TLD and Monte Carlo Techniques for Reference-Quality Brachytherapy Dosimetry

AAPM Summer School
23 June 2009

Jeffrey F. Williamson, Ph.D.
Virginia Commonwealth University

Mark R. Rivard, Ph.D.
Tufts-New England Medical Center

VCU Radiation Oncology
Virginia Commonwealth University
Learning Objectives

• To review the requirements and challenges of quantitative brachytherapy dosimetry
  – Detector selection
  – Roles of experimental and computational dosimetry

• To review the formalism, techniques, and associated uncertainties of
  – Current TLD dosimetry practices
  – Current Monte Carlo simulation dose-estimation practices

• To review emerging developments
  – Improved energy-response corrections for TLD-100
  – New detector systems
  – Model-based dose-calculation algorithms
Potential COI Disclosures

• Williamson
  – Research grants supported by Varian and Philips

• Rivard
  – Research grants supported by Nucletron, Varian, and IsoRay

(Radiumhemmet, Stockholm: 1945)
What is “Quantitative Dosimetry?”

- Williamson’s definition: absorbed dose estimation method providing
  - Accurate representation of well-defined physical quality
  - Rigorous uncertainty analysis \( \Rightarrow <10\% \) uncertainty 0.5 to 5 cm in liquid water
  - Traceable to NIST primary standards \( (S_{K,N99}) \)
- Applications
  - Single-source dose-rate arrays for TG-43 parameter determination ("Reference quality" dose distributions)
  - Direct treatment planning
  - Validating semi-empirical algorithms
Single-Source Dose Distributions
Superposition Model

Single-source dose distribution = Dosimetry
Superposition of multiple source doses = Treatment Planning
Criteria for experimental dosimeters

• Dosimetric environment
  – Large Dose Gradients
  – Wide Range of Dose Rates
  – Low Photon Energies

• Signal stability and reproducibility
  – Spatially and temporally constant Sensitivity (signal/dose)
  – Free of fading, dose-rate effects

• Small size, high sensitivity, large dynamic range
  – Small size: avoid averaging dose gradients
  – Large size: Good signal at low doses

• ±20 µm positioning accuracy needed for 2% accuracy

• Support measurements at many points
Solid Water Phantoms for TLD Dosimetry

Transverse Axis Measurement Phantom

Polar Dose Profile Measurement Phantom

100-200 μm positional accuracy achievable
TLD Detectors

- Use TLD-100 LiF extruded ribbons (‘chips’) 
  1 x 1 x 1 mm$^3$ at distances < 2 cm
  3 x 3 x 0.9 mm$^3$ at distances ≥ 2 cm

- Use RMI 453 Machined Solid Water Phantom
  - Composition (CaCO$_3$ + organic foam) not stable
  - Either perform chemical assay or use high purity PMMA

- Annealing protocol
  1 hour 400° C followed by 24 hours of 80° C pre-irradiation
  
  OR

  1 hour 400° C pre-irradiation followed by 10 minutes at 100° C Post-irradiation
• **Given:** $M(r) = \text{dosimeter (TLD or Diode) reading in geometry } G_{\text{exp}}$

• **Desired:** $\left( \frac{D_{\text{med}}(r)}{S_K} \right) = \text{absorbed dose rate to water in reference geometry, } G_{\text{ref}}$

• **Many Corrections**
  - Detector sensitivity
  - Phantom vs reference geometry
  - Radiation field Perturbation
  - Detector response artifacts
Experimental Dose Measurement-I

\[
\frac{D_{med}(r)}{S_K} = \frac{M \cdot k_l(M) \cdot g(\Delta T) \cdot p_{phant}(r)}{S_K \cdot S_{AD}(M_0) \cdot S_{AD}^{rel}(r)}
\]

\[
M(r) \cdot k_l(M \rightarrow M_0) \cdot g(\Delta T) \cdot p_{phant}(Q_{exp}, G_{exp} \rightarrow Q_{ref}, G_{ref}; r)
\]

\[
S_K \cdot S_{AD}(M_0, Q_0, G_0) \cdot S_{AD}^{rel}(Q_0, G_0 \rightarrow Q_{exp}, G_{exp}, r)
\]

- **M** = reading at position \( r \) in geometry \( G_{exp} \) and spectrum \( Q_{exp} \)
- **\( S_K \) =** Measured Air-Kerma Strength
- **\( g(T) \) =** decay correction over integration interval, \( \Delta T \)
- **\( K_l(M) \) =** linearity correction relative to reference level, \( M_0 \)
- **\( S_{AD} = M_0/D_{med0} \) =** absorbed dose sensitivity in calibration beam with geometry \( G_0 \) and spectrum, \( Q_0 \)
Experimental Dose Measurement-II

\[
\frac{D_{\text{med}}(r)}{S_K} = \frac{M \cdot k_l(M) \cdot g(\Delta T) \cdot p_{\text{phant}}(r)}{S_K \cdot S_{\text{AD}}(M_0) \cdot S_{\text{AD}}^{\text{rel}}(r)}
\]

- **Relative absorbed dose sensitivity:** corrects for impact of \(G_0/Q_0\) vs. \(G_{\text{exp}}/Q_{\text{exp}}\) differences on dosimeter response

\[
S_{\text{AD}}^{\text{rel}}(Q_0, G_0 \rightarrow Q_{\text{exp}}, G_{\text{exp}}, r) = \frac{S_{\text{AD, wat}}(r, M_0, Q_{\text{exp}}, G_{\text{exp}})}{S_{\text{AD, med}}(M_0, Q_0, G_0)}
\]

- **Phantom correction factor:** impact of \(G_{\text{exp}}/Q_{\text{exp}}\) vs. \(G_{\text{ref}}/Q_{\text{ref}}\) differences on dosimeter response

\[
p_{\text{phant, wat}}(Q_{\text{exp}}, G_{\text{exp}} \rightarrow Q_{\text{ref}}, G_{\text{ref}}, r) = \frac{D_{\text{wat}}(r, Q_{\text{ref}}, G_{\text{ref}})}{D_{\text{wat}}(r, Q_{\text{exp}}, G_{\text{exp}})}
\]
TLD readings

\[ M(r) = \frac{1}{n} \sum_{i=1}^{n} \frac{(T_{L_i} - T_{L_{bkgd}})}{S_i} \]

- \( T_{L_i} \) is Measured Response of i-th detector at \( r \)
- \( S_i \) is relative sensitivity of i-th detector derived from reading TLDs exposed to uniform doses
- TG-43 recommends \( n = 5-15 \)
Relative Energy Response

\[ E(Q_0, G_0 \rightarrow Q_{\text{ref}}, G_{\text{ref}}, r; G_{\text{exp}}) = \frac{S^{\text{rel}}_{\text{AD}}(Q_0, G_0 \rightarrow Q_{\text{exp}}, G_{\text{exp}}, r)}{p_{\text{phant, wat}}(Q_{\text{exp}}, G_{\text{exp}} \rightarrow Q_{\text{ref}}, G_{\text{ref}}; r)} \]

\[ = k^{\text{rel}}_{\text{bq}}(Q_0 \rightarrow Q_{\text{exp}}; M_0) \cdot f^{\text{rel}}(Q_0, G_0 \rightarrow Q_{\text{exp}}, G_{\text{exp}}, r) \]

\[ \frac{p_{\text{phant}}(Q_{\text{exp}}, G_{\text{exp}} \rightarrow Q_{\text{ref}}, G_{\text{ref}}; r)}{p_{\text{phant}}(Q_{\text{exp}}, G_{\text{exp}} \rightarrow Q_{\text{ref}}, G_{\text{ref}}; r)} \]

- Absorbed dose energy dependence

\[ f^{\text{rel}}(Q_0, G_0 \rightarrow Q_{\text{exp}}, G_{\text{exp}}, r) \equiv \frac{f(r, Q_0, G_0)}{f(r, Q_{\text{exp}}, G_{\text{exp}})} = \frac{(\bar{D}_{\text{det}}/D_{\text{wat}})(r, Q_{\text{exp}}, G_{\text{exp}})}{(\bar{D}_{\text{det}}/D_{\text{med}_0})(Q_0, G_0)} \]

- Relative intrinsic energy dependence

\[ k^{\text{rel}}_{\text{bq}}(Q_0 \rightarrow Q_{\text{exp}}; M_0) \equiv \frac{k_{\text{bq}}(M_0, Q_0)}{k_{\text{bq}}(M_0, Q_{\text{exp}})} = \frac{(M_0/\bar{D}_{\text{det}})(r, Q_{\text{exp}}, G_{\text{exp}})}{(M_0/\bar{D}_{\text{det}})(Q_0, G_0)} \]
Estimation of Energy-Response Corrections

- Theoretical Approximation

\[
E_{Thy}(r;G_{exp}) \approx \frac{f^{rel}(Q_0,G_0 \rightarrow Q_{exp},G_{exp},r)}{p_{phant}(Q_{exp},G_{exp} \rightarrow Q_{ref},G_{ref},r)}
\]

assuming \( k_{bq}^{rel}(Q_0 \rightarrow Q_{exp};M_0) \approx 1 \)

- Direct measurement: x-ray beam with spectrum \( Q_{FS} \approx Q_{exp} \)

\[
E_{meas}(r;G_{exp}) = \frac{S_{K,air}(M_0, Q_{exp}, G_{FS})}{S_{AD,med_0}(M_0, Q_0, G_0)} \times \frac{\left( K_{air}/D_{wat} \right)(Q_{FS}, G_{FS})}{p_{disp}(r, G_{exp}) \cdot p_{VolAvg}(r, G_{exp}) \cdot p_{phant, wat}(G_{exp} \rightarrow G_{ref}, Q_{exp}, r)}
\]
Compare detector to “matched” X-ray Beam calibration in Free-Air

\[ Q_{FS} = 40-120 \text{ kVp} \]

\[
S_{K,\text{air}}(Q_{FS}) = M(Q_{FS}, G_{FS}) / K_{\text{air}}^{FS}
\]

\[
E(r) = \left( \frac{S_{K,\text{air}}(Q_{FS})}{S_{AD}(Q_0)} \right) \cdot \left( \frac{\mu_{en} / \rho_{\text{air}}}{\rho_{\text{wat}}} \right) \cdot \mu_{\text{wat}}(Q_{FS}) \cdot p_{\text{VolAvg}} \cdot p_{\text{disp}}(r) \cdot p_{\text{disp}}
\]

\[
p_{\text{disp}} \left( G_{FS} \rightarrow G_{\text{exp}} \right) = \frac{D_{\text{wat}} \text{ in medium}}{K_{\text{wat}}^{FS} \text{ in cavity}} \approx 0.97
\]

\[
p_{\text{VolAvg}}(Q_{\text{exp}}, G_{\text{exp}}) = \frac{D_{\text{wat}}(r)}{D_{\text{wat}}(r)} = \frac{D_{\text{wat}}(r) \text{ at point } r}{V^{-1} \int_{V(r)} D_{\text{wat}}(r')dV'} \subseteq (0.80 - 1.00)
\]
**Measured TLD-100 relative Energy Response**

- $E_{\text{thy}}(1 \text{ cm}) = 1.42$
  - Dolan (2006) in water medium
  - $^{125}I$
- $E_{\text{meas}} = 1.39-1.44$ for $^{125}I$
  - 1980-1990 in-air measurements
- **Conclusion:**
  
  $E_{\text{Thy}} \approx E_{\text{meas}}$

  $$\Rightarrow k_{\text{rel}}^{\text{rel}}(4 \text{ MV} \rightarrow ^{125}I) \approx 1$$

- Conventional choice: $E = 1.4$ w/o regard to details
- 2004 TG-43 U1 has assigned 5% uncertainty to E
Monte Carlo vs. TLD Dose Rates

$^{125}$I Seeds: 14 Models and 25 comparisons

$$\left\langle \frac{MC}{TLD} \right\rangle = \begin{cases} 0.979 \pm 0.045 \text{ (1 cm)} \\ 1.002 \pm 0.066 \text{ (5 cm)} \end{cases}$$

$^{103}$Pd Seeds: 5 Models and 10 comparisons

$$\left\langle \frac{MC}{TLD} \right\rangle = \begin{cases} 0.982 \pm 0.028 \text{ (1 cm)} \\ 1.045 \pm 0.106 \text{ (5 cm)} \end{cases}$$
Modern Measurements: $k_{bg} \neq 1$

Nunn 2008, Davis 2003, and Das 1995

Energy linearity of TLD is controversial
Impact of $k^{rel}$ Revisions on MC-TLD Agreement

- Rivard comparisons of TLD and MC at 1 cm and 5 cm for $^{125}I$ and $^{103}Pd$ sources
- Revised $k_{rel} > 1.05$ will significantly worsen agreement

<table>
<thead>
<tr>
<th>Source</th>
<th>Distance</th>
<th>$K_{rel} = 1.00$</th>
<th>$K_{rel} = 1.05$</th>
<th>$K_{rel} = 1.075$</th>
<th>$K_{rel} = 1.10$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{125}I$</td>
<td>1 cm</td>
<td>0.979 ± 0.045</td>
<td>1.028</td>
<td>1.052</td>
<td>1.077</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>1.002 ± 0.066</td>
<td>1.052</td>
<td>1.077</td>
<td>1.102</td>
</tr>
<tr>
<td>$^{103}Pd$</td>
<td>1 cm</td>
<td>0.982 ± 0.028</td>
<td>1.031</td>
<td>1.056</td>
<td>1.080</td>
</tr>
<tr>
<td></td>
<td>5 cm</td>
<td>1.045 ± 0.106</td>
<td>1.097</td>
<td>1.123</td>
<td>1.150</td>
</tr>
</tbody>
</table>
Absorbed Dose Energy Response Correction

- $E_{thy}$ is not a constant
  - 4% variation with distance even in water
  - Displacement correction $\approx 4\%$ for 1 mm mini-cubes
- Solid-to-Liquid Water correction: 4%-15% at 1-5 cm
  - 10-30% variations in SW [Ca] reported $\Rightarrow 5\%-20\%$ dosimetric errors
Absorbed Dose Energy Response Correction

Relative $E_{thy}(1 \text{ cm, } \theta)$ for Model 6711 $^{125}$I Source

- Up to 22% variation in $E(r, \theta)$ with polar angle
### TLD uncertainties: $\frac{\tilde{D}_\text{wat}(r)}{S_K}$ for Model 6711 $^{125}$I in PMMA

<table>
<thead>
<tr>
<th>Component</th>
<th>1 cm distance</th>
<th>5 cm distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$%\sigma_x$</td>
<td>Type</td>
</tr>
<tr>
<td>TLD reading statistics</td>
<td>1.3%</td>
<td>A</td>
</tr>
<tr>
<td>TLD calibration (including Linac calibration)</td>
<td>1.8%</td>
<td>A+B</td>
</tr>
<tr>
<td>$f^\text{rel}(Q_0 \rightarrow Q_\text{exp}, r)$ and $p_{\text{phant}}(G_\text{exp} \rightarrow G_\text{ref}, r)$</td>
<td>0.7%</td>
<td>B</td>
</tr>
<tr>
<td>Seed/TLD positioning ($\Delta d = 100 , \mu m$)</td>
<td>1.2%</td>
<td>B</td>
</tr>
<tr>
<td>$k^\text{rel}<em>{bq}(Q_0 \rightarrow Q</em>\text{exp})$</td>
<td>5%</td>
<td>B</td>
</tr>
<tr>
<td>NIST $S_K$ + one local transfer</td>
<td>1%</td>
<td>B</td>
</tr>
<tr>
<td>Combined std. uncertainty ($k = 1$)</td>
<td><strong>5.7%</strong></td>
<td></td>
</tr>
</tbody>
</table>

#### Monte Carlo uncertainties: Model 6711 seed in liquid water

<table>
<thead>
<tr>
<th>Distance</th>
<th>1 cm</th>
<th>5 cm</th>
<th>10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Photon cross-sections</td>
<td>0.7%</td>
<td>2.4%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Seed geometry</td>
<td>1.1%</td>
<td>0.9%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Source energy spectrum</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Combined std. uncertainty ($k = 1$)</td>
<td><strong>1.3%</strong></td>
<td><strong>2.6%</strong></td>
<td><strong>4.3%</strong></td>
</tr>
</tbody>
</table>

Adapted from Dolan et al. Med Phys 2006
Other dosimetry systems

• Single element detectors
  – High sensitivity, small size, good SNR, and waterproof
  – Plastic scintillator
    » Used as transfer/relative dosimeters for beta sources
    » Large (30%) energy nonlinearity
  – Diode: underutilized in presenter’s opinion
    » Energy linearity well established
    » Large E(d) variation for medium energy sources
    » Established as relative dosimeter for low-energy

• 2D/3D dosimetry media
  – Radiochromic film and polymer gels
  – Improved positional accuracy and spatial resolution
Radiochromic Film

- **Le and Williamson 2006**
  - MD-55-2 RCF with LDR $^{137}$Cs source
  - 6 day exposure
  - Uncertainty (k = 1) < 3.4% for D>5 Gy, 0.1 mm spatial resolution, double-exposure technique
  - Agreement with MC ≈ 3%

- **Chiu-Tsao 2008**
  - EBT RCF with Model 3500 $^{125}$I seed
  - 0.6 to 279 h exposures
  - Relative dose mapping (k=1) uncertainty ≈ 4% at 0.2 mm spatial resolution
  - Good agreement with TG-43
Summary: TLD phantom dosimetry

- 1-3 mm size $\Rightarrow$ precision: 2-5% above 1 cGy
- Energy response corrections
  - Distance independent, excluding phantom corrections
  - Value of $k_{bq}$ is controversial (<10%)
  - Highly approximate $f_{rel}$ values are routinely used
- Widely-used SW phantom has uncertain composition
  - High-purity industrial plastics recommended
- Extensive benchmarking of TLD vs Monte Carlo
  - 2-10% agreement for Pd-103 and I-125 sources
  - 6%-10% absolute dose measurement uncertainty
Basic Discrete Event Monte Carlo Algorithm

Randomly select Location, direction & energy of primary photon

select distance to next collision

Select type of collision

Select type of collision

Select Energy and angle of photon leaving collision

Score collision’s dose contribution
Collisional Physics Requirements for Low-Energy Brachytherapy

- Only photon transport needed
  - Secondary CPE obtains (Dose $\approx$ Kerma)
  - Neutral-particle variance reduction techniques useful
- Comprehensive model of photon collisions
  - NIST EXCOM or EPDL97 Cross sections are essential!!
  - Coherent scattering and electron binding corrections
    » Use molecular/condensed medium form factors
  - Characteristic x-ray emission from photo effect
- Options: MCNP, EGSnrc, VCU’s PTRAN_CCG, GEANT, Penelope
6711 silver rod end
Electron microscopy

6711 contact radiographs

Geometric Model Validation

DraxImage I-125 Seed

Contact Radiograph

Final Model
MCPT calculates per disintegration within source:
- Dose to medium, $\Delta D_{\text{med}}(r)$, near source in phantom geometry: usually 30 cm liquid water sphere
- Air-kerma strength, $\Delta S_K$, in free-air geometry usually 5 m air sphere or detailed model of calibration vault

\[
\Lambda = \frac{\Delta D_{\text{wat}}(r = 1 \text{ cm}, \theta = \pi/2)}{\Delta S_K}
\]

\[
g(r) = \frac{\Delta D_{\text{wat}}(r, \pi/2) \cdot G(1 \text{ cm}, \pi/2)}{\Delta D_{\text{wat}}(1 \text{ cm}, \pi/2) \cdot G(r, \pi/2)}
\]
Analog and Tracklength Dose Estimation

Need cubic array of voxels:

1x1x1 mm³ to 2x2x2 mm³

Analogue Estimator (EGS method)

\[
D_{2,3} \text{ from } n+1 = \frac{\text{Energy in} - \text{Energy out}}{\text{voxel mass}}
\]

Expected Value Tracklength Estimator

\[
D_{1,4} \text{ from } n \propto E_n \cdot \frac{\Delta s_{1,4}}{\text{voxel volume}} \cdot \left(\frac{\mu_{en}}{\rho}\right)
\]
Wide-angle Free Air Chamber

NIST Primary Standard interstitial sources photons < 50 keV

\[
S_{K,99N} = \frac{(I_{153} - I_{11})d^2}{\rho_{air}(V_{153} - V_{11})(W/e)\prod_{i} k_i}
\]
$\Delta D(r')$ from $n \propto p \left( \Omega_{n,r'} \right) \cdot E_{n,r'} \cdot \left( \mu_{en} / \rho \right) \cdot e^{-\mu \cdot |r' - r_n|} / \left| r - r_n \right|^2$
Calculation of $\Delta S_K$

**Extrapolated Point-Kerma method**

- Place sealed source model at center of large air sphere
- Calculate air-kerma/disintegration, $\Delta K_{\text{air}}(d)$, as function transverse axis distance, $d$
- Extrapolate to free-space geometry by curve fitting

\[ \Delta K_{\text{air}}(d) \cdot d^2 = \Delta S_K \cdot (1 + \alpha d) \cdot e^{-\mu d} \]

Where $\Delta S_K$ and $\alpha$ are unknowns

$(1 + \alpha d)$ - SPR accounts for scatter buildup

$\mu = $ primary photon attenuation coefficient
Next-Flight Estimator Application

Use point dose at center of 60 μm x 3 mm Si active volume to approximate \( \bar{D} \)

\[
\frac{1}{k_{bg}(d)} = \left[ \frac{D(d)}{M(d)} \right]_{MC} \approx \left[ \frac{D_{NF}(d)}{M(d)} \right]_{MC}
\]
### Monte Carlo quantities and estimators for typical seed study

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta D_{\text{wat}}$ (cGy/simulated photon):</td>
<td>Transverse axis angular dose profiles</td>
</tr>
<tr>
<td></td>
<td>Next-flight estimator for all distances</td>
</tr>
<tr>
<td></td>
<td>Track-length estimator for RTP voxel grid</td>
</tr>
<tr>
<td>$\Delta E_{\text{ab}}$</td>
<td>Energy imparted to WAFAC volume/simulated photon</td>
</tr>
<tr>
<td></td>
<td>Track-length estimator when fluence varies over detector</td>
</tr>
<tr>
<td></td>
<td>Next-flight point dose estimator for TLD/diode detectors</td>
</tr>
<tr>
<td>$&gt; 2 \text{ cm from source}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta K_{\text{air}}$</td>
<td>Transverse-axis angular fluence profile (30 cm)</td>
</tr>
<tr>
<td>at geometric points in free air</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Track length for WAFAC</td>
</tr>
<tr>
<td></td>
<td>Next-flight for transverse axis distribution</td>
</tr>
</tbody>
</table>
Models 200 ($^{103}$Pd), 6702 ($^{125}$I) and 6711 ($^{125}$I) Seeds

- **Model 200**
  - $^{103}$Pd distributed in thin (2-25 $\mu$m) Pd metal coating of right circular graphite cylinder

- **Model 6702**
  - $^{125}$I distributed on surface of radio transparent resin spheres

- **Model 6711**
  - $^{125}$I distributed in thin ($\approx$3 $\mu$m) silver-halide coating of right circular Ag cylinder
Sharp corners and opaque coatings

Near transverse-axis:
- Anisotropic at long distances
- Isotropic at short distances
- Inverse square-law deviations

Anisotropic at long and short distances
Circular ends contribute at

$$\theta = \tan^{-1}\left[ \frac{L}{2 \times d} \right] = \begin{cases} 8^\circ & d = 1 \text{ cm} \\ 0.3^\circ & d = 30 \text{ cm} \end{cases}$$

Isotropic at both long and short distances
Polar Anisotropy in Air (30 cm)

Model 6702 I-125
Model 6711 I-125
Model 200 Pd-103
'WAFAC:' Wide Angle Free-Air Chamber

Rotating Seed Holder

Diagram:
- Source
- 0.08 mm Al filter
- 1 mm thick tungsten collimator
- Collecting volume
- 250 mm diameter
- 153 mm Long
- 80 mm
- V
- V/2
- 0 (Guard Ring)
\[
\Delta S_K = \frac{(\Delta E_{ab}^{153} - \Delta E_{ab}^{11}) \cdot d^2}{\rho_{air} \cdot (V_{153} - V_{11})} \cdot k_{\text{inv}} \cdot k_{\text{att}}
\]

where \(\Delta E_{ab}^x\) = Energy absorbed/disintegration in WAFAC volume of length \(x\)

\(d = 38\) cm = seed-to-WAFAC volume center

\[k_{\text{att}} = \frac{(\Delta S_K)_{\text{extr}}}{k_{\text{inv}} \cdot (\Delta K \cdot d^2)_{\text{WFC}}}\]

for a point source = \(\{1.025\quad \text{Pd-103} \quad 1.013\quad \text{I-125}\}\)

\[k_{\text{inv}} = \text{inverse-square correction} = \frac{\int \Phi(\ell) \cdot dA}{\Phi(d) \cdot A} = 1.0089\]
## Pd-103 Dose-Rate Constants

<table>
<thead>
<tr>
<th>Source</th>
<th>Investigator</th>
<th>$\Lambda_{\text{xxD}, N99S}$</th>
<th>TLD</th>
<th>MC Extrap.</th>
<th>MC WAFAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>Monroe 2002</td>
<td>____</td>
<td>0.683</td>
<td>0.683</td>
<td></td>
</tr>
<tr>
<td>Model 200 (light)</td>
<td>Monroe 2002</td>
<td>---</td>
<td>0.684</td>
<td>0.797</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>Nath 2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model 200 (heavy)</td>
<td>Monroe 2002</td>
<td>-----</td>
<td>0.744</td>
<td>0.694</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ICWG 1989</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAS MED 3633</td>
<td>Li</td>
<td>0.693</td>
<td>0.677</td>
<td>0.68</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Wallace 1998</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TLD uncertainties: $\hat{D}_{\text{wat}}(r)/S_{K}$ for Model 6711 $^{125}$I in PMMA

<table>
<thead>
<tr>
<th>Component</th>
<th>1 cm distance</th>
<th>5 cm distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%$\sigma_{x_{i}}$</td>
<td>Type</td>
</tr>
<tr>
<td>TLD reading statistics</td>
<td>1.3%</td>
<td>A</td>
</tr>
<tr>
<td>TLD calibration (including Linac calibration)</td>
<td>1.8%</td>
<td>A+B</td>
</tr>
<tr>
<td>$f_{\text{rel}}^{r}(Q_{0} \rightarrow Q_{\exp}, r)$ and $p_{\text{phant}}(G_{\exp} \rightarrow G_{\text{ref}}, r)$</td>
<td>0.7%</td>
<td>B</td>
</tr>
<tr>
<td>Seed/TLD positioning ($\Delta d = 100$ $\mu$m)</td>
<td>1.2%</td>
<td>B</td>
</tr>
<tr>
<td>$k_{\text{bq}}^{r}(Q_{0} \rightarrow Q_{\exp})$</td>
<td>5%</td>
<td>B</td>
</tr>
<tr>
<td>NIST $S_{K}$ + one local transfer</td>
<td>1%</td>
<td>B</td>
</tr>
<tr>
<td>Combined std. uncertainty ($k = 1$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Monte Carlo uncertainties: Model 6711 seed in liquid water

<table>
<thead>
<tr>
<th>Distance</th>
<th>1 cm</th>
<th>5 cm</th>
<th>10 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistics</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Photon cross-sections</td>
<td>0.7%</td>
<td>2.4%</td>
<td>4.1%</td>
</tr>
<tr>
<td>Seed geometry</td>
<td>1.1%</td>
<td>0.9%</td>
<td>0.8%</td>
</tr>
<tr>
<td>Source energy spectrum</td>
<td>0.2%</td>
<td>0.3%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Combined std. uncertainty ($k =1$)</td>
<td>1.3%</td>
<td>2.6%</td>
<td>4.3%</td>
</tr>
</tbody>
</table>

Adapted from Dolan et al. Med Phys 2006
Monte Carlo-based Treatment planning
Consolidating Dosimetry and treatment planning into a single process

- Permanent seed APBI: 70 $^{125}$I seeds, $D_{90} = 115$ Gy
- 0.7 mm voxels, average SD = 1.2%, single-processor CPU time = 30 min
Monte Carlo vs TLD

• Measurement Pros and Cons
  – Large uncertainties and many artifacts
  – Tests conjunction of all a priori assumptions: geometry, detector response corrections, calibration etc

• Monte Carlo Pros and Cons
  – Artifact-free, low uncertainty, and unlimited spatial resolution
  – Garbage in-Garbage out
    » Seed geometry errors
    » Will not anticipate contaminant radionuclides etc., $S_k$ errors
  – Does not model detector signal formation process

• Hence: TG-43 continues to require both measured and Monte Carlo single-seed dose distributions
Dosimetry: Conclusions

- Low energy brachytherapy: main catalyst for improving dosimetry and source standardization for 30 years
  - Single-source dose distributions have 5% uncertainty
  - Both MC and measurement have important roles

- Current Role
  - Monte Carlo: primary source of dosimetric data
    » Soon: MC dosimetry and planning will be a single process
  - Measurement: Confirm Monte Carlo assumptions

- Major needs: more accurate and efficient dose-measurement systems for low energy sources
  - Test batch-to-batch and/or source-to-source variations during manufacturing process