Electron beam quality $k_{Q,Q_0}$ factors for various ionization chambers: a Monte Carlo investigation with PENELOPE

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Abstract

In this work we calculate the beam quality correction factor $k_{Q,Q_0}$ for various plane-parallel ionization chambers. A set of Monte Carlo calculations using the code PENELOPE/PENEasy have been carried out to calculate the overall correction factor $f_{c,Q}$ for eight electron beams corresponding to a Varian Clinac 2100 C/D, with nominal energies ranging between 6 MeV and 22 MeV, for a $^{60}$Co beam, that has been used as the reference quality $Q_0$ and also for eight monoenergetic electron beams reproducing the quality index $R_{50}$ of the Clinac beams. Two field sizes, $10 \times 10$ cm$^2$ and $20 \times 20$ cm$^2$ have been considered. The $k_{Q,Q_0}$ factors have been calculated as the ratio between $f_{c,Q}$ and $f_{c,Q_0}$. Values for the Extradin A10, A11, A11TW, P11, P11TW, T11 and T11TW ionization chambers, manufactured by Standard Imaging, as well as for the NACP-02 have been obtained. The results found with the Clinac beams for the two field sizes analyzed show differences below 0.6%, even in the case of the higher energy electron beams. The $k_{Q,Q_0}$ values obtained with the Clinac beams are 1% larger than those found with the monoenergetic beams for the higher energies, above 12 MeV. This difference can be ascribed to secondary photons produced in the linac head and the air path towards the phantom. Contrary to what was quoted in a previous work (Sempau et al 2004 Phys. Med. Biol. 49 4427–44), the beam quality correction factors obtained with the complete Clinac geometries and with the monoenergetic beams differ significantly for energies above 12 MeV. Material differences existing between chambers that have the same geometry produce non-negligible modifications in the value of these correction factors.
1. Introduction

Both TG-51 (Almond et al 1999) and TRS-398 (IAEA et al 2000) protocols use standards based on water to evaluate absorbed doses. According to the Bragg-Gray theory, the absorbed dose at a point in water, $D_{w,Q}$, for a certain beam quality $Q$, can be related to the mean absorbed dose in an air cavity, $D_{air,Q}$, as

$$D_{w,Q} = D_{air,Q} (S_{w,air})_Q,$$

(1)

where $(S_{w,air})_Q$ is the stopping power ratio between water and air (Nahum 1978, Siebers et al 2000, Jang et al 2007, Fernández-Varea et al 2007). In this expression it is assumed that the presence of the ideal detector does not modify the electron fluence at the measuring point in the medium. In general, a real detector, e.g. a plane parallel ionization chamber, shows some deviations from the ideal detector considered in the theory and a factor, $p_{c,Q}$, must be included to account for these deviations:

$$D_{w,Q} = D_{air,Q} p_{c,Q} (S_{w,air})_Q.$$

(2)

Here $p_{c,Q}$ is named as a ‘perturbation’ factor because it takes into account the fact that the electron fluence at the measuring position in the water medium is perturbed by the presence of the detector. It can be factorized in terms of individual correction factors, assumed to be independent from each other and uncorrelated among them, that take into account the various effects produced by the detector (IAEA et al 2000): (i) the in-scattering of electrons that changes the electron fluence inside a cavity with respect to that in the water medium in absence of the cavity; (ii) the fact that detector wall material and that of any waterproof sleeve present, is different from water; (iii) the effect on the chamber response of the central electrode during in-phantom measurements in high energy particle beams and (iv) the effect due to the replacement of a water volume with the detector cavity when the reference point is assumed at the chamber center (not required for plane-parallel ionization chambers).

The previous equation requires that $p_{c,Q}$ and $(S_{w,air})_Q$ are uncorrelated, something that cannot be ensured in all situations. To avoid that, some authors (Capote et al 2004, Sempau et al 2004) proposed an alternative expression in which $D_{w,Q}$ is related directly to the absorbed dose in the air cavity of the real detector $D_{c,Q}$:

$$D_{w,Q} = D_{c,Q} f_{c,Q}.$$

(3)

The obvious advantage is that the overall perturbation factor $f_{c,Q}$ can be calculated using a realistic description of the geometry of the detector. The overall perturbation factor takes care in a direct way of the complete effect produced by the presence of the detector in the medium.

Ideally, reference laboratories should have the same beam quality $Q$ than the user. In that case, the absorbed dose to water, at the reference depth $z_{ref}$ in water, and in the absence of the chamber is given by (IAEA et al 2000)

$$D_{w,Q} = M_Q N_{D,w,Q}.$$

(4)
where $M_Q$ is the reading of the ionization chamber, corrected for the temperature, pressure, electrometer calibration, polarity effect and ion recombination and $N_{D,w,Q}$ is the calibration factor in terms of absorbed dose to water for the ionization chamber at the quality Q. However, reference laboratories usually calibrate the detector to a given calibration quality $Q_0$ and equation (4) must be written as

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

where $N_{D,w,Q_0}$ is the calibration factor at the reference quality $Q_0$ and $k_{Q,Q_0}$ is a chamber-specific factor that takes into account the differences between the beam quality $Q_0$ used in the chamber calibration and the beam quality Q available for the user. Usually a $^{60}$Co gamma beam is considered as the $Q_0$ reference quality.

According to the works of Sempau et al (2004) and Capote et al (2004) the beam quality correction factor can be calculated as

$$k_{Q,Q_0} = \frac{f_{c,Q}}{f_{c,Q_0}},$$

an expression that has been widely used for different chambers and radiation sources (Zink and Wulff 2008, González-Castaño et al 2009, Muir and Rogers 2010, Erazo and Lallena 2013, Muir and Rogers 2013). The previous equation is based on the assumption that $(W/e)_{air}$, the average energy lost per unit charge released by electrons stopped in air, is independent of the beam energy. According to Svensson and Brahme (1986) it may vary 0.5 eV (1.5%) with respect to $^{60}$Co, for electron energies ranging between 0 MeV and 40 MeV. This introduces an uncertainty in calculated $k_{Q,Q_0}$ of about 0.5% (Muir and Rogers 2013).

The aim of the present work is to calculate the correction factor $k_{Q,Q_0}$ for seven Exradin plane-parallel ionization chambers using the Monte Carlo radiation transport code Penelope (Salvat et al 2011). Eight electron beams, of nominal energies between 6 MeV and 22 MeV, corresponding to a Varian Clinac 2100 C/D (Varian Medical Systems, Palo Alto, USA) are considered.

Sempau et al (2004) found that the perturbation factors $f_{c,Q}$ obtained for the NACP-02, PPC-05 and PPC-40 ionization chambers coincide when they are irradiated with a beam generated with a complete linac head model and with a monoenergetic beam having the same $R_{50}$. We check if this also occurs for the seven Exradin chambers under study. To do that, we consider several monoenergetic electron beams that reproduce the $R_{50}$ of the Clinac beams mentioned. For comparison with the work of Sempau et al (2004), the correction factor is also determined for the NACP-02 ionization chamber and the same radiation sources. The effect of the irradiation field size is studied by comparing the results obtained for fields of 10 $\times$ 10 cm$^2$ and 20 $\times$ 20 cm$^2$. Finally and taking advantage of the fact that some of the chambers under study share the same geometry, the effect of the different materials conforming some of the elements of that geometries is also analyzed.

2. Material and methods

2.1. Ionization chambers

The Exradin ionization chambers A10, A11, A11TW, P11, P11TW, T11 and T11TW manufactured by Standard Imaging (Middleton, USA) were studied. Three of these chambers (A11TW, P11TW and T11TW) have an active volume of 0.92 cm$^3$; other three (A11, P11 and T11) have a smaller volume of 0.62 cm$^3$ and, finally, the A10 chamber is much smaller than
Detailed chamber models were considered in dose to air cavity simulation including dimensions and materials provided by the manufacturer. Schemes of the A10, A11 and A11TW chambers are drawn in figure 1. The ionization chambers A11, P11 and T11 have the same geometry; the same happens with the A11TW, P11TW and T11TW chambers. The only difference is in the material conforming the collector, the guard, the thin-windows rings and the window (see figure 1). The air equivalent plastic C552

Figure 1. Scheme of the geometry of the Exradin ionization chambers A10, A11 and A11TW considered in our simulations. A11, P11 and T11 chambers have the same geometry. The same occurs for A11TW, P11TW and T11TW. The only differences are changes in some of the materials (see text for details.)
used in the A11 and A11TW chambers in those elements of the geometry is substituted by polystyrene equivalent plastic D400 (with density 1.16 g cm\(^{-3}\)) in the P11 and P11TW chambers and by tissue equivalent plastic A150 (with density 1.13 g cm\(^{-3}\)) in the T11 and T11TW chambers. C552 is also employed in the case of the A10 chamber.

As indicated in the Introduction the NACP-02 ionization chamber has been also studied. Figure 2 shows the geometry of the NACP-02 chamber considered in our simulations, which has been taken from the work of Williams et al (1998). The active volume of this chamber (plotted with a square in the figure) is 0.157 cm\(^3\).

The correction factors \(k_{Q,0}\) were calculated for these chambers using equation (6). The \(f_{c,Q}\) perturbation factor was obtained from equation (3). The absorbed doses at the medium, \(D_{w,Q}\) and the detector, \(D_{c,Q}\), were calculated in a series of Monte Carlo simulations run with the main program PENEASY (Sempau 2009). This code is a main steering program that uses the PENELOPE system (Salvat et al 2011).

2.2. Monte Carlo code PENELOPE

PENELOPE is a Monte Carlo general-purpose code that simulates the coupled transport of photons, electrons and positrons in matter, makes a good description of the particle transport through the material interfaces and provides very good accuracy at low energies (Sempau et al 2003, Faddegon et al 2008, Faddegon et al 2009, Salvat and Fernández-Varea 2009, Vilches et al 2009). The capabilities of the code when simulating ionization chamber responses have been previously studied (Sempau and Andreo 2006, Yi et al 2006).

Photons are transported within the conventional detailed method, in which all the interaction events are described in sequential order. Electrons and positrons are simulated using a
mixed scheme where collisions are classified into hard and soft. Hard collisions are simulated, as photons, in a detailed way and are characterized by a polar deflection angle or energy loss above user-selectable threshold values. All soft interactions occurring between two consecutive hard collisions are described using a multiple scattering approximation. Electron and positron simulation is controlled by eight parameters: $C_1$, $C_2$, $W_{CC}$, $W_{CR}$, $E_{ABS}(\gamma)$, $E_{ABS}(e^-)$, $E_{ABS}(e^+)$ and $s_{\text{max}}$. $C_1$ is linked to the average angular deflection produced by all soft interactions occurring along a path length equal to the mean free path between consecutive hard elastic events. $C_2$ is the maximum average fractional energy loss between consecutive hard elastic events. $W_{CC}$ and $W_{CR}$ are cut-off energy values for hard inelastic collisions and bremsstrahlung emission, respectively. When the kinetic energy of a given particle becomes smaller than its corresponding $E_{ABS}$, the simulation of this particle is stopped and the energy of the particle is deposited locally. Finally, $s_{\text{max}}$ is the maximum length permitted to a simulation step.

In all our simulations, we have followed the prescription of Sempau and Andreo (2006) who studied in a very detailed way the optimal values of the penelope tracking parameters to simulate the response of ionization chambers. Specifically we have used $C_1 = C_2 = 0.02$ for all the materials forming the ionization chamber and a water volume extending 2 cm around it. For the rest of the materials in the simulation geometry we have fixed $C_1 = C_2 = 0.1$. In addition we have used $E_{ABS}(e^-) = E_{ABS}(e^+) = 10$ keV, $E_{ABS}(\gamma) = 1$ keV, $W_{CC} = 10$ keV and $W_{CR} = 1$ keV for all materials. The values of the parameter $s_{\text{max}}$ have been fixed, as recommended in the code user manual (Salvat et al 2011) to one tenth of the thickness of the corresponding material.

To test the feasibility of the values chosen for $C_1$ and $C_2$, we have performed a complete calculation for the A11TW chamber, with the $10 \times 10$ cm$^2$ field, in which the simulation in the close region around the chamber have been carried out as analogue.

2.3. Radiation sources

We simulated the irradiation of the ionization chambers described above with beams of a Varian Clinac 2100 C/D with nominal electron energies of 6, 9, 12, 15, 16, 18, 20 and 22 MeV. The linac geometries were generated with the code penEasyLinac (Brualla et al 2009, Sempau et al 2011). This is a code that generates the necessary input files for the simulation with penelope of most Varian linacs according to the Monte Carlo package distributed by this company. The code requires as input the type of linac used, the irradiation mode (electron or photon), the nominal energy of the beam, the field size and the type and position of additional collimation devices such as multileaf collimators or electron applicators. Using a database of modularized Varian linac components, penEasyLinac generates the material files, the configuration file (description of the initial beam parameters and tallies included in the simulation) and the geometry file (description of the linac by means of quadric surfaces using the syntax defined by pengeom, the geometry package distributed with penelope). The quality of the geometry files produced by penEasyLinac has been extensively tested by comparing the simulated dose profiles produced with these geometries with experimental data (Brualla et al 2009, Isambert et al 2010, Sempau et al 2011, Brualla et al 2012).

The simulations of these beams have been carried out in two steps. In the first one, phase-space files (PSFs) have been generated at a surface normal to the beam axis and immediately upstream the phantom entrance. These PSFs have been used in a second step as sources of particles to be transported through the water phantom.

Monoenergetic beams reproducing the $R_{50}$ values of the eight aforementioned Clinac beams have been also considered. In order to tune these monoenergetic beams, the percentage depth
dose curves for a 10 × 10 cm² radiation field (with a source-to-surface distance of 100 cm) have been estimated and compared to those produced by the PSFs of the linacs. Cylindrical scoring voxels of 0.5 cm of radial thickness (that is, the difference between the outer and the inner radii defining the voxel) and 0.2 cm of height, concentrical to the beam axis were used. Type A statistical uncertainties were maintained below 0.01%. In the case of these monoenergetic beams, a mathematical collimation has been used to conform the radiation fields. This was done by discontinuing the transport of the particles arriving at the phantom entrance outside the defined square field.

Table 1 shows the values of \( R_{50} \) obtained for the different beams considered. The relative differences between the values corresponding to the full linac models and those found after tuning the monoenergetic beams are below 0.3%. Just for comparison we can say that these \( R_{50} \) agree within the statistical uncertainties with those quoted by Ding and Rogers (1995) for a Varian Clinac 2100 C, the differences being of 0.20–0.27 cm for all energies except for 6 MeV where the difference is 0.09 cm.

### 2.4. Simulation geometry

The simulation geometry was in accordance to the measuring conditions established in the TRS-398 protocol (IAEA et al 2000). A water phantom of 50 × 50 × 50 cm³ was situated at a source-to-surface distance of 100 cm. Results for irradiation fields of 10 × 10 cm² and 20 × 20 cm² were obtained. The reference point was at a depth \( z_{\text{ref}} = 0.6 R_{50} \) = 0.1 cm. The ionization chamber was situated in such a way that the surface separating the window (or the entrance widow) and the active collecting region was at \( z_{\text{ref}} \). The absorbed dose scored within
its active volume yields $D_{c,Q}$. In these simulations standard type A uncertainties were below 0.4% for the A10 chamber and 0.2% for all the other chambers. As reference we used a $^{60}$Co gamma beam whose spectrum was taken from Mora and Maio (1999).

The scoring voxel considered to estimate the dose absorbed in water, $D_{w,Q}$, was a cylinder with a radius of 1 cm and a height of 0.025 cm centered in the beam axis and situated at the reference depth. It is similar to that used by other authors in previous calculations (Zink and Wulff 2008, Zink and Wulff 2009, Zink and Wulff 2012, Muir and Rogers 2013).

3. Results

Figure 3 shows the $k_{Q,Q_0}$ calculated for the seven ionization chambers studied and for radiation fields of 10 × 10 cm$^2$ (open squares) and 20 × 20 cm$^2$ (solid circles). Relative differences between both results are shown in the insets. The dotted curve for the P11 chamber was obtained from TG-51 (Almond et al 1999) and TRS-398 (IAEA et al 2000) and is shown for comparison. As we can see, the result of our simulations for the lowest energy beam (6 MeV) is slightly larger than the $k_{Q,Q_0}$ value of these protocols. For larger energies the TG-51/TRS-398 values agree reasonably well with those we have found.

The values of $k_{Q,Q_0}$ found for 10 × 10 cm$^2$ are slightly above those obtained for 20 × 20 cm$^2$ and the effect becomes more evident for higher values of $R_{50}$. In the case of the A10 chamber, the maximum relative difference is ~0.8% for $R_{50} \sim 3.7$ cm and the statistical uncertainties in the relative differences are 0.5–0.6%. In all other cases, these uncertainties are around 0.3% with a maximum relative difference of 0.6% for the P11 chamber at $R_{50} \sim 7.5$ cm. The results obtained with the two field sizes are statistically compatible in all cases at 2$\sigma$ level.

In what refers to the values of the tracking parameters $C_1$ and $C_2$, the differences found between the results obtained for the A11TW chamber, with the 10 × 10 cm$^2$ field, with $C_1 = C_2 = 0.02$ and with the analogue simulation in the chamber and the region around it have been smaller than 0.2%, in agreement with the findings of Sempau and Andreo (2006).

Figure 4 compares the results obtained with the PSFs for the detailed Clinac model beams (open squares) with those provided by the monoenergetic beams reproducing their $R_{50}$ values (solid triangles). These results correspond to a 10 × 10 cm$^2$ radiation field and the relative differences are shown in the insets. Again, the dotted curve for the P11 chamber corresponds to data from TG-51 (Almond et al 1999) and TRS-398 (IAEA et al 2000). As it can be seen, they show a reasonable agreement with those we have found for the complete linac models.

The values obtained with the monoenergetic beams differ from those found for the detailed linac models for large energies and the discrepancies increase as $R_{50}$ grows from ~6 cm until 9 cm reaching relative differences around 1% in all cases. The largest one is 1.2% and has been found for the T11TW chamber irradiated with the 22 MeV beam.

This was not the situation found by Sempau et al (2004) who studied the beam quality correction factor for the Scanditronix NACP-02 and the Wellhöfer PPC-05 and PPC-40 ionization chambers. In that work a Siemens Mevatron KDS and a Varian Clinac 2300 C were considered and one of the main conclusions was that the results obtained with monoenergetic electron beams and with the complete linac geometries showed negligible differences for similar $R_{50}$ values. This can be seen in the lower panel of figure 5 where the results of Sempau et al are plotted with solid symbols.
To investigate this point we have repeated the calculations of Sempau et al. (2004) for the NACP-02 ionization chamber. The value of $f_{c,Q}$ that we have obtained for $^{60}$Co, using the spectrum of Mora and Maio (1999), was $1.1509 \pm 0.0018$ while that quoted by Panettieri et al...

Figure 3. $k_{Q,Q_0}$ calculated for the seven Exradin ionization chambers studied. Results obtained for the Clinac beams and for radiation fields of $10 \times 10$ cm$^2$ (open squares) and $20 \times 20$ cm$^2$ (solid circles) are shown. The insets show the relative differences, in percentage, between the values obtained for both field sizes. Statistical uncertainties are given with a coverage factor $k = 1$. The dotted curve for the P11 chamber corresponds to the Exradin P11 chamber whose data have been taken from TG-51 (Almond et al. 1999) and TRS-398 (IAEA et al. 2000) protocols. Numerical values of our results can be found in table A1.

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(2008) is $1.1575 \pm 0.0012$, the uncertainty being given in both cases with a coverage factor $k = 1$. The relative difference of 0.6% between both results can be ascribed to differences in the geometries used, in the spectra of the $^{60}$Co source and in the PENELope code version. In

Figure 4. $k_{Q,Q_0}$ calculated for the seven Exradin ionization chambers studied. Results obtained for the Clinac beams (open squares) are compared to those found with the monoenergetic beams reproducing their $R_{50}$ values (solid triangles). Results shown are for a radiation field of $10 \times 10$ cm$^2$. The insets show the relative differences, in percentage, between the values obtained for both calculations. Statistical uncertainties are given with a coverage factor $k = 1$. The dotted curve for the P11 chamber corresponds to the Exradin P11 chamber whose data have been taken from TG-51 (Almond et al 1999) and TRS-398 (IAEA et al 2000) protocols. Numerical values of our results can be found in table A1.
this respect it is worth mentioning that (Muir et al 2012) found that the changes in the details concerning the electrode at the rear of this chamber may account for up to 0.5% differences in $f_{c,Q}$ for $^{60}$Co.
The results obtained with the complete linac model (open squares) and with the monoenergetic beam (open circles) are shown in figure 5, where they are compared to the values quoted in different previous works and to the values indicated in TG-51 (Almond et al 1999) and TRS-398 (IAEA et al 2000) protocols (dotted curve). In the upper panel, the $k_{Q,Q_0}$ values are compared to four sets of experimental data taken from McEwen and DuSautoy (2009) (solid symbols). The agreement between our results and the experimental ones is reasonably good. Also TG-51/TRS-398 values agree with our results. The fact that in this case the calibration quality is $Q_{int} = 7.5 \text{ g cm}^{-2}$ hides to a large extent the differences existing between the results that we have obtained with our PSF and monoenergetic calculations. However, these differences are apparent in the other two panels of figure 5 where $f_{c,Q}$ values are shown. In the central panel our results are compared to those obtained by Buckley and Rogers (2006) (solid circles) and Araki (2008) (solid squares) in Monte Carlo simulations performed with the EGSnrc code for various linac models. The values quoted by these authors agree with those we have obtained with the complete linac models, while those we have found in the simulations with the monoenergetic beams are clearly below them and agree very well with the data obtained from TG-51/TRS-398.

In the lower panel, our $f_{c,Q}$ values are compared to the aforementioned results of Sempau et al (2004). The results of these authors are in good agreement with those we have obtained in our calculations for the monoenergetic beams that, on the other hand, show differences with those found for the detailed linac models at high beam energies. These differences are similar to those observed for the Exradin ionization chambers. The maximum relative difference corresponds to the 22 MeV beam and is 0.87%, which is of the same order (though slightly smaller) than the differences observed for the Exradin chambers.

It is not simple to identify the reasons of the differences observed. The calculations done by Sempau et al (2004) for the detailed linac models were carried out with PSFs generated with a code developed by Sempau et al (2001), in the case of the Siemens Mevatron KDS and PSFs provided by Ma (as a private communication), in the case of the Varian Clinac 2300 C (that, a priori, shares the same geometry with the 2100 C/D model considered in
In this last case, the PSFs generated by Ma at that time may had been subjected to the geometry deficiencies that (Chibani and Ma 2007) pointed out later. One of the main points in this respect was the absence of the secondary collimator (lead shield). In order to understand the effect that this collimator could produce, we have performed a new set of calculations with PSFs generated with the complete geometry of the linac head by eliminating the secondary collimator in our geometry. The results obtained have not shown statistically significant differences with those found for the complete linac head. This is

**Figure 7.** Ratios of $k_{Q,Q_0}$ values for ionization chamber couples: A and P (upper panel), A and T (medium panel) and P and T (lower panel). Circles correspond to TW chambers and squares to other model. Open symbols show the results obtained for the Clinac beams and solid symbols to the monoenergetic ones. Statistical uncertainties are given with a coverage factor $k = 1$. 

our calculations). In this last case, the PSFs generated by Ma at that time may had been subjected to the geometry deficiencies that (Chibani and Ma 2007) pointed out later. One of the main points in this respect was the absence of the secondary collimator (lead shield). In order to understand the effect that this collimator could produce, we have performed a new set of calculations with PSFs generated with the complete geometry of the linac head by eliminating the secondary collimator in our geometry. The results obtained have not shown statistically significant differences with those found for the complete linac head. This is
due to the fact that in the case of electron beams the electron applicator, which is present to guarantee the radiation field size, is the main responsible for the beam definition at the phantom entrance.

Finally, we have performed an additional calculation considering the complete Clinac geometry but stopping all photons generated in the head and the air path to the phantom at its entrance. The results obtained in this ‘incomplete’ simulation are shown for the A11TW ionization chamber in figure 6 (solid circles). It is observed how these results are close to those found for the monenergetic beams (open circles) and differ significantly at large energies from those found with the complete linac geometries (open squares). This indicates that a large part of the differences observed between the $k_{Q,0}$ obtained for the detailed linac models and for the monoenergetic beams are due to the presence of the photons produced as secondary particles in the various elements of the linac geometry as well as in the air path between the linac head and the phantom surface. This is not surprising because, as quoted in table 1 the contribution of the Bremsstrahlung tail is not negligible and grows with the energy of the beam. Muir and Rogers (2013) found a similar effect in the PTW Roos ionization chamber for $R_{50} \geq 7$ cm. The reason for this behavior may be linked to the increase of the stopping-power ratios (up to ~0.5%, depending on the particular linac considered) due to contaminant photons (Ding et al 1995). It is worth mentioning that these results disagree with the findings of Sempau et al (2004) who stated that for the Siemens Mevatron at 18 MeV there was no difference between the $k_{Q,0}$ calculated with and without considering the photons present in the PSF.

The fact that some of the chambers studied share the same geometry, with changes in the material conforming some of their constituent elements, has permitted us to study the effect that these material changes produce in the quality correction factor. In figure 7 we show the ratios of $k_{Q,0}$ values obtained for couples of chambers, specifically ‘A’ and ‘P’ (upper panel), ‘A’ and ‘T’ (central panel) and ‘P’ and ‘T’ (lower panel). Circles correspond to the ‘TW’ chamber type and squares to the other ones. Finally, open symbols show the results obtained for the various Clinac qualities whereas solid symbols correspond to the monoenergetic beams.

A first point to note is the overall agreement between the results obtained with the Clinac PSFs and the monoenergetic beams. The discrepancies observed at the larger energies in figure 4 disappear, showing that the effect of the change of material is the same independently of the radiation source considered.

The new materials used in the ‘P’ and ‘T’ chambers instead of the C552 (used in the ‘A’ chambers), D400 and A150, respectively, have similar densities (1.16 g cm$^{-3}$ and 1.13 g cm$^{-3}$). However, the material change does not affect in the same way the response of the ‘P’ and ‘T’ chambers as it can be seen in the two upper panels of figure 7. The corresponding differences are summarized in the lower panel of this figure. Therein it is seen that the ratio of the $k_{Q,0}$ values obtained for the P11TW and T11TW chambers remains almost constant and close to 1 for all beam qualities considered. The ratio for the P11 and T11 chambers is also approximately constant but ~1% smaller. Looking at the chamber geometries in figure 1, we see that the main difference between A11 (P11 and T11) chambers and the ‘TW’ partners is the presence of the thin-window support rings that produces a notable modification of the geometry structure. There is also a difference in the active volume of the chambers (see section 2.1). Finally, though the densities are similar, the material compositions are different: D100 is CH, A150 has, apart from C and H, a non-negligible quantity of both N and O and a small quantity of F and Ca and C552 is basically H, C and F in similar quantity plus small parts of O and Si. The combined
effect of these differences does not factorize in the calculated ratios and the difference commented appears.

4. Conclusions

In this work, the Monte Carlo code penelope/penEasy was used to calculate the beam quality correction factor, $k_{Q,Q_0}$ for seven Exradin ionization chambers. Electron beams, with nominal electron energies ranging between 6 MeV and 22 MeV, were simulated for a Varian Clinac 2100 C/D using geometries generated with the penEasyLinac code. Those simulations tallied PSFs at the phantom surface. In a second step of the calculation, these PSFs were transported through the phantom to calculate the absorbed dose in water and in the air cavity of the real detector that permitted to determine the overall perturbation factor $f_{c,Q}$ and the corresponding $k_{Q,Q_0}$. These factors were also calculated for monoenergetic beams that reproduced the $R_{50}$ quality index of the Varian beams.

No differences in the correction factor were found when a different radiation field size is considered. In fact, the results obtained for a 10 × 10 cm$^2$ and a 20 × 20 cm$^2$ were statistically compatible.

For the lower energy beams, below 12 MeV, the values of $k_{Q,Q_0}$ determined for both the Clinac and the monoenergetic beams were in agreement, as quoted in previous works. However, with increasing energies, the values found for the electron beams produced from linacs were ~1% above those obtained with the monoenergetic beams, something that was not observed in a previous work in which the agreement between both types of calculations was excellent. It has been proved that a major part of this discrepancy can be ascribed to the secondary photons produced in the geometry elements of the linacs as well as in the air path between the linac head and the phantom. This discrepancy between the results obtained for monoenergetic and linac beams at large values of $R_{50}$ has been quoted in previous works for other ionization chambers and linac models.

The use of the D400 and A150 plastics instead of the C552 in some of the chambers analyzed gives rise to modifications of the quality correction factor that depend on the specific geometry of the chamber.

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Appendix

In this appendix we summarize the values of the $k_{Q,Q_0}$ factors obtained in our simulations and corresponding to the Standard Imaging Exradin ionization chambers, as well as those of the NACP-02 chamber.
Table A1. \(k_{Q,Q_0}\) values obtained in our simulations for the seven Exradin ionization chambers. The results found for the Clinac (with 10 × 10 cm\(^2\) and 20 × 20 cm\(^2\) fields) and monoenergetic (with a field of 10 × 10 cm\(^2\)) beams are shown. The uncertainty (with a coverage factor \(k = 1\)) is given between parentheses; thus, 0.925(3) means 0.925 ± 0.003.

\[
\begin{array}{cccccc}
\text{Chamber} & \text{Clinac} & \text{Monoenergetic} \\
 & \text{\(R_{50}\) [cm]} & \text{10 × 10 cm\(^2\)} & \text{20 × 20 cm\(^2\)} & \text{\(R_{50}\) [cm]} & \text{10 × 10 cm\(^2\)} \\
A10 & 2.54 & 0.952(3) & 0.953(4) & 2.53 & 0.944(3) \\
 & 3.73 & 0.938(3) & 0.931(4) & 3.73 & 0.932(3) \\
 & 4.98 & 0.927(3) & 0.929(4) & 4.98 & 0.925(3) \\
 & 6.27 & 0.921(3) & 0.926(4) & 6.27 & 0.916(3) \\
 & 6.70 & 0.922(3) & 0.919(5) & 6.72 & 0.913(3) \\
 & 7.50 & 0.918(3) & 0.915(5) & 7.51 & 0.913(3) \\
 & 8.24 & 0.909(3) & 0.913(5) & 8.25 & 0.907(3) \\
 & 9.01 & 0.911(3) & 0.909(5) & 9.03 & 0.902(3) \\
A11 & 2.54 & 0.946(2) & 0.947(2) & 2.53 & 0.944(2) \\
 & 3.73 & 0.934(2) & 0.934(2) & 3.73 & 0.932(2) \\
 & 4.98 & 0.925(2) & 0.924(2) & 4.98 & 0.924(2) \\
 & 6.27 & 0.922(2) & 0.920(2) & 6.27 & 0.918(2) \\
 & 6.70 & 0.919(2) & 0.918(2) & 6.72 & 0.914(2) \\
 & 7.50 & 0.917(2) & 0.914(2) & 7.51 & 0.910(2) \\
 & 8.24 & 0.915(2) & 0.913(2) & 8.25 & 0.907(2) \\
 & 9.01 & 0.912(2) & 0.910(2) & 9.03 & 0.903(2) \\
A11TW & 2.54 & 0.952(2) & 0.951(2) & 2.53 & 0.950(2) \\
 & 3.73 & 0.937(2) & 0.936(2) & 3.73 & 0.936(2) \\
 & 4.98 & 0.930(2) & 0.928(2) & 4.98 & 0.929(2) \\
 & 6.27 & 0.925(2) & 0.924(2) & 6.27 & 0.921(2) \\
 & 6.70 & 0.924(2) & 0.923(2) & 6.72 & 0.919(2) \\
 & 7.50 & 0.922(2) & 0.920(2) & 7.51 & 0.918(2) \\
 & 8.24 & 0.921(2) & 0.917(2) & 8.25 & 0.913(2) \\
 & 9.01 & 0.917(2) & 0.916(2) & 9.03 & 0.910(2) \\
P11 & 2.54 & 0.938(2) & 0.937(2) & 2.53 & 0.939(2) \\
 & 3.73 & 0.917(2) & 0.918(2) & 3.73 & 0.921(2) \\
 & 4.98 & 0.904(2) & 0.903(2) & 4.98 & 0.903(1) \\
 & 6.27 & 0.895(2) & 0.893(2) & 6.27 & 0.890(1) \\
 & 6.70 & 0.894(2) & 0.890(2) & 6.72 & 0.887(2) \\
 & 7.50 & 0.890(2) & 0.885(2) & 7.51 & 0.882(1) \\
 & 8.24 & 0.886(2) & 0.883(2) & 8.25 & 0.878(1) \\
 & 9.01 & 0.882(2) & 0.878(2) & 9.03 & 0.872(1) \\
P11TW & 2.54 & 0.926(2) & 0.927(2) & 2.53 & 0.928(2) \\
 & 3.73 & 0.907(2) & 0.907(2) & 3.73 & 0.908(2) \\
 & 4.98 & 0.896(2) & 0.894(2) & 4.98 & 0.896(2) \\
 & 6.27 & 0.887(2) & 0.887(2) & 6.27 & 0.885(2) \\
 & 6.70 & 0.886(2) & 0.886(2) & 6.72 & 0.882(2) \\
 & 7.50 & 0.882(2) & 0.880(2) & 7.51 & 0.878(1) \\
 & 8.24 & 0.879(2) & 0.877(2) & 8.25 & 0.871(1) \\
 & 9.01 & 0.877(2) & 0.873(2) & 9.03 & 0.867(1) \\
T11 & 2.54 & 0.936(2) & 0.936(2) & 2.53 & 0.937(2) \\
\end{array}
\]
Table A1. (Continued)

| Chamber | \( k_{Q,Q} \) | Clinac | Monoenergetic |
|---------|----------------|--------|---------------|
|         | \( R_{50} \) [cm] | \( 10 \times 10 \text{ cm}^2 \) | \( 20 \times 20 \text{ cm}^2 \) | \( R_{50} \) [cm] | \( 10 \times 10 \text{ cm}^2 \) |
| NACP-02 | 3.73 | 0.917(2) | 0.916(2) | 3.73 | 0.917(1) |
|         | 4.98 | 0.904(2) | 0.903(2) | 4.98 | 0.901(1) |
|         | 6.27 | 0.894(2) | 0.893(2) | 6.27 | 0.890(1) |
|         | 6.70 | 0.891(2) | 0.892(2) | 6.72 | 0.887(1) |
|         | 7.50 | 0.887(2) | 0.885(2) | 7.51 | 0.882(1) |
|         | 8.24 | 0.883(2) | 0.882(2) | 8.25 | 0.878(1) |
|         | 9.01 | 0.881(2) | 0.877(2) | 9.03 | 0.871(1) |
| T11TW   | 2.54 | 0.934(2) | 0.934(2) | 2.53 | 0.935(2) |
|         | 3.73 | 0.915(2) | 0.917(2) | 3.73 | 0.915(2) |
|         | 4.98 | 0.905(2) | 0.903(2) | 4.98 | 0.902(2) |
|         | 6.27 | 0.895(2) | 0.893(2) | 6.27 | 0.893(2) |
|         | 6.70 | 0.895(2) | 0.891(2) | 6.72 | 0.888(2) |
|         | 7.50 | 0.891(2) | 0.889(2) | 7.51 | 0.886(2) |
|         | 8.24 | 0.889(2) | 0.884(2) | 8.25 | 0.882(1) |
|         | 9.01 | 0.884(2) | 0.883(2) | 9.03 | 0.874(1) |

Table A2. \( k_{Q,Q_0} (Q_{\text{int}} = 7.5 \text{ g cm}^{-2}) \) and \( f_{c,Q} \) values obtained in our simulations for the NACP-02 ionization chamber. The results found for the Clinac and monoenergetic beams, with a field of \( 10 \times 10 \text{ cm}^2 \), are shown. The uncertainty (with a coverage factor \( k = 1 \)) is given between parentheses; thus, 1.031(2) means 1.031 ± 0.002.

| Chamber | \( k_{Q,Q_0} \) | Clinac | Monoenergetic |
|---------|----------------|--------|---------------|
|         | \( R_{50} \) [cm] | \( 10 \times 10 \text{ cm}^2 \) | \( 20 \times 20 \text{ cm}^2 \) | \( R_{50} \) [cm] | \( 10 \times 10 \text{ cm}^2 \) |
| NACP-02 | 2.54 | 1.048(2) | 2.53 | 1.052(1) |
|         | 3.73 | 1.031(2) | 3.73 | 1.030(2) |
|         | 4.98 | 1.018(2) | 4.98 | 1.017(1) |
|         | 6.27 | 1.009(2) | 6.27 | 1.010(1) |
|         | 6.70 | 1.004(2) | 6.72 | 1.005(1) |
|         | 7.45 | 1.001(2) | 7.51 | 1.000(1) |
|         | 8.24 | 0.998(2) | 8.25 | 0.997(1) |
|         | 9.01 | 0.994(2) | 9.03 | 0.988(1) |
| T11TW   | 2.54 | 1.081(2) | 2.53 | 1.078(1) |
|         | 3.73 | 1.063(2) | 3.73 | 1.055(1) |
|         | 4.98 | 1.050(2) | 4.98 | 1.042(1) |
|         | 6.27 | 1.040(2) | 6.27 | 1.034(1) |
|         | 6.70 | 1.036(2) | 6.72 | 1.029(1) |
|         | 7.50 | 1.032(2) | 7.51 | 1.024(1) |
|         | 8.24 | 1.029(2) | 8.25 | 1.021(1) |
|         | 9.01 | 1.025(2) | 9.03 | 1.012(1) |
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