Physics of the TG-51 dosimetry protocol

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Used by 88% of RPC-monitored clinics

1330/1508 active in NA
=> 88% adoption

http://rpc.mdanderson.org/RPC with permission from Radiological Physics Center in Houston

Which statement applies to you?

0% 1. My clinic still uses TG-21 (or equivalent air-kerma based protocol).
0% 2. I have only used TG-51 (or equivalent absorbed-dose based protocol) at the clinic where I currently work, but I have used TG-21 in the past.
0% 3. I have only used TG-51 (or equivalent absorbed-dose based protocol) at the clinic where I currently work, and I have never used TG-21.
0% 4. I made the transition from TG-21 to TG-51 at the clinic where I currently work.
0% 5. I am not at a radiotherapy clinic so the question does not apply.
**Why change from TG-21?**

- TG-51 is simpler since it avoids in-air quantities
- TG-51 is much less numerical work
- TG-51 is easier to teach and has fewer errors
- TG-51 has improved accuracy
- Formalism allows measurement of main quantities $(k_Q, k_{cal}, k_{50})$
- TG-51 is AAPM and COMP policy and RPC has switched

**General formalism**

$$D_{w}^{Q} = MN_{D,w}^{Q}$$  

defines: absorbed dose calibration coefficient

$$N_{D,w}^{Q} = k_{Q}N_{D,w}^{60Co}$$  

defines: beam quality conversion factor
- it accounts for $N_{D,w}$ variation with $Q$

$$D_{w}^{Q} = M k_{Q}N_{D,w}^{60Co}$$  

fundamental dose equation of TG-51: based on absorbed dose calibration coefficient

**Overview - photons**

- get a traceable $N_{D,w}^{60Co}$
- measure photon beam quality, $Q$
- look up appropriate $k_Q$ factor
- measure ion chamber reading $M_{raw}$ at 10 g/cm$^2$ and convert to fully corrected charge $M$
- apply $D_{w}^{Q} = M k_{Q}N_{D,w}^{60Co}$

**Spencer-Attix cavity theory**

$$D_{w}^{Q} = D_{air} \left( \frac{L}{\rho} \right)_{med} P_{wall}P_{f}P_{gr}P_{col}$$

$$D_{air} = K_h \left( \frac{W}{e} \right)_{air} \frac{M}{m_{air}}$$

$K_h$ is humidity correction
-- needed since air is humid
-- but we use dry air values

$$N_{D,w}^{Q} = \frac{D_{w}^{Q}}{M}$$

- combining $D_{med}$ & $D_{air}$ eqns gives

$$N_{D,w}^{Q} = \frac{K_h}{m_{air}} \left( \frac{W}{e} \right)_{air} \left( \frac{L}{\rho} \right)_{air} P_{wall}P_{f}P_{gr}P_{col}$$

**Question:** where does $k_Q$ come from?
Equation for $k_Q$

- defn of $k_Q$ implies
- and from before $N_{D_{w_w}}^{Q} = \frac{N_{D_{w_w}}^{Q}}{N_{D_{w_w}}^{Q}}$
  - assuming $W/e$ constant gives
  $$k_Q = \frac{\left(\frac{\tau}{\rho}\right)_{w} \cdot \frac{P_{w}}{P_{w} \cdot P_{e}}}{\left(\frac{\tau}{\rho}\right)_{w} \cdot \frac{P_{w}}{P_{w} \cdot P_{e}}}$$

- applies to electrons and photons
  but for e-, see later

$k_Q$ components

$P_{wall}$

- accounts for wall not being water
  - unity for electrons
  - same as TG-21 for photons

For walls 0.05g/cm²

Changes due to better cross sections
Recent Monte Carlo values of $P_{\text{wall}}$

Buckley et al MP 33(2006) 455
MP 33(2006) 1788
TG51 uses 1.000

$P_{\text{repl}} = P_{\text{gr}} P_{\text{fl}}$

$P_{\text{repl}}$ replacement correction: accounts for changes caused by the cavity

$P_{\text{fl}}$: fluence correction: changes due to cavity other than gradient effects

$P_{\text{gr}}$: gradient correction
fluence moves upstream because of air’s low density
$P_{\text{gr}}$ is a function of dose gradient & chamber radius
-taken as 1.00 at $d_{\text{max}}$

Two approaches
-effective point of measurement for depth-dose curves

$P_{\text{gr}}$: multiplicative correction for absolute dose measurements

Effective point of measurement

Johansson et al (1977)
electrons
0.5 $r_{\text{cav}}$ upstream of central axis
photons
0.6 $r_{\text{cav}}$ (was 0.75 $r_{\text{cav}}$ previously)

Only used for depth-dose curves with cylindrical chambers
For plane parallel chambers, effective point of measurement and point of measurement are front face of cavity
i.e. $P_{\text{gr}} = 1.00$

$P_{\text{gr}}$ in dose equations

electron beams
for cylindrical chambers

$$P_{\text{gr}} = \frac{M_{\text{raw}}(d_{\text{ref}} + 0.5r_{\text{cav}})}{M_{\text{raw}}(d_{\text{ref}})}$$

-equivalent to using the effective point of measurement
-but allows rigorous definition of calibration factor

photon beams
-TG-51 uses calculations of Cunningham and Sontag (1980) (as did TG-21)
-there is considerable variation in data on this correction
Prepl: photon beams (= P_{gr})

TG-51 uses the ratio \( P_{\text{repl}} / P_{\text{repl,Co}} \) => reduced uncertainty

P_{\text{repl}} = \text{TPR}_0 \text{ for } 6.4 \text{ mm}

\[ \frac{P_{\text{repl}}}{P_{\text{repl,Co}}} \]

\[ \text{TPR}_0 \]

Fluence correction (P_{fl})

- Fluence corrections not needed due to transient CPE
- Electron beams: TG-51 uses the same factors as TG-21 for cylindrical chambers and same factors as TG-39 for plane-parallel

P_{fl}: cylindrical (e-)

Newer data agrees well with that used in TG-51
Need \( E_z \) as a function of \( R_{50} \) at \( d_{\text{ref}} \)

Wittkammer et al. PMB 38 (1991) 1639

\[ P_{\text{fl}} = \text{constant} \]

\[ 0.26\% \]

6.3 mm cavity diameter

\[ \text{TG-21/Johansson et al} \]

P_{fl}: plane-parallel

TG-51 uses TG-39 data with a new fit

\[ E_z = R_{50} \left( 1 - \frac{2}{R_{50}} \right) \]

\[ R_0 = 1.271 R_{50} - 0.23 \]

\[ E_z = 2.33 R_{50} \left( 1 - \frac{2}{1.271 R_{50} - 0.23} \right) \]

Wittkammer et al. PMB 38 (1991) 1639
**$P_{cel}$: Al electrode correction**

- For electrode same as wall material, any effect is in $P_{fl}$
- Ma and Nahum (93) showed aluminum electrodes have an effect
  - Larger in photon beams
  - But biggest effect is in electron beams because it cancels in photons

Ma & Nahum PMB 38 (1993) 267

**Beam quality specification**

- Need to specify beam quality to select $k_Q$ and $k_{iso}$
- Goal is to uniquely determine a single $k_Q$ value for a given beam quality
  - This depends mostly on specifying a single stopping-power ratio

**Photon beams**

$\%dd(10)_X$ is the photon component of the percentage depth-dose at 10 cm depth in a 10x10 cm$^2$ field defined on the surface of a water phantom at 100 cm SSD

TG-51 uses $\%dd(10)_X$ because it makes $k_Q$ values independent of what beam they are in.
Removing e- contamination effects

e- contamination affects D_max and hence %dd(10) at or above 10 MV

%dd(10)_x = %dd(10) (below 10 MV)

else

%dd(10)_x = 1.267%dd(10) - 20.0

for 75% < %dd(10) < 90% with 50 cm clearance (±2%)

The above is based on very scattered data and only approximate.
Can we do better?

Electron contamination

Variable e+

accelerator head

1 mm lead removes variable e+

Variable e+

accelerator head

adds known e+

Correction for e- contamination

\[ f'_e = \frac{%dd(10)_x}{%dd(10)_Pb} \]

BEAM code + "tricks" used to calculate with high precision

The PDD measurements with the lead foil in place are used to extract the PDD for the photon only component of the beam.

Correction vs %dd(10)_Pb

MP 26 (1999) 533

\[ %dd(10)_x = 0.8116 + 0.00264(%dd(10)_Pb)%dd(10)_Pb \]

foil at 30 cm, %dd(10)_Pb ≥ 71%
How important is correction?

Say $f_x$ wrong by 1% (ie, a 50% error) near $\%dd(10)$, $x = 80\%$.  

$\Rightarrow \%dd(10)$ is 80.8%, not 80.0%  

$\Rightarrow$ error in $k_Q$ is 0.17%  

Ignore correction $\Rightarrow$ 0.35% error in $k_Q$

TG-51 is not sensitive to measuring electron contamination accurately.

TG-51 uses $\%dd(10), x$ as a beam quality specifier because:

0% 1. it uniquely determines the stopping-power ratio to be used in that beam  
0% 2. it uniquely determines the $k_Q$ value to be used  
0% 3. it is independent of electron contamination effects  
0% 4. the TPR$_{20,10}$ specifier does not work well for some standards labs accelerators which have beams that are not like those in the clinic, whereas $\%dd(10), x$ does.  
0% 5. all of the above  
0% 6. only (2) and (4)

Answer is 5: all of the above

- 1) it uniquely determines the stopping-power ratio  
is correct since the major component of the $k_Q$ values is the stopping-power ratio and hence it must be specified uniquely.  
- 2) it uniquely determines the $k_Q$ value to be used  
is correct since $k_Q$ is the only quantity which needs to be determined based on the beam quality for photon beams, so clearly it must be uniquely determined. If we use TPR$_{20,10}$ as a beam quality specifier, then for a given value of TPR$_{20,10}$ there could be a range of $k_Q$ values, especially when using beams that are not clinical in primary standards laboratories

Answer is 5: all of the above

- 3) it is independent of electron contamination effects  
is correct since by definition $\%dd(10), x$ does not include electron contamination. TG51 provides methods for taking into account electron contamination  
- 4) TPR$_{20,10}$ specifier does not work for some accelerators  
is correct. During the talk, and in the Kosunen paper (see ref list) data were presented which showed an example of beams at the NPL and NRC which both had a TPR of 0.79 but their measured $k_Q$ values in those beams differed by over 1%. However, using $\%dd(10), x$ these beams had very different beam qualities and the overall $k_Q$ vs $\%dd(10), x$ curves in both labs were close to identical.  

Hence answer 5 (all of the above) is correct.
**Overview - electrons**

- get a traceable \( \frac{N_{\text{elec}}^{\text{con}}}{D_{\text{con}}} \) \( R_{50} \).
- measure \( I_{90} \) to give \( k_{Q} \).
- deduce \( d_{\text{ref}} = 0.6 R_{50} - 0.1 \text{ cm} \).
- measure ion chamber reading, \( M_{\text{raw}} \) at \( d_{\text{ref}} \).
- convert to fully corrected charge \( (M = P_{\text{ion}} P_{\text{elec}} M_{\text{raw}}) \).
- lookup \( k_{\text{ecal}} \) for your chamber.
- determine \( k'_{R_{50}} \) (fig, formula).
- establish \( D_{\text{con}}^{Q} (M_{\text{raw}} \text{ at two depths}) \).
- apply \( D_{\text{con}}^{Q} = M_{\text{ecal}} P_{\text{con}} k_{R_{50}} k_{\text{ecal}} N_{\text{elec}}^{\text{con}} \).

**e- beams: calibration coefficients**

**Equations for \( k_{\text{ecal}} \) & \( k'_{R_{50}} \)**

- from defns of \( k_{\text{ecal}} \) & \( k'_{R_{50}} \):

\[
\begin{align*}
  k_{\text{ecal}} &= \frac{\left[ \frac{L}{\rho} \right]_{\text{wall}} P_{\text{wall}} P_{\text{val}}}{\left[ \frac{L}{\rho} \right]_{\text{air}} P_{\text{wall}} P_{\text{val}} P_{\text{pol}}} Q_{\text{con}} \\
  k'_{R_{50}} &= \frac{\left[ \frac{L}{\rho} \right]_{\text{wall}} P_{\text{wall}} P_{\text{val}}}{\left[ \frac{L}{\rho} \right]_{\text{air}} P_{\text{wall}} P_{\text{val}} P_{\text{pol}}} Q_{\text{con}}
\end{align*}
\]

- a constant for a given chamber

\(= 1.00 \) for \( R_{50} = Q_{\text{ecal}} \)

**Why is it done this way for e-?**

- parallel to photon formalism as much as possible
- \( k_{\text{ecal}} \) and \( k'_{R_{50}} \) can be measured directly
- \( k_{\text{ecal}} \) useful in cross-calibration for plane-parallel chambers
- \( R_{50} \) used as a beam quality specifier since
  - \( E_{0} \) has significant problems
  - realistic stopping power ratios at \( d_{\text{ref}} \) are well specified by \( R_{50} \)
Realistic electron beam sprs


Effects of realistic sprs


Realistic sprs: \( d_{\text{ref}} = 0.6R_{50} - 0.1 \)


\( k_{R_{50}} \) for cylindrical chambers

The TG-51 equations e-beams are more complex than those for photon beams because:

1. Stopping-power ratios in electron beams change with depth, unlike those in photon beams which are nearly constant.
2. Gradient correction factors must be measured in each user's beam and thus $P_{gr}$ cannot be included in the protocol's $k_Q$ values as done for photon beams.
3. Electron beams have a finite range in the patient.
4. There is an intrinsic complexity added because the calibration coefficient is for a photon beam and we need the dose in an electron beam.
5. All of the above.

Ans is 5: (2) & (4) make e-beam formalism more complex.

Summary so far:
- Have reviewed
  - the formalism
  - the equations
  - how each factor is obtained
  - the effects of different data bases
- How good is it?
Measurement of photon $k_Q$

Seuntjens et al at NRC measured $k_Q$ for $\geq 3$ of each of 6 chamber types

Measurement accuracy $\pm 0.5$

$k_Q$ consistent for each type

RMS deviation TG-51 vs expt for 60 data points is 0.4%

Based on this agreement with measurements, a reasonable uncertainty on TG-51 photon beam $k_Q$ values is 0.5%

What is uncertainty on dose?

$D_w^Q = M k_Q N_{D,w}^{0.0} C_{o}$

- Uncertainties (photons)
  - on $N_{D,w}$ is 0.5-0.6%
  - on $k_Q$ is 0.5%
  - on $M$ ($k_{dd}(10)$, monitor etc) 0.7%
  - total uncertainty 1.0%

TG-51 is more accurate than TG-21 because:

0% 1. TG-51 properly accounts for an aluminum central electrode
0% 2. TG-51 uses a more up-to-date and consistent set of stopping powers
0% 3. TG-51 takes into account realistic stopping-power ratios in electron beams
0% 4. TG-51 avoids the conversion from air-kerma-based quantities to absorbed-dose-based quantities
0% 5. all of the above
0% 6. only (1) and (3)
Ans is 5:
TG-51 is more accurate than TG-21 because:

1. TG-51 accounts for an aluminum central electrode is correct since TG-21 ignored the central electrode effect which is an 0.8% effect in Co-60 beams and somewhat less at higher energies and much less in electron beams.

2. TG-51 uses a more up-to-date and consistent set of stopping powers is correct since TG-21 used ICRU Report 35 stopping powers for photon beams and those from Report 37 for electron beams. The Reports’ values differed by up to 1%. ICRU Report 37 is now considered the gold standard for stopping powers and TG-51 uses these stopping powers consistently.

3. TG-51 takes into account realistic stopping power ratios in electron beams is correct because the switch to $d_{eq}$ and use of the spr data from Burns et al means that the values used correspond to realistic electron beams rather than to mono-energetic electron beams as used in TG-21.

4. TG-51 avoids conversion from air-kerma to absorbed dose-based quantities is correct because the use of absorbed dose to water calibration coefficients means that there is no need to convert from the air kerma calibration coefficients to an absorbed dose quantity. This avoids the use of the extensive theory needed to make this conversion.

5. Hence the correct answer is (5), all of the above.

Odds and ends

- $P_{ion}$
  - new equations
  - problems with the theory

- stopping power ratios for depth-dose curves
  - need sprs for realistic beams

$P_{ion}$ equations

- $P_{ion}$ continuous beams (as TG-21)
  \[
P_{ion}(V_{eq}) = \frac{1 - (\frac{V_{eq}}{V_{c}})^{2}}{\frac{M_{eq}}{M_{c}} - \frac{V_{eq}}{V_{c}}}
\]

- $P_{ion}$ pulsed or pulsed swept ($P_{ion} < 1.05$)
  \[
P_{ion}(V_{eq}) = \frac{1 - \frac{V_{eq}}{V_{c}}}{\frac{M_{eq}}{M_{c}} - \frac{V_{eq}}{V_{c}}}
\]

Do not increase voltage to get $P_{ion} < 1.05$
Pion equations

For $P_{\text{ion}} < 1.05$
TG-51 eqn is good to 0.2% for pulsed beams
or to 0.4% for pulsed-swept beams

$sprs$ for depth-dose curves

TG-51 gives the dose at $d_{\text{ref}}$
To get the dose at $d_{\text{max}}$ requires a high-quality depth-dose curve

Need to correct for $spr$ and $P_{\text{fl}}$ (cylindrical chambers)

Need realistic $spr$ vs depth to be consistent with $spr$ at $d_{\text{ref}}$

$L/\rho(R_{50}, z)$

Burns et al gave a fit to the Monte Carlo realistic $spr$ values

$$
\frac{L}{\rho(R_{50}, z)} = \frac{a + b(I_{\text{mon}}) + c(I_{\text{mon}}) + d(I_{\text{mon}})}{1 + e(I_{\text{mon}}) + f(I_{\text{mon}}) + g(I_{\text{mon}}) + h(I_{\text{mon}})}
$$

$$
\begin{align*}
L/\rho &\approx 3.7705 \quad b = -0.000077 \\
R_{50} &\approx 0.000076 \quad d = -0.000022 \\
z &\approx 0.42906 \quad g = -0.000065 \\
L/\rho &\approx 3.7705 \quad b = -0.000077 \\
R_{50} &\approx 0.000076 \quad d = -0.000022 \\
z &\approx 0.42906 \quad g = -0.000065
\end{align*}
$$

Tabulated vs $R_{50}$ and $z/R_{50}$ at
http://www.physics.carleton.ca/~drogers/pubs/papers

NOTE: Formula is good over a limited range ($0.02 < z/R_{50} < 1.2$) and has limited accuracy away from $d_{\text{eff}}$ (about 1%).


Conclusion

There is too much in TG-51 to cover in 1 lecture

Thank you for your attention
Resources/References

- TG-51 protocol MP 26 (1999) 1847 -- 1870
- Burns et al, \( R_{50} \) as a beam quality specifier for selecting stopping-power ratios and reference depths for electron dosimetry MP 23 (1996) 383
- Rogers, A new approach to electron beam reference dosimetry, MP 25 (1998) 310

EXTRAS

Mass energy absorption coefficients

TG-51 data is based on Hubbell's 1982 data set and Cunningham's MC tables.

- http://rpc.mdanderson.org/RPC and click on TG-51 on left
Measuring depth-dose curves

- Shift measured curve upstream by 0.6 $r_{eq}$

- Depth-ionization curve - depth at chamber center

- 10 cm depth

- %dd(10)

- Depth-dose

- Measured $k_Q$ vs TG-51

- $k_3$

- $k_{e\text{ cal}}$

- $k_{E}\sqrt{R}$

- Measuring depth-dose curves

- $k_{e\text{ cal}}$

- E-beams: absorbed-dose calibration factors

- $N_Q^{\text{cal}} = \frac{P^Q_{\text{cal}}}{P^Q_{\text{cal}} k_{\text{cal}}} N_{\text{D},w}^\text{Co}$

- $N_Q^{\text{cal}} = \frac{P^Q}{P^Q_{\text{cal}} k_{\text{cal}}} N_{\text{D},w}^{\text{cal}}$

- These can be used to measure $k_{\text{cal}}$ and $k_{e\text{ cal}}$

- E-contamination can be calculated

- Mora et al., MP 26(1999)2494