Comparison between TG-51 and TG-21: Calibration of photon and electron beams in water using cylindrical chambers

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A new calibration protocol, developed by the AAPM Task Group 51 (TG-51) to replace the TG-21 protocol, is based on an absorbed-dose to water standard and calibration factor \( (N_{D,w}) \), while the TG-21 protocol is based on an exposure (or air-kerma) standard and calibration factor \( (N_x) \). Because of differences between these standards and the two protocols, the results of clinical reference dosimetry based on TG-51 may be somewhat different from those based on TG-21. The Radiological Physics Center has conducted a systematic comparison between the two protocols, in which photon and electron beam outputs following both protocols were compared under identical conditions. Cylindrical chambers used in this study were selected from the list given in the TG-51 report, covering the majority of current manufacturers. Measured ratios between absorbed-dose and air-kerma calibration factors, derived from the standards traceable to the NIST, were compared with calculated values using the TG-21 protocol. The comparison suggests that there is roughly a 1% discrepancy between measured and calculated ratios. This discrepancy may provide a reasonable measure of possible changes between the absorbed-dose to water determined by TG-51 and that determined by TG-21 for photon beam calibrations. The typical change in a 6 MV photon beam calibration following the implementation of the TG-51 protocol was about 1%, regardless of the chamber used, and the change was somewhat smaller for an 18 MV photon beam. On the other hand, the results for 9 and 16 MeV electron beams show larger changes up to 2%, perhaps because of the updated electron stopping power data used for the TG-51 protocol, in addition to the inherent 1% discrepancy presented in the calibration factors. The results also indicate that the changes may be dependent on the electron energy. © 2000 American College of Medical Physics.

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INTRODUCTION

Recently, the AAPM Task Group 51 (TG-51) introduced a new calibration protocol for clinical high-energy photon and electron beams.1 The protocol (generally known as TG-51) relies on an absorbed-dose to water standard and calibration factor \( (N_{D,w}) \) while its predecessor, the TG-21 protocol,2 is based on an exposure (or air-kerma) standard and calibration factor \( (N_x) \). Also, there are some differences between these protocols in the following aspects: (a) the electron stopping-power data, (b) the energy-dependent correction factors, and (c) the procedures for beam calibration.1,2 Due to these differences, the results of clinical reference dosimetry based on TG-51 may be somewhat different from those based on TG-21.
The Radiological Physics Center (RPC) has conducted a systematic comparison between these two protocols, in which photon and electron outputs following both protocols were compared under identical conditions. This comparison would provide the magnitude of anticipated changes in photon and electron beam output calibrations after the implementation of the TG-51 protocol. This study was conducted with cylindrical chambers selected from the list given in the TG-51 report,1 covering the majority of current manufacturers.

METHODS AND MATERIALS

Basic equations and definitions

For the sake of brevity, only a brief explanation for each dosimetric parameter is provided here. More details can be found in the original task group reports.1,2 Note some of the notations used in the TG-21 report are changed here for an easier comparison with those used in the TG-51 report.

TG-51 protocol

In the TG-51 protocol,1 the fully corrected ion chamber reading, \( M \), is defined as

\[
M = P_{\text{ion}} P_{T,P} P_{\text{elec}} P_{\text{pol}} M_{\text{raw}},
\]

where \( P_{\text{ion}} \) is a correction factor to take into account the incomplete collection of charge from an ion chamber; \( P_{T,P} \) is the temperature-pressure correction factor; \( P_{\text{elec}} \) is the electrometer correction factor (\( C/r\text{dg} \)); \( P_{\text{pol}} \) is the polarity correction factor; and \( M_{\text{raw}} \) is the uncorrected ion chamber reading at the point of measurements (\( r\text{dg} \)).

The beam quality (\( Q \)) for photon beams is defined by the following quantities:

\[
\% \text{dd}(10): \text{the photon component of the percentage depth-dose at 10 cm depth in a 10} \times 10 \text{cm}^2 \text{field at an SSD (source-to-surface distance) of 100 cm.}
\]

\[
\% \text{dd}(10): \text{the measured percentage depth-dose at 10 cm depth in a 10} \times 10 \text{cm}^2 \text{field at an SSD of 100 cm. Thus %dd}(10) \text{ includes the effects of electron contamination in the beam.}
\]

For an arbitrary photon beam with a beam quality \( Q \), the absorbed-dose to water (\( D_w^Q \)) is given by the TG-51 report1 as

\[
D_w^Q = M_k Q N_{D,w}^{60\text{Co}} [\text{Gy}],
\]

where

\[
k_Q: \text{the beam quality conversion factor, a chamber specific factor which accounts for the change in the absorbed-dose to water calibration factor between the beam quality of interest, } Q, \text{ and the beam quality for which the absorbed-dose calibration factor applies (i.e., } 60\text{Co}),
\]

\[
N_{D,w}^{60\text{Co}}: \text{the absorbed-dose calibration factor under reference conditions in a } 60\text{Co beam.}
\]

For an electron beam, the beam quality (\( Q \)) is represented by \( R_{50} \), the depth in water in a 10 \( \times \) 10 cm\(^2\) or larger beam of electrons at an SSD of 100 cm at which the absorbed-dose falls to 50\% of the dose maximum.1 The absorbed-dose to water (\( D_w^Q \)) is given by the TG-51 report1 as

\[
D_w^Q = M P_{g}^Q k_{R_{50}}' k_{\text{ecal}} N_{D,w}^{60\text{Co}} [\text{Gy}],
\]

where \( P_{g}^Q \) is the gradient correction factor; \( k_{R_{50}}' \) is the electron quality conversion factor to convert \( N_{D,w}^{Q_{\text{ecal}}} \) into \( N_{D,w}^Q \) for any beam quality \( Q \); \( k_{\text{ecal}} \) is the photon-electron conversion factor to convert...
$^{60}\text{Co}$ into an electron beam absorbed-dose calibration factor $N_{D,w}^{Q_{\text{ecal}}}$ for a selected electron beam quality $Q_{\text{ecal}}$ (i.e., $R_{50}=7.5$ cm). Note the product, $P_{Q_{\text{ecal}}}^{Q_{r}} k_{Q_{r}} P_{N_{D,w}}$, is equivalent to $k_{Q}$ for electron beams.

**TG-21 protocol**

Following the TG-21 protocol, the corrected ion chamber reading, $M$, can be defined as

$$M = P_{\text{ion}} P_{T,P} P_{\text{elec}} M_{\text{raw}},$$

(4)

Note that $P_{\text{pol}}$ is discussed in the protocol but not explicitly included in the equations for the TG-21 protocol. Therefore, no polarity correction was applied for TG-21 calculations in this study. The absorbed-dose to water due to a photon beam is then given by

$$D_{\text{water}} = N N_{\text{gas}} \left( \frac{L}{\rho} \right)_{\text{air}} P_{\text{wall}} P_{\text{repl}} [\text{Gy}],$$

(5)

where $N_{\text{gas}}$ is the cavity-gas calibration factor; $(L/\rho)_{\text{air}}$ is the ratio of the mean, restricted, collision mass stopping power between water and air; $P_{\text{wall}}$ is the wall correction factor; $P_{\text{repl}}$ is the correction factor for replacement of the phantom material by an air cavity. The absorbed dose to water due to an electron beam is calculated by the TG-21 protocol as

$$D_{\text{water}} = N N_{\text{gas}} \left( \frac{L}{\rho} \right)_{\text{air}} P_{\text{repl}} [\text{Gy}].$$

(6)

**Relation between absorbed-dose (TG-51) and air-kerma (TG-21) standards**

A theoretical relationship between absorbed-dose and air-kerma standards (or calibration factors) can be derived by comparing the absorbed-dose to water determined for a $^{60}\text{Co}$ beam using the TG-51 and TG-21 protocols. Using $k_{Q}=1.0$ and assuming $P_{\text{pol}}=1.0$, the following relationship for a $^{60}\text{Co}$ beam can be obtained by taking the ratio between Eqs. (2) and (5):

$$\frac{D_{w}}{D_{\text{water}}} = \frac{N_{D,w}}{N_{\text{air}}},$$

(7)

where the value 0.8791 is the conversion factor from exposure to air-kerma (kinetic energy released in air); $N_{\text{air}}$ and $N_{\text{k}}$ are the air-kerma and exposure calibration factors, respectively. If no systematic difference exists in both calibration standards and protocols, Eq. (7) should be equal to unity and, as a result, the ratio, $N_{D,w}/N_{\text{air}}$, can be calculated as

$$\left( \frac{N_{D,w}}{N_{\text{air}}} \right)_{\text{calc}} = (0.8791)^{-1} \left( \frac{N_{\text{gas}}}{N_{x}} \right) P_{\text{repl}} P_{\text{wall}} \left( \frac{L}{\rho} \right)_{\text{air}}.$$

(8)

Note that no measured value is necessary for Eq. (8). All the required numerical values can be obtained from the TG-21 report. The ratio, $N_{D,w}/N_{\text{air}}$, can also be directly determined using the absorbed-dose and air-kerma calibration factors measured at the calibration laboratory and is denoted as $(N_{D,w}/N_{\text{air}})_{\text{meas}}$ in this study.

**Measurements**

All measurements were performed with selected cylindrical chambers from the list given in the TG-51 report, in a $30\times40\times40$ cm$^3$ water phantom. For nonwaterproof chambers, a waterproofing sleeve with a 1-mm-thick polymethylmethacrylate (PMMA) wall was used. The makes and mod-
els of the chambers are given in Table I. Both absorbed-dose and air-kerma calibration factors were obtained from the Accredited Dosimetry Calibration Laboratory (ADCL) at the M.D. Anderson Cancer Center (MDACC) based on standards traceable to the National Institute of Standards and Technology (NIST). The electrometer (Keithley model 602) was also calibrated at the MDACC ADCL. Beam outputs were determined for 6 and 18 MV photon beams, and 9 and 16 MeV electron beams from a Clinac 2100C (Varian Oncology Systems, Palo Alto, CA) following TG-51 and TG-21. Beams were incident on the phantom surface, vertically (i.e., at gantry 180°), at an SSD of 100 cm. All measurements were repeated at least three times to ensure the reproducibility of each measurement.

**Photon beam**

The beam quality of the photon beams for the TG-51 protocol was determined in the following manner: First, the depth of maximum ionization was searched. Then, the chamber was positioned at (10 cm + 0.6rcav) to determine %dd(10), where rcav is the radius of the air cavity in an ion chamber.\(^1\) For the 6 MV photon beam, %dd(10) was taken to be equal to %dd(10),. For the 18 MV photon beam, %dd(10), was obtained following the procedure described in the TG-51 report\(^1\) using a 1 mm lead foil located at 55 cm from the phantom. After determining the quality of the photon beams, relevant kQ factors were obtained from the table given in the TG-51 report.\(^1\) The beam quality of the photon beams for the TG-21 protocol\(^2\) was determined as the ratio of the TMRs (tissue maximum ratio) between 10 and 20 cm depths in water from the institution’s clinical dosimetry data.

Calibrations were performed with the chamber center positioned at 10 cm depth in water. Readings for 200 Monitor Units (MU) were taken at three different voltage settings (i.e., –300, –150 and +300 V) to determine Ppol and Pin and an appropriate correction was applied for temperature and pressure (PT,P). Note Ppol for photon and electron beams was typically less than 0.2% for all the chambers used in this study. Using the corrected readings, absorbed doses at 10 cm depth were determined for TG-51 and TG-21 protocols using Eqs. (2) and (5), respectively.

**Electron beam**

Electron beam outputs were measured at dref for TG-51 and at dmax for TG-21 (Table II), respectively. The reference depth (dref) and related dosimetric quantities were determined follow-

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**Table I. Makes and models of the chambers used.**

| Ion chamber | Serial number | Wall material | Al electrode | N_D, (10^7 Gy/C) | N x (10^9 R/C) |
|-------------|---------------|---------------|--------------|-----------------|---------------|
| NEL 2571    | 1503          | graphite      | yes          | 4.5873          | 4.7331        |
| NEL 2571    | 1864          | graphite      | yes          | 4.5257          | 4.6799        |
| PTW N23333  | 1516          | PMMA          | yes          | 5.0913          | 5.2690        |
| PTW N30001  | 1483          | PMMA          | yes          | 5.2844          | 5.4712        |
| Capintec PR06C | 174        | C-552         | no           | 4.7445          | 4.9290        |

**Table II. d_ref and d_max for electron calibration.**

| Electron energy (MeV) | d_ref (cm) | d_max (cm) |
|-----------------------|------------|------------|
| 9                     | 2.0        | 2.1        |
| 16                    | 3.8        | 3.4        |
ing the procedure described in the TG-51 report, while the depth of maximum dose ($d_{\text{max}}$) and necessary data (e.g., $E_0$, $R_p$, etc.) for the TG-21 protocol were obtained from the institution’s clinical dosimetry data. Note $d_{\text{max}}$ in this study was an effective point of measurements with an appropriate shift in chamber location, as recommended by the TG-25 report. Similar to photon beam calibration, readings for 200 MUs were taken at three different voltage settings (i.e., 2300, 2150 and 1300 V) to determine $P_{\text{pol}}$ and $P_{\text{ion}}$ and an appropriate correction was applied for temperature and pressure ($P_T$, $P_{\text{wall}}$). For the TG-51 protocol, additional readings were taken at ($d_{\text{ref}}$, 0.5 $r_{\text{cav}}$) to determine the gradient correction factor ($P_{\text{gr}}$). Outputs at $d_{\text{ref}}$ were converted to the dose rates at $d_{\text{max}}$ using the clinical depth dose data and compared with the values from the TG-21 protocol.

**RESULTS**

**Photon beam**

To investigate the basic difference between the absorbed-dose and air-kerma standards (or calibration factors), the absorbed-dose to water for a $^{60}$Co beam can be determined using the TG-51 and TG-21 protocols. Alternatively, if a $^{60}$Co beam is unavailable, the ratio between the absorbed-dose and air-kerma calibration factors obtained from the standards lab, i.e., $(N_{D,w}/N_k)_{\text{meas}}$, can be compared with the same ratio calculated using Eq. (8). The ratio between $(N_{D,w}/N_k)_{\text{meas}}$ and $(N_{D,w}/N_k)_{\text{calc}}$ then yields the difference in the absorbed-dose to water for a $^{60}$Co beam following the TG-51 and TG-21 protocols. Table III shows the ratio between the measured and calculated ratios. The discrepancy between measured and calculated values is about 1% for all chambers tested. This means that the absorbed-dose to water for a $^{60}$Co beam determined by the TG-51 protocol will be about 1% higher than that determined by the TG-21 protocol.

Table IV lists the ratio of absorbed-dose to water determined by TG-51 to that determined by TG-21 for the 6 and 18 MV photon beams. Note the results from both NEL and PTW chambers in Table I are averaged here and the average values for a $^{60}$Co beam from Table III are also included. The same 1% discrepancy observed for the $^{60}$Co beam is seen for a 6 MV photon beam. The discrepancy is somewhat smaller for the 18 MV photon beam, indicating that the discrepancy might decrease with increasing photon energy. This could be partially due to some compensating effect between various dosimetric parameters in both calibration protocols.

**Electron beam**

Table V lists the ratio of absorbed-dose to water determined by TG-51 to that determined by TG-21 for 9 and 16 MV electron beams. The discrepancies are somewhat larger than those for photon beams, approaching 2% at 16 MeV. Note the electron stopping power data used in TG-51 are based on realistic clinical electron beams, whereas the data used in TG-21 are based on

| Ion chamber       | Serial number | $N_{D,w}/N_k$ (Meas.) | $N_{D,w}/N_k$ (Calc.) | Meas./Calc. |
|-------------------|---------------|-----------------------|-----------------------|-------------|
| NEL 2571          | 1503          | 1.102                 | 1.088                 | 1.013       |
| NEL 2571          | 1864          | 1.100                 | 1.088                 | 1.011       |
| PTW N23333        | 1516          | 1.099                 | 1.086                 | 1.012       |
| PTW N30001        | 1483          | 1.099                 | 1.086                 | 1.012       |
| Capintec PR06C    | CII.68624     | 1.095                 | 1.079                 | 1.015       |
| Extradin A-12     | 174           | 1.105                 | 1.093                 | 1.011       |

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mono-energetic electrons. This may explain a somewhat larger discrepancy for electrons than that seen for photons. The results also indicate that the magnitude of changes may be dependent on the electron energy.

**DISCUSSION**

Table III suggests an approximate 1% discrepancy between the absorbed-dose to water determined for a $^{60}$Co beam by TG-51 based on an absorbed-dose standard and that determined by TG-21 based on an air-kerma (or exposure) standard. This result implies that either one of the following could be possible: (a) an inherent discrepancy in either of the standards or (b) an inaccuracy in the TG-21 formalism for converting air-kerma to absorbed dose. This question may be pursued, somewhat indirectly, by investigating the difference between the national standards, especially between the US and Canada where the same calibration protocol is being used. The US standards lab (NIST) and the Canadian standards lab (National Research Council of Canada (NRCC)) are aware of the difference, up to 1%, between their air-kerma standards and a somewhat smaller discrepancy for their absorbed-dose standards.$^{6,7}$ There is also an additional uncertainty for the transfer of the standards from NIST through the ADCL to a user’s chamber. Therefore, most probably, the results presented in Table III of this study would be different if the air-kerma and absorbed-dose calibration factors were derived from a different ADCL or from the Canadian standards. In fact, an investigation by a Canadian group shows better agreement (within 0.5%) in measured and calculated ratios between absorbed-dose and air-kerma calibration factors.$^{8}$ Therefore, we may argue that a consistent 1% discrepancy in our results is mostly due to the uncertainties in the two standards, absorbed-dose and air-kerma.

The implication of our analysis on the nature of the discrepancy is that any user may be able to estimate the magnitude of changes resulting from the implementation of the TG-51 protocol by

| Ion chamber | $^{60}$Co (TG-51/TG-21) | 6 MV (TG-51/TG-21) | 18 MV (TG-51/TG-21) |
|-------------|-------------------------|-------------------|-------------------|
| NEL 2571    | 1.012                   | 1.010             | 1.007             |
| PTW N23333 & N30001 | 1.012                   | 1.010             | 1.006             |
| Capintec PR06C | 1.015                   | 1.011             | 1.004             |
| Exradin A-12 | 1.011                   | 1.008             | 1.002             |

Table V. Comparison between TG-51 and TG-21 calibrations (electron beam). Note the ratios represent the comparison at $d_{\text{max}}$ in water for each electron energy. Presented results have an estimated uncertainty of less than ±0.2% excluding the inherent uncertainty associated with the calibration factors.

| Ion chamber | 9 MeV (TG-51/TG-21) | 16 MeV (TG-51/TG-21) |
|-------------|---------------------|---------------------|
| NEL 2571    | 1.015               | 1.021               |
| PTW N23333 & N30001 | 1.014               | 1.017               |
| Capintec PR06C | 1.014               | 1.016               |
| Exradin A-12 | 1.014               | 1.016               |
performing the comparison shown in Table III of this study. Thus it is important for a first-time-
TG-51-user to obtain both the absorbed-dose and air-kerma calibration factors on the same cham-
ber and to perform a comparison similar to that we have made in this work. The discrepancies
between TG-51 and TG-21 for all photon beam calibrations are not expected to be significantly
larger than the difference observed from this comparison for a $^{60}$Co beam. If the changes are more
than expected, the users should suspect some other errors in the implementation of the TG-51 or
TG-21 protocols. As mentioned previously, the discrepancy for electron beam calibrations is
expected to be slightly larger than that for a $^{60}$Co beam and the discrepancy more than 2% may
still be possible. However, if the changes are excessive (>3%), the users should check other
sources of error as well.

CONCLUSIONS

Photon and electron beam outputs were measured in water following both TG-51 and TG-21
protocols using cylindrical chambers under identical conditions. Measured ratios between
absorbed-dose and air-kerma calibration factors, based on the standards traceable to the NIST,
were compared with calculated values based on the TG-21 protocol. The comparison shows
approximately a 1% discrepancy between measured and calculated ratios. This discrepancy may
provide a reasonable measure of possible changes between the absorbed-dose to water determined
by TG-51 and that determined by TG-21 for photon beam calibrations. Therefore, it is recom-

mended that a first-time-TG-51-user should obtain both the absorbed dose and air-kerma calibra-
tion factors on the same chamber, and perform an initial comparison as described in this study to

estimate the inherent discrepancy expected from the implementation of the TG-51 protocol. The
typical change in a 6 MV photon beam calibration following the implementation of the TG-51
protocol was about 1%, regardless of the chamber used, reflecting the 1% discrepancy presented in
the calibration factors. The change was somewhat smaller for an 18 MV photon beam, indicating
that the magnitude of change might decrease with increasing photon energy. The changes were
somewhat larger for electron beams, perhaps because of the new electron stopping power data
used for the TG-51 protocol, in addition to the inherent 1% discrepancy in the calibration factors.
The electron results show changes up to 2% and also indicate that the changes may be dependent
on the electron energy.

If the changes in the absorbed-dose to water, after the implementation of the TG-51 protocol,
are more than the discrepancy in the calibration factors for photons or are more than 3% for
electrons, the users should suspect some errors in their implementation of the TG-51 protocol and
may want to contact the authors for data comparison.

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