Determination of absorbed dose to water for high-energy photon and electron beams—comparison of the standards DIN 6800-2 (1997), IAEA TRS 398 (2000) and DIN 6800-2 (2006)

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ABSTRACT

For the determination of the absorbed dose to water for high-energy photon and electron beams the IAEA code of practice TRS-398 (2000) is applied internationally. In Germany, the German dosimetry protocol DIN 6800-2 (1997) is used. Recently, the DIN standard has been revised and published as Draft National Standard DIN 6800-2 (2006). It has adopted widely the methodology and dosimetric data of the code of practice. This paper compares these three dosimetry protocols systematically and identifies similarities as well as differences. The investigation was done with 6 and 18 MV photon as well as 5 to 21 MeV electron beams. While only cylindrical chambers were used for photon beams, measurements of electron beams were performed using cylindrical as well as plane-parallel chambers. The discrepancies in the determination of absorbed dose to water between the three protocols were 0.4% for photon beams and 1.5% for electron beams. Comparative measurements showed a deviation of less than 0.5% between our measurements following protocol DIN 6800-2 (2006) and TLD inter-comparison procedure in an external audit.

Key words: Absorbed dose to water, DIN 6800-2 protocol (1997), DIN 6800-2 protocol (Draft National Standard 2006), external beam photons and electrons, IAEA TRS-398 protocol (2000)

The determination of the absorbed dose to water for high-energy photon and electron beams is performed in Germany according to the German dosimetry protocol DIN 6800-2 (1997).[1] This protocol is based on the use of ionization chambers calibrated in terms of absorbed dose to water in a cobalt-60 gamma radiation beam. The protocol has been revised by a German task group and published as “Draft National Standard (DNS)” DIN 6800-2 (2006) in March 2006.[2] The new version has adopted widely the methodology and dosimetric data of the Code of practice TRS-398 published in 2000.[3] The main part of the revised protocol consists of the measurement procedures, parameters for various chambers and the evaluation of uncertainties. The physical backgrounds are described in detail in the appendix of the protocol.

The DIN 6800-2 (DNS 2006) took over the data of IAEA TRS 398 for the calculation of correction factors and interaction coefficients and therefore has improved its consistency with the international practice of dose determinations. But the DIN 6800-2 (DNS 2006) did not simply take over the said data; it considered the clinical demands of Germany. The gist of its changes lies in the electron dosimetry and in the introduction of the evaluation of uncertainties in measurements.

In an earlier work we compared the DIN 6800-2 (1997) to the protocols AAPM TG 51[4] and IAEA TRS 398 and presented the results in detail.[5] In this work the clinical application of DIN 6800-2 (DNS 2006) has been investigated in comparison to the previous protocol DIN 6800-2 (1997) as well as to protocol IAEA TRS 398 as the basis of the future improvements.
Materials and Methods

The measurements were performed in a Wellhoefer water phantom (blue phantom). Depth dose distributions (depth ionization curves) were measured with a Wellhoefer CC-13 and a plane-parallel type (PTW-34001 Roos chamber) ionization chamber. We used the plane-parallel Roos chamber to make accurate measurements in the build-up region. Absolute dosimetry in terms of absorbed dose to water has been performed with a cylindrical (PTW-M31013 chamber) and a plane-parallel PTW-34001 (Roos chamber) ionization chamber. All ionization chambers used and their characteristics are listed in Table 1.

The relative measurements were done and evaluated by Scanditronix-Wellhoefer software OmniPro-Accept 6.3. A Scanditronix-Wellhoefer chamber served as reference chamber. The absolute charge was measured with the electrometer models UNIDOS and UNIDOS E (PTW Freiburg). The operating voltage for the cylindrical chamber PTW-31013 was 400V, whereas for the Roos chamber the voltage was 100V.

All the measurements were performed under reference conditions. The reference point of the cylindrical chamber in the phantom was positioned according to the reference condition of each protocol. For plane-parallel chamber the reference point is taken to be on the inner surface of the entrance window, at the centre of the window. Reference conditions for the determination of absorbed dose to water in high-energy photon and electron beams are given in Table 2.

The irradiation units used are the Siemens linear accelerators, ONCOR Impression (6 MV photon and 5, 7, 8, 10, 12, 14 MeV electron beams, assigned as Acc. 1) and ONCOR Avant garde (6 and 18 MV photon and 6, 9, 12, 15, 18 and 21 MeV electron beams, assigned as Acc. 2).

Table 3 represents the possible ranges of application for different beam qualities and chambers in each of the dosimetry protocols.

**Table 1: Characteristics of the ionization chambers**

| Chamber | PTW-31013 (Cylinder) | PTW-30006 (Farmer) | PTW-23343 (Markus) | PTW-34001 (Roos) |
|---------|----------------------|--------------------|--------------------|------------------|
| Outer electr.-Ø | 5.5 mm | 6.1 mm | - | - |
| Inner electr.-Ø | 1.0 mm | 1.1 mm | - | - |
| Wall material | PMMA | PMMA + graphit | - | - |
| Wall thickness | 0.75 mm | 0.335 mm | - | - |
| Electrode spacing | - | - | 2.0 mm | 2.0 mm |
| Chamber-Ø | - | - | 6.0 mm | 15.0 mm |
| Membrane material | - | - | Polyaethylen | PMMA |
| Membrane thickness | - | - | 0.03 mm | 1.0 mm |
| Guard ring width | - | - | 4 mm | 0.2 mm |
| Cavity volume | 0.3 cm³ | 0.6 cm³ | 0.055 cm³ | 0.35 cm³ |
| Voltage | 400V | 400V | 300V | 100V |

**Table 2: Reference conditions for the determination of depth dose curve and absorbed dose to water in high-energy photon and electron beams (z_{ref} = reference depth) for all three protocols. IAEA recommends a field size of 10x10 cm² for electron beams, but we have chosen a field size of 20x20 cm² for all three protocols for comparison**

| Field size at | Depth dose distribution | Absorbed dose to water |
|---------------|-------------------------|------------------------|
| SSD: 10x10 cm² | 10x10 cm² | 20x20 cm² |
| SSD: 100 cm | 100 cm | 100 cm |
| Measurement | - | z_{ref} = 10 cm z_{ref} = 0.6*R50 - 0.1 |

The absorbed dose to water for high-energy photon or electron beams is calculated by the following general formula (1):

\[ D_w(z) = M(z) N_w k_p k_s k_\rho k_Q°(z) \]  

where \( D_w(z) \) = absorbed dose to water at depth \( z \), \( M(z) \) = reading of the dosimeter, \( N_w \) = calibration factor for absorbed dose to water for cobalt 60 beams, \( k_p \) = polarity correction factor, \( k_s \) = ion recombination factor, \( k_\rho \) = air density correction, \( k_Q° \) = an “equivalent” quality correction factor in all three protocols.

Table 3: Field size at

The procedure of the determination of the correction factors \( k_p \) and \( k_s \) as well as the quality correction factor \( k_Q° \) are different in each of these protocols. The quality correction factor is designated in the general formula for all the three protocols by an equivalent term \( k_Q° \). Other factors (such as the gradient correction factor, the perturbation correction factor, etc.) are considered in the formula of each protocol separately. Although the above formalism allows the determination of absorbed dose for electron beams by
the use of plane-parallel chambers calibrated in cobalt beams, it is recommended that the plane-parallel chambers are calibrated in a high-energy electron beam against a reference cylindrical chamber calibrated in a Co-60 beam (cross-calibration). This is because we don’t know the exact values for perturbation correction factors (wall correction factors) at a cobalt beam for plane-parallel chambers.

Table 4 briefly shows the reference conditions and the formalism for the determination of the quality correction factors in the respective protocol where the different terms used are described in the legend of the table. Further details of practical procedures in the determination of correction factors are described below.

For the purpose of this work we have participated in an external audit (Messtechnische Kontrolle, MTK) based on measurements with thermoluminescent dosemeters (TLD).[6] The dosimetric intercomparison measurements were done in a special type of water phantom PTW-4322 with TLD in combination with a cylindrical chamber for photon beams and with a Roos chamber for electron beams.

### Determination of the individual correction factors

**Air density correction factor**

Air density correction factor $k_ρ$ can be determined directly from the temperature and pressure at the measuring spot ($t$ and $p$ method) or by using the check source method (the reference values of the temperature = 293.3 K and pressure = 1013.25 hPa). The check source is heavily shielded. Thus, it takes a long time to achieve the surrounding temperature. Moreover, the temperature of the water phantom is not necessarily the same as the temperature of the surrounding air. Our experience showed that a deviation of up to 1%

| Table 3: Possible ranges of application for different beam qualities and chambers in each dosimetry protocol |
|--------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Dosimetry protocol                              | DIN 6800-2 (1997)            | IAEA 398 (2000)               | DIN 6800-2 (DNS 2006)        |
| Beam quality                                    | Photons | Electrons | Photons | Electrons | Photons | Electrons | Photons | Electrons |
| Cylindrical chamber PTW-31013                   |         |           |         |           |         |           |         |           |
| (Flexible chamber)                              | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  |
| Cylindrical chamber PTW-30006                   |         |           |         |           |         |           |         |           |
| (Farmer chamber)                                | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  | X       | ≥ 10 MeV  |
| Plane-parallel chamber PTW-34001 (Roos chamber) | not     |           | not     |           | not     |           | not     |           |
| Plane-parallel chamber PTW-23343 (Markus chamber) | not     |           | not     |           | not     |           | not     |           |
| X = (here) unrestricted application             |         |           |         |           |         |           |         |           |

| Table 4: The reference conditions and the formalism of determination of the quality correction factors for photon beams $k_q$ and electron beams $k_e(z_{ref})$ in different protocols ($k_r = gradient correction factor, eff. point of measurement: the effective point of measurement is located at reference depth $z_{ref}$ ref. point of chamber axis: the effective point of measurement is located at $z_{ref} + 0.5 \cdot r_{cav}$ [$r_{cav} = inner radius of the sensitive volume$]) |
|--------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Dosimetry protocol                              | DIN 6800-2 (1997)            | IAEA 398 (2000)               | DIN 6800-2 (DNS 2006)        |
| Radiation Reference depth $z_{ref}$             | Photons | Electrons | Photons | Electrons | Photons | Electrons | Photons | Electrons |
| Cylindrical chamber                              | 10 cm  | 0.6*R_{so} - 0.1 cm |          |           | 10 cm  | 0.6*R_{so} - 0.1 cm |          |           | 10 cm  | 0.6*R_{so} - 0.1 cm |
| Plane-parallel chamber                            |        |           |        |           |        |           |        |           |        |           |
| Plane-parallel chamber                            |        |           |        |           |        |           |        |           |        |           |
| Plane-parallel chamber                            |        |           |        |           |        |           |        |           |        |           |
| Plane-parallel chamber                            |        |           |        |           |        |           |        |           |        |           |
occurred between the two methods. Therefore we preferred to use the t and p method for our measurements. The air density correction factor is given by the equation (2):

\[ k_\rho = \frac{273.2 + \frac{t}{0.006}}{293.2} \times \frac{1013.25}{p}\text{hPa} \]  

(2)

where \( t \) = temperature at measuring phantom and \( p \) = current air pressure at measuring spot.

**Ion recombination correction factor \( k_S \)**

The incomplete collection of charge due to ion recombination in an ionization chamber requires correction factor \( k_S \). This factor can be measured or calculated by different empirical formula depending on radiation and chamber types. The correction factor is determined by using the following methods given in the protocols for pulsed beams.

DIN 6800-2 (1997)

Theoretical

\[ k_S = 1 + 0.54 \times D_i \times d^2 / U_1 \]  

(3)

IAEA TRS 398 (2000)

Experimental

\[ k_S = \frac{M_1 / M_2 - 1}{U_1 / U_2 - 1} \]  

(4)

DIN 6800-2 (DNS 2006)

Theoretical

\[ k_S = 1 + (\gamma + \delta \times D) / U_1 \]  

(5)

where:

\( d \) = electrode distance

\( D_i \) = dose per radiation pulse in mGy

\( U_1 \) = normal chamber operating voltage

\( U_2 \) = lower chamber voltage

\( M_1 \) = measured values at \( U_1 \)

\( M_2 \) = measured values at \( U_2 \)

\( \gamma \) and \( \delta \) constants taken from DIN 6800-2 (DNS 2006) in Table 4.

For the determination of \( k_S \) for the DIN 6800-2 (1997) protocol, the Derikum formula

\[ k_S = 1 + (0.12 + 0.46 \times D_i \times d^2) \]  

(6)

has been used because the Boag formula given in the DIN 6800-2 (1997) does not account for chambers with shorter electrode distance like the Roos chamber. The maximal deviation between the values calculated by DIN 6800-2 (DNS 2006) and Derikum is approximately 0.5%.

The dose per radiation pulse \( D_i \) can be calculated from the pulse-repetition-frequency PRF and the dose rate DL during a pulse in Gy/min under reference condition:

\[ D_i = \frac{(DL \times PRF)}{60} \]  

(7)

The service engineer supplies (acceptance testing) the value of PRF where \( 1/PRF \) is equal to the time between the rising of two radiation pulses in ms.

**The polarity effect correction factor**

For the determination of \( k_p \) according to the recommendation of the protocols, a \(^{60}\)Co gamma radiation source is needed. Many hospitals, like ours for example, do not have any \(^{60}\)Co gamma radiation unit. For the determination of \( k_p \) we used 6MV Photon beams instead of \(^{60}\)Co gamma radiation using the following formulas:

DIN 6800-2 (1997)

\[ k_p = \frac{(M_1 + M_2)}{M_1 / [(M_1 + M_2)/M_1]_{\text{Co}}} \]  

(8)

IAEA TRS 398 (2000)

\[ k_p = \frac{[M_+ + M_-]}{[M_+ + M_-]} \]  

(9)

DIN 6800-2 (DNS 2006)

\[ k_p = \frac{(M_1 + M_2)}{M_1 / [(M_1 + M_2)/M_1]_{\text{Co}}} \]  

(10)

where \( M_1 \) or \( M_2 \) is the absolute value of reading obtained with the usual polarity and \( M_1 \) or \( M_2 \) the absolute value of reading obtained with the opposite polarity.

**Displacement correction factor \( k_r \)**

This correction factor \( k_r \) is a special case for both German protocols for photon and electron beams. The measurement is always done at an effective point of measurement in the phantom, but calibration refers to the chamber centre. According to both DIN protocols, the effective point of measurement is shifted for cylindrical chambers in photon and electron beams from the chamber axis towards the radiation source, whereas TRS recommends the shift only for electron beams. The correction factor takes into account the different placement effects during calibration and measurement in a beam of high-energy photon and electron radiation. In contrast to TRS-398 the displacement correction factor is not included in the quality correction factor in DIN 6800-2 (1997) as well as DIN 6800-2 (DNS 2006). We have calculated the \( k_r \) according to DIN 6800-2 (DNS 2006):

\[ k_r = 1 + r/2 \times \delta \]  

(11)

where \( r \) is the inner radius of the sensitive volume of a cylindrical chamber and \( \delta \) the relative gradient of the depth dose curve in reference depth during calibration with \(^{60}\)Co
radiation (for $^{60}$Co radiation: $\delta = 0.006 \text{ l/mm}$). The displacement correction factor for the cylindrical chamber PTW-31013 ($r = 2.8 \text{ mm}$) is given in Table 5.

### Determination of the quality correction factor $k_Q$ for the beam quality index $Q$ for photons

The beam quality index $Q$ must be known to determine the quality correction factor $k_Q$. The quality index $Q$ for photon beams can be obtained for both protocols DIN 6800-2 (DNS 2006) and IAEA TRS-398 (2000) from the equation (12):

$$Q = 1.2661 \times \frac{\text{PDD} \ (d = 20 \text{ cm})}{\text{PDD} \ (d = 10 \text{ cm})} - 0.0595$$

where PDD is the percentage depth dose at depth $d$ for a field size of 10 cm x 10 cm defined at the phantom surface with an SSD of 100 cm. Quality index $Q$ is specified by tissue phantom ratio TPR$_{20,10}$ in IAEA TRS-398.

According to protocol DIN 6800-2 (1997), quality index $Q'$ should first be calculated from the depth dose curve by using the following formula (13):

$$Q' = \frac{\text{PDD} \ (d = 10 \text{ cm}, \ SSD = 100 \text{ cm})}{\text{PDD} \ (d = 20 \text{ cm}, \ SSD = 100 \text{ cm})}$$

The relation between $Q$ and $Q'$ is given by the equation (14) in DIN 6800-2 (1997):

$$Q = 2.012 - 1.050 \times Q' + 0.1265 \times Q'^2 + 0.01887 \times Q'^3$$

Calculated values of the factors $k_Q$ are given in Table 6 of DIN 6800-2 (DNS 2006), in Table 14 of IAEA TRS 398 and in Table 4 of DIN 6800-2 (1997) for various cylindrical ionization chambers as a function of beam quality index $Q$.

The Data of Table 6 in DIN 6800-2 (DNS 2006) for our cylindrical chamber PTW-31013 were fitted with the following polynomial equation (15) so that we can easily calculate $k_Q$ for any $Q$.

$$k_{Q,31013} = 0.584322 + 3.295307 \times Q - 9.246571 \times Q^2 + 11.275614 \times Q^3 - 5.175615 \times Q^4$$

Similar approximation equations were also fitted for chamber PTW-31013 for TRS 398 and DIN 6800-2 (1997) protocols.

The quality correction factors $k_Q$ as a function of beam quality $Q$ for those three protocols are given in Table 6. The values of $k_Q$ showed a maximum discrepancy of 0.2% between the protocols. The discrepancy can be explained by the fact that the method of beam quality specification as well as the data used for calculating $k_Q$ slightly differ between the protocols.

### Determination of correction factor $k_E$ for beam quality index of electrons

According to DIN 6800-2 (1997) the beam quality index for electrons is a function of half-value depth $R_{50}$ and practical range $R_p$ in water, whereas only $R_{50}$ characterizes the beam quality index for DIN 6800-2 (DNS 2006) and IAEA TRS 398.

For both German protocols correction factor $k_E$ is the product of two factors. The first factor $k_E'$ is a quality-specific one, it is defined as the quotient of water/air stopping-power ratios at the beam qualities $Q$ and $^{60}$Co. The second one, $k_E''$, is a chamber-specific factor consisting of overall perturbation correction factors for the beam qualities $Q$ and $^{60}$Co.

On the other hand $k_E$ is not split up in protocol TRS-398. While in DIN 6800-2 (1997) the determination of $k_E'$ is followed by the virtual energy method developed by Harder.[8] For the determination of $k_E''$, DIN 6800-2 (DNS 2006) has adopted a method given in TRS 398 (TRS 398, Appendix II).

DIN 6800-2 (1997) recommends to measure the absorbed dose to water for electron beams at the depth of maximum dose or at an energy-dependent reference depth. The users are advised to calibrate a plane-parallel chamber for the use of electron beams against a reference cylinder chamber.

### Table 5: Displacement from the chamber axis towards the radiation source (effective point of measurement) and displacement correction factor for the cylindrical chamber PTW 31013

| Radiation   | Parameter | DIN 6800-2 (1997) | DIN 6800-2 (DNS 2006) | TRS 398 (2000) |
|-------------|-----------|-------------------|-----------------------|----------------|
| Photons     | Displacement correction factor $k_r$ | 1.007 | 1.0084 | k_r not used |
|             | Displacement from the chamber axis | 1.4 mm | 1.4 mm | 0 |
| Electrons   | Displacement correction factor $k_r$ | 1.007 | 1.0084 | k_r in k_Q |
|             | Displacement from the chamber axis | 1.4 mm | 1.4 mm | 1.4 mm |

### Table 6: Beam quality $Q$ and beam quality correction factor $k_Q$ for different photon energies and protocols

| Photon energy | DIN 6800-2 (1997) | DIN 6800-2 (DNS 2006) | TRS398 (2000) |
|---------------|-------------------|-----------------------|---------------|
| 6MV-Photons   | $Q$               | $k_Q$                 |               |
| Acc. 1        | 0.6747            | 0.9881                | 0.6751        |
|               | 0.6751            | 0.9890                | 0.6751        |
| 6MV-Photons   | 0.6701            | 0.9887                | 0.6707        |
| Acc. 2        | 0.6701            | 0.9896                | 0.6707        |
| 18MV-Photons  | 0.7743            | 0.9655                | 0.7732        |
| Acc. 2        | 0.7743            | 0.9666                | 0.7732        |

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calibrated in $^{60}$Co gamma radiation in a higher energy electron beam (cross-calibration). Our reference radiation for cross-calibration was a 21MeV electron beam.\cite{1,5}

In contrast to DIN 6800-2 (1997), DIN 6800-2 (DNS 2006) and the IAEA TRS 398 serve $R_{50}$ as the beam quality index. The half-value of the depth dose distribution in water $R_{50}$ is obtained from the depth ionization distribution, $R_{50, \text{ion}}$, using equation (16) (valid $R_{50, \text{ion}} < 10$ cm and corresponds to an energy $< 25$MeV):

$$R_{50} = 1.029 \times R_{50, \text{ion}} - 0.06$$ (16)

The reference depth can be obtained from $R_{50}$ given by equation (17):

$$z_{\text{ref}} = 0.6 \times R_{50} - 0.1$$ (17)

Quality-specific factor $k_{E}'$ at reference depth $z_{\text{ref}}$ can also be calculated following DIN 6800-2 (DNS 2006) using $R_{50}$:

$$k_{E}'(z_{\text{ref}}) = 1.106 - 0.1312 \times R_{50, 0.214}$$ (18)

For various cylindrical chambers, the chamber-specific factor $k_{E}''$ are given in DIN 6800-2 (DNS 2006), Table 7, as a function of beam quality $R_{50}$. The data of our cylindrical chamber PTW-31013 are fitted into the following polynomial so that quality correction factor $k_{E}''$ for $R_{50}$ can easily be calculated:

$$k_{E}''(z_{\text{ref}})_{31013} = 0.945103 + 0.005644 \times R_{50} - 0.000202 \times R_{50}^2 + 0.000002 \times R_{50}^3$$ (19)

$k_{E}''$ for a plane-parallel chamber can be found out from the perturbation correction factor for $^{60}$Co gamma radiation. For the Roos chamber, the value of this factor is according to DIN 6800-2 (DNS 2006), Table 9:

$$k_{E}''(z_{\text{ref}})_{\text{Roos}} = 0.9806$$ (20)

According to DIN 6800-2 (DNS 2006) we do not need to perform the time-consuming cross-calibration for most of the plane-parallel chambers. The cross-calibration has to be done for new chambers only.

In TRS 398 protocol, the calculated values of the product of $k_{E}' \times k_{E}''$ (= $k_{E}$ in TRS denoted by $k_{E, \text{Q}}$) are given in Table 18 for a number of chamber types and for a series of beam quality $R_{50}$ at the reference depth. The value for our cylindrical chamber PTW-31013 may be obtained by interpolation or by fitting a similar polynomial as described above.

Like DIN 6800-2 (1997), IAEA recommends cross-calibration for plane-parallel chambers.

For our purpose the highest energy 21MeV was used for cross-calibration to determine the chamber calibration factor for the Roos chamber.

The calibration factor $N_{w, \text{pp}}$ can be obtained using equation (21):

$$N_{w, \text{Qcross}} = \frac{D_{w, \text{Qcross}}}{(k_{p} k_{s} k_{\rho} k_{Q, \text{Qint}} N_{\text{pp}} w, \text{Qcross})}$$ (21)

The absorbed dose to water $D_{w}$ at $z_{\text{ref}}$ for cross-calibrated plane-parallel chamber is given by:

$$D_{w} = k_{p} k_{s} k_{\rho} k_{Q, \text{Qint}} N_{\text{pp}} w, \text{Qcross} M$$ (22)

with the values of $k_{p}$ for the calculating electron energy and $k_{Q, \text{Qint}}$ for 21 MeV. These values are given in Table 19 of TRS 398.

We have presented the beam quality correction factors $k_{E}$ for different electron energies following different protocols in Table 8.

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Table 7: Influence quantities and their contributions to total uncertainties

| Influence quantities | Source | Cylindrical chamber Photon beams | Cylindrical chamber Electron beams | Roos chamber Electron beams |
|----------------------|--------|---------------------------------|----------------------------------|---------------------------|
| $N_{w}$              | DIN 6800-2 (2006) | 0.45                           | 0.45                             | 0.45                      |
| Depth of measurement | Estimation       | 0.1                            | 0.1                              | 0.1                       |
| FOA                  | Estimation       | 0.1                            | 0.1                              | 0.1                       |
| Leakage current      | Manufacturer's figure | 0.2                         | 0.2                              | 0.2                       |
| $k_{p}$              | DIN 6800-2 (2006) | 0.1                            | 0.1                              | 0.1                       |
| $k_{s}$              | DIN 6800-2 (2006) | 0.1                            | 0.1                              | 0.1                       |
| $k_{\rho}$           | DIN 6800-2 (2006) | 0.17                           | 0.17                             | 0.17                      |
| $k_{Q}$ or $k_{E}$   | IAEA TRS 398     | 1.0                            | 0.9                              | 0.6                       |
| $k_{Q}$ or $k_{E}$   | DIN 6800-2 (2006) | 1.0                            | 1.2                              | 1.3                       |
| Dosimeter reading    | Manual PTW-UNIDOS | 0.5                           | 0.5                              | 0.5                       |
| Long-term stability  | Manual PTW-UNIDOS | 0.5                           | 0.5                              | 0.5                       |
| Total uncertainty according to TRS 398 | 1.25                     | 1.17                           | 0.96                             |
| Total uncertainty according to DIN 6800-2 (2006) | 1.25                     | 1.42                           | 1.50                             |
Results and Discussion

Figures 1-3 represent the ratios of absorbed doses as a function of beam energies determined by these three dosimetry protocols under reference conditions for photon and electron beams using both chambers. The ratios are obtained by dividing the doses of the protocols by the doses of dosimetry protocol DIN 6800-2 (DNS 2006) for respective energies.

While only cylindrical chambers were used for photon beams, measurements of electron beams were performed using cylindrical as well as plane-parallel chambers. We observe that for the cylindrical chamber the maximum dose ratio discrepancy of the the DIN 6800-2 (1997) and TRS 398 (2000) with reference to DIN 6800-2 (DNS 2006) in photon beams varies between -0.4% to + 0.2% and in electron beams between -0.9% to + 1.1% respectively. With reference to DIN 6800-2 (DNS 2006) for the plane-parallel chamber, the discrepancy amounts to +0.5% for DIN 6800-2 (1997) and +1.5% for TRS 398 (2000).

Figure 1 shows that in general the values for photon beams are approximately the same for protocols DIN 6800-2 (DNS 2006) and TRS-398 (2000). A minor deviation can only be observed for the protocol DIN 6800-2 (1997) compared to the other two protocols.

The values in Figures 2 and 3 for electron beams show a higher difference than that for photon beams. While the values for the plane-parallel chamber according to the IAEA TRS 398 protocol show a tendency of relatively higher deviations, the values for the cylindrical chamber prove a better agreement for all protocols. In contrary to protocol IAEA TRS 398, the protocols of both DIN provide the formalism to calculate the quality correction factor $k_E$. Therefore the cylindrical chambers can be used for the measurement of electron energies less than 10 MeV.

In an earlier work we compared protocols of IAEA TRS 398 and AAPM TG 51 against DIN 6800-2 (1997). The discrepancies in the determination of absorbed dose to water for photon beams were within 1.0% and for electron beams 1.6%. The better agreement of this work in comparison to our earlier work can probably be explained by two facts. First, we have used Dosimeter system PTW-UNIDOS in the present work instead of the PTW-Dosimentor system. Secondly, the air density correction was done from the direct measurement of temperature and pressure instead of using the radioactive check source method. Moreover DIN 6800-2 (DNS 2006) protocol is used as a reference protocol.

The combined uncertainty for the determination of absorbed dose to water is calculated from the geometric summation of the different single uncertainties. Dosimetry protocol DIN 6800-2 (1997) does not mention any uncertainty estimation. But both DIN 6800-2 (DNS 2006) and IAEA TRS 398 protocols provide the method of...
evaluation of uncertainties for the determination of the quality correction factors. For all other correction factors we have estimated the respective uncertainties or they were taken from the instructions for use.

In Table 7 we present a list of factors that influence significantly the dosimetry and their respective uncertainties.

The maximal uncertainty for the determination of absorbed dose for photon and electron beams with the cylindrical chamber is estimated to be 1.25% following protocol TRS 398 and 1.42% for the DIN protocol. For the electron beam, the corresponding uncertainties are 0.96% and 1.50% for the Roos chamber. According to the German medical products law LMKM (2002) the dosimetry protocol DIN 6800-2 is mandatory in Germany for the basic dosimetry.

The results following the protocol DIN 6800-2 (DNS 2006) have been checked with TLD inter-comparison by MTK. Our measurements following DIN 6800-2 (DNS 2006) showed deviations of less than 0.5% compared to the TLD measurements. An optimal level of quality assurance is assumed if the deviation is less than 3% (in Category A).

**Conclusion**

DIN 6800-2 has been altered extensively and adopted to the IAEA TRS 398. In the protocols of IAEA and DIN 6800-2 (1997), cross-calibration is recommended for plane-parallel chambers against a calibrated cylindrical chamber, whereas in DIN 6800-2 (DNS 2006) experimental derived calibration factors are given for various types of plane-parallel chambers. Therefore the users do not need to perform the time-consuming and possibly inaccurate cross-calibration measurements. In the new DIN 6800-2 the evaluation of standard uncertainties of dose measurements is mentioned for the first time.

For electron beams, in DIN 6800-2 (DNS 2006) the measurement of the absorbed dose to water is recommended at the reference depth $z_{ref}$, similar to protocol TRS 398. The characterization of the electron beam quality is a function of $R_{50}$ instead of both quantities $R_{50}$ and $R_{p}$ as mentioned in the previous DIN protocol. In contrast to the IAEA protocol, the DIN protocol considers the quality correction factors for electron beams further on as a product of the two factors $k_{\text{ref}}$ and $k_{\text{DIN}}$.

The discrepancies in the determination of absorbed dose to water between the three protocols were 0.4% for photon beams and 1.5% for electron beams. For the measurement of electron beams with cylindrical chambers, the effective point of measurement is shifted according to all three protocols from the chamber axis towards the radiation source. The quality correction factor in the IAEA protocol is considered for the cylindrical chamber in electron beam including displacement correction factor $k_{\text{DIN}}$ whereas that factor is not included in the quality correction factor of DIN. Therefore it should be considered separately.

For clinical dosimetry, our experiments showed that the time required is approximately the same for all three protocols. The advantage of the new protocol DIN 6800-2 (DNS 2006) lies in the renouncement of the cross-calibration as well as in its clear presentation of formulas and parameters.

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