Physics of the TG-51 dosimetry protocol

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Ch 9 of book
**General formalism: definitions**

\[ D^Q_w = MN^Q_{D,w} \]

defines: chamber's absorbed dose calibration coefficient

\[ N^Q_{D,w} = k_Q N^{60Co}_{D,w} \]

defines \( k_Q \): chamber specific beam quality conversion factor

-accounts for \( N_{D,w} \) variation with \( Q \)

for e- beams

\[ k_Q = P^Q_{gr} k_{R50} \]

defines \( k_{R50} \): component of \( k_Q \) which is independent of \( P_{gr} \), the gradient at point of measurement.
**General formalism: definitions**

\[ k_{\text{ecal}} = k_{R^{50}}^{Q_{\text{ecal}}} \]

defines \( k_{\text{ecal}} \): chamber specific photon-electron conversion factor
- \( Q_{\text{ecal}} \) an arbitrary e- energy
- accounts for \( N_{D,w} \) variation between \( ^{60}\text{Co} \) and \( Q_{\text{ecal}} \)

\[ k_{R^{50}} = k_{R^{50}}' k_{\text{ecal}} \]

defines \( k_{R^{50}}' \): chamber specific electron quality conversion factor
- accounts for \( N_{D,w} \) variation between \( Q_{\text{ecal}} \) and \( R^{50} \)
These 5 definitions lead to two dose equations

### Photons

\[ D_{w}^{Q} = M k_{Q} N_{D,w}^{60C_{o}} \]

### Electrons

\[ D_{w}^{Q} = M P_{gr}^{Q} k'_{R50} k_{ecal} N_{D,w}^{60C_{o}} \]

*\( P_{gr} \) is part of \( k_{Q} \) for photon beams since the same for all beams of same quality.*

*For e- beams \( P_{gr} \) varies for a give beam quality, \( R_{50} \), - thus must be explicitly found for each beam*
General formalism: $N_{D,w}$ relationships
Where does \( k_Q \) come from?

Basically - same physics as TG-21, ie Spencer-Attix cavity theory but without the complexity of changing from an air kerma calibration coefficient to an absorbed-dose measurement.

\[
D_{\text{med}} = D_{\text{air}} \left( \frac{L}{\rho} \right)_{\text{air}}^{\text{med}} \cdot P_{\text{wall}} P_{fl} P_{gr} P_{\text{cel}} K_h
\]

- \( P_{\text{wall}} \) corrects for the wall not being the same as medi
- \( P_{\text{cel}} \) corrects for an aluminum central electrode not being wall material
- \( K_h \) accounts for measurements being in humid air but all factors refer to dry air (\( K_h = 0.997 \))
\[ P_{\text{repl}} = P_{\text{gr}} P_{\text{fl}} \]

\( P_{\text{repl}} \) accounts for effects of cavity on electron spectrum that would be present at point of measurement.

\( P_{\text{gr}} \): that part of \( P_{\text{repl}} \) which accounts for less attenuation in cavity than in phantom.
- Usually only thought to apply to cylindrical chambers.
- Depends on local gradient \( \Rightarrow \) no effect at \( d_{\text{max}} \).
- Handled by:
  - Effective point of measurement when measuring dose distributions (0.5/0.6 \( r_{\text{cav}} \) offset for e-/photon beams).
  - Measuring at \( d_{\text{max}} \) in e- beams (TG-21).
  - \( P_{\text{gr}} \), a correction factor: for e- beams
    \[ P_{\text{gr}} = \frac{M_{\text{raw}}(d_{\text{ref}} + 0.5r_{\text{cav}})}{M_{\text{raw}}(d_{\text{ref}})} \]
- Photon beams dealt with later.
\[ P_{\text{repl}} = P_{\text{gr}} P_{\text{fl}} \]

\( P_{\text{fl}} \): that part of \( P_{\text{repl}} \) which accounts for other changes in the spectrum in the cavity.

**Photon beams**

Not required past \( d_{\text{max}} \) because of transient charged particle equilibrium and

Fano theorem tells us spectrum is independent of density and to extent that water is like air, the theorem applies.

**Electron beams**

Fluence in cavity increases due to lack of out-scatter and hence \( P_{\text{fl}} < 1 \)
Deriving equations for $k_Q$ etc

$$D_{med} = D_{air} \left( \frac{L}{\rho} \right)_{med} \quad P_{wall} P_{fl} P_{gr} P_{cel} K_h$$

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

$\text{-}M$ is fully corrected charge

From defn

$$N^Q_{D,w} = \frac{D^Q_w}{M}$$

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

$$N^Q_{D,w} = \frac{K_h}{m_{air}} \left( \frac{W}{e} \right)_{air} \left( \frac{L}{\rho} \right)_{air} ^w \quad P_{wall} P_{fl} P_{gr} P_{cel}$$
Equation for $k_Q$

- defn of $k_Q$ implies

$$k_Q = \frac{N_{Q,D,w}}{N_{D,Co}^{60}}$$

- and from before:

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

- assuming $W/e$ constant gives

$$k_Q = \frac{\left[ \left( \frac{L}{\rho} \right)_{air} P_{wall} P_{fl} P_{gr} P_{cel} \right]^w}{\left[ \left( \frac{L}{\rho} \right)_{air} P_{wall} P_{fl} P_{gr} P_{cel} \right]_{60}^{Co}}$$

- applies to electrons and photons
  - but only used for photons
Equations for $k_{\text{ecal}}$ and $k'_{R_{50}}$

- From definitions of $k_{\text{ecal}}$ and $k'_{R_{50}}$

$$k_Q = P_{gr}^Q k_{R_{50}}$$
$$k_{\text{ecal}} = k_{Q_{\text{ecal}}}$$
$$k_{R_{50}} = k'_{R_{50}} k_{\text{ecal}}$$

$$k_{\text{ecal}} = \frac{\left[ \left( \frac{L}{\rho} \right)_{\text{air}}^w P_{\text{wall}} P_{\text{fl}} P_{\text{cel}} \right] Q_{\text{ecal}}}{\left[ \left( \frac{L}{\rho} \right)_{\text{air}}^w P_{\text{wall}} P_{\text{fl}} P_{\text{gr}} P_{\text{cel}} \right]_{60 \text{Co}}}$$

$$k'_{R_{50}} = \frac{\left[ \left( \frac{L}{\rho} \right)_{\text{air}}^w P_{\text{wall}} P_{\text{fl}} P_{\text{cel}} \right] Q}{\left[ \left( \frac{L}{\rho} \right)_{\text{air}}^w P_{\text{wall}} P_{\text{fl}} P_{\text{cel}} \right] Q_{\text{ecal}}}$$

$a$ constant for a given chamber

$= 1.00$ for $R_{50} = Q_{\text{ecal}}$
Beam quality specification

- need to specify beam quality to select \( k_Q \) and \( k'_{R50} \)
- 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 photon component of percentage depth-dose at 10 cm depth in a 10x10 cm\(^2\) field defined on surface of water phantom at 100 cm SSD

TG-51 uses \( \%dd(10)_X \) because it makes \( k_Q \) values independent of what type of beam they are in.
Beam quality specification: Why TPR is not ideal

Heavily filtered "clinical" beams are on upper curve.

NRC soft beams (used to measure $k_Q$) and FFF beams are below.

Beam quality specification: Why use \( \%dd(10)_x \)
Extracting photon component of %dd(10)
removing e- contamination effects

\( e^- \) contamination affects \( D_{\text{max}} \) and hence %dd(10) at or above 10 MV

\[
%\text{dd}(10)_x = %\text{dd}(10) \quad \text{(below 10 MV)}
\]

\[
%\text{dd}(10)_x = 1.267%\text{dd}(10) - 20.0 \quad \text{else}
\]

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 \( e^+ \) is added to known \( e^- \) and 1mm lead removes variable \( e^+ \).
Correction for e\textsuperscript{-} contamination

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

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 $\%dd(10)_{\text{Pb}}$

\[
%dd(10)_{x} = [0.8116 + 0.00264%dd(10)_{\text{Pb}}] %dd(10)_{\text{Pb}}
\]

[foil at 30 cm, $%dd(10)_{\text{Pb}} \geq 71\%$]
How important is correction?

Say $f_e'$ wrong by 1% (ie. a 50% error) near $%dd(10)_x = 80\%$.

$\Rightarrow %dd(10)_x$ 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 accounting accurately for e- contamination.
Beam quality specification in e-beams: What’s wrong with $E_o = 2.33R_{50}$?

It doesn’t work
- parallel beams
- mono-energetic

Realistic beams at SSD=100 show variation

Ding et al Med Phys 23 (1996) 361
Beam quality specification in e- beams: realistic electron beam sprs

$R_{50}=8.1 \text{ cm}$

$D_{ref}=4.8 \text{ cm}$

Ding et al Med Phys 22 (1995)489
Effects of realistic sprs

% correction at $d_{\text{max}}$

bremsstrahlung tail $D_x$

- Clinac 2100C
- SL75–20
- KD2
- Therac 20
- Racetrack

Ding et al Med Phys 22 (1995) 489
Solution re realistic sprs-change dref:

\[ d_{\text{ref}} = 0.6R_{50} - 0.1 \]
Measuring $R_{50}$ via $I_{50}$

We measure $I_{50}$ but need $R_{50}$

Calculations ignore all corrections except spr going from dose to ionization

$$R_{50} = 1.029I_{50} - 0.063 \quad (I_{50} \leq 10 \text{ cm})$$

$$R_{50} = 1.059I_{50} - 0.37 \quad (I_{50} > 10 \text{ cm})$$

Ding et al Med Phys 22 (1995) 489
Physical data sets in TG-51

Much of data comes directly from TG-21 and/or IAEA's TRS-277 (1987 Code of Practice).

TG-21 used different stopping power data for e- and photon beams (ICRU Reports 37 and 35 respectively).

TG-51 consistently uses ICRU Report 35 stopping powers. For photon beams, based on Monte Carlo calculations for 25 different beams:

\[
\left(\frac{L}{\rho}\right)_{\text{water}} = 1.275 - 0.00231(\%dd(10)_x) \quad \%dd(10)_x \geq 63.35\%
\]

Burns et al eqn for e- beams is also based on ICRU Report 37 stopping powers
photon stopping power ratios

TG-51 uses stopping powers from ICRU Report 37

This is biggest difference from TG21.

Due to underlying stopping powers

-TG-51 values from Rogers and Yang Med Phys 26 (1999) 536
Uncertainties are related to uncertainties in underlying stopping powers

- **I-values**: most recent water I-value measurement is 6% different from that used
  => 0.1 to 0.4% change in $k_Q$.

Calculations with full photon beam phase-space (with horns and varying energy cross beam) rather than calc with realistic spectra but uniform point sources show no significant changes.

Similarly, the sprs as a function of %dd(10)$_x$ do not change when flattening filter is removed (they change as a function of TPR)
Calculation of TG-51 factors

To calculate $k_Q$, $k_{ecal}$, etc we need:

- sprs, $P_{wall}$, $P_{cel}$, $P_{fl}$, $P_{gr}$
- plus a method to convert $TPR_{20,10}$ to $\%dd(10)_x$

since much of original data is in terms of $TPR_{20,10}$

Ch 9 gives details for each of these.
\[ TPR_{20,10} \leftrightarrow \%dd(10)_x \]

This applies to heavily filtered beams only.

\[ TPR^{20}_{10} = -0.8228 + 0.0342 (\%dd(10)_x) - 0.0001776 (\%dd(10)_x)^2 \]

\[ \%dd(10)_x = -430.62 + 2181.9 \left( TPR^{20}_{10} \right) - 3318.3 \left( TPR^{20}_{10} \right)^2 + 1746.5 \left( TPR^{20}_{10} \right)^3 \]
$P_{cell}$: Al electrode correction

- For electrode same as wall material, any effect is in $P_{fl}$
- Ma & Nahum showed aluminum electrodes have an effect
  - Larger in photon beams
- But biggest effect in TG-51 is in electron beams because it cancels in photons
- Was not included in TG-21

Ma & Nahum PMB 38 (1993) 267
$P_{\text{cel}}$: Al electrode correction

-expts confirm calns

-more accurate recent calculations are in good agreement

-effect much smaller in e-beams (<0.2%)
\( P_{\text{wall}} \)

- accounts for wall not being water
  - unity for electrons
  - same as TG-21 for photons (Almond-Svensson eqn)

\[
P_{\text{wall}} = \alpha \left( \frac{L}{\rho} \right)_{\text{wall}} \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{wall}} + \tau \left( \frac{L}{\rho} \right)_{\text{sheath}} \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{sheath}} + (1 - \alpha - \tau) \left( \frac{L}{\rho} \right)_{\text{air}}
\]

For walls 0.05g/cm\(^2\)

Changes vs TG-21 due to better cross sections
Recent Monte Carlo values of $P_{wall}$

Buckley et al MP 33(2006) 455
MP 33(2006) 1788

TG51 uses 1.000
EGSnrc results supersede EGS4 results used in TG-51.

$k_{\text{ecal}}$ values will decrease since

\[ k_{\text{ecal}}^{pp} = \frac{0.9038}{P_{\text{wall}}^{60\text{Co}}} \]

(note Ch9 misleading)
**P\textsubscript{fl} for cylindrical chambers**

\[ P_{\text{fl}} = 1.000 \text{ in photon beams at 10 cm depth because of transient charged particle equilibrium} \]

For **cylindrical chambers in e- beams**, TG-51 uses values as a function of \( E_z \) and \( r_{\text{cav}} \). These are from TG-21 based on measurements by Johansson et al (1977) at \( d_{\text{max}} \).

More recent but less extensive measurements by Wittkamper and others confirmed the original measurements.
**P_{fl} for cylindrical chambers**

Tabulated vs $E_z$ at $d_{max}$, but we need values at $d_{ref}$. Calculate $E_z$ at $d_{ref}$ and use tabulated values for $d_{max}$.

**How do we get $E_z$ at $d_{ref}$ given $R_{50}$?**

Harder relationship:

$$E_z = E_0 \left(1 - \frac{z}{R_p}\right)$$

Figure shows linear relationship between $R_{50}$ & $R_p$ for many calculated depth-dose curves.

$$E_z = 2.33R_{50} \left(1 - \frac{z}{1.2709R_{50} - 0.23}\right)$$
$P_{fl}$ for plane-parallel chambers

Based on values in TG-39: Unity for “well-guarded” chambers and less than 1.0 for others.

Markus & Capintec values based on many measurements with large uncertainties.
As discussed previously, e-beams use a simple measurement to obtain $P_{gr}$.

**Photon beams**

TG-51 & TG-21 use values of Cunningham & Sontag (1980) - values buried in $k_Q$ values

IAEA uses values from Johansson et al (1977) which also led to the 0.75 $r_{cav}$ and 0.6 $r_{cav}$ offsets used for the effective point of measurement approach

Offset values can lead to equivalent correction factors

$$P_{gr}^{\text{offset}} = 1 + \left( \frac{1}{10} \ln \frac{D_{20}}{D_{10}} \right) \Delta z$$

$$\frac{D_{20}}{D_{10}} = 0.05607 + 0.77639 \ TPR_{10}^{20}$$
$P_{gr}$ for cylindrical chambers

$P_{gr}$ is largest difference between TG-51 and TRS-398.

Wang’s MC calns disagree with both: and can explain previous measurements.

$P_{gr}$ ratio used in TG-51 hardly changes since lines parallel.
**ion recombination: \( P_{\text{ion}} \)**

Corrects reading to 100% collection efficiency.

For pulsed beams a then "new" linearized form of the TG-21 eqn is used.

\[
P_{\text{ion}}(V_H) = 1 - \frac{V_H}{V_L} \frac{M^H_{\text{raw}}}{M^L_{\text{raw}}} - \frac{V_H}{V_L}
\]

Must be measured at dose-rate to be used at
experimental verification of \( k_Q \)

Expts agree with TG-51 values within experimental uncertainties.

Experimental verification of $k_Q$

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

Measured against primary standards.

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?

\[ D^Q_w = M k_Q N_{D,w}^{60Co} \]

- Uncertainties (photons)
  - on \( N_{D,w} \) is 0.5-0.6%
  - on \( k_Q \) is 0.5%
  - on \( M \) (%dd(10)_x, monitor etc) 0.7%
- total uncertainty 1.0%
The photon beam $P_{\text{wall}}$ and $P_{\text{repl}}$ values in TG-51 have been shown to be wrong.

What is overall effect on $k_Q$?

Bryan Muir, AAPM 09: preliminary results

Carleton University
Conclusion

Despite various improvements in our understanding of the details of corrections used in TG-51, the overall accuracy is still thought to be of the order of 1% or better, at least for photon beams. We still need some more experimental confirmations in electron beams.

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Resources/References

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- 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
Resources/References

- Rogers, Fundamentals of Dosimetry Based on Absorbed-Dose Standards in 1996 AAPM Summer School book (
  http://www.physics.carleton.ca/~drogers/pubs/papers)

- http://rpc.mdanderson.org/RPC and click on TG-51 on left

- Rogers, Fundamentals of high energy x-ray and electron dosimetry protocols in 1990 AAPM Summer School book
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