR programme, grant 16NRM03 'k_Q factors in modern external beam radiotherapy applications to update IAEA TRS-398', co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

The computing resources and the related technical support used for this work have been provided by CRESCO/ENEAGRID High Performance Computing infrastructure and its staff (see http://www.cresco.enea.it for information).

Conflicts of interest

None.

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