Impact of new ICRU Report 90 recommendations on calculated correction factors for reference dosimetry

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Abstract

In 2016 the ICRU published a new report dealing with key data for ionizing radiation dosimetry (ICRU Report 90). New recommendations have been made for the mean excitation energies \( I \) for air, graphite and liquid water as well as for the graphite density to use when evaluating the density effect. In addition, the ICRU Report 90 discusses renormalized photoelectric cross sections, but refuses to give a recommendation on the use of renormalization factors. However, the Consultative Committee for Ionizing Radiation recommends to use renormalized photoeffect cross sections. Goal of the present work is to evaluate the impact of these new recommendations on clinical reference dosimetry for high energy photon and electron beams.

The beam quality correction factor \( k_Q \) was calculated by Monte Carlo simulations for compact and parallel plate ionization chambers. In case of photons seven phase space files from clinical accelerators and twelve spectra taken from literature from 4 MV to 24 MV and additionally a \( ^{60}\text{Co} \) source were applied. As electron source thirteen electron spectra available in literature were used in the range of 4 MeV–21 MeV.

The new ICRU recommendations have a small impact on Monte Carlo calculated \( k_Q \) values for the chosen ionization chambers in the range of 0.1%–0.35% only—the difference increases for higher photon energies.

The impact of the ICRU Report 90 recommendations on Monte Carlo calculated stopping power ratios \( s_{\text{wat}} \), perturbation factors \( p \) and beam quality correction factors \( k_Q \) was investigated and confirmed a decrease of \( s_{\text{wat}} \) by a fraction of a percent for photon and electron beams. This study indicates that the impact of the new ICRU recommendation is within 0.35%. The determined deviations should be taken into account, when widely published Monte Carlo calculated values are examined.

1. Introduction

Monte Carlo simulations are widely used in the reference dosimetry of ionizing radiation to calculate correction factors. Recent years have seen numerous studies using Monte Carlo calculations to determine beam quality correction factors \( k_Q \) for measurements in high energy photon (Wulff et al 2008a, González-Castaño et al 2009, Muir et al 2011, Erazo and Lallena 2013), electron (Sempau et al 2004, Verhaegen et al 2006, Zink and Wulff 2008) and proton (Palmins et al 2001, Gomà et al 2016) radiation fields. With high computational effort, Monte Carlo calculations can be done with an indefinitely low statistical uncertainty (type A uncertainty), but apart from that, the calculated values are limited to type B uncertainties. These include errors in the particle transport algorithm, inaccurate data of the geometry in which the radiation transport is simulated and uncertainties of cross section data. The consistence of electron boundary crossing algorithms should be determined by the Fano cavity.
test. The accuracy of the geometry model depends on the quality of the available data of the ionization chamber. However the cross-section data also have a significant influence on the results of a Monte Carlo simulation.

In this respect, the ICRU Report 37 (Berger et al. 1984) recommends values for the mean excitation energy \( I \) and the density of elements and compounds. Based on newer measurements, recommendations for the \( I \) values for graphite \( I_{g} \) and water \( I_{w} \) have been revised in the recent published ICRU Report 90 (Seltzer et al. 2014), i.e. \( I_{g} = 81 \) eV and \( I_{w} = 78 \) eV. Moreover, the ICRU Report 90 recommends using the grain density of graphite in the evaluation of the density effect. A recent study (Andreo et al. 2013) investigated the impact of the increase of the \( I_{w} \) value from 75 eV (ICRU 37) to 78 eV (ICRU 90) on stopping-power ratios water to air for photon, electron and proton beams by Monte Carlo simulations. Moreover, potential changes in dosimetric quantities for the Farmer-type ionization chamber NE2571 in a \(^{60}\text{Co}\) radiation source due to the new \( I \) values for water and graphite were discussed. A recent publication (Gomà et al. 2016) investigated the impact of the new \( I \) values for water and graphite on the beam quality correction factor for a wide range of ionization chambers in monoenergetic proton beams.

Apart from the recommendations on the \( I \) value and density, the ICRU Report 90 discusses the use of renormalized photoelectric cross sections. Based on a review of this discussion in the ICRU Report 90, the Consultative Committee for Ionizing Radiation (CCRI) recommends the use of renormalized photoelectric cross sections (McEwen et al. 2017).

According to the investigations published by Andreo et al. (2013), the impact of these new key data for clinical reference dosimetry was evaluated. Following the results of Andreo et al. (2013), stopping-power ratios water to air for high energy photon and electron beams were calculated according to the recommendations of the ICRU Report 37 (Berger et al. 1984) and 90 (Seltzer et al. 2014). Extending the investigation of Andreo et al. (2013), the impact on the beam quality correction factor \( k_{Q} \) according to the IAEA dosimetry protocol TRS-398 (Andreo et al. 2001) due to adoption of the new \( I \) values and using the grain density of graphite to evaluate density correction, was investigated by Monte Carlo simulations for high energy photon and electron beams. In addition to that, the impact on the perturbation factor \( p \) for the ionization chamber NE2571 was investigated for high energy photon fields. Thereby the present work expanded the study of Andreo et al. (2013) to high energy photon beams and also includes the impact of the new recommendations on the \( k_{Q} \) values of two widely used parallel-plate ionization chambers in high energy electron beams.

2. Material and methods

2.1. Calculation of the beam quality correction factor

The ratio between absorbed dose to water \( D_{w} \) and absorbed dose to air \( D_{a} \) of an ionization chamber is related to the Spencer–Attix stopping power ratio water to air \( s_{w,a} \) and a perturbation factor \( p \), which takes the fluence perturbation of non-ideal Spencer–Attix cavities occurring in real ionization chambers into account.

\[
\frac{D_{w}}{D_{a}} = s_{w,a} p.
\]  

Based on equation (1) the beam quality correction factor \( k_{Q} \) can be calculated theoretically as shown by Andreo (1992)

\[
k_{Q} = \frac{(s_{w,a} p)_{Q} W_{air,Q}}{(s_{w,a} p)_{60Co} W_{air,60Co}} = \frac{\left(\frac{D_{w}}{D_{a}}\right)_{Q}}{\left(\frac{D_{w}}{D_{a}}\right)_{60Co}} \times \frac{W_{air,60Co}}{W_{air,Q}}
\]  

where the indices \( Q \) and \(^{60}\text{Co}\) represent the considered beam quality and the reference radiation field of a \(^{60}\text{Co}\) \( \gamma \)-ray beam, respectively. \( W_{air} \) is the mean energy to create an ion pair in air at the beam qualities \( Q \) and \(^{60}\text{Co}\). For electron and photon radiation fields \( W_{air} \) can be assumed to be independent from energy (Burns et al. 2014).

The aim of this work was to compare Monte Carlo calculated \( k_{Q} \) values according to the recommendations of the new ICRU Report 90 (Seltzer et al. 2014) and the ICRU Report 37 (Berger et al. 1984). For this purpose the ratio of Monte Carlo calculated \( k_{Q} \) values according to the ICRU Report 90 and 37 were determined. For shorter notation this ratio is symbolized by a \( \Delta \) throughout this work, as can be seen in equation (3) for the restricted water-to-air mass collision stopping power ratio \( s_{w,a} \).

\[
\Delta s_{w,a} = \frac{(s_{w,a})_{ICRU–90}}{(s_{w,a})_{ICRU–37}}.
\]

The applied reference conditions to determine the absorbed dose in \(^{60}\text{Co}\) and high-energy photon and electron beams were chosen according to the recommendations of the TRS-398 dosimetry report (see table 1).
It should be noted that the water density $\rho$ in the ICRU Report 90 is provided with more decimals, so that the influence of the temperature under atmospheric pressure on the density of water is noticeable. Therefore, the calculated values according to ICRU Report 37 and 90 refer to the same water depth $d$ but not to the same radiological depth $d\rho$. However, the difference in radiological depth between the simulations according to ICRU-90 and ICRU-37 is only 0.018 g cm$^{-2}$ and should therefore not influence the results calculated according to the ICRU Report 90 for photon beams. For this reason, the reference depth of 10 cm was used also for calculations according to ICRU Report 90. The beam quality correction factor $TPR_{10}^{20}$ for calculations according to ICRU Report 90 was also calculated from the dose ratio in 20 cm and 10 cm water depth. The depth $R_{50}$ for electron beams was determined from calculated depth-dose curves according to ICRU Report 37 and 90.

### 2.2. Monte Carlo simulation

This Monte Carlo study is documented according to the recommendations of the report No. 268 of the AAPM T 268 (Sechopoulos et al. 2017). Monte Carlo simulations of photon and electron radiation fields have been performed with the EGSnrc code system (Version 2017) (Kawrakow et al. 2010).

#### 2.2.1. Radiation source and geometry definition

The radiation fields of photon and electron beams were generated by a collimated isotropic radiation source. The spectral energy distributions of the electron beams are taken from Ding et al. (2010). The absorbed dose to water $D_w$ and absorbed dose to air of the sensitive volume $D_{det}$ of the ionization chamber NE2571, NACP-02 and Roos were calculated in a $30 \times 30 \times 30$ cm$^3$ water phantom with the egs_chamber user code (Wulff et al. 2008b). The absorbed dose to water $D_w$ was calculated in a small cylindrical water voxel of 0.25 cm radius and 0.1 cm height. The cylinder was positioned symmetrical around the point of measurement. The dose $D_{det}$ was calculated in detailed models of the investigated ionization chambers using the egs++ class library (Kawrakow et al. 2009). The detailed geometry of the NE2571 Farmer-type chamber was adopted from Andreo et al. (2013). All chambers did pass the Fano cavity test (see appendix A). The geometry of the NACP-02 and Roos chamber was taken from a previous work (Zink and Wulff 2012).

The variance reduction techniques implemented in the user code egs_chamber were used to improve the efficiency of the Monte Carlo simulations (Wulff et al. 2008b). The following variance reduction techniques have been used: intermediate phase space storage; photon cross-section enhancement (XCSE) volume with an XCSE factor of 256 (only for photon beams) and the Russian Roulette range rejection technique with a survival probability of 1/512.

The absorption factor $k_Q$ calculations, the restricted water-to-air mass collision stopping-power ratio $s_{sw,a}$ was calculated with the user code SPRRZnrc in a small cylindrical volume of 0.25 cm radius and 0.1 cm height for reference conditions. The perturbation factor $p$ was determined from the calculated dose ratio $D_{det}/D_w$ and the stopping power ratio $s_{sw,a}$ according to equation (1).

#### 2.2.2. Radiation transport parameters

A transport and particle production threshold energy of $ECUT = AE = 512$ keV for electrons and $PCUT = AP = 1$ keV for photons was used to calculate $D_w$ and $D_{det}$. To calculate $s_{sw,a}$ the ECUT and PCUT values were set to 521 keV and 10 keV, respectively.

All Monte Carlo calculations were performed with two different sets of the materials, water and graphite, following the recommendations of the ICRU Report 37 and 90. Table 2 shows the different material properties of the two sets. The $I$ value of air has remained at 85.7 eV but the uncertainty has been reduced to 1.2 eV in the new ICRU Report 90.

The ICRU Report 37 notes that the available density effect theory provides no indication as to which assumed density value would provide the best approximation. However, the ICRU Report 37 prefers to use a value equal

| Radiation source       | $^{60}$Co beam | MV photon beam | MV electron beam |
|------------------------|----------------|---------------|-----------------|
| Measurement depth      | 5 cm           | 10 cm         | 0.6 $R_{50} - 0.1$ g cm$^{-1}$ |
| Source to surface distance | 100 cm       | 100 cm        | 100 cm          |
| Field size at surface  | $10 \times 10$ cm$^2$ | $10 \times 10$ cm$^2$ | $10 \times 10$ cm$^2$ |

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**Table 1.** Reference conditions for the investigated radiation sources.
to or close to the bulk density of graphite (1.7 g cm$^{-3}$) to calculate the density correction factor. For this reason the density of 1.7 g cm$^{-3}$ was chosen for evaluating the density effect correction according to ICRU Report 37, although the density of the graphite used in the chamber was 1.8 g cm$^{-3}$. Beside the new $I$ values, the ICRU Report 90 recommends to use the grain density of graphite (2.265 g cm$^{-3}$) to evaluate the density effect correction.

Further transport parameter settings used in all Monte Carlo simulations with the EGSnrc code system are summarized in table 3.

3. Results

In the recent published ICRU Report 90, new recommendations were made on $I$ values and density of water (see table 2). The impact of these recommendations on the calculation of the beam quality specifier $TPR_{20}^{10}$ and $R_{50}$ is presented in figure 1.

The difference between $TPR_{20}^{10}$ values calculated according to the ICRU Report 37 and 90 is below 0.24%. This difference is within the statistical uncertainty ($2\sigma$) of the calculated data. However, a change of 0.24% has a negligible effect on the $k_Q$ value. A change in $TPR_{20}^{10}$ of 0.25% would cause a change in $k_Q$ value of approximately 0.015% and 0.05% for lower photon energies ($TPR_{20}^{10} \approx 0.65$) and high photon energies ($TPR_{20}^{10} \approx 0.75$), respectively. The difference between the water depths $R_{50}$ as well as $z_{eq}$ according to ICRU Report 37 and 90 increases with the energy of the electron radiation field, but is still in the submillimeter range.

In the following figures all determined ratios between values calculated according to ICRU Report 37 and 90 are presented as a function of beam quality specifier $TPR_{20}^{10}$ and $R_{50}$ for photon and electron beams, respectively. In the 60Co radiation field the $k_Q$ values are the same within the statistical uncertainty.

### Table 2. Summary of the key data of the two investigated material data sets biased on the ICRU Report 37 and ICRU Report 90.

|                         | ICRU Report 37 | ICRU Report 90 |
|-------------------------|----------------|----------------|
|                         | Water          | Graphite       | Water          | Graphite       |
| Mean excitation energy $I$ | (75 ± 2) eV    | (78 ± 4) eV    | (78 ± 2) eV    | (81 ± 1.8) eV  |
| Density $\rho$            | 1.00 g cm$^{-3}$ | 1.8 g cm$^{-3}$ | 0.9982 g cm$^{-3}$ | 1.8 g cm$^{-3}$ |
| Density for evaluation of | 1.00 g cm$^{-3}$ | 1.7 g cm$^{-3}$ | 0.9982 g cm$^{-3}$ | 2.265 g cm$^{-3}$ |
| Density effect correction |                |                |                |                |

### Table 3. Summary of used transport parameters for Monte Carlo simulations with the EGSnrc code system in this work.

| Transport parameter                        | Setting         |
|--------------------------------------------|-----------------|
| Photon cross sections                      | xcom            |
| Brems cross sections                       | NIST            |
| Brems angular sampling                     | KM              |
| Electron impact ionization                 | I$_k$           |
| Rayleigh scattering                        | On              |
| Spin effects                               | On              |
| Bound Compton scattering                   | On              |
| Radiative Compton corrections              | On              |
| Atomic relaxations                          | On              |
| Pair angular sampling                      | KM              |
| Triplet production                         | On              |
| PE angular sampling                        | On              |
| Photomuclear attenuation                   | On              |
| Photomuclear cross sections                | default         |
| Boundary crossing algorithm                 | Exact           |
| Skin depth for BCA                         | 3               |
| Electron-step algorithm                    | EGSnrc          |

The ratio of the Monte Carlo calculated perturbation factors $p$ between the ICRU Report 90 and 37 recommendations is given in figure 3 for the cylindrical ionization chamber NE2571 in photon fields and the two parallel plate ionization chambers NACP-02 and Roos in electron fields. The ratio $\Delta p$ is shown as a function of the beam quality specifier $TPR_{20}^{10}$ and $R_{50}$ for photon and electron beams, respectively. In the 60Co radiation field the $k_Q$ values are the same within the statistical uncertainty.
The ratio $\Delta p$ for the NACP-02 and Roos ionization chamber was $\Delta p = 1.0011 \pm 0.0006$ and $\Delta p = 1.0028 \pm 0.0005$, respectively.

The impact of the new ICRU Report 90 on the dose ratio $D_w/D_{det}$ or rather on the quantity $(s_{w,a})$ (see equation (1)) for the used ion chambers is given in figure 4. In the $^{60}$Co radiation field the ratio $\Delta (s_{w,a})$ for the NACP-02 and Roos ionization chamber was $\Delta (s_{w,a}) = 0.9955 \pm 0.0006$ and $\Delta (s_{w,a}) = 0.9972 \pm 0.0005$, respectively.

The resulting $k_Q$ factors according to ICRU Report 37 and 90 for the NE2571 thimble chamber are given in figure 5. The left panel of figure 5 presents Monte Carlo calculated $k_Q$ values with clinical spectra (circles) and Monte Carlo simulations through the linac treatment head as a radiation source. A closer look on the data in the left panel of figures 5 and B1 reveals, that the $k_Q$ values differ systematically for the two different source models. This difference is caused by the different radial dose distributions of the source models as shown in appendix B. The $k_Q$ values are compared to the data given by the IAEA dosimetry protocol TRS-398 and polynomial fits through experimental data and Monte Carlo calculated data determined by Andreo et al (2013). The ratios $\Delta k_Q$ are shown in the right panel of figure 5.
4. Discussion

4.1. Stopping power ratios and perturbation factors

The $s_{\text{n,d}}$ values for photon beams vary between $-0.6\%$ ($^{60}\text{Co}$ beam) and $-0.3\%$ (high energy photon beams) between the ICRU 37 and the new ICRU 90 recommendation—the $s_{\text{n,d}}$ values for electron beams vary $-0.3\%$ and $-0.2\%$. The calculated $\Delta s_{\text{n,d}}$ values are in good agreement with the results published by Andreo et al (2013) which are also given in the ICRU Report 90 (Seltzer et al 2014).

The perturbation factor of the NE2571 increased between 0.1\% and 0.3\% when the new ICRU Report 90 (Seltzer et al 2014) recommendations were applied. For the $^{60}\text{Co}$ beam an increase of 0.2\% was observed. This results are in good agreement with Monte Carlo calculated data shown in table 3 in the work of Andreo et al (2013).
The new recommendations had a small impact on the parallel plate ionization chambers in an electron field. The impact on the perturbation factor $p$ of the NACP-02 chamber was smaller than $-0.2\%$. The $p$ values of the Roos chamber vary between $0\%$ and $-0.1\%$. The small impact on the $p$ value of the Roos chamber may be due to the small amount of graphite in the ionization chamber.

4.2. Beam quality correction factor

For all chambers the factor $(s_{w,a})$ decreased when the new recommendations were applied. For the NE2571 chamber in photon fields a difference between $-0.15\%$ and $-0.4\%$ was observed, primarily due to the change in mass-stopping power ratio $s_{w,a}$. Looking at the results for $^{60}\text{Co}$ beam, Andreo et al (2013) published a Monte Carlo calculated ratio of 0.996 between $F_{\text{ch},\text{Co60}} = s_{w,a}$ using present $I$ values (referring to the recommendations of ICRU Report 37) and updated $I$ values (as recommended in ICRU Report 90). This ratio is in good agreement

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**Figure 4.** Ratio between the calculated $(D_{w}/D_{det} = s_{w,a})$ according to the ICRU Report 90 and Report 37 as a function of TPR$_{10}^{20}$ for the NE2571 in photon fields and as a function of $R_{50}$ for the NACP-02 and Roos chamber in electron fields. The filled circles represent Monte-Carlo calculations using a clinical spectrum as a radiation source. The linear regression lines are provided just for a better visualization of the data as a function of the used beam quality specifiers. The error bars show the Monte Carlo statistical uncertainty ($1\sigma$).
with the findings presented in this publication. Using the new recommendations to calculate \( s_{sw,ap} \) for the parallel plate ionization chambers NACP-02 and Roos in clinical electron beams would change the values by around \(-0.3\%\) compared to the recommendations in the ICRU Report 37. In contrast to photon fields, \( s_{sw,ap} \) was energy independent for electron fields. As a result, \( k_Q \) was also energy independent. Using the data from figure 4 and applying the change of the \( 60\text{Co} \) value of \( \Delta (s_{sw,ap}) = 0.9955 \) and \( \Delta (s_{sw,ap}) = 0.9972 \) for the NACP-02 and Roos chamber a change of the \( k_Q \) values for these chambers due to the new ICRU recommendation is in the range of \( 0.16\% \).

The \( k_Q \) values for the NE2571 calculated in this work are in good agreement with the fit through Monte Carlo calculated data given by Andreo et al (2013)–the root-mean-square deviation is \( 0.0014 \). However, as can be seen in figure 5 there is a discrepancy between Monte Carlo calculated and experimentally determined \( k_Q \) values. Even with recently renewed \( I \) values, the discrepancy cannot be explained. However, Monte Carlo calculated \( k_Q \) values according to the new recommendations of the ICRU Report 90 resulted in an increase of the \( k_Q \) values of up to \( 0.35\% \) for high photon energies.

**Figure 5.** Monte Carlo calculated \( k_Q \) for the NE2571 ionization chamber using the recommendations of the ICRU Report 90 (full symbols) and ICRU Report 37 (open symbols). As radiation source clinical spectra (circles) and simulations through the full treatment head (triangles) were used. The ratio \( \Delta k_Q \) as a function of TPR\(_{20}^{10} \) is shown in the right panel. The linear regression line calculated from all data in the right panel is provided just for a better visualization of the \( \Delta k_Q \) values as a function of TPR\(_{20}^{10} \). The error bars are partly within symbol size in the left panel. All error bars represent the Monte Carlo statistical uncertainty (1 \( \sigma \)).

**Table 4.** Contribution of the uncertainty of \( I \) values according to ICRU Report 37 and 90 to the type-B uncertainty of the Monte Carlo based \( k_Q \) value of the NE2571 chamber in a high energy photon beam (24 MV, TPR\(_{20}^{10} \) = 0.806). The sensitivity coefficient \( \partial (\Delta k_Q/k_Q) / \partial x_i \) was taken from the work of Wulff et al (2010).

| ICRU Report 37 | Medium | \( I \) in eV | \( \Delta I \) in eV | \( \Delta I \) in % | \( \partial (\Delta k_Q/k_Q) / \partial x_i \) | \( \Delta k_Q \) in % |
|---------------|--------|-------------|----------------|----------------|--------------------------------|-----------------|
| \( H_2O \)    | 75     | 2           | 2.7            | 0.022          | 0.06                          |
| \( C \)       | 78     | 4           | 5.1            | 0.061          | 0.31                          |
| \( Air \)     | 85.7   | 1.7         | 2.0            | 0.024          | 0.05                          |
| **Sum:**      |        |             |                |                | **0.32**                      |

| ICRU Report 90 | Medium | \( I \) in eV | \( \Delta I \) in eV | \( \Delta I \) in % | \( \partial (\Delta k_Q/k_Q) / \partial x_i \) | \( \Delta k_Q \) in % |
|---------------|--------|-------------|----------------|----------------|--------------------------------|-----------------|
| \( H_2O \)    | 78     | 2           | 2.6            | 0.022          | 0.06                          |
| \( C \)       | 81     | 1.8         | 2.2            | 0.061          | 0.14                          |
| \( Air \)     | 85.7   | 1.2         | 1.4            | 0.024          | 0.03                          |
| **Sum:**      |        |             |                |                | **0.15**                      |
4.3. Renormalized photoelectric cross sections

Furthermore, within the framework of this study the developer version of EGSnrc was used to investigate the impact of using multiconfiguration Dirac-Fock (MCDF) renormalization factors for photoelectric cross sections to calculate $k_Q$ values. As expected, renormalized photoelectric cross sections did not effect the $k_Q$ values since the photonelectric effect in the used materials is only dominant at very low photon energies ($<$100 keV). It has to be mentioned that applying MCDF renormalization factors to cross sections for the photoelectric effect was only discussed, but not recommended in the ICRU Report 90.

4.4. Uncertainties of $I$ values

Besides new $I$ values for the materials water and graphite, the ICRU Report 90 also includes new data on the uncertainties of the $I$ values for these materials and also for air. The impact of these new type-B-uncertainties on resulting $k_Q$ values can be estimated by the method applied in one of our previous publications (Wulff et al 2010). In this paper the $I$ value of different materials was varied, i.e. new cross section data were calculated and the $k_Q$ value for the NE2571 chamber was recalculated with the new cross section data. This was done for the highest available photon energy (24 MV, $TPR_{20}^{20}$ = 0.806) as the impact of changed $I$ values is largest for high energy photon beams. From these calculations a sensitivity coefficient $\frac{\partial (\Delta k_Q/k_Q)}{\partial I}$ for every material or $I$ value $x_i$ was calculated. Applying these coefficients to the type-B-uncertainties given in ICRU Report 37 and ICRU Report 90, respectively, the standard uncertainties given in table 4 are resulting. The data show that the standard uncertainty of the Monte Carlo based $k_Q$ factor of the NE2571 chamber is halved, especially due to the strong decrease of $\Delta I$ for the material graphite. According to Wulff et al (2010), the uncertainty of the $I$ values is by far the largest contribution to the total uncertainty of Monte Carlo based $k_Q$ values. Beyond this background the new ICRU recommendation regarding the $\Delta I$ values is of great importance for the direct comparison of future Monte Carlo based and experimental based $k_Q$ determinations.

5. Conclusion

The impact of the new ICRU Report 90 recommendations on Monte Carlo calculated dosimetric quantities was investigated, confirming the decrease of $s_{\text{peak}}$ by a fraction of a percent for photon and electron beams. The study showed good agreements with the work published by Andreo et al (2013) and extended the investigation to clinical linear accelerators. However, in this work only three ionization chambers were investigated; the results may vary for other ionization chamber types, but the results should be comparable. According to the results, the impact of the new recommendations of the ICRU Report 90 on $k_Q$ values is within 0.35%. This deviation should be taken into account when widely published Monte Carlo calculated values are examined. In addition, data based on Monte Carlo simulations in the current dosimetry protocols should be revised with regard to the recommendations of the ICRU Report 90.

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Appendix A. Fano cavity test

The cavity Fano test was performed using egs_chamber with the egs_fano_source using monoenergetic electrons with an energy of 1.25 MeV. All materials in the chamber were replaced by water with the density of the replaced material. The source distributes electrons in the whole geometry proportional to the density of the material, and as a result a charged particle equilibrium occurs in all regions of the chamber. When photon transport is disabled by setting the PCUT value to 1.25 MeV, the dose in each geometry per particle history must be 1.25 MeV/$m_{\text{geom}}$, where $m_{\text{geom}}$ is the mass of the considered geometry. Figure A1 shows the ratio between calculated and expected values for all regions of the build ionization chambers: Farmer-type NE2571 (top panel), NACP-02 (middle panel) and Roos (bottom panel).

The Monte Carlo calculated values agreed to the theoretical values within an accuracy of 0.05%. This indicates that the consistency of the Monte Carlo simulations was preserved throughout the geometry model of the ionization chamber.
Appendix B. Volume perturbation

Monte Carlo calculated $k_Q$ values for the NE2571 chamber using a full linac treatment head simulation as particle source differ systematically from $k_Q$ values calculated using collimated isotropic radiation source with spectral energy distributions of the respective linac, as can be seen in figure 5 and left panel of figure B1. The $k_Q$ values calculated using a full treatment head are systematically below the $k_Q$ values when using collimated isotropic spectra as a particle sources. These are caused primarily by the different radial dose distributions of the two particle sources. Using only spectra as particle source results in concave radial dose distributions with a volume perturbation factor $p_{vol} \geq 1$. On the other hand, full treatment head simulations of conventional linac with flattening filter generate radial dose distributions with a tendency to be convex, resulting in a volume perturbation $p_{vol} \leq 1$. Dividing $k_Q$ values by $p_{vol}$ eliminated the deviation between $k_Q$ values from different source models (see figure B1).

Figure A1. Relative deviation of dose in the cavity regions of the three investigated ionization chamber (NE2571, NACP-02 and Roos) from the expected value as a function of the geometry region. The error bars represent the Monte Carlo statistical uncertainty (1σ).
Figure B1. The left panel shows Monte Carlo calculated beam quality correction factor $k_Q$ as a function of $TPR_{20}^{10}$ for the ionization chamber NE2571 using full linac head simulations (open symbols) and spectra (filled symbols) as a particle source of the Varian Clinac 6 MV, 10 MV and 18 MV. Inside the left panel the corresponding lateral profiles in 10 cm water depth are presented. Right panel provides the beam quality correction factors shown in the left panel divided by the perturbation factor $p_{vol}$ (calculated accordingly to Bouchard et al (2009)). The error bars represent the Monte Carlo statistical uncertainty (1 $\sigma$). The Monte Carlo statistical uncertainty of the calculated dose profiles are not shown for the sake of clarity and are within 0.12%.

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