Physics in Medicine & Biology

ADDENDUM

Direct determination of $k_Q$ for Farmer-type ionization chambers in a clinical scanned carbon-ion beam using water calorimetry

Kim Marina Holm1,2,3, Oliver Jäkel1,4 and Achim Krauss2

1 Department of Radiation Oncology, Heidelberg University Hospital, Im Neuenheimer Feld 400, D-69120 Heidelberg, Germany
2 Department of Dosimetry for Radiation Therapy and Diagnostic Radiology, Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, D-38116 Braunschweig, Germany
3 Department of Medical Physics in Radiation Oncology, German Cancer Research Center (DKFZ), Im Neuenheimer Feld 280, D-69120 Heidelberg, Germany
4 Heidelberg Ion Beam Therapy Center (HIT), Heidelberg University Hospital, Im Neuenheimer Feld 450, D-69120 Heidelberg, Germany

E-mail: achim.krauss@ptb.de

Keywords: carbon-ion beams, water calorimetry, kQ factors, entrance channel, SOBP

Abstract
Within two studies, $k_Q$ factors for two Farmer-type ionization chambers have been experimentally determined by means of water calorimetry in the entrance channel (EC) of a monoenergetic carbon-ion beam (Osinga-Blättermann et al 2017 Phys. Med. Biol. 62 2033–54) and for a passively modulated spread-out Bragg peak (SOBP) (Holm et al 2021 Phys. Med. Biol. 66 145012). Both studies were performed at the Heidelberg Ion Beam Therapy Center (HIT) using the PTB portable water calorimeter but applying different initial beam energies of 429 MeV u$^{-1}$ for the EC and 278 MeV u$^{-1}$ for the SOBP as well as different scanning patterns of the irradiated field. Comparing their results revealed differences between the experimental $k_Q$ factors of up to 1.9% between the EC and the SOBP. To further investigate this unexpected difference, we performed additional $k_Q$ determinations for the EC of an 278 MeV u$^{-1}$ monoenergetic carbon-ion beam and reevaluated the original data of Osinga-Blättermann et al (2017 Phys. Med. Biol. 62 2033–54). This new experimental data indicated no difference between the $k_Q$ factors for the EC and the SOBP and the reevaluation led to a substantial reduction of the originally published $k_Q$ factors for the EC of the 429 MeV u$^{-1}$ beam (Osinga-Blättermann et al 2017 Phys. Med. Biol. 62 2033–54). Finally, no significant difference between the data for the EC and the data for the SOBP can be found within the standard measurement uncertainty of experimental $k_Q$ factors of 0.8%. The results presented here are intended to correct and replace the $k_Q$ data published by Osinga-Blättermann et al (2017 Phys. Med. Biol. 62 2033–54) and in Osinga-Blättermann and Krauss (2018 Phys. Med. Biol. 64 015009).

1. Introduction

In order to reduce the high standard uncertainty of beam quality correction factors $k_Q$ based on theoretical calculations as stated in the International Code of Practice for the Dosimetry of External Radiotherapy Beams (TRS–398) (Andreo et al 2006) as well as in the DIN 6801–1 protocol (Germany) (DIN-Normenausschuss Radiologie (NAR), 2016), $k_Q$ factors have been experimentally determined for two PTW 30013 and IBA FC65G Farmer-type ionization chambers (ICs) in the entrance channel (EC) of a 429 MeV u$^{-1}$ monoenergetic carbon-ion beam (Osinga-Blättermann et al 2017) as well as in the passively modulated spread-out Bragg peak (SOBP) of a 278 MeV u$^{-1}$ carbon-ion beam (Holm et al 2021). Both experiments were performed at the Heidelberg Ion-Beam Therapy Center (HIT) using the PTB water calorimeter.

According to TRS–398 and DIN 6801–1, no difference in the $k_Q$ factors is expected between the EC and the SOBP. However, the experimental data obtained by means of water calorimetry by (Osinga-Blättermann et al 2017) and (Holm et al 2021) shows a difference of 1.1%–1.9% for the two different ICs used.
Because of this discrepancy from the theoretical expectation, further investigations have now been performed concerning this issue. Calorimetric measurements were performed to determine $k_Q$ factors for both ICs in the EC of a 278 MeV u$^{-1}$ beam, and a review of the original data of Osinga-Blättermann et al with an emphasis on the determination of the calorimetric correction factors was conducted.

2. Material and methods

The details of the experimental methods are discussed in detail in the original publications and are therefore only briefly described in the following.

2.1. Irradiation technique and dose distribution measurement

All new measurements were performed at the HIT (Haberer et al 2004) using pencil beam raster scanning (Haberer et al 1993), as was also the case in (Osinga-Blättermann et al 2017) and (Holm et al 2021). The beam had a pulsed structure with 2.6–4.6 s per spill (length of the extraction pulse of the synchrotron) and a mean spill break (beam-off time) of 4.1 s.

The same irradiation plan as that used in (Holm et al 2021) was applied here; this plan is described in detail in (Holm et al 2020). Briefly, four monoeenergetic layers, each consisting of 36 x 36 spots and a spot distance of 2 mm, were irradiated in a sequence. Here, the layers were shifted against each other by 1 mm in the x-, y- and xy-directions, thus improving the field’s lateral uniformity. Each spot had a focus size of 8.2 mm full width at half maximum (FWHM); an initial beam energy of 278.29 MeV u$^{-1}$ was used.

In contrast to the measurements performed in the middle of a passively modulated SOBP using a 2D range modulator (2DRM) as described in (Simeonov et al 2017), no additional material was positioned in the beam path between the nozzle and the calorimeter for the measurements in the EC. The measurement took place at about a 5 cm depth in water inside the calorimeter for a flat depth dose distribution around the measurement position. At this position, a total dose of about 1.3 Gy was delivered to an irradiation field size of 6 x 6 cm$^2$ within an irradiation time of 90 s using the highest available clinically used particle flux of 8 x 10$^5$ ions per second.

All differences between the irradiation conditions used here and those presented by (Osinga-Blättermann et al 2017) and (Holm et al 2021) are summarized in table 1.

The resulting dose distribution was characterized in detail by measuring the 3D dose distribution with an IC array (Octavius 1000p, PTW, Germany). Via remote control, the array was depth-adjusted inside a water phantom over a range of 25 mm in steps of 2.5 mm, corresponding to 37.5–62.5 mm depth inside the water calorimeter (water calorimetric measurement position at 50 mm depth). This setup is described in detail in (Holm et al 2020).

The only difference between the irradiation technique of Holm et al and this study was to omit the 2DRM. This allowed measurements to be taken at a 5 cm water depth in the EC of the 278 MeV u$^{-1}$ beam. One might expect that the 2D lateral dose distribution of the radiation field would not change substantially when replacing the 2DRM, as the beam energy and the raster scan method stayed the same. Consequently, one might also expect that the radiation field-related correction factors required for the $k_Q$ determination in the EC would be nearly the same as the corrections previously determined for the SOBP measurement condition.

2.2. Experimental determination of $k_Q$ factors.

$k_Q$ factors were determined experimentally by means of water calorimetry using the PTB water calorimeter as described in recent publications, for example (Krauss et al 2012, Osinga-Blättermann et al 2017,

| Quantity | This study | (Osinga-Blättermann et al 2017) | (Holm et al 2021) |
|----------|-----------|-------------------------------|------------------|
| Irradiation modality | EC (no additional mat.) | EC (no additional mat.) | SOBP (using the 2DRM) |
| Measurement depth | 5 cm | 5 cm | 10 cm (middle of SOBP) |
| Initial beam energy | 278.29 MeV u$^{-1}$ | 428.77 MeV u$^{-1}$ | 278.29 MeV u$^{-1}$ |
| Focus size | 8.2 mm FWHM | 5.5 mm FWHM | 8.2 mm FWHM |
| Irradiation pattern | | | |
| No. of layers | 4 | 2 | 4 |
| Spots per layer | $36 \times 36$ | $26 \times 26$ | $36 \times 36$ |
| Spot distance | 2.0 mm | 2.3 mm | 2.0 mm |
| Layers shifted by | 1.0 mm | 1.15 mm | 1.0 mm |
| Irradiation time | $\approx 90$ s | $\approx 95$ s | $\approx 90$ s |
Holm et al. (2021). For a brief overview, the calorimeter consists of an insulated cubic water phantom with an edge length of 30 cm surrounded by actively cooled aluminum plates. It was operated at a water temperature of 4 °C. The calorimetric detector placed inside the water phantom consists of a thin-walled plane-parallel glass cylinder filled with purified water. Two thermostors fused into glass pipettes are mounted inside the cylinder perpendicular to the cylinder axis and opposite each other. By measuring the thermostor’s resistance change, the radiation-induced change in temperature was determined.

$k_Q$ factors were determined within a two-step procedure. First, the water calorimeter was used to measure the absorbed dose to water $D_{w,Q}$ for the actual irradiation condition at a 5 cm water depth. Second, after replacing the calorimetric detector with an IC inside the water phantom of the calorimeter, the IC’s charge during the irradiation was measured. After applying all necessary correction factors (for example, for heat conduction effects or perturbation effects in the case of calorimetric measurements, or for saturation and perturbation effects in the case of ionometric measurements), $k_Q$ factors were obtained from the ratio of $D_{w,Q}$ and the corrected IC reading $M_Q$ in accordance with

$$k_Q = \frac{N_{D_{w,Q}}}{N_{D_{w,Q_0}}} = \frac{D_{w,Q}}{M_Q},$$

(1)

with the chamber-specific calibration factors $N_{D_{w,Q}}$ and $N_{D_{w,Q_0}}$ for the given beam quality $Q$ and the reference beam quality $Q_0$ at which the chamber was calibrated.

The experimental $k_Q$ values found were expressed in accordance with TRS-398 (Andre et al. 2006) and DIN 6801-1 (DIN-Normenausschuss Radiologie (NAR), 2016) taking the different IC positioning (the center of the chamber $p_{ref}$ is positioned 0.75 · rIC, deeper than the measurement position $z$) and the treatment of the displacement effect in $^{60}$Co into account by applying the following equations:

$$k_Q^{\text{DIN}} = k_Q \left(1 + 0.75_{\text{IC}} \cdot \delta_{\text{IC}}\right)^{-1},$$

(2)

$$k_Q^{\text{TRS}} = k_Q \left(1 + 0.75_{\text{IC}} \cdot \delta_{\text{IC}}\right)^{-1}.$$

(3)

Here, $\delta_{\text{IC}}$ denotes the relative depth dose gradient of the irradiation field at the measurement position; $k_r = 1.009$ (for both ICs used within this study) was calculated in accordance with DIN 6801-1 (DIN-Normenausschuss Radiologie (NAR), 2016).

2.3. Reevaluation of the former EC data

In terms of theoretical considerations, no difference between $k_Q$ factors in the EC and the SOBP of the carbon-ion beam was expected; thus a decision was made to reanalyze both the calorimetric and ionometric data that had been used as the basis of the $k_Q$ factors presented by (Osinga-Blättermann et al. 2017) for the EC of the 429 MeV/u beam. Special emphasis was given to the determination of the heat conduction correction required for the calorimetric measurements. To this end, the results of the corresponding heat transport calculations were also reanalyzed.

In (Osinga-Blättermann et al. 2017), a computational model was developed to calculate the heat conduction effects in the most realistic way possible. The model considered the superposition of the temperature distribution of each single spot according to the real spatial irradiation pattern and the real time structure of the raster scan. The time-dependent temperature distribution during and after the irradiation of a single spot was calculated before using the COMSOL Multiphysics software. The details of the computational model as well as the details of the corresponding heat conduction calculations can be found in (Osinga-Blättermann et al. 2017).

For the reanalysis, new heat conduction calculations were performed using the same methods as those described by (Holm et al. 2021) but considering the original dose distribution of (Osinga-Blättermann et al. 2017). For these calculations, the entire irradiation field was divided into single parts, assuming that each part of the field was constantly irradiated over the total time of one spill followed by a spill break in accordance with the irradiation time structure described in (Osinga-Blättermann et al. 2017).

3. Results and discussion

3.1. Experimental $k_Q$ factors for the EC

3.1.1. Dose distributions

The dose distribution measured at the EC of the 278 MeV u$^{-1}$ beam is shown in figure 1.

The data measured with the IC array agrees very well with the HIT data for the given beam energy and shows a mean deviation of 0.65%. The measurement depth at 61.3 mm water-equivalent depth from the isocenter, corresponding to 5 cm depth from the inner wall inside the water calorimeter, is indicated by the red dashed line. The standard deviation of measured dose values within a sphere of 10 mm radius around the center of the
and the SOBP
Heat transport effects
Correction factor $EC_{278\text{ MeV \ u}}$ given.

In Perturbation effect
Lateral displacement
Heat defect
distribution (carbon-ion beam
Table 2.
of the SOBP at a 10 cm water depth, slight changes can be seen, while the main shape of the distributions remains (especially for the heat conduction correction effect. However, compared to the factors determined by Osinga-Blättermann et al, greater discrepancies appear, especially for the heat conduction correction (see section 3.2). The uncertainties of the individual factors are essentially the same compared to the SOBP, for the 429 MeV u$^{-1}$ EC, slightly different uncertainties were stated for $k_I$ (0.56%), $k_d$ (0.01%) and $k_Q$ (0.21%) (Osinga-Blättermann et al 2017).

![Image](image_url)

**Figure 1.** Dose distribution measured with the IC array (PTW Octavius 1000p) inside a water phantom. Left: Comparison of measured depth dose values (red) and Monte Carlo simulated HIT base data (blue) (Parodi et al 2012): the calorimetric measurement depth is indicated by the red dashed line, dose values are normalized to this point, depth coordinates (z) are given as water-equivalent depths from the isocenter. Right: One-dimensional dose distributions across the $x$- and $y$-axis at the measurement depth for the EC (5 cm inside the calorimeter, measured within this study, solid lines) and, for comparison, the SOBP (10 cm inside the calorimeter (Holm et al 2021), dashed lines); the lateral measurement positions of the thermistor probes inside the calorimetric detector are indicated by the black dashed lines, the data is normalized to the central dose value.

**Table 2.** Correction factors for the calorimetric determination of $D_{\text{abs,SOBP}}$ with their relative standard uncertainties for the EC of a 278 MeV u$^{-1}$ carbon-ion beam (determined within this study) compared to the values found for the 429 MeV u$^{-1}$ EC (Osinga-Blättermann et al 2017) and the SOBP (Holm et al 2021) (in parentheses). For the $k_I$ and $k_Q$, the mean of the different values for each of the two thermistors applied are given.

| Correction factor | EC 278 MeV u$^{-1}$ (EC 429 MeV/u / SOBP) | Rel. std. uncertainty/% |
|------------------|-------------------------------------------|------------------------|
| Heat transport effects $k_I$ | 0.9976 (1.0177/0.9979) | 0.40 |
| Heat defect $k_h$ | 1.0000 (1.0000/1.0000) | 0.14 |
| Lateral displacement $k_d$ | 1.0021 (1.0102/1.0021) | 0.08 |
| Measurement depth at different water temp. $k_d$ | 0.9998 (0.9990/1.0001) | 0.10 |
| Perturbation effect $k_p$ | 0.9978 (1.0021/1.0000) | 0.09 |
| Influence of the thermistors’ electrical power $k_e$ | 1.0002 (1.0004/1.0003) | 0.01 |

distribution ($x = 0$, $y = 0$) at the measurement depth was 0.93%. This lies within the same range as for the SOBP (Holm et al 2020).

Comparing the horizontal and vertical dose distributions in the EC at a 5 cm water depth and in the middle of the SOBP at a 10 cm water depth, slight changes can be seen, while the main shape of the distributions remains unchanged. This supports the expectation that the correction factors needed for the $k_I$ determination in the EC are essentially the same as for the SOBP.

3.1.2. Correction factors
Using the water calorimeter, 74 calorimetric measurements were performed, yielding a mean measured rise in temperature of $2.98 \cdot 10^{-4}$ C with a relative standard uncertainty of 1.4%, from which an absorbed dose to water of 1.25 Gy was determined. The correction factors for the calorimetric measurements are given in table 2.

All individual correction factors with their standard uncertainties were determined following the same procedures as those described in (Holm et al 2021). As a basis for the determination of $k_Q$, $k_I$ and $k_h$, the dose distribution measured for the EC (see section 3.1.1) was used. For $k_p$, again, a zero heat defect ($k_h = 1$) was assumed (Domen 1994, Palmins et al 1996, Sassowsky and Pedroni 2005) with a standard uncertainty of 0.14% (Krauss 2006). For the determination of $k_p$, the same measurements were performed with an IC inside and without a glass cylinder comparable to the cylinder of the calorimetric detector; here as well, the pipettes’ effect was assumed to be negligible. $k_e$ was calculated for each thermistor individually based on the thermal coupling between the thermistor and the water as well as the setup of the resistance-measuring circuit.

Compared to the correction factors for the SOBP only small differences were found, as was expected, such as the slightly reduced correction for the measurement depth at different water temperatures or the perturbation effect. However, compared to the factors determined by Osinga-Blättermann et al, greater discrepancies appear, especially for the heat conduction correction (see section 3.2). The uncertainties of the individual factors are essentially the same compared to the SOBP, for the 429 MeV u$^{-1}$ EC, slightly different uncertainties were stated for $k_I$ (0.56%), $k_d$ (0.01%) and $k_Q$ (0.21%) (Osinga-Blättermann et al 2017).
Table 3. Correction factors determined for the ionometric measurements in the EC of the 278 MeV u⁻¹ carbon-ion beam within this study for each IC and their relative standard uncertainties, compared to the correction factors found for the measurements at the 429 MeV u⁻¹ EC (Osinga-Blättermann et al 2017) and the SOBP (Holm et al 2021) (in parentheses).

| Correction factor   | PTW 30013 | IBA FC65G | Rel. std. uncertainty/% |
|---------------------|-----------|-----------|-------------------------|
| Polarity effect kₚ₀ₕ | 1.0012 (0.9993/1.0015) | 0.9993 (1.0012/0.9998) | 0.08 |
| Saturation effect kₛ | 1.0008 (1.0023/1.0028) | 1.0020 (1.0022/1.0056) | 0.20 |
| Volume effect kᵥ | 1.0031 (1.0129/1.0047) | 1.0031 (1.0129/1.0047) | 0.21 |

Table 4. Experimental kₒ factors for the PTW 30013 and the IBA FC65G determined at the EC for an initial beam energy of 278.29 MeV/u with an overall standard uncertainty of 0.69% (see below). Values are expressed in accordance with TRS-398 (Andreo et al 2006) and DIN 6801-1 (DIN-Normenausschuss Radiologie (NAR), 2016) (3).

|                     | PTW 30013 | IBA FC65G |
|---------------------|-----------|-----------|
| TRS                 | 1.012     | 1.013     |
| DIN                 | 1.003     | 1.004     |

For each IC, 20 repeated measurements were performed at positive operating voltages, yielding a mean relative standard deviation of the IC reading (corrected for air density and electrometer calibration) of 0.18% for the PTW 30 013 and 0.16% for the IBA FC65G. Mₒ was then calculated by applying the correction factors for the polarity, saturation and volume effects listed in table 3.

The correction factors for the ionometric measurements as well as their standard uncertainties were determined for the EC as described in (Holm et al 2021). For the determination of kᵥ, the dose distribution at the EC measured within this study was used. Compared to the values applied for the measurements at the SOBP by Holm et al, only slight changes occur, as expected. The standard uncertainties for the factors in the 429 MeV u⁻¹ EC and the SOBP are essentially the same (Osinga-Blättermann et al 2017, Holm et al 2021).

3.1.3. kₒ factors
The experimental kₒ values for the EC determined as described above were expressed in accordance with TRS-398 and DIN 6801-1 (equation (3)). The resulting factors are given in table 4.

The resulting kₒ factors for the PTW 30013 and the IBA FC65G chamber are 2.3% and 1.7% smaller than those determined by (Osinga-Blättermann et al 2017) in the EC of the 429 MeV u⁻¹ beam. But within their standard uncertainties, they agree with the values found by (Holm et al 2021) for the SOBP.

An overall uncertainty budget for the resulting kₒ factors at the EC was determined in accordance with the Guide to the Expression of Uncertainty in Measurement (GUM) (Joint Committee for Guides in Metrology 2008) using the GUM workbench (Metrodata 2017). Most of the uncertainties of the influencing quantities remained the same compared to the budget for the kₒ values at the SOBP (detailed budget see (Holm et al 2021)); only slight changes in, for example, the standard deviation of the repeated measurements of ΔT (0.38%) were observed. Nevertheless, this still resulted in an overall standard uncertainty of kₒ of 0.69%, as was also given for the SOBP.

3.2. Impact of reevaluations
3.2.1. Recalculation of heat transport effects
In water calorimetry, the total heat conduction correction strongly depends on the dose distribution if large dose inhomogeneities occur at the point of measurement. This is the case for the dose distribution of (Osinga-Blättermann et al 2017). Figure 2 shows the horizontal and vertical dose distributions over a limited range of ±20 mm from (Holm et al 2021) in comparison with the dose distribution of (Osinga-Blättermann et al 2017). It can be seen that the dose distribution of Osinga-Blättermann et al has a peak in the region of the central axis of the radiation field, whereas the dose distribution is more homogeneous in the case of (Holm et al 2021). During and after the irradiation, the temperature distribution (which is related to the initial dose distribution) will dissolve to a large extent if such a peak structure is present, causing a large heat conduction correction which is very sensitive to the exact measurement position.
During the reevaluation of the original heat transport calculations performed by (Osinga-Blättermann et al 2017), it became apparent that all results were related to a measurement position of the temperature sensors of the calorimetric detector located at the central axis of the radiation field (i.e. at the top of the peak structure shown in figure 2). Furthermore, the dependency on the exact measurement position was also underestimated. But in reality, the two temperature sensors of the calorimetric detector were mounted opposite each other at a distance of about 3 mm from the central axis. The new heat conduction calculations were performed considering the realistic measurement positions; this led to a reduction in the correction factor kc by 0.70% compared to the original value. However, it should be noted that the results of the new heat transport calculations agree with the former results when the same position at the central axis of the radiation field is considered.

As a further consequence of the reanalysis of the heat transport calculations, it was also found that the initial calculations by (Osinga-Blättermann et al 2017) only considered the heat conduction in fluence of the dose distribution and of the glass cylinder of the calorimetric detector, but not the influence due to the irradiation of the temperature sensors. This contribution was therefore calculated, resulting in a correction factor of 0.9973 for the temperature sensors whose diameter was about 0.70 mm. This decreased the total heat conduction correction kc by a further 0.27%.

In summary, it must be concluded that, because of the reduction in the correction factor kc, all final values of the kQ factors determined in the EC of the 429 MeV u⁻¹ carbon-ion beam must be reduced by 0.97%. Consequently, the same holds true for the kQ factors published in (Osinga-Blättermann and Krauss 2018), which were determined by means of cross-calibrations using the two Farmer-type ICs used in (Osinga-Blättermann et al 2017) as a reference.

This reevaluation of the present data illustrates once again that a homogeneous dose distribution is essential for a low overall uncertainty of the heat conduction corrections, as it was also discussed in detail in (Holm et al 2020).

3.2.2. Correction of ionometric data
As the correction mentioned above influences the results of all measurements performed in the EC of the 429 MeV u⁻¹ beam, the reanalysis of the experimental data demonstrated the need for an additional adjustment in the result of a single IC measurement.

In the first measurement campaign in the EC of the 429 MeV u⁻¹ beam, the result of the PTW 30013 seemed to be too large. During all investigations, the same individual ICs were used. It can therefore be expected that, in all investigations, the ratio of the corrected dose measurement of the PTW 30013 and the IBA FC65G chamber will always be nearly the same. However, in the first measurement campaign, this ratio was about 1.010, whereas for all other measurements, it was between 0.998 and 1.002. Hints in handwritten records as well as the reevaluation of the data led to the conclusion that (erroneously) no air-density correction was performed during the first measurement with the PTW 30013 using a PTW UNIDOS electrometer. The IBA FC65G was measured about one hour after the PTW 30013 but with a different measurement device developed at PTB that
automatically included the air-density correction. The data of this device considered an air-density correction of 1.009 for the IBA FC65G. If this correction were also applied to the PTW 30013 chamber, the ratio of the dose measurement with both chambers would decrease to 1.001, which seems to be more plausible than the ratio of 1.010. Consequently, the $k_Q$ factor determined for the PTW 30013 chamber from this measurement would be smaller by 0.90%.

### 3.3. Comparison of experimental $k_Q$ factors

The $k_Q$ factors resulting from this study were compared to the experimental values obtained for the SOBP (Holm et al 2021) and for the EC by (Oisinga-Blättermann et al 2017). The $k_Q$ factors for the EC determined within this study lie within the standard uncertainty of the factors determined for the SOBP (Holm et al 2021) and support the theoretical expectation that the $k_Q$ factors do not depend on the LET of the radiation.

For the values presented by (Oisinga-Blättermann et al 2017) corrected as discussed in section 3.2, differences of 0.6% / 1.0% (compared to SOBP / EC) for the PTW 30013 and 0.2% / 0.7% (compared to SOBP / EC) for the IBA FC65G appear. An overview of these results is shown in figure 3. The final mean experimental $k_Q$ values for the different irradiation conditions are summarized in table 5. The overall mean $k_Q$ values calculated for both chambers are between 0.4% and 0.6% smaller than the theoretical $k_Q$ factors from DIN 6801-1, and between 1.5% and 2.4% smaller than the data from TRS-398.

If the conclusions from section 3.2 are also considered for the $k_Q$ factors presented in (Oisinga-Blättermann and Krauss 2018), which were determined by means of cross-calibrations for several additional cylindrical and plane-parallel ICs, then the corrected $k_Q$ factors given in table 6 result. During the cross-calibrations, the mean dose measurements with the PTW 30013 and the IBA FC65G chambers were used as a reference, considering the original $k_Q$ factors from (Oisinga-Blättermann et al 2017).

---

Table 5. Summary of experimental $k_Q$ factors in carbon-ion beams for the PTW 30013 and the IBA FC65G: Corrected values (see section 3.2) for the EC of an 429 MeV $u^{-1}$ beam with a relative standard uncertainty of 0.8% (Oisinga-Blättermann et al 2017), as well as for a passively modulated SOBP (Holm et al 2021) and for the EC of a 278 MeV $u^{-1}$ beam, both with a relative standard uncertainty of 0.7%. Values are expressed in accordance with TRS-398 (Andreo et al 2006) and DIN 6801-1 (DIN-Normenausschuss Radiologie (NAR), 2016) (see equation (3)).

|               | EC (429 MeV $u^{-1}$) | SOBP (278 MeV $u^{-1}$) | EC (278 MeV $u^{-1}$) |
|---------------|-----------------------|-------------------------|-----------------------|
| PTW 30013     | TRS 1.022              | 1.016                   | 1.012                 |
|               | DIN 1.013              | 1.007                   | 1.003                 |
| IBA FC65G     | TRS 1.020              | 1.018                   | 1.013                 |
|               | DIN 1.011              | 1.009                   | 1.004                 |

Figure 3. Experimental $k_Q$ values for the PTW 30013 (left) and the IBA FC65G (right): For the entrance channel presented by (Oisinga-Blättermann et al 2017) (EC 429 MeV $u^{-1}$, grey) and corrected with new $k_i$ values (black), for the SOBP (Holm et al 2021) and for the EC presented in this study (EC 278 MeV $u^{-1}$). Error bars show their combined overall standard uncertainty; the mean value of the respective study is indicated by the solid lines. For comparison, data from DIN 6801-1 (DIN-Normenausschuss Radiologie (NAR), 2016) (red) and TRS-398 (Andreo et al 2006) (blue) is given by the dashed lines. The experimental values are calculated in accordance with TRS (see equation (3)); the value taken from DIN was multiplied by a value $k_i = 1.009$ for a better comparison with the TRS data (see section 2.2).
4. Conclusion

By considering the new corrections that have been applied to the data determined by (Osinga-Blättermann et al 2017) (see section 3.2), the $k_Q$ values are now in good agreement with the data presented for the SOBP by (Holm et al 2021) within the given standard uncertainty. Good agreement with the SOBP values was also found for the $k_Q$ values in the EC of a 278 MeV u$^{-1}$ carbon-ion beam presented in this study. This means that no significant LET dependence of $k_Q$ was observed, as it was speculated in (Holm et al 2021). If such an effect does exist, it can be concluded from the results presented here that its magnitude is below the accuracy of the experimental method used.

Acknowledgments

We would like to thank Stephan Brons and his colleagues from HIT for their help with technical issues concerning the irradiations. We are grateful to Andreas Schlesner and Thomas Hackel for their help during the measurements, and especially to Andreas Schlesner for his support concerning the measurement equipment and software.

ORCID iDs

Kim Marina Holm  https://orcid.org/0000-0002-7977-082X
Oliver Jakel  https://orcid.org/0000-0002-6056-9747

References

Andreo P, Burns D, Hohlfeld K, Saiful Huq M, Kanai T, Laitano F, Smyth V and Vynckier S 2006 Absorbed Dose Determination in External Beam Radiotherapy: an International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water (IAEA TRS-398, V.12) (Vienna: International Atomic Energy Agency)

DIN-Normenausschuss Radiologie (NAR) 2016 DIN 6801-1: Dosismessverfahren nach der Sondenmethode für Protonen- und Ionenstrahlung - Teil 1: Ionisationskammern Deutsches Institut für Normung e.V.

Domen S R 1994 A sealed water calorimeter for measuring absorbed dose J. Res. Nat. Inst. Stdnd. Technol. 99 121–41

Haberer T, Becher W, Schardt D and Kraft G 1993 Magnetic scanning system for heavy ion therapy Nucl. Instrum. Methods Phys. Res. A 330 296–305

Haberer T, Debus J, Eickoff H, Jakel O, Schulz-Ertner D and Weber U 2004 The Heidelberg ion therapy center Radiother. Oncol. 73 S186–S190

Holm K M, Jakel O and Krauss A 2021 Water calorimetry-based kQ-factors for Farmer-type ionization chambers in the SOBP of a carbon-ion beam Phys. Med. Biol. 66 145012
Holm K M, Weber U, Simeonov Y, Krauss A, Jäkel O and Greilich S 2020 2D range modulator for high-precision water calorimetry in scanned carbon-ion beams Phys. Med. Biol. 65 215003

Joint Committee for Guides in Metrology 2008 Evaluation of measurement data—Guide to the expression of uncertainty in measurement JCGM 100 1–132

Krauss A 2006 The PTB water calorimeter for the absolute determination of absorbed dose to water in 60Co radiation Metrologia 43 259–72

Krauss A, Buermann L, Kramer H-M and Selbach H-J 2012 Calorimetric determination of the absorbed dose to water for medium-energy x-rays with generating voltages from 70 to 280 kV Phys. Med. Biol. 57 6245–68

Metrodata GmbH 2017 GUM Workbench Pro Version 2.4.1.392 (http://metrodata.de/ver24_en.html)

Osinga-Blättermann J-M, Brons S, Greilich S, Jäkel O and Krauss A 2017 Direct determination of kQ for Farmer-type ionization chambers in a clinical scanned carbon ion beam using water calorimetry Phys. Med. Biol. 62 2033–54

Osinga-Blättermann J-M and Krauss A 2018 Determination of kQ factors for cylindrical and plane-parallel ionization chambers in a scanned carbon ion beam by means of cross calibration Phys. Med. Biol. 64 015009

Palmans H, Seuntjens J, Verhaegen F, Denis J M, Vynckier S and Thierens H 1996 Water calorimetry and ionization chamber dosimetry in an 85 MeV clinical proton beam Med. Phys. 23 643–50

Parodi K, Mairani A, Brons S, Hasch B G, Sommerer F, Naumann J, Jäkel O, Haberer T and Debus J 2012 Monte Carlo simulations to support start-up and treatment planning of scanned proton and carbon-ion therapy at a synchrotron-based facility Phys. Med. Biol. 57 3759–84

Sassowsky M and Pedroni E 2005 On the feasibility of water calorimetry with scanned proton radiation Phys. Med. Biol. 50 5381–400

Simeonov Y, Weber U, Penchev P, Ringbk T, Schuy C, Brons S, Engenhart-Cabillic R, Bliedtner J and Zink K 2017 3D range-modulator for scanned particle therapy: development, Monte Carlo simulations and experimental evaluation Phys. Med. Biol. 62 7075–96