Corrigendum: Comparison of $k_Q$ factors measured with a water calorimeter in flattening filter free (FFF) and conventional flattening filter (cFF) photon beams (de Prez et al 2018 Phys. Med. Biol. 63 045023)

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This corrigendum corrects some errors in our recent publication (de Prez et al 2018 Phys. Med. Biol. 63 045023).

There is an error in the scale of the horizontal axis of figure 3 and equivalent values of the second row of table 3. The correct figure is shown in the following. The values in the second row of table 3 should be 0.19 mGy, 0.47 mGy, 0.31 mGy and 0.75 mGy, respectively.

![Figure 3](image)

**Figure 3.** Recombination correction, $k_s$, for the three chamber types used in this study as a function of dose per pulse, DPP in mGy. The black dotted lines are linear fits through the points measured in the accelerator beams, extrapolated in grey to the vertical axis. The points at the vertical axis are $k_s$ measured for $^{60}$Co and assumed only to be a result of initial recombination.

There are small errors in the values of the heat transport correction, $k_C$, and a correction of $-0.08\%$ in the absorbed dose to water calibrations of the ion chambers. These affect the values in the original table 2 that consequently affect the original tables 4 and 6 and figure 4. The corrected figure and tables are given here with changes in bold. These corrections have small effects on the results but no effect on the overall conclusion of the original publication.
The resulting changes (in bold) in the abstract are:

For the TPR 20,10 based CoPs differences less than 0.19% were found in \( k_Q \) factors between the corresponding FFF-cFF beams with standard uncertainties smaller than 0.35%, while for the \( \%dd \) these differences were smaller than 0.42% and within the expanded uncertainty of the measurements.

The resulting changes (in bold) in the Discussion and Conclusion are:

Table 4. Ion chamber calibration coefficient in \( ^{60}\text{Co} \) and \( k_{Q,Q_0} \) factors as if measured directly in water (i.e. without the use of a waterproof sleeve). Values between brackets are the standard deviations, represented as the least significant digit(s) of the reported value, obtained for the individual chambers (2 \( \times \) PTW 30013, 3 \( \times \) PTW 30012 and 3 \( \times \) NE2571).

Table 5. \( \Delta k_{\text{FFF},\text{cFF}} \) conform equation (5) for the FFF-cFF beam pairs in an Elekta Versa HD accelerator.

* NCS-18 does not provide \( k_Q \) data for this chamber type.

Figure 4. Measured \( k_Q \) factors for the two NE2571 (left) and PTW 30012 (right) type chambers in relation to the TPR_20,10 based CoPs applied in this study. The error bars represent the standard uncertainties (\( k = 1 \)) given in table 5. Note that both the TRS-398 and NCS-18 \( k_Q \) factors include a correction for the presence of the PMMA sleeve which is smaller than 0.1%, while the measured \( k_Q \) factors obtained in this study do not. The standard uncertainty of the \( k_Q \) factor on the NCS-18 and TRS-398 curve are 0.4% and 1.0%, respectively.
Differences between $k_Q$ of the FFF and cFF beams were smaller than 0.19% for TPR$_{20,10}$ based protocols NCS-18 and TRS-398 and within the standard uncertainties of 0.35% for 6 MV and 0.30% for 10 MV beams. In contrast to the study by Xiong and Rogers, the biggest difference of 0.42% was found for the NE2571 chambers at 10 MV for $k_Q$ when %$dd(10)_x$ was applied, however, within the expanded uncertainty of the measurements.

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Comparison of $k_Q$ factors measured with a water calorimeter in flattening filter free (FFF) and conventional flattening filter (cFF) photon beams

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Abstract
Recently flattening filter free (FFF) beams became available for application in modern radiotherapy. There are several advantages of FFF beams over conventional flattening filtered (cFF) beams, however differences in beam spectra at the point of interest in a phantom potentially affect the ion chamber response. Beams are also non-uniform over the length of a typical reference ion chamber and recombination is usually larger. Despite several studies describing FFF beam characteristics, only a limited number of studies investigated their effect on $k_Q$ factors. Some of those studies predicted significant discrepancies in $k_Q$ factors (0.4% up to 1.0%) if TPR20,10 based codes of practice (CoPs) were to be used. This study addresses the question to which extent $k_Q$ factors, based on a TPR20,10 CoP, can be applied in clinical reference dosimetry. It is the first study that compares $k_Q$ factors measured directly with an absorbed dose to water primary standard in FFF-cFF pairs of clinical photon beams. This was done with a transportable water calorimeter described elsewhere. The measurements corrected for recombination and beam radial non-uniformity were performed in FFF-cFF beam pairs at 6 MV and 10 MV of an Elekta Versa HD for a selection of three different Farmer-type ion chambers (eight serial numbers). The ratio of measured $k_Q$ factors of the FFF-cFF beam pairs were compared with the TPR20,10 CoPs of the NCS and IAEA and the %dd(10) CoP of the AAPM. For the TPR20,10 based CoPs differences less than 0.23% were found in $k_Q$ factors between the corresponding FFF-cFF beams with standard uncertainties smaller than 0.35%, while for the %dd(10), these differences were smaller than 0.46% and within the expanded uncertainty of the measurements. Based on the measurements made with the equipment described in this study the authors conclude that the $k_Q$ factors provided by the NCS-18 and IAEA TRS-398 codes of practice can be applied for flattening filter free beams without additional correction. However, existing codes of practice cannot be applied ignoring the significant volume averaging effect of the FFF beams over the ion chamber cavity. For this a corresponding volume averaging correction must be applied.

1. Introduction

High-energy photon beams from clinical linear accelerators operating in flattening filter free (FFF) mode have been available since the early 1980s (Brahme et al 1980). They have been applied and characterized for application in radiosurgery (O’Brien 1991). Recently FFF beams became available for application in other radiotherapy techniques such as intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) (Georg et al 2011, Paynter et al 2014). The main advantages of FFF compared to conventional flattening filtered (cFF) beams are the increased dose rate, resulting in reduced treatment time, reduced lateral beam quality variation and a reduced out of field dose to the patient (Robar et al 2002, Titt et al 2006, Vassiliev et al 2006).

Differences between CFF and FFF beams, their consequences and relevant literature have been described by working groups of the American Association of Physicists in Medicine (Xiao et al 2015) and the Institute of Physics and Engineering in Medicine (Budgell et al 2016). The modifications of FFF beams compared to cFF beams...
result in a greater low-energy spectral component, which is partly reduced by the backscatter plate and, in some cases, an added thin filter. FFF beams are also non-uniform over the length of a typical ion chamber used in reference dosimetry, and can have a significantly higher dose rate in the chamber volume (Lye et al. 2016). Despite a number of studies describing differences in beam characteristics between FFF and cFF beams only a limited number of studies investigated the effect of FFF beams on \( k_Q \) factors in reference dosimetry. These were based on Monte Carlo simulations, and none of them performed direct \( k_Q \) measurements with a primary standard in a clinical linear accelerator. One of these studies is a Monte Carlo study by Xiong and Rogers (2008), who calculated restricted stopping power ratios where flattening filters of conventional linac beams were removed. Other corrections were not taken into account. This study concluded that differences between \( k_Q \) factors determined for FFF and cFF beams could lead up to 0.4% errors when applying \( %dd(10) \), 0.2% with a new \( %dd(10) \) fit, or 1% when applying TPR\(_{20,10}\) for photon energies up to 25 MV. The AAPM TG-51 addendum (McEwen et al. 2014) implemented the new \( %dd(10) \) fit proposed by Xiong and Rogers (2008). A similar Monte Carlo study reported by Dalaryd et al. (2014) was based on more realistic clinical FFF beams. Their study showed smaller differences for TPR\(_{20,10}\) than predicted by Xiong and Rogers. Lye et al. (2016) found differences smaller than 0.2% comparing absorbed dose measurements based on the TPR\(_{20,10}\) based code of practice IAEA TRS-398, or the \( %dd(10) \) based code of practice, AAPM TG-51 for FFF-cFF beam pairs of 6 MV and 10 MV in different accelerator beams.

Despite the relevance of these studies, Monte Carlo studies are limited by the use of models for both ion chambers and accelerator beams. Direct measurement of \( k_Q \) factors with primary standards are essential to understand the individual behaviour of physical chambers in real clinical accelerators. This study aims to answer the question to which extent \( k_Q \) factors based on a TPR\(_{20,10}\) and \( %dd(10) \) protocol for cFF beams can be applied in clinical reference dosimetry for FFF beams. In contrast to previous studies, this is done by direct comparison of \( k_Q \) factors measured with a primary standard in clinical FFF and cFF beams of 6 MV and 10 MV for a single accelerator for a selection of eight ion chambers of three types.

2. Materials and methods

2.1. Measurement of \( k_Q \)

The most direct way to determine absorbed dose to water, \( D_w \), and \( k_Q \) in various photon beams is a carefully conducted measurement (Andreo et al. 2000, Seuntjens and Duane 2009). This is done by calibrating the ion chamber in beam quality \( Q \), resulting in a calibration coefficient \( N_{D_w,Q} \), and in the reference beam quality \( Q_0 \), \( N_{D_w,Q_0} \). It involves two absorbed dose to water measurements with a primary standard, and two ion chamber measurements, \( M \), under the same reference conditions in beam quality \( Q \) and \( Q_0 \) (Hohlfeld 1988, Andreo 1992, Rogers 1992):

\[
k_Q = \frac{N_{D_w,Q}}{N_{D_w,Q_0}} = \left( \frac{D_w}{M} \right)_Q \left( \frac{D_w}{M} \right)_{Q_0}.
\]

Generally, \( k_Q \) is expressed as a function of a beam quality specifier, \( %dd(10) \), or TPR\(_{20,10}\) respectively applied in the AAPM TG-51 code of practice and its addendum (Almond et al. 1999) and the codes of practice of the International Atomic Energy Agency (IAEA) TRS-398 (Andreo et al. 2000), IPEM (Lillicrap et al. 1990), Deutsche Industrie Norm 6800-2 (DIN 2008) and Nederlandse Commissie voor Stralingsdosimetrie (NCS) report 18 (Aalbers et al. 2008). The results of this study will be compared with the codes of practice of the NCS, IAEA and AAPM, further referred to as NCS-18, TRS-398 and TG-51, respectively.

2.2. Measurement of \( k_Q \) for FFF-cFF beam pairs

The comparison of \( k_Q \) factors in FFF and cFF beam pairs of 6 MV and 10 MV is done in a similar fashion as expressed by equation (1), where the beam quality specifiers of both FFF and cFF beams have the same value \( Q \), and cFF is considered the reference beam. This can be expressed as a ratio:

\[
\frac{k_{Q,FF}}{k_{Q,cFF}} = \frac{N_{D_w,Q_{FF}}}{N_{D_w,Q_{cFF}}}.
\]

Note that the value of \( Q \) depends on the selected beam quality specifier (i.e. TPR\(_{20,10}\) or \( %dd(10) \)). However, unless the FFF and cFF beams are matched with respect to the selected beam quality specifier, such that the values of \( Q \) for both beams are the same, the measured \( k_Q \) of the cFF beam quality, here \( Q \), needs to be normalized to its value at beam quality of the FFF beam, \( Q \). Hence, the ratio, \( R \), of calibration coefficients for FFF and cFF beams, normalized to the beam quality value of the FFF beam becomes:

\[
R = \frac{N_{D_w,Q_{FF}}}{N_{D_w,Q_{cFF}}}.
\]

\(3\) Budgell et al. (2016) report directly measured \( k_Q \) factors with the National Physical Laboratory (NPL, Teddington, UK) primary standard in lightly filtered non-clinical research linac formerly used at NPL.
applying the values of $Q_{NCS-18}$ and $TRS-398$. Note that $D_w$ can be measured directly inside the calorimeter phantom as explained in section 2.5. NCS-18, based on TPR 20, 10, $Q$-choice of chamber type with code of practice, CoP (i.e. $Q_{CoP}$, respectively). The second term on the right-hand side is the normalization of the cFF $k_Q$ with beam quality $Q$ to the beam with the beam quality, $Q$, of the FFF beam. This normalization depends on the choice of chamber type with code of practice, CoP (i.e. $Q_{CoP}$ dataset and beam quality specifier). It is determined by applying the values of $Q'$ with respect to the chamber type according to the respective CoP:

$$k_{Q',Q} = \left\{ \frac{k_Q}{Q_{CoP}} \right\}_{chamber type}.$$  

The difference between $k_Q$ of an FFF beam compared to a cFF beam can then be expressed as:

$$\Delta k_{FFF,cFF} = R - 1.$$  

In this study, uncertainties are expressed as relative standard uncertainties ($k = 1$), in some cases represented between brackets as the least significant digits of the reported value.

### 2.3. Choice of ion chambers and beam qualities

Eight ion chambers of three types (2 × PTW 30013; 3 × PTW 30012 and 3 × NE2571, from PTW Freiburg GmbH Freiburg, Germany and Phoenix Dosimetry Ltd Sandhurst, UK, respectively) were calibrated in two FFF-cFF beam pairs. The choice of chambers was based on their availability at the time of the measurements and the availability of $k_Q$ datasets in the applied CoPs. At least one of the chamber types needed to be waterproof to be measured directly inside the calorimeter phantom as explained in section 2.5. NCS-18, based on TPR$_{20,10}$ provides measured $k_Q$ data for two of the chamber types used in this study, the PTW 30012 and the NE2571 among other chambers, but not for the waterproof PTW 30013 chamber. For all chambers used in this study, $k_Q$ data is available in TRS-398 using TPR20,10 and in TG-51 using % $dd$(10).

Table 1 shows the beam qualities used in this study and $k_{Q',Q}$ with respect to the NCS-18 and TRS-398 CoP and chamber types. Note that $k_{Q',Q}$ for % $dd$(10) is unity because the beams are energy matched with respect to PDD(10), resulting in equal values for % $dd$(10).

### 2.4. Water calorimetric determination of absorbed dose

The water calorimetric determination of absorbed-dose, $D_{w0}$ requires a measurement of radiation-induced temperature rise in water, $\Delta T_w$, multiplied by the specific heat capacity of water, $c_p$, and is given by the expression:

$$D_{w0} = \Delta T_w \cdot c_p \cdot (1 - h)^{-1} \cdot k_C \cdot k_{HPC} \cdot k_{nu}.$$  

| Beams          | % $dd$(10)$_x$ | TPR$_{20,10}$ | Chamber type | NCS-18$^a$ | TRS-398 |
|----------------|----------------|---------------|--------------|------------|---------|
| 6 MV cFF       | 67.5%          | 0.680         | PTW 30013    | —          | 0.9994  |
| 6 MV FFF       | 67.5%          | 0.675         | PTW 30012    | 0.9994     | 0.9997  |
| 10 MV cFF      | 73.0%          | 0.735         | PTW 30013    | —          | 0.9969  |
| 10 MV FFF      | 73.0%          | 0.720         | PTW 30012    | 0.9968     | 0.9977  |

$^a$ NCS-18 makes no distinction between reported 0.6 cm$^3$ Farmer-type chambers.
The chemical heat-defect, $h$, is caused by radiation-induced exo- or endothermic chemical reactions. For photon beams this effect is described by various authors, e.g. Domen (1982), Klassen and Ross (1997), Seuntjens and Palmans (1999) and Krauss and Kramer (2003). The $k$-factors in expression (6) correct for: the conductive heat flow, $k_C$, caused by relative excess temperature rise, $R_{XS}$, due to non-water materials and the non-uniform 3D-dose distributions (Krauss 2006); the perturbation due to the presence of non-water materials (mostly glass), $k_{HPC}$; and the deviation of the measurement conditions from the reference conditions, radial non-uniformity, $k_{nu}$. Because the water calorimeter is operated at 4 °C, the temperature at which the density of water is maximal, it is assumed that no convection takes place (Domen 1988). The energy dependence of $k_C$ due to stopping power ratios material-water, between $^{60}$Co and 30 MV is less than 0.1% as shown, for instance, by Seuntjens et al (2000). Radiative heat transfer is insignificant for the small temperature differences generated in a water calorimeter (Seuntjens and Duane 2009).

The VSL calorimeter, described in detail by de Prez et al (2016) and shown in figure 1, consists of a cylindrical water phantom made of aluminium and surrounded by a temperature controlled thermostat. The beam enters the calorimeter at the centre of a removable lid through a square radiation window and passes through several thin layers of material. A PMMA radiation entrance window is in contact with the water surface. A cylindrical high-purity water cell (HPC) made of glass with a thin wall contains two negative temperature coefficient (NTC) thermistors embedded in miniature glass pipettes. These are used to measure the radiation induced temperature change in water, $\Delta T_w$ in equation (6). The thermistor probes are mounted 10 mm apart inside the HPC filled with argon saturated ultra-pure water.

With respect to FFF and cFF beams, special attention was paid to the modelled heat conduction correction, $k_C$, the radial non-uniformity of the field at the position of the thermists, $k_{nu}$, and the measured correction due to perturbation and scatter of the glass cell, $k_{HPC}$. The perturbation and scatter effect due to the presence of the thermistor probes was measured previously in $^{60}$Co and showed to be negligible within the uncertainty of 0.05%. $k_C$ was determined with finite element simulation according to the heat transfer models described by de Prez et al (2016). This correction depends on lateral and depth dose profiles and the radiation induced temperature increase of materials, which in turn depends on material specific heat capacity and electron stopping power ratios of those materials to water. The calorimeter correction for beam radial non-uniformity, $k_{nu}$, at the position of the probe tips, 5 mm off-axis, was based on the in-line measured lateral dose profile and determined by the measured ratio at beam centre and 5 mm off-axis.

The influence of the presence of the calorimeter thermostat (i.e. calorimeter phantom and lid) was measured to quantify potential changes in beam qualities. It was measured with the waterproof chambers inside the calorimeter thermostat (directly in water) and inside a 1 mm PMMA sleeve in the calibration water phantom ($30 \times 30 \times 30$ cm$^3$).

2.5. Ion chamber calibration
Two waterproof PTW 30013 ion chambers were calibrated directly inside the calorimeter thermostat without waterproofing sleeve. Subsequently, the other six non-waterproof chambers were cross-calibrated against the
two waterproof chambers inside the PMMA sleeve in the calibration phantom placed on the treatment couch as shown in figure 1. The chambers were positioned in-line with the accelerator in both measurement setups. The measurements were done according to NCS-18 at a nominal source surface distance (SSD) of 90 cm and depth of 10 g·cm⁻². Water depth was corrected for water density due to the different temperatures applied during calorimetry at 4 °C and ion chamber measurements at room temperature. The field size at the isocentre was 10 × 10 cm². The chambers were calibrated with a bias voltage supplied by the electrometer (Keithley 6517B, Tektronix Ltd. Bracknell, UK) with the thimble connected to ground. Bias and polarity were either −300 V, collecting positive charge (CEN) or +350 V collecting negative charge (CEP), depending on the bias convention used by the chamber owner (VSL or the Netherlands Cancer Institute). The leakage corrected raw ion chamber measurements, \( M_{\text{raw}} \), were corrected for electrometer calibration, \( k_{\text{elec}} \), air density inside the cavity as a result of the actual temperature and pressure, \( k_{p,T} \), polarity, \( k_{\text{pol}} \) and saturation, \( k_{s} \), in agreement with NCS-18 and TRS-398. For these corrections, difference in reference conditions and methods described by TG-51 are not expected to affect the \( k_{Q} \) values.

Additionally, a correction was applied for beam radial non-uniformity due to the volume averaging effects of the dose over the ion chamber, \( k_{v} \). This was determined using a simple 1D integration of the beams lateral dose profiles along the thimble chamber dimension positioned in-line with the accelerator similar to the method described by Lye et al (2016) and Palmans et al (2017). The diameter (6 mm) of the thimble is considerably smaller than the length (23 mm) therefore, despite the relative large lateral dose gradient in FFF beams, the non-uniformity along the direction of the radius (i.e. in cross-line direction) was found to be smaller than 0.01% in all cases and therefore neglected.

No correction was applied for humidity of the air inside the chamber cavity since all measurements were performed at a humidity close to 50% (±10%). The applied formalism for the ion chamber measurements was (Almond et al 1999, Andreo et al 2000):

\[
M = M_{\text{raw}} \cdot k_{\text{elec}} \cdot k_{p,T} \cdot k_{\text{pol}} \cdot k_{s} \cdot k_{v}.
\]

Just as with the calorimeter measurements, no correction was applied for the presence of the calorimeter thermostat, \( k_{\text{phantom}} \), and the presence of the calorimeter entrance window was not expected to influence the beam quality significantly for any of the measured photon beams.

It must be noted that the calibration coefficients of the non-waterproof chambers in beam quality Q were determined without the effect of the waterproof sleeve, generally considered to be small (Ross and Shortt 1992). After all, during the cross-calibration both waterproof and non-waterproof chambers were placed inside the sleeve and the effect cancels. This has no effect on the results of this study, however, it must be considered when comparing \( k_{Q} \) between studies.

The calorimeter measurements took place over several days prior to the measurements of the waterproof chamber inside the calorimeter phantom. This was followed by the cross calibration of the non-waterproof chambers in the standard calibration phantom using an ‘intermediate working standard ionization chamber’ as described by McEwen (2010). The calibration coefficient of the ‘intermediate working standard ionization chamber’ is determined according to:

\[
N_{D_{w},w} = \frac{(D_{w}/MU) - (D_{w}/MU)_{\text{ref}}}{(MU/MU)}.
\]

Here \( D_{w} \) is the absorbed dose to water, measured inside the water calorimeter thermostat and \( M \) the corrected ion chamber reading. Both \( D_{w} \) and \( M \) are normalized to an independent transmission monitor ion chamber (PTW 34014) with signal \( MU \), mounted on the accelerator tray.

The ratio of calibration coefficients of FFF and cFF beams, combining equations(2), (6) and (7), can be expressed as a ratio of measurements and their relevant correction factors:

\[
\frac{N_{D_{w},w,Q}^{\text{FFF}}}{N_{D_{w},w,Q}^{\text{cFF}}} = \frac{[(\Delta T_{w}/MU) \cdot c_{p} \cdot (1 - h)^{-1} \cdot k_{C} \cdot k_{\text{HCPC}} \cdot k_{\text{nu}}]^{\text{FFF}}}{[(\Delta T_{w}/MU) \cdot c_{p} \cdot (1 - h)^{-1} \cdot k_{C} \cdot k_{\text{HCPC}} \cdot k_{\text{nu}}]^{\text{cFF}}},
\]

\[
\frac{N_{D_{w},w,Q}^{\text{FFF}}}{N_{D_{w},w,Q}^{\text{cFF}}} = \frac{[(M_{\text{raw}}/MU) \cdot k_{\text{elec}} \cdot k_{p,T} \cdot k_{\text{pol}} \cdot k_{s} \cdot k_{v}]^{\text{FFF}}}{[(M_{\text{raw}}/MU) \cdot k_{\text{elec}} \cdot k_{p,T} \cdot k_{\text{pol}} \cdot k_{s} \cdot k_{v}]^{\text{cFF}}}
\]

3. Results

3.1. Water calorimetric determination of absorbed dose

Calorimeter correction factors can be found elsewhere (de Prez et al 2016, Picard et al 2017). Specific correction factors, relevant for this study, are \( k_{C} \), \( k_{\text{HCPC}} \) and \( k_{\text{nu}} \) given in table 2 and equation (6). The influence of the presence of the calorimeter thermostat, was measured and was always smaller than 1.6%, confirming insignificant effects on the beam qualities.
The excess temperature effects from the presence of the high-purity cell, HPC ($R_{XS,HPC}$), and probes ($R_{XS,probes}$) were the same for all cFF and FFF beams within 0.01%, with values of $R_{XS,HPC} = -0.01\%$ and $R_{XS,probes} = 0.28\%$, respectively. Differences in $R_{XS}$ due to variations in dose profiles, i.e. $R_{XS,y,pdd}$, were significantly larger (figure 2).

Thus, $k_C$ mainly varies with the beam dose profiles and its effect is strongest for the flat cFF beams.

The results of the absorbed dose to water measurements are presented in table 2. The accelerator monitor units and dose rate were chosen such that the irradiation time was close to 60 s, one of the input variables of the heat transport calculations. For the VSL $^{60}\text{Co}$ source a start-stop effect resulted in a longer irradiation than the setting of the source timer, also referred to as the timer error (Andreo et al 2000).

The number of runs per beam was chosen such that the type A standard uncertainty of the repeated calorimeter runs ($\Delta R/R$) was smaller than 0.20%. The dose per pulse, DPP in mGy, was based on the measured absorbed dose to water and the accelerator pulse rate frequency. The indicated absorbed dose to water, $D_w$, is the average absorbed dose per calorimeter run.

### Table 2. Water calorimeter correction factors and measurements.

| Beam ID | $k_C$ | $k_{HPC}$ | $k_{nu}$ | set # MU | Time/s | Runs | $D_w$/Gy | $u_d$/% |
|---------|-------|-----------|----------|---------|--------|------|----------|--------|
| $^{60}\text{Co}$ | 0.9994 | 1.0018 | 1.0000 | 180 | 181.0 | 192 | 1.94 | 0.10 |
| 6 MV cFF | 0.9983 | 1.0013 | 0.9999 | 575 | 61.1 | 24 | 4.63 | 0.17 |
| 6 MV FFF | 0.9996 | 1.0013 | 1.0019 | 720 | 61.7 | 27 | 5.79 | 0.18 |
| 10 MV cFF | 0.9975 | 1.0011 | 0.9999 | 435 | 61.9 | 21 | 3.80 | 0.11 |
| 10 MV FFF | 0.9995 | 1.0006 | 1.0031 | 1000 | 58.6 | 18 | 8.82 | 0.11 |

* For $^{60}\text{Co}$ the irradiator timer setting in seconds; for MV x-rays the institute $D_{max}$ in cGy at an SSD of 100 cm; the accelerator dose rate was not always set to its maximum value.

$R_{XS}$ is based on the average relative excess temperature rise, $R_{XS}$, simulated for the first 10 calorimeter runs. The excess temperature effects from the presence of the high-purity cell, HPC ($R_{XS,HPC}$), and probes ($R_{XS,probes}$) were the same for all cFF and FFF beams within 0.01%, with values of $R_{XS,HPC} = -0.01\%$ and $R_{XS,probes} = 0.28\%$, respectively. Differences in $R_{XS}$ due to variations in dose profiles, i.e. $R_{XS,y,pdd}$, were significantly larger (figure 2). Thus, $k_C$ mainly varies with the beam dose profiles and its effect is strongest for the flat cFF beams.

The results of the absorbed dose to water measurements are presented in table 2. The accelerator monitor units and dose rate were chosen such that the irradiation time was close to 60 s, one of the input variables of the heat transport calculations. For the VSL $^{60}\text{Co}$ source a start-stop effect resulted in a longer irradiation than the setting of the source timer, also referred to as the timer error (Andreo et al 2000).

The number of runs per beam was chosen such that the type A standard uncertainty of the repeated calorimeter runs ($\Delta R/R$) was smaller than 0.20%. The dose per pulse, DPP in mGy, was based on the measured absorbed dose to water and the accelerator pulse rate frequency. The indicated absorbed dose to water, $D_w$, is the average absorbed dose per calorimeter run.

### 3.2. Ion chamber results

The ion chamber correction factors, specifically relevant for this study are: $k_{pol}$, $k_s$ and $k_v$. The other chamber correction factors can be found elsewhere (Almond et al 1999, Andreo et al 2000). All chamber corrections are applied per individual chamber but in table 3 reported as average per chamber type. It turned out that differences in $k_{pol}$, $k_s$ and $k_v$ for PTW 30013 and PTW 30012 chamber types, which have identical dimensions, were indistinguishable within their respective standard deviations. These chamber types are reported together. Table 4 gives the $^{60}\text{Co}$ ion chamber calibration coefficients averaged per chamber type and their $k_{Q,Q0}$ values. Note that these values are reported as if all chambers were measured directly in water, i.e. without the use of a waterproof sleeve.

![Figure 2.](image)
The polarity correction was measured for all chambers and is reported for negative potential applied to the central electrode (regardless of the actual potential used, explained in section 2.5). The values obtained in this study confirmed that $k_{\text{pol}}$ is independent of photon beam quality or dose rate for these chamber types (Seuntjens et al 2000, McEwen 2010). The reported uncertainty on $k_{\text{pol}}$ per chamber type is estimated to be 0.06% and based on the quadratic sum of the largest standard deviation of the values for the individual chambers, 0.03%, and the uncertainty in the charge measurements, 0.05%.

### Table 3. Ion chamber correction factors. Values between brackets are the standard deviations, represented as the least significant digit of the reported value, obtained for the individual chambers ($2 \times $PTW 30013, $3 \times $PTW 30012 and $3 \times $NE2571).

| Chamber Type | 60Co $k_s$ | 6 MV cFF $k_s$ | 6 MV FFF $k_s$ | 10 MV cFF $k_s$ | 10 MV FFF $k_s$ |
|--------------|------------|----------------|----------------|----------------|----------------|
| PTW 30013/30012 | 1.0004 (1) | 1.0028 (2) | 1.0061 (1) | 1.0045 (2) | 1.0101 (4) |
| PTW 30013/30012 | 1.0010 (1) | 1.0035 (1) | 1.0075 (2) | 1.0051 (2) | 1.0127 (4) |
| PTW 30013/30012 | 1.0040 (1) | 1.0060 (1) | 1.0095 (2) | 1.0065 (3) | 1.010 (3) |
| PTW 30013/30012 | 0.9991 (2) | 0.9992 (2) | 0.9993 (3) | 0.9994 (3) | 0.9991 (2) |
| PTW 30013/30012 | 1.0000 | 0.9999 | 1.0033 | 0.9998 | 1.0054 |
| PTW 30013/30012 | 1.0000 | 0.9999 | 1.0036 | 0.9998 | 1.0059 |

### Table 4. Ion chamber calibration coefficient in $^{60}$Co and $k_{Q,Q_0}$ factors as if measured directly in water (i.e. without the use of a waterproof sleeve). Values between brackets are the standard deviations, represented as the least significant digit(s) of the reported value, obtained for the individual chambers ($2 \times $PTW 30013, $3 \times $PTW 30012 and $3 \times $NE2571).

| Chamber Type | %dd(10)$_x$ | 67.5% TPR$_{20,10}$ | 73.0% TPR$_{20,10}$ |
|--------------|-------------|------------------|------------------|
| $^{60}$Co | 0.680 | 0.675 | 0.735 | 0.720 |
| 6 MV cFF | 0.9880 (10) | 0.9866 (10) | 0.9759 (12) | 0.9775 (16) |
| 6 MV FFF | 0.9903 (9) | 0.9896 (10) | 0.9802 (7) | 0.9826 (13) |
| 10 MV cFF | 0.9906 (11) | 0.9908 (12) | 0.9809 (7) | 0.9855 (12) |
| 10 MV FFF | 0.9906 (11) | 0.9908 (12) | 0.9809 (7) | 0.9855 (12) |

### Figure 3. Recombination correction, $k_s$, for the three chamber types used in this study as a function of dose per pulse, DPP in mGy (see table 3). The black dotted lines are linear fits through the points measured in the accelerator beams, extrapolated in grey to the vertical axis. The points at the vertical axis are $k_s$ measured for $^{60}$Co and assumed only to be a result of initial recombination.
The uncertainty on $k$ from Andreo was 0.02%. Using a two-point Jaffé plot normalized to their corrections. The effect on the input data for the heat transport model, used to calculate the measured $k$ for the chambers owned by the Netherlands Cancer Institute were normalized to 300 V as follows. $k_s$ was determined with the method described by Weinhous and Meli (1984) and also, using the same two points, by applying a Jaffé plot (Jaffé 1940) described by, e.g. Burns and McEwen (1998) and Bruggmoser et al (2007). The agreement of $k_s$ determined with both methods was always better than 0.05% and in most cases better than 0.02%. Using a two-point Jaffé plot $k_s$ values of the chambers measured at a negative bias of 350 V were normalized to $k_s$ at 300 V such that $k_s$ could be compared between the chambers. The reported uncertainty on the $k_s$ per chamber type is estimated to be 0.08%, based on the quadratic sum of largest standard deviation of the values for the individual chambers, 0.04%, and the uncertainty in the charge measurements, 0.07%.

The correction for volume averaging, $k_v$, is given in table 3. The dimensions of the chamber air cavity are taken from Andreo et al (2000) neglecting any reduction in dose response near the chamber stem (Butler et al 2015). The uncertainty on $k_v$ is estimated to be 0.10% and based on the chamber geometry, positioning, and the measured lateral profiles in the direction of the thimble. Contribution in the direction of the chamber’s diameter, always smaller than 0.01%, was neglected and added to the uncertainty.

### 3.3. Uncertainties in $k_{FFE,cFF}$

The combined standard uncertainty is determined according to the Guide to the expression of uncertainty in measurement (Lequin 2004). Uncertainty budgets for absorbed dose to water calibrations in 60Co and MV-photon beams are given elsewhere (de Prez et al 2016, Picard et al 2017). The uncertainty budget for $R$ determined with equation (3) is given in table 5.

Most uncertainty contributions cancel (partially) due to correlations in the measured and calculated quantities found in both the nominator and denominator of equation (9). Most of these correlations result from the use of the same instruments for the measurements in the cFF and the FFF beams. The main remaining contributions are the type A uncertainty of the calorimeter measurements, $D_\omega/MU$, and ion chamber measurements including their corrections. The effect on the input data for the heat transport model, used to calculate $k_c$ (from $R_{XS,ykppdd}$) is estimated to be smaller than 0.10%. An additional uncertainty contribution for the cross-calibration of the chambers inside the calibration phantom was estimated to be 0.07%. Uncertainties for SSD and depth variations inside the calibration phantom were considered negligible.

The reproducibility of the calorimetric $D_\omega$ measurements in 60Co before and after the measurements at the Netherlands Cancer Institute was better than 0.1%, providing confidence on the performance of the HPC preparation and the long-term stability of the water calorimeter measurements. However, this was not taken into account since we are only interested in the short term $D_\omega$ determination performed during a couple of days.

Uncertainty contributions for the normalization of the cFF $k_Q$ to the FFF beam quality (equation (3) and table 1) was omitted because this normalization is based on convention by the published values of the relevant codes of practice.

### 3.4. Comparison of $k_Q$ factors within FFF-cFF beam pairs

Table 6 gives the results for $\Delta k_{FFE,cFF}$ according to equation (5). Differences between cFF and FFF beam pairs are always smaller than the standard uncertainty, except for NE2571 at the 10 MV beam for $%ddl(10)$, for which $Q = Q'$ in equation (4) and $k_{Q',Q''} = 1$ (see table 1). In all cases, differences are smaller than two standard uncertainties. In addition, differences between FFF-cFF beam pairs are smaller than the standard uncertainties.

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Table 5. Uncertainty budgets for $R$ in equation (3) of ion chambers in MV-photon beams in this study.

| Source of uncertainty                                      | 6 MV        |          | 10 MV        |          |
|------------------------------------------------------------|-------------|----------|-------------|----------|
|                                                            | cFF | FFF | cFF | FFF |
| $D_\omega/MU$ type A (table 2)                             | 0.17 | 0.18 | 0.11 | 0.11 |
| Ratio of calorimeter $k_c$ (heat conduction)               | <0.10       |          |          |          |
| Ratio of calorimeter $k_m$ (radial non-uniformity)         | 0.05         |          |          |          |
| Charge measurement ($M_{cal}/MU$), type A                  | 0.07         |          |          |          |
| Ratios of $k_s$ (saturation) and $k_p$ (polarity)          | 0.07         |          |          |          |
| Ratio ion chamber $k_v$ (volume averaging)                 | 0.05         |          |          |          |
| Ratio of ion chamber $k_{v,cal}$ and $k_{v,rel}$          | 0.05         |          |          |          |
| Cross-calibration charge measurement ($M_{cal}/MU$), type A| 0.07         |          |          |          |
| Combined: ratio measurement in the MV-photon beams         | 0.25         | 0.25 | 0.21 | 0.21 |
| Combined: ratio of $k_Q$ in FFF-cFF beams $R$ from equation (3) | 0.35 |          | 0.30 |          |

Figure 3 shows the recombination correction as a function of dose per pulse, DPP in mGy. Values are given in table 3. $k_s$ was measured for the applied chamber voltage, i.e. 300 V (CEN) for the chambers owned by VSL and 350 V (CEP) for the chambers owned by the Netherlands Cancer Institute. To enable comparison of all chambers, the measured $k_s$ of the chambers owned by the Netherlands Cancer Institute were normalized to 300 V as follows.
L de Prez et al reported by the protocols mentioned in table 6: for the TPR20,10 based CoPs this is 0.04% for NCS-18 (Aalbers et al 2008), 1.0% for TRS-398 (Andreo et al 2000). The comparison based on %ddx is independent of the protocol used since the Elekta FFF-cFF beam pairs are energy-matched with respect to this beam quality specifier.

Figure 4 shows the kQ factors obtained in this study in relation to the kQ factors provided by NCS-18 and TRS-398. kQ values provided in this study were measured without the influence of a PMMA sleeve. However, NCS-18 and TRS-398 provide kQ factors for Farmer-type chambers including a 1 mm and 0.5 mm PMMA sleeve, respectively. The effect of a 1 mm PMMA sleeve at 60Co, 6 MV and 10 MV is known to be small and between −0.05% and −0.10% for Farmer-type chambers (Ross and Shortt 1992, Andreo et al 2000). These effects have not been corrected for the measurements shown in figure 4.

4. Discussion and conclusion

The application of existing kQ factors for flattening filter free (FFF) photon beams based on existing codes of practice, using different beam quality specifiers is not trivial. Some Monte Carlo studies assumed a sole dependence on stopping power ratios and disagreed depending on the used beam models (Xiong and Rogers 2008, Dalaryd et al 2014). Lye et al (2016) showed good agreement in measurements between %ddx and TPR20,10 based codes of practice (Almond et al 1999, Andreo et al 2000, McEwen et al 2014) and confirmed this with Monte Carlo simulations for realistic chambers and beams. In all cases the volume averaging effect of chambers in the FFF beams was treated independently from kQ. In the Monte Carlo studies it was either ignored by only considering stopping power ratios (Xiong and Rogers 2008) or included in both the calculated dose to the chamber cavity and dose to an equivalent water volume (Lye et al 2012). However, when performing ion chamber measurements it is essential that the volume averaging correction is applied as a separate correction in addition to the existing code of practice in a similar way as implemented by the TG-51 addendum (McEwen et al 2014). A recent publication by the IAEA (Palmans et al 2017) implemented kQ as an integral part of the FFF beam’s kQ. This approach assumes that the chamber perturbation, excluding volume averaging effects, in FFF beams compared to cFF beams remains unchanged and that the volume averaging effect for cFF beams is negligible.

Despite the relevance of the mentioned Monte Carlo studies and other methods, they are limited by the models for both ion chambers and accelerator beams. Therefore, direct measurement of kQ factors with primary standards are essential to understand the individual behaviour of physical chambers in real clinical accelerators. This is the first study that directly measured and compared kQ factor of ion chambers in clinical flattening

| Chamber type | ΔkQFF,cFF/% 6 MV | ΔkQFF,cFF/% 10 MV |
|--------------|------------------|--------------------|
| PTW 30013    | −0.14            | −0.20              |
| PTW 30012    | −0.07            | −0.13              |
| NE2571       | 0.02             | 0.04               | 0.01               | 0.35               |

* NCS-18 does not provide kQ data for this chamber type.

Figure 4. Measured kQ factors for the two NE2571 (left) and PTW 30012 (right) type chambers in relation to the TPR20,10 based CoPs applied in this study. The error bars represent the standard uncertainties (k = 1) given in table 5. Note that both the TRS-398 and NCS-18 kQ factors include a correction for the presence of the PMMA sleeve which is smaller than 0.1%, while the measured kQ factors obtained in this study do not. The standard uncertainty of the kQ factor on the NCS-18 and TRS-398 curve are 0.4% and 1.0%, respectively.
filter free (FFF) and conventional flattening filter (cFF) MV-photon beams. This was done with a transportable absorbed dose to water primary standard, a water calorimeter, described elsewhere (de Prez et al 2016, Picard et al 2017). The measurements were performed in energy-matched FFF-cFF beam pairs of 6 MV and 10 MV photon beams of an Elekta Versa HD accelerator with a selection of three Farmer-type chambers of in total 8 serial numbers. Measured $k_Q$ factors in the beam pairs were corrected for volume averaging in the direction of the cavity length and normalized to the FFF beam quality, expressed in $TPR_{20,10}$, in combination with either NCS-18, based on measured $k_Q$ factors (Aalbers et al 2008), or IAEA TRS-398, based on calculated $k_Q$ factors (Andreò et al 2000). Differences between $k_Q$ of the FFF and cFF beams were smaller than 0.23% for $TPR_{20,10}$ based protocols NCS-18 and TRS-398 and within the standard uncertainties of 0.35% for 6 MV and 0.30% for 10 MV beams. In contrast to the study by Xiong and Rogers, the biggest difference of 0.46% was found for the NE2571 chambers at 10 MV for $k_Q$ when $\%dd(10)_x$ was applied, however within the expanded uncertainty of the measurements. Therefore the difference is not considered significant.

This study was not able to reproduce the differences of 0.5%–0.7% between $k_Q$ factors in two pairs of FFF and cFF beams when applying $TPR_{20,10}$ as a beam quality specifier, predicted by the Monte Carlo study of Xiong and Rogers (2008). However, it confirms the results reported by Lye et al (2016) who performed ion chamber measurements based on TRS-398, TG-51 and Monte Carlo calculations. Lye et al concluded that, despite a change in stopping power ratios for FFF beams compared to cFF beams, the addition of a thin metal filter, at the position of the flattening filter, produces a beam that is similar enough in spectra compared to cFF beams. Based on measurements in this study and specifically for the combination of accelerator type, beams and ion chambers, the authors conclude that the $k_Q$ factors for cFF beams based on $TPR_{20,10}$ and based on $\%dd(10)_x$ can be applied for FFF beams within the specified measurement uncertainties of 0.7% ($k = 2$). In addition, the user must be aware of the volume averaging effect due to radial non-uniformity and correct for this accordingly.

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Disclaimer

Identification of certain commercial equipment, instruments, or materials are identified in this study to specify the experimental procedure adequately. Such identification does not imply recommendation or endorsement by the authors, nor does it imply that products identified are necessarily the best available for purpose.

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