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Original paper

Monte Carlo calculated beam quality correction factors for two cylindrical ionization chambers in photon beams

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ABSTRACT

Purpose: Although several studies provide data for reference dosimetry, the SNC600c and SNC125c ionization chambers (Sun Nuclear Corporation, Melbourne, FL) are in clinical use worldwide for which no beam quality correction factors k_Q are available. The goal of this study was to calculate beam quality correction factors k_Q for these ionization chambers according to dosimetry protocols TG-51, TRS 398 and DIN 6800-2.

Methods: Monte Carlo simulations using EGSnrc have been performed to calculate the absorbed dose to water and the dose to air within the active volume of ionization chamber models. Both spectra and simulations of beam transport through linear accelerator head models were used as radiation sources for the Monte Carlo calculations.

Results: k_Q values as a function of the respective beam quality specifier Q were fitted against recommended equations for photon beam dosimetry in the range of 4 MV to 25 MV. The fitting curves through the calculated values showed a root mean square deviation between 0.0010 and 0.0017.

Conclusions: The investigated ionization chamber models (SNC600c, SNC125c) are not included in above mentioned dosimetry protocols, but are in clinical use worldwide. This study covered this knowledge gap and compared the calculated results with published k_Q values for similar ionization chambers. Agreements with published data were observed in the 95% confidence interval, confirming the use of data for similar ionization chambers, when there are no k_Q values available for a given ionization chamber.

1. Introduction

Ionization chamber measurements of the absorbed dose to water in high energy photon beams are described in national and international dosimetry protocols. Therein, the water calibration factor $N_{\mathrm{D,w,Co-60}}$ and the beam quality correction factor k_Q, also called conversion factor k_Q, are used to determine the dose to water in photon fields of the radiation quality Q. The determination of k_Q values with high accuracy and the investigation of its influencing quantities are essential to reduce the uncertainties of dose measurements. However, k_Q values depend on the design and size of an ionization chamber, as well as on the materials of the chamber components.

Numerous research groups have published experimental and Monte Carlo based correction factors k_Q which may be used for an update of national and international dosimetry protocols [1–3]. Data sets obtained by Monte Carlo simulations and measurements at primary standards laboratories have been used to derive consensus data for beam quality correction factors k_Q according to the international dosimetry protocol TRS 398 of the IAEA (International Atomic Energy Agency) [4]. The underling study by Andreo et al. [4] summarized k_Q data of 23 widely used cylindrical ionization chamber types, but more chamber types are in clinical use worldwide. Moreover, k_Q values are only valid in the respective reference conditions, which vary between different dosimetry protocols.

In this Monte Carlo based study, the beam quality correction factor k_Q was calculated for a Farmer-type ionization chamber, the SNC600c, and a small volume ionization chamber, the SNC125c, both Sun Nuclear Corporation (Melbourne, FL). These ionization chambers are widely

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Table 1
Reference conditions used according to the dosimetry protocols TG-51, TRS 398 and DIN 6800-2 for high energy photon and ^{60}Co γ-beams. r_{cyl} denotes the radius of the cylindrical sensitive volume of the ionization chamber.

Influencing quantity	High energy photon beams			^{60}Co γ-beam
	TG-51	TRS 398	DIN 6800-2	
Beam quality specifier	$\%dd(10)_x$	TPR_{10}^{20}	TPR_{10}^{20}	–
Measurement depths	10 g/cm^2			5 g/cm^2
Field size at a 100 cm distance from source	10×10 cm^2			10×10 cm^2
Position of reference point of chamber	10 g/cm^2		10 g/cm^2+0.5r_{cyl}	5 g/cm^2
Source to phantom surface distance (SSD)	100 cm			95 cm
Source to chamber distance (SCD)	110 cm			100 cm

used in radiation therapy facilities. As far as we know, there are no k_Q values published for these ionization chambers in high energy photon beams. In such case, the TG-51 dosimetry protocol [2] of the American Association of Physicists in Medicine (AAPM) recommends to use available data of similar ionization chambers, where the wall material is the most critical property. The closest match to the chamber SNC600c is the Farmer-type ionization chamber PTW30012 (PTW, Freiburg, Germany). Both ionization chambers feature a Farmer type chamber design with a 0.43 mm graphite wall and 0.6 cm^3 active volume. However, the wall material of SNC600c is not pure graphite but rather resin impregnated graphite. There has been no clarity on how this may affect the correction factor k_Q and the uncertainty of dose measurements with the given ionization chamber. To address this knowledge gap, values for k_Q were calculated according to the dosimetry protocol TG-51 [2], TRS 398 [3] and DIN 6800-2 [1] of the German Institute for Standardization.

2. Materials and methods

2.1. The beam quality correction factor in dosimetry protocols

According to the ICRU Report 90 [5] it can be assumed that the average amount of energy W_{air} required to create an ion pair in dry air is constant for the investigated beam qualities Q. Therefore, the beam quality correction factor k_Q can be calculated using:

$$k_Q = \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{det}}}\right)_Q \Big/ \left(\frac{D_{\mathrm{w}}}{D_{\mathrm{det}}}\right)_{^{60}\mathrm{Co}} \tag{1}$$

where D_{w} is the absorbed dose to water at the reference depth and D_{det} is the absorbed dose in the sensitive volume of the ionization chamber. The input quantities of Equation (1) are calculated using Monte Carlo simulations. The indices Q and ^{60}Co represent the beam qualities of a high-energy photon beam and the ^{60}Co γ-ray beam, respectively. It should be noted that the calculated values D_{w} and D_{det} are determined under reference conditions defined respectively in the above mentioned dosimetry protocols. Table 1 summarizes the different reference conditions of the applied dosimetry protocols. The reference point given in Table 1 is on the long axis of the ionization chamber. All dosimetry protocols allow two different setups for reference dose measurements: a setup with a source to surface distance (SSD) of 100 cm and a setup with a source to chamber distance (SCD) of 100 cm. In this study we calculated the beam quality correction factor for the SSD $= 100$ cm setup. The impact of both setups on the k_Q values was investigated.

In the dosimetry protocols the beam quality correction factor k_Q is presented as a function of the beam quality specifier Q. In the international dosimetry protocol TRS 398 and the German dosimetry protocol DIN 6800-2 the beam quality specifier for high energy photon fields is the tissue phantom ratio TPR_{10}^{20}:

$$TPR_{10}^{20} = \frac{D_{\mathrm{w}}^{\mathrm{SSD=80}}(z = 20\ \mathrm{cm})}{D_{\mathrm{w}}^{\mathrm{SSD=90}}(z = 10\ \mathrm{cm})} \tag{2}$$

where $D_{\mathrm{w}}^{\mathrm{SSD=80}}(z = 20\ \mathrm{cm})$ is the dose to water in 20 cm water depth in a water phantom placed at a SSD of 80 cm and $D_{\mathrm{w}}^{\mathrm{SSD=90}}(z = 10\ \mathrm{cm})$ is the dose to water in 10 cm water depth and an SSD of 90 cm. The AAPM dosimetry protocol TG-51 uses $\%dd(10)_x$ as the beam quality specifier for high energy photon beams. According to the dosimetry protocol $\%dd(10)_x$ is the percentage depth dose at 10 cm depth in a water phantom placed at an SSD of 100 cm. Note that the depth dose curve is caused only by photon (e.g. all electrons reaching the water phantom from the LINAC are excluded from the radiation field). Both beam quality specifier are measured in a 10 x 10 cm radiation field. The Monte Carlo calculated beam quality specifiers were determined according to these definitions from Monte Carlo calculated absorbed dose to water.

2.2. Beam quality correction factor k_Q as a function of beam quality specifier Q

As proposed by Muir and Rogers [6], the beam quality correction factor k_Q can be fitted by a polynomial function of $\%dd(10)_x$:

$$k_Q = a + b \cdot 10^{-3}\left(\%dd(10)_x\right) + c \cdot 10^{-5}\left(\%dd(10)_x\right)^2 \tag{3}$$

This function has been included in the Addendum of the TG-51 dosimetry protocol [7].

The beam quality correction factor k_Q as a function of TPR_{10}^{20} was fitted according to Andreo *et al.* [4] using

$$k_Q\left(\mathrm{TPR}_{10}^{20}\right) = \frac{1 + \exp\left(\frac{a-0.572}{b}\right)}{1 + \exp\left(\frac{a-\mathrm{TPR}_{10}^{20}}{b}\right)} \tag{4}$$

According to Giménez-Alventosa *et al.* [8], the equation is very likely to be adopted in the upcoming TRS 398 update. The equation is designed to be unity at $TPR_{10}^{20} = 0.572$, i.e. the TPR_{10}^{20} value of ^{60}Co beam quality. The TPR_{10}^{20} value of ^{60}Co calculated by Monte Carlo simulation in this work is 0.571. However, the equation has not been adjusted for better comparability with literature.

To fit the k_Q values according to DIN 6800-2, the equation has to be extended by the additional fitting parameter $k_{\mathrm{Co-60}}$. This parameter takes into account the influence of two different positioning of the ionization chamber during calibration and measurement. According to the dosimetry protocol DIN 6800-2, the gradient effect is corrected by a shift of the effective point of measurement when measuring in the clinical reference field with beam quality Q. However, an effective point of measurement shift is not applied under reference conditions for calibration at the beam quality of ^{60}Co. This results in a beam quality correction factor that is not unity at a beam quality Q which equals the beam quality of a ^{60}Co beam [1]. Thus,$k_{\mathrm{Co-60}}$ is the beam quality correction factor k_Q at $TPR_{10}^{20} = 0.572$, i.e. the beam quality of a ^{60}Co radiation source. This results in the following fit function for k_Q as a function of TPR_{10}^{20} for the dosimetry protocol DIN 6800-2:

$$k_Q\left(\mathrm{TPR}_{10}^{20}\right) = k_{\mathrm{Co-60}} \frac{1 + \exp\left(\frac{a-0.572}{b}\right)}{1 + \exp\left(\frac{a-\mathrm{TPR}_{10}^{20}}{b}\right)} \tag{5}$$

It should be noted that the parameter a and b in Eq. (4) and (5) have different numerical values.

Table 2
Summary of simulation properties and parameters with EGSnrc used by THM and NRC.

Item	Description	References
Code	EGSnrc code system, egs++ library, egs_chamber	Kawrakow et al. [9] Kawrakow et al. [14] Wulff et al. [15]
Validation	Fano cavity test	Results in Appendix
Timing	Absorbed dose to water D_w in the sensitive volume of chamber for photon spectra and full linac head simulations took 2800 and 11000 single CPU hours (2.1 GHz), respectively, for each energy and ionization chamber.	
Source description	Collimated isotropic MV photon energy spectra and full linac head simulations.	See Tables 3 and 4
Cross-sections	XCOM photon cross section with multiconfiguration DiracFock renormalization factor for the photoelectric effect (mcdf-xcom).	
Transport parameters	Boundary crossing algorithm: Exact; transport and particle production threshold energy of 512 keV (THM), 521 keV (NRC) for electrons and 1 keV (THM), 10 keV (NRC) for photons.	
Variance reduction techniques	Intermediate phase space storage (IPSS); Photon cross-section enhancement (XCSE) volume with an XCSE factor of 128 (THM), 32 (NRC) and Russian Roulette range rejection technique with a survival probability of 1/128 (THM), 1/64 (NRC).	Wulff et al. [15]
Scored quantities	Absorbed dose to water and dose to air	
Statistical uncertainties	⩽0.1% for all calculated quantities	
Statistical method	History-by-history	
Postprocessing	None	

Table 3
Photon beam radiation sources applied at THM.

Source		TPR_{10}^{20}	$\%dd(10)_x$
Linac head models			
Elekta Precise	6 MV	0.659	66.1
Siemens KD	15 MV	0.777	80.3
Varian Clinac	6 MV	0.659	66.1
	10 MV	0.735	73.7
	15 MV	0.758	78.0
	18 MV	0.780	82.4
Photon spectrum			
Varian Clinac [20]	4 MV	0.629	63.4
	6 MV	0.672	67.5
	10 MV	0.732	73.2
	15 MV	0.764	78.2
Varian Clinac [21]	4 MV	0.621	62.8
	6 MV	0.662	66.1
	10 MV	0.729	74.2
	15 MV	0.755	77.9
	18 MV	0.766	81.9

2.3. Monte Carlo simulation

The Monte Carlo calculations presented in this publication were performed with EGSnrc 2020 [9]. The EGSnrc code system was used, since it has been shown that EGSnrc is able to calculate the dose to the cavity of an ionization chamber with a systematic accuracy of 0.1% or better relative to the cross sections [10,11]. Moreover, EGSnrc is available with a wide range of applications designed for the simulation of the radiation transport through ionization chambers, such as variance reduction technics for an efficient dose calculation in ionization chambers in a high energy photon field [12]. The Monte Carlo calculations and the processing of the simulation results were performed independently by two research groups, THM (Technische Hochschule Mittelhessen University of Applied Sciences, Giessen, Germany) and NRC (National Research Council Canada, Ottawa, Canada). All details of the Monte Carlo simulations are summarized in Table 2 according to the recommendations of AAPM TG-268 [13].

Table 4
Tabulated photon spectra applied at NRC.

Source		TPR_{10}^{20}	$\%dd(10)_x$
Varian Clinac [20]	4 MV	0.623	62.7
	6 MV	0.666	66.5
	10 MV	0.734	73.8
	15 MV	0.763	77.8
	18 MV	0.785	81.5
	24 MV	0.805	86.1
Siemens KD [21]	6 MV	0.671	67.0
	18 MV	0.762	77.7
Elekta SL25 [21]	6 MV	0.672	67.3
	25 MV	0.791	82.8

2.3.1. Radiation sources

The research groups THM and NRC used different radiation sources, except for an overlap of benchmark sources available in literature.

At THM, particle transport simulations through linear accelerator head models, as well as MV photon spectra were used as radiation sources (see Table 3) for the Monte Carlo simulations. The Monte Carlo based linac head models have been investigated in previous studies [16–19]. Moreover, five standard photon spectra of a Varian Clinac, which were published by Mohan et al. [20] and are included in the standard EGSnrc installation, and five Varian Clinac photon spectra published by Sheikh-Bagheri and Rogers [21] were used as radiation sources.

The calculations at NRC were performed using an incident beam with spectral point sources of photons collimated to a field size of 10 × 10 cm^2 at isocenter. The tabulated spectral photon distributions were taken from Mohan et al. [20] as well as Sheikh-Bagheri and Rogers [21]. Table 4 summarizes all applied radiation sources and their respective beam quality specifiers TPR_{10}^{20} and $\%dd(10)_x$.

Comparing the radiation sources used by both research groups, a difference can be observed between the calculated beam quality specifiers in Table 3 and 4. The difference between the values of the beam quality specifier for the same radiation source may be explained by the statistical uncertainty of the Monte Carlo simulation (0.4%) and systematic uncertainties in the determination of the beam quality, e.g., the determination of the maximum of the depth dose curve. It should be emphasized that this difference does not have an impact on the determined functional relationship between k_Q and the beam quality specifiers TPR_{10}^{20} as well as $\%dd(10)_x$.

2.3.2. Ionization chamber models

Two different ionization chambers have been investigated - a ”Farmer type” ionization chamber (SNC600c, Sun Nuclear Corporation, Melbourne, FL) and a ”scanning” ionization chamber (SNC125c, Sun Nuclear Corporation, Melbourne, FL) with sensitive volumes of 0.6 cm^3 and 0.1 cm^3, respectively. Table 5 lists further specifications of the investigated ionization chambers. Detailed ionization chamber models were built independently by THM and NRC according to manufacturer data using the egs++ class library [14].

The cross sections of the models are displayed in Fig. 1. The ionization chamber models of the two research groups differ in some details. In particular, the stem sections of the chambers were modeled in greater detail at NRC. Furthermore, it is noticeable that the chamber tip of the

Table 5
A summary of the materials and geometric data of the ionization chambers.

Ionization chamber	Wall		Central electrode		Sensitive volume	
	Material	Thickness	Material	Radius	Radius	Length
SNC125c	Graphite	0.25 mm	Al	0.4 mm	2.375 mm	7.05 mm
	PMMA	0.30 mm				
	Paint	0.05 mm				
SNC600c	Graphite	0.43 mm	Al	0.55 mm	3.05 mm	22.7 mm
	Paint	0.05 mm				

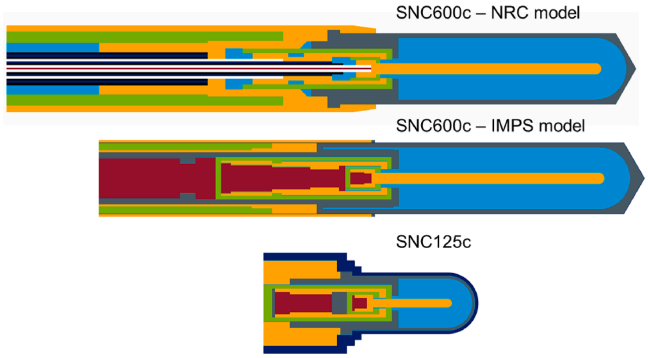

Fig. 1. Cross sections of the Monte Carlo based models of the investigated ionization chambers. The images of the chambers are not to scale. Different colors represent different materials.

THM model of the SNC600c has a slightly thicker wall.

It should be noted that the SNC600c wall consists of resin impregnated graphite, while the chamber wall of the SNC125c is made of high purity graphite. Consequently, two different graphite materials were generated. The density effect correction for the two wall materials was used according to the recommendations of ICRU Report 90 [5]. The material properties of water were as specified in the ICRU Report 90 [5].

3. Results

Fig. 2 presents the beam quality correction factor k_Q for the SNC600c ionization chamber according to all considered dosimetry protocols TG-51, TRS 398 and DIN 6800-2. The data sets were calculated by THM and NRC independently. Fig. 2 (a) shows k_Q values as a function of the beam quality specifier %dd(10)$_x$. The polynomial function proposed by Muir and Rogers [6] (see Eq. (3)) was fitted to the joint data sets calculated by THM as well as NRC. Fig. 2 (b) presents beam quality correction factors k_Q according to TRS 398 and DIN 6800-2 dosimetry protocols as a function of the beam quality specifier TPR_{10}^{20}. The values of k_Q according to DIN 6800-2 are greater than TRS 398 k_Q values due to the shift of the effective point of measurement. The k_Q values according to TRS 398 are fitted by the function given in Eq. (4) of the forthcoming update of TRS 398. The k_Q values for the DIN 6800-2 dosimetry protocol are fitted by the function given in Eq. (5). The presentation of all fit functions includes the 95% confidence interval indicated by a shaded area. The Monte Carlo calculated data are presented in comparison with calorimetric measurements of two SNC600c ionization chambers that have been taken from NRC Report PIRS 3327 [22].

Moreover, the calculated k_Q values in this work were compared to published data of the PTW 30012. Both ionization chambers have an aluminum electrode with an approximate diameter of 1.1 mm and a chamber wall made of graphite. It is worth noting that PTW 30012 is not waterproof. For a more realistic simulation Muir and Rogers [6] included a waterproof PMMA sleeve around the PTW 30012 model of 1 mm thickness. However, McEwen 2010 *et al.* [23] and Ross and Shortt *et al.* [24] have confirmed, that a 1 mm PMMA sleeve has a significant effect only for photon beam energies higher than 10 MV and is within 0.3% independent of the chamber within the sleeve.

In Fig. 2 (a) and (b), the polynomial fit of the PTW 30012's k_Q values published by Muir and Rogers [6] is represented by a dashed green line. The Monte Carlo calculated k_Q values in Fig. 2 are supported by calorimetric measurements published by Aalbers *et al.* [25] and McEwen [26]. In addition, the fitted k_Q data of the PTW 30012 published by Giménez-Alventosa et al. [8] is shown in Fig. 2 (b).

In analogy to Fig. 2, the correction factors k_Q for the SNC125c ionization chamber are presented in Fig. 3. The k_Q values calculated

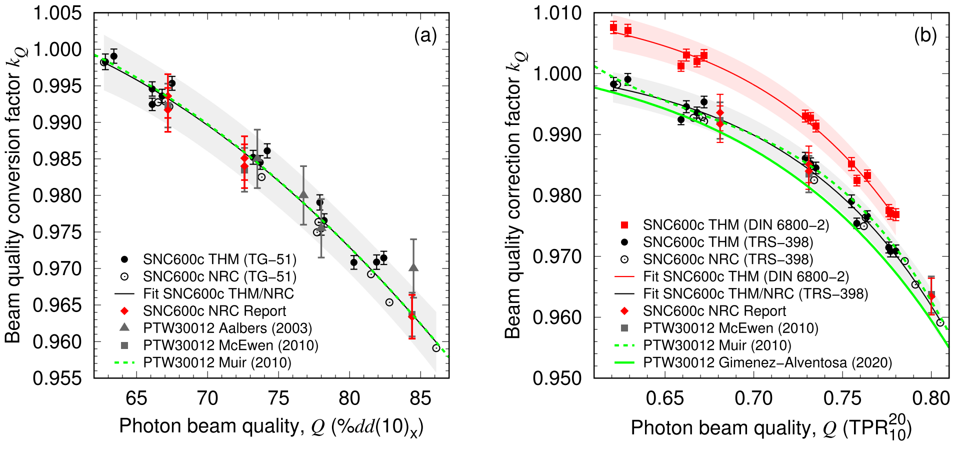

Fig. 2. Monte Carlo calculated beam quality correction factor k_Q for the Farmer-type ionization chamber SNC600c as a function of %dd(10)$_x$ (a) and TPR_{10}^{20} (b). k_Q values were calculated independently by THM (black filled circles) and NRC (open black circles) using different radiation sources and chamber models. Figure (b) shows k_Q values according to the TRS 398 (black) and DIN 6800-2 dosimetry protocols (red). The error bars indicate the statistical uncertainties (1 σ). The statistical uncertainty of the NRC calculated values are within the symbol size. The fits describing the THM and NRC data sets are shown with 95% confidence intervals, as represented by the shaded areas. The results are compered to experimentally determined k_Q values (red diamonds) from the NRC Report [22]. Figure (a) and (b) additionally shows experimentally determined k_Q values of the similarly built PTW 30012 ionization chamber published by McEwen *et al.* [26]. Figure (a) also presents experimentally determined k_Q values for the PTW 30012 published by Aalbers *et al.* [25]. The error bars of the experimental data represent type A and B uncertainties. Fit functions of k_Q values of the PTW 30012 published by Muir and Rogers [6] and Giménez-Alventosa et al. [8] are represented by dashed green lines and solid green line, respectively.

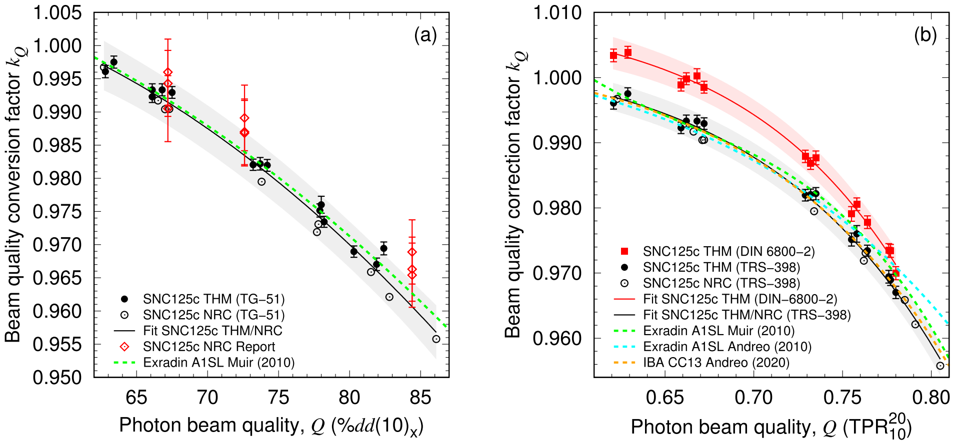

Fig. 3. Monte Carlo calculated beam quality correction factor k_Q of the SNC125c ionization chamber as a function of $\%dd(10)_x$ (a) and TPR_{10}^{20} (b). k_Q values were calculated independently by THM (black filled circles) and NRC (open black circles) using different radiation sources and chamber models. Figure (b) shows k_Q values according to the TRS 398 (black) and DIN 6800-2 dosimetry protocols (red). The error bars indicate the statistical uncertainties (1 σ). The statistical uncertainty of the NRC calculated values are within the symbol size. The fits describing the THM and NRC data sets are shown with 95% confidence intervals represented by the shaded areas. Figure (a) additionally shows experimentally determined k_Q values of the SNC125c chamber taken from the NRC Report PIRS-3224 [27]. The error bars of the experimental data represent type A and B uncertainties. The data sets are compared to fit functions published by Muir and Rogers [6] (dashed green line) and Andreo *et al.* [4] (dashed blue line) for the similar ionization chamber Exradin A1SL. The orange dashed line represents the fit function for the IBA CC13 ionization chamber taken from Andreo *et al.* [4].

Table 6
Fitting parameters of functions (3), (4) and (5) for the SNC600c and SNC125c ionization chambers.

Function	Parameter	SNC600c	SNC125c
$k_Q(\%dd(10)_x)$	a	0.9468	0.9649
Eq. (3)	b	2.607	2.134
	c	−2.852	−2.589
$k_Q(\mathrm{TPR}_{10}^{20})$	a	1.068	1.097
Eq. (4)	b	−0.08485	−0.09749
$k_Q(\mathrm{TPR}_{10}^{20})$	$k_{\mathrm{Co-60}}$	1.009	1.007
Eq. (5)	a	1.056	1.061
	b	−0.08386	−0.08721

according to TG-51, TRS 398 and DIN 6800-2 were fitted by the corresponding functions, see Eqs. ()()()(3)–(5). The calculated k_Q values are compared to calorimetric measurements of three SNC125c ionization chambers reported in NRC Report PIRS 3224 [27]. As reference, Fig. 3 shows k_Q values of the similar Exradin A1SL ionization chamber (Standard Imaging, Middleton, Wisconsin) and IBA CC13 (Schwarzenbruck, Germany) displayed as fit function according to Muir and Rogers [6] and Andreo *et al.* [4]. All fit parameters calculated in this work are summarized in Table 6.

4. Discussion

4.1. Ionization chamber models

This study provides calculated k_Q data for reference dosimetry according to three different dosimetry protocols (TG-51, TRS 398 and DIN 6800-2). Beam quality correction factors k_Q according to the TG-51 and TRS 398 dosimetry protocols were calculated independently by two research groups (THM and NRC). The resulting data sets are in good agreement, although the underlying ionization chamber models of the research groups differed slightly (see Fig. 1). The provided technical drawings of manufacturers are often very detailed at some points and some aspects of the ionization chamber underlie fabrication tolerances or are even unknown. However mostly small details of an ionization chamber have no impact on the simulation results. On the other hand, a Monte Carlo model of an ionization chamber cannot be arbitrary complex, since this would result in a lot of small geometrical regions in which the radiation transport must be simulated. This would be computing time and RAM consuming with no significant gain in accuracy of the calculated result. For this reason, Monte Carlo based models may vary even when modeled with the same information provided by the manufacturer. During the creation of the Monte Carlo model of an ionization chamber the level of detail can be reduced in selected parts of the chamber without affecting the simulation results. These generalizations must often be made to improve computation time and reduce the number of potential errors. Consequently, the visual representation of a chamber model depends on the creator and can differ from other implementations. The extent to which an ionization chamber can be simplified without having a significant effect on the calculated k_Q values must be clarified in further investigations.

In this study we observed that the modeled cable in the chamber stem did not affect the dose within the cavity. In addition, we observed that the different wall thickness of the chamber tip as well as the small air gap around the guard ring had no significant effect on the beam quality correction factor k_Q.

It should be noted that the data from Muir and Rogers [6] referred in this work were published before the ICRU Report 90 [5]. Thus, the calculations were not performed according to the recommendations of the ICRU Report 90. However, Mainegra-Hing and Muir [28] have shown that the impact of changes in recommendations between ICRU Report 37 [29] and 90 [5] is less than 0.15% for k_Q values of a similar Farmer-type ionization chamber NE2571. Czarnecki *et al.* [30] achieved similar results, observing a maximum change of up to 0.35% for the highest investigated energy (24 MV, $TPR_{10}^{20} = 0.806$). Additional calculations (not presented in this work) indicate that the change recommendations between ICRU Report 37 and 90 for the density correction parameter of graphite as well as the updated ionization constants of graphite and water result in a difference of the k_Q values of up to 0.5% for the SNC600c ionization chamber. The increased impact of the ICRU Report 90 recommendation on k_Q values of the SNC600c may be due to the thicker graphite chamber wall compered to the NE2571.

4.2. Beam quality correction factors for different dosimetry protocols

A source to surface distance (SSD) of 100 cm was chosen for all simulations presented in this study. Further investigations were made showing no significant difference between calculated k_Q values at SSD $=$ 100 cm and SCD $=$ 100 cm (SSD $=$ 90 cm).

The k_Q values of the large-volume SNC600c ionization chamber calculated with a full treatment head as a particle source are systemat-

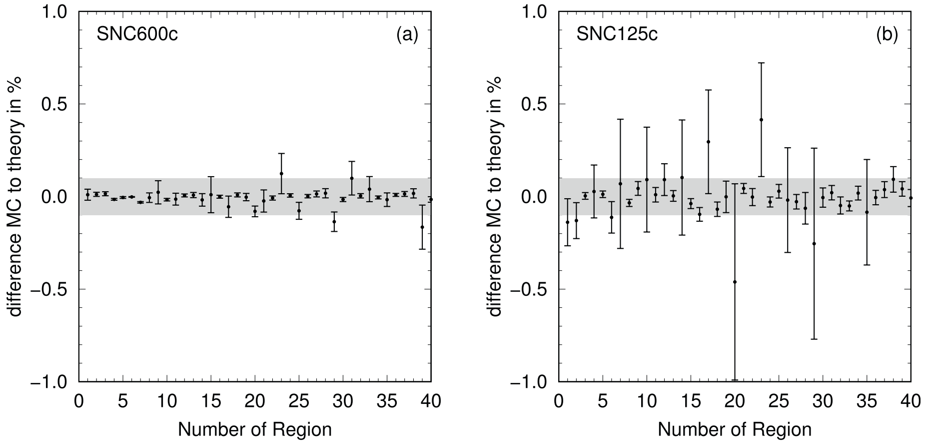

Fig. 4. Results of the Fano cavity test for the SNC600c and SNC125c. The left and right panels show the relative deviation from the expected value for each geometrical region in the ionisation chamber modell SNC600c and SNC125c, respectively.

ically smaller than those with collimated isotropic spectra as particle sources. This effect has been investigated in previous studyies [30,31] and can be traced back to the volume averaging effect. Therefore, this systematic deviation of the k_Q values of the smaller SNC125c ionization chamber is less pronounced. The fitting curves through the Monte Carlo calculated k_Q values showed a root mean square deviation between 0.0010 and 0.0017.

In accordance with the recommendations of the TG-51 dosimetry protocol, the results have provided further evidence that identical or similar ionization chambers have comparable beam quality correction factors k_Q. The published fits for the ionization chamber PTW 30012 and Exradin A1SL or IBA CC13 were within the 95% confidence intervals determined in this work for the ionization chamber SNC600c and SNC125c, respectively.

5. Conclusion

The goal of this study was to provide data for reference dosimetry using the ionization chambers SNC600c as well as SNC125c with regard to the recommendations of the ICRU Report 90 [5]. The beam quality correction factor k_Q was calculated for clinical photon beams from 4 MV up to 25 MV. The data was fitted by the recommended fitting functions of the respective dosimetry protocols. Following the fit function that will be adopted by the TRS 398 protocol, a fit function was also introduced for the DIN 6800-2 dosimetry protocol.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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Appendix A. Appendix

Fano tests were performed on the investigated ionization chamber models using the egs_fano_source of EGSnrc C++ class library [14]. To perform the Fano test, all materials in the ionization chamber models were replaced with water having the corresponding density of the replaced material. Fig. 4 shows the ratio between calculated and expected values for all created geometric regions of the ionization chambers SNC600c and SNC125c. In Fig. 4 (a) the regions 2 and 6 correspond to the sensitve volume and regions > 8 belong to the chamber stem of the ionization chamber SNC600c. In Fig. 4 (b) the Regions 2 und 4 are the sensitive volume and regions > 10 belong to the chamber stem of the ionization chamber SNC125c.

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