Developments in clinical reference dosimetry: Updates to reference dosimetry protocols

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Background

- Based on ion chamber calibrated in cobalt-60
- Simple ‘recipe’ for beam calibration
- Covers photon and electron beams

AAPM’s TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams

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A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between $^6$Co and 50 MeV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) and has been formally approved by the AAPM for clinical use. The protocol uses ion chambers with absorbed-dose-to-water calibration factors, $N_{ph}$, which are traceable to national primary standards, and the quantity $D_{ph} = M_{ph} N_{ph}(p)$, where $Q$ is the beam quality of the clinical beam. $D_{ph}$ is the absorbed dose to water at the point of measurement of the ion chamber placed under reference conditions, $M_{ph}$ is the fully corrected ion chamber reading, and $N_{ph}$ is the quality correction factor which converts the calibration factor for a $^6$Co beam to that for a beam of quality Q. Values of $Q_{ph}$ are presented as a function of $Q$ for many ion chambers. The value of $M$ is given by $M = P_{RM} P_{PD} P_{MA} M_{MA}$, where $P_{RM}$ is the raw, uncorrected ion chamber reading and $P_{RM}$ corrects for ion recombination, $P_{PD}$ for temperature and pressure variations, and $P_{MA}$ for chamber polarity effects. Beam quality, $Q$, is specified (i) for photon beams, by $Q_{ph} = 10 Q_{ph}$, the photon component of the percentage depth dose at 10 cm depth for a field size of $10 \times 10$ cm$^2$ on the surface of a phantom at an SSD of 100 cm and (ii) for electron beams, by $E_{50}$, the depth at which the absorbed-dose falls to 50% of the maximum dose in a beam with field size $10 \times 10$ cm$^2$ on the surface of the phantom ($=20 \times 20$ cm$^2$ for $E_{50} \geq 5.0$ cm) at an SSD of 100 cm. $E_{50}$ is determined directly from the measured value of $P_{50}$, the depth at which the ionization falls to 50% of its maximum value. All clinical reference dosimetry is performed in a water phantom. The reference depth for calibration purposes is 10 cm for photon beams and 0.6 $E_{50}$ - 0.1 cm for electron beams. For photon beams clinical reference dosimetry is performed in either an SSD or SAD setup with a $10 \times 10$ cm$^2$ field size defined on the phantom surface for an SSD setup or at the depth of the detector for an SAD setup. For electron beams clinical reference dosimetry is performed with a field size of $10 \times 10$ cm$^2$ ($=20 \times 20$ cm$^2$ for $E_{50} \geq 5.0$ cm) at an SSD between 90 and 110 cm. This protocol represents a major simplification compared to the AAPM’s (TG-23) protocol in the sense that large tables of stopping-power ratios and mono-energy absorption coefficients are not needed and the user does not need to calculate any fractional dosimetry factors. Workshops for various situations are presented along with a list of equipment required. © 1999 American Association of Physicists in Medicine. [SL0044-2405(99)00209-6]
Review – reference dosimetry with TG-51

- Starting point is $N_{D,w}^{60Co}$ for your chamber (ADCL)

- $D_w$ required in clinical beam (quality $Q \neq$ cobalt-60)

  $$D_w^Q = MN_{D,w}^Q = Mk_QN_{D,w}^{60Co}$$

- Requires $M$ with $N_{D,w}^{60Co}$ and beam quality conversion factor, $k_Q$
Why update?

- Advances since 1999 publication
- Semi-analytic approach:

$$k_Q = \left[ \left( \frac{L}{\rho} \right)_{\text{water}} P_{\text{cell}} P_{\text{repl}} P_{\text{wall}} \right]_Q$$

- New chambers available
- Deliberately avoided uncertainties
- Extensive revision for electron beams

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A protocol is prescribed for clinical reference dosimetry of external beam radiation therapy using photon beams with nominal energies between 10 MeV and 50 MeV and electron beams with nominal energies between 4 and 50 MeV. The protocol was written by Task Group 51 (TG-51) of the Radiation Therapy Committee of the American Association of Physicists in Medicine (AAPM) and has been formally approved by the AAPM for clinical use. The protocol uses ion chambers with absorbed-dose-to-water calibration factors, $N_{Qo}$, which are traceable to national primary standards, and the equation $D_{Qo} = M_{Qo}R_{Qo}$, where $Q$ is the beam quality of the clinical beam. $D_{Qo}$ is the absorbed dose to water at the point of measurement of the ion chamber placed under reference conditions. $M_{Qo}$ is the fully corrected ion chamber reading, and $R_{Qo}$ is the quality correction factor, which converts the calibration factor for a 50 MeV beam to that for a beam of quality $Q$. Values of $R_{Qo}$ are presented as a function of $Q$ for many ion chambers. The value of $M_{Qo}$ is given by $M_{Qo} = P_{\text{pm}} P_{\text{iso}} P_{\text{pol}}$, where $P_{\text{pm}}$ is the ion chamber reading and $P_{\text{pol}}$ corrects for ion reconstruction. $P_{\text{pm}}$ is corrected for any correction of the electrometer if calibrated separately. $P_{\text{pol}}$ and $P_{\text{iso}}$ for chamber polarity effects. Beam quality, $Q$, is specified (a) for photon beams, by $\%/100 \text{ Gy}$, the photon component of the percentage depth dose at 10 cm depth for a field size of 10 cm × 10 cm on the surface of a phantom at an SSD of 100 cm and (b) for electron beams, by $R_{Qo}$, the depth at which the absorbed-dose-to-water dose is 50% of the maximum dose in a beam with field size $= 10 \times 10$ cm$^2$ on the surface of the phantom ($= 20 \times 20$ cm$^2$ for $E_{Qo} > 8.5$ cm) at an SSD of 100 cm. $R_{Qo}$ is determined directly from the measured value of $D_{Qo}$, the depth at which the ionization falls to 50% of its maximum value. All clinical reference dosimetry is performed in a water phantom. The reference depth for calibration purposes is 10 cm for photon beams and 0.5 cm for electron beams. For photon beams, clinical reference dosimetry is performed in either an SSD or SAD setup with a $10 \times 10$ cm$^2$ field size defined on the phantom surface for an SSD setup or at the depth of the detector for SAD setup. For electron beams, clinical reference dosimetry is performed with a field size of $= 10 \times 10$ cm$^2$ ($= 20 \times 20$ cm$^2$ for $E_{Qo} > 8.5$ cm) at an SSD between 90 and 110 cm. This protocol represents a major simplification compared to the AAPM’s (TG-21) protocol in that large tables of stopping-power ratios and mono-energetic absorption coefficients are not needed and the user does not need to calculate any fluences or dosimetric factors. Workflows for various situations are presented along with a list of appendices. © 1999 American Association of Physicists in Medicine. [S0009-2409(99)00209-6]
What stays?

- Procedure and formalism remains the same
- Still based on ion chamber calibrated in cobalt-60
- Calculated (but updated with accurate Monte Carlo) $k_Q$ factors
- Solid phantoms still prohibited
- $%dd(10)_x$ and $R_{50}$ for beam quality specification
- Addendum published (2014) for photon beams, wider revision for electron beams
Photon beam addendum to the TG-51 protocol

- $k_Q$ data sets
- Specifications for reference chambers
- Bias voltage and ion recombination, $P_{ion}$
- Polarity correction, $P_{pol}$
- Application to FFF linacs
- Uncertainties
What has been the impact?

- Addendum published three years ago
- WGTG51 conducted online survey

Has your clinic implemented the addendum to the TG-51 protocol (McEwen et al., Med. Phys. 2014)?

- Yes: 71%  
- No: 29%

If yes, what was the maximum calibration difference for any photon beam when switching from the original TG-51 protocol to the 2014 addendum?

- < 1%: 100%  
- > 1%
What has been the impact?

- Addendum published three years ago
- WGTG51 conducted online survey
- Impact has been minor (expected)
- Manufacturers developing new designs to address reference-class issues (small volume chambers)
Now for electron beams – more complicated, wider revision
The problems with electron beams

- Steep dose gradients and chamber positioning

Issue independent of chamber type

Not much we can do – take care when positioning!

Assumes accurate positioning to 0.5 mm

Muir et al., PMB 5953 (2014)
The problems with electron beams

- Steep dose gradients and chamber positioning

- Plane-parallel vs cylindrical
  - Plane-parallel variability and stability
  - Cross-calibration against cylindrical
  - Cylindrical not allowed in low-energy beams
  - Measured $P_{gr}$ required for cylindrical

\[
k_Q = P_{gr}^Q \cdot k'_{R50} \cdot k_{ecal}
\]

Complicated procedures in TG-51
Can we simplify?
The problems with electron beams

- Steep dose gradients and chamber positioning

- Plane-parallel vs cylindrical
  - Plane-parallel variability and stability
  - Cross-calibration against cylindrical
  - Cylindrical not allowed in low-energy beams
  - Measured $P_{gr}$ required for cylindrical

- Higher uncertainty in TG-51 $k_Q$

$\begin{align*}
k_Q &= \frac{\left(\frac{L}{\rho}\right)_{water} P_{cell} P_{repl} P_{wall}}{\left(\frac{L}{\rho}\right)_{air} P_{cell} P_{repl} P_{wall}}
\end{align*}$

Need more accurate data
Plane-parallel vs cylindrical chambers

Plane-parallel: PTW Roos

- Recommended for low-energy e-beams
- Cross-calibration procedure
- $k_Q$ required several assumptions ($P_{\text{repl}}=P_{\text{wall}}=1$)
- Measurement performance: may not be stable$^{1,2}$

Cylindrical: NE2571

- Not recommended for low-energy e-beams
  - but based on assumptions for plane-parallel$^3$ – variation in $k_Q$ with large (~5 %) corrections
- **Very well behaved** - stability in photon beams at 0.1 %

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Can we simplify by using cylindrical chambers for all e⁻ beams?

• Would eliminate problems using plane-parallel, cross-calibration
• In fact, recent survey indicates clinical physicists already doing this

“No: 18%
Yes: 82%

“Do you use the same chamber for photon beam calibration as for e⁻ beams?”

Muir et al., JACMP 182 (2017).
Revisit older experiments with focus on variability

So, are corrections really more variable for cylindrical chambers?

4-5 %
Revisit older experiments with focus on variability

\[
\begin{bmatrix}
M_2 \\
M_1
\end{bmatrix}_Q^{Q_{\text{ecal}}} = \begin{bmatrix}
P_{Q,1} \\
P_{Q,2}
\end{bmatrix}_Q^{Q_{\text{ecal}}}
\]

• Measure corrected M for several chambers in electron beams

• Normalize in 18 MeV beam \( Q_{\text{ecal}} \)

• Variation/uncertainty in overall perturbation correction \( P_Q \) \( k_Q \) for similar chambers
Revisit older experiments with focus on variability

- M measured vs. depth in 8 and 18 MeV
No, corrections aren’t more variable using cylindrical chambers!

- Variability at +/- 0.4 %, no worse than plane-parallel chambers\(^1\)

- Appropriate to use cylindrical chambers in all beams using generic \(k_Q\)

What about $k_Q$ and $P_{gr}$?

Use Monte Carlo

- **Equation defining $k_Q$:**
  \[
  D_w^Q = M N_{D,w}^Q = M k_Q N_{D,w}^{60Co}
  \]

- **Absorbed dose to the air in an ion chamber:**
  \[
  D_{air} = \frac{M}{m_{air}} \left( \frac{W}{e} \right)_{air}
  \]

- **Combine and assume** $(W/e)_{air}$ **constant with beam energy**

$$
\begin{align*}
  k_Q &= \frac{\left[ \frac{D_w}{D_{air}} \right]^Q}{\left[ \frac{D_w}{D_{air}} \right]^{60Co}} \\
  &\quad \text{All quantities can be calculated} \\
  &\quad \text{with Monte Carlo simulations}
\end{align*}
$$

- **Aside:** this is the principle behind photon beam $k_Q$ factors in addendum
Absorbed dose simulations for $k_Q$ factors

- Sources: realistic accelerator models or electron beam spectra
- Simulations with EGSnrc `egs_chamber`\textsuperscript{1} user-code
- $D_w$ in small disc vs depth in water

$$k_Q = \frac{\begin{bmatrix} D_w \\ D_{air} \end{bmatrix}}{\begin{bmatrix} D_w \\ D_{air} \end{bmatrix} \times 60 C_0}$$

\textsuperscript{1}J. Wulff et al., Med. Phys. 1328 (2008).
Ion chamber simulations for $k_Q$ factors

\[ k_Q = \frac{D_w}{D_{air}} Q \]

$D_{air}$ in fully modeled chambers vs depth in water
Comparison to high-quality literature results

• Publications report $k'_R_{50}$: normalized $k_R_{50}$

• Excellent agreement with published data

PTW Roos

Comparison to high-quality literature results

- Recent calorimetry measurements in high-energy beams for $k_{\text{ecal}}$
- Very good agreement for commonly used chambers

<table>
<thead>
<tr>
<th>Plane-parallel</th>
<th>Difference between MC and calorimetry (%)</th>
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<tbody>
<tr>
<td>PTW Roos</td>
<td>-0.28</td>
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<tr>
<td>PTW Markus</td>
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<tr>
<td>Exradin A1SL</td>
<td>0.10</td>
</tr>
</tbody>
</table>

What about the gradient correction?

Where is the electron fluence really sampled?

At the center of the chamber?

Closer to the curved front surface?

How can we account for this?

- Shift or correction

\[ k_Q = P_{gr}^Q k_{R50} \rightarrow P_{gr} = \frac{M(d_{ref} + 0.5r_{cav})}{M(d_{ref})} \]
What about the gradient correction?

Using TG-51 recommendation – scattered results

What about the gradient correction?

Can use different shift for $P_{gr}$ to reduce scatter

This is getting pretty small (0.6 mm)

What if we take $\lim f \to 0$?

That is, let MC $k_Q$ take care of $P_{gr}$

Can we avoid use of $P_{gr}$?

- Most common source of electron beam calibration errors

- Using MC calculated $k_Q$ includes gradient effects
Can we avoid use of $P_{gr}$?

- Most common source of electron beam calibration errors

- Using MC calculated $k_Q$ includes gradient effects and simplifies procedure
The (resolved) problems with electron beams

• Steep dose gradients and chamber positioning
  → Take care when positioning chambers\(^1\)

• Plane-parallel vs cylindrical
  • Plane-parallel variability and stability
  • Cross-calibration against cylindrical
  • Cylindrical not allowed in low-energy beams
  • Measured \(P_{gr}\) required for cylindrical

• Higher uncertainty in TG-51 \(k_Q\)
  → Can use cylindrical chambers for all beams
  → Monte Carlo \(k_Q\) include \(P_{gr}\), can remove requirement
  → Now have high-quality data

Summary

- Reviewed TG-51 protocol – problems and reasons to update

- Review of addendum published April 2014
  - As expected, impact has been minor

- Much wider revision for electron beams
  - Just use cylindrical chambers
  - No cross-calibration or $P_{gr}$
  - Updated, accurate $k_Q$ factors

Simplified (more like photons) to make life easier, reduce errors!
Thank you

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