What is “Quantitative Dosimetry?”

• Williamson’s definition: absorbed dose estimation method providing
  – Accurate representation of well-defined physical quality
  – Rigorous uncertainty analysis ⇒ <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
Outline

• Experimental Techniques
  – TLD dosimetry: current standard of practice
  – Emerging experimental techniques
• Monte Carlo-based dosimetry
• Results of TLD and MC dosimetry
  – Uncertainty analysis
  – Agreement
Quantitative Dosimetry Era: 1980-

<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Contribution</th>
</tr>
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<tbody>
<tr>
<td>1955</td>
<td>Tochlin:</td>
<td>Film Dosimetry</td>
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<td>1966</td>
<td>Lin &amp; Kenny:</td>
<td>TLD dosimetry in medium</td>
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<tr>
<td>1983</td>
<td>Ling:</td>
<td>Diode dosimetry of I-125 seeds</td>
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<td>1985</td>
<td>Loftus:</td>
<td>I-125 exposure standard</td>
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<td>1986</td>
<td>NIH ICWG contract</td>
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<td></td>
<td>Nath, Anderson, Weaver:</td>
<td>Validation of TLD dosimetry</td>
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<td>1983</td>
<td>Williamson:</td>
<td>Monte Carlo dosimetry</td>
</tr>
<tr>
<td>1994</td>
<td>Task Group 43 Report</td>
<td></td>
</tr>
</tbody>
</table>
TLD dose measurements around $^{226}$Ra Needle
Lin and Cameron: Univ. of Wisconsin, 1965
Dosimetric Environment

• Large Dose Gradients
  – Wide Range of Dose Rates
  – Positioning accuracy needed for 2 % dose accuracy

  2 mm Distance    ±20 \( \mu \text{m} \)
  5 mm Distance    ±50 \( \mu \text{m} \)
  10 mm Distance   ±100 \( \mu \text{m} \)

  – Large Number of Measurements Needed

• Low Photon Energies

• Relatively Low Dose Rates
Criteria for experimental dosimeters

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

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

• Good positioning accuracy

• Support measurements at many points
Sensitivity (10 cm)/Sensitivity (1 cm) vs energy

- Sensitivity (reading/Dwat): 10 cm/1 cm

---

LiF TLD
Polyvinyl Toluene
Silicon diode

---

Energy (KeV):
- 20
- 200
- 500
- 1000

Sensitivity vs Energy graph:
- Red line: LiF TLD
- Blue line: Polyvinyl Toluene
- Green line: Silicon diode
Localization via Digital Dosimeters

2D dose distribution

Profile A

$X_c = (X_2 - X_1)/2$

30-100 μm positional accuracy achievable
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
**Brachytherapy Dosimetry**

- **Given:** \( R_{\text{det}}(\vec{r}) \)  
  Relative solid state dosimeter reading (TLD or Diode)

- **Desired:** \( D_{\text{wat}}(\vec{r}) \) absorbed dose to water

- **Corrected for:**
  - Detector sensitivity
  - Measurement vs reference geometry
  - Radiation field Perturbation
  - Detector response artifacts
Brachytherapy Dose Measurement

\[
\left[ \frac{D_{\text{wat}}(\vec{r})}{S_K} \right]^{\text{BRx}}_{\text{meas}} = \frac{R_{\text{det}}(\vec{r}) \cdot g(T)}{S_K \cdot \varepsilon_\lambda \cdot E(\vec{r})}
\]

\[\varepsilon_\lambda = \left[ \frac{R_{\text{det}}}{D_{\text{med}}} \right]^{\lambda}_{\text{meas}}\]

\[E(\vec{r}) = \left[ \frac{R_{\text{det}}}{D_{\text{wat}}} \right]^{\text{BRx}}_{\text{at } \vec{r}} \cdot \varepsilon_\lambda\]

- \(S_K\) = Measured Air-Kerma Strength
- \(g(T)\) = \(1/\text{effective exposure time (decay correction)}\)
• TL\textsubscript{i} is Measured Response of i-th detector at r

• F\textsubscript{lin}(TL) is non-linearity correction for net response TL

• S\textsubscript{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

\[
E(\bar{r}) = \frac{[\langle TL(\bar{r})\rangle / D_{\text{wat}}(\bar{r})]}{[\langle TL\rangle / D_{\text{med}}]} \text{ for Brachy Source}
\]

\[
= \frac{\varepsilon_{BRx}(TL_0, \bar{r})}{\varepsilon_\lambda(TL_0)} \text{ for same } TL_0
\]

- **E(d) obtained by**
  - Measuring TLD response in free air as function of average energy in low energy x-ray beams
  - Monte Carlo calculations
  - Analytic calculations

- Generally assumed to be independent of position
Compare detector to “matched” X-ray Beam calibration in Free-Air $h_\nu = 40-120$ kVp

$$TL = \text{TLD mean net reading}$$

$$K_{FS}^{air} = \text{measured air kerma}$$

$$E(r) = \left( \frac{TL}{K_{FS}^{air}} \right)^{h_\nu} \cdot \left( \frac{K_{air} / D_{wat}}{D_{wat} \cdot c_{repl} \cdot c_{disp}(r) \cdot \varepsilon_\lambda} \right)^{h_\nu}_{MC}$$

$$c_{repl} = \frac{D_{wat \, \text{in medium}}^{FS}}{K_{wat \, \text{in cavity}}^{FS}} \approx 0.97$$

$$c_{disp}(r) = D_{wat}(\vec{r}) \text{ at point} \left[ \frac{1}{V(\vec{r})} \int_{V(\vec{r})} D_{wat}(\vec{r}') dV' \right] \in (0.80 - 1.00)$$
• Conventional choice: $E=1.4$ w/o regard to details
• Hence, 2004 TG-43 has assigned 5% uncertainty to $E$
Monte Carlo Evaluation of E(d)

- E(d) Corrects for
  - Measurement medium and geometry vs water
  - Calibration medium vs. water
  - Detector artifacts: Energy response, volume averaging, angular anisotropy, self attenuation

- Assume: Detector response $\otimes$ energy imparted to active volume for beam qualities $\lambda$

$$\text{If } R^\lambda_{\text{det}} = \alpha \cdot D^\lambda_{\text{det}}$$

$$\text{Then } E(\bar{r}) = \left[ \frac{\Delta D^\lambda_{\text{det}}(\bar{r})}{\Delta D^\lambda_{\text{wat}}(\bar{r})} \right]^\text{MC}_{\text{BRx}} \text{MC}$$

$$\left[ \frac{\Delta D^\lambda_{\text{det}}}{\Delta D^\lambda_{\text{med}}} \right]_\lambda$$
Energy linearity of TLD is controversial

\[ R_\lambda = \frac{\text{TL at energy } \lambda}{\text{measured air kerma}} \]

\[ K_{\lambda \text{air}} = \text{measured air kerma} \]

\[ \alpha_\lambda = \frac{(\frac{\text{TL}}{K_{\text{air}}})^\lambda_{\text{Meas}}}{(\frac{D_{\text{TLD}}}{K_{\text{air}}})^\lambda_{\text{MC}}} \]
I-125 Seed $E(d)$ in Solid Water

- Solid-to-Liquid Water correction: 4%-15% at 1-5 cm
- 10-30% variations in SW composition reported: 5%-20% dosimetric errors
Summary: TLD phantom dosimetry

• 1-3 mm size ⇒ precision: 2-5% above 1 cGy
• Energy response corrections
  – Distance independent, excluding phantom corrections
  – Energy linearity is controversial (<10%)
  – Many corrections routinely ignored
• Widely-used SW phantom has uncertain composition
  – High-purity industrial plastics recommended
• Extensive benchmarking of TLD vs Monte Carlo
  – 3-10% agreement for Pd-103 and I-125 sources
  – 7%-10% absolute dose measurement uncertainty
Other dosimetry systems

• Plastic scintillator (PS) and diode probes
  – High sensitivity, small size, good SNR, and waterproof
  – Single element detectors requiring water scanning system
• PS: established as transfer/relative dosimeter 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
  – Well established as relative dosimeter
Emerging Dosimetry Systems
2D RadioChromic Film
Ir-192 HDR Source
Absolute RCF Dose Measurement vs Monte Carlo HDR $^{192}$Ir Source
RCF $2\sigma$ uncertainty: 4.6%
Absolute RCF dosimetry for LDR Sources
Cs-137: RCF/MC vs. Exposure-to-densitometry time interval

- Mean error vs dose
- 6 day exposure
- Very high 100 μm spatial resolution
- Fading artifacts not significant
- Energy linearity within 5%
Monte Carlo Simulation

Typical Trajectory

\[(r_1, \Omega_1, E_1, W_1) \rightarrow \]

\[(r_0, \Omega_0, E_0, W_0) \]

\[\Omega_0, E_0 \]

\[r_1 \]

\[\Omega_1, E_1 \]

\[\Omega_2, E_2 \]

\[r_3 \]

\[\Omega_3, E_3 \]

Ag core

Ti capsule

I-125 Seed

Photon Collision

Heterogeneity

Scoring Bin, \( \Delta V \)
Monte Carlo Technical Issues

Particle Collision Dynamics
Total and differential cross sections for all collision processes and media

Geometric Model
Size, location, shape, composition and topology of each material object

Detector Model
relationship between dose and collision density
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
  – Approximations OK for some RTP applications

• Options: MCNP, EGSnrc and VCU’s PTRAN_CCG
Geometric Model Validation

DraxImage I-125 Seed

6711 silver rod end
Electron microscopy

6711 contact radiographs

Contact Radiograph

Final Model
Wide-angle Free Air Chamber

NIST Primary Standard interstitial sources photons < 50 keV

\[ S_{K,99N} = \frac{(I_{153} - I_{11})d^2}{\rho_{air} (V_{153} - V_{11})} (W/e) \prod_{i} k_i \]
Analog and Tracklength Dose Estimation

Need cubic array of voxels:
1x1x1 mm$^3$ to 2x2x2 mm$^3$

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

\[
D_{1,4} \text{ from } n \propto E_n \cdot \frac{\Delta S_{1,4}}{\text{voxel volume}} \cdot (\mu_{en}/\rho)
\]
Estimator Use

• **Tracklength estimators**
  – 20-50X more efficient than analog
  – Models volume averaging and medium replacement by extended detectors
  – 3D patient (voxel array) calculations

• **Next flight estimators: dose-at-a-point**
  – Condensed-medium dose calculations at least 1-2 mm from interfaces
  – Dilute-medium (air) kerma calculations
  – 0.1% - 2% statistical precision for I-125 dosimetry

• **Kalli/Cashwell “Once-more-collided Flux”**
  – Point doses near media interfaces
  – Energy imparted to small detectors
Monte Carlo quantities for typical seed study

\[ \Delta D_{\text{wat}} \text{ (cGy/simulated photon):} \begin{cases} \text{Transverse axis} \\ \text{angular dose profiles} \end{cases} \]

- Bounded next-flight estimator for most distances

\[ \Delta E_{\text{ab}} \text{ Energy imparted to WAFAC volume/simulated photon} \]

- Track-length estimator when fluence varies over detector

\[ \Delta K_{\text{air}} \text{ at geometric points} \begin{cases} \text{Transverse-axis} \\ \text{angular fluence profile (30 cm)} \end{cases} \]

- Track length for WAFAC

Next-flight point dose estimator for TLD/diode detectors

> 2 cm from source

Next-flight for transverse axis distribution
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

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

$$g(r) = \frac{\Delta D_{\text{wat}}(r, \pi/2) \cdot G(1 \text{ cm}, \pi/2)}{\Delta D_{\text{wat}}(1 \text{ cm}, \pi/2) \cdot G(r, \pi/2)}$$
Calculation of $\Delta S_K$

Extrapolated Point-Kerma method

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

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

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

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

$\mu = \text{primary photon attenuation coefficient}$
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

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

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
ΔS_K: Point-Extrapolation Method

Data Points: MCPT
Solid Lines: Fit

ΔK_{air} (d) \cdot d^2
cGy cm^2 h^{-1} (mCi h^{-1})

Distance (cm)

Model 200 (2 μm Pd) Pd-103
Model 6702 I-125
Model 6711 I-125
‘WAFAC:’ Wide Angle Free-Air Chamber

Rotating Seed Holder

Diagram:
- Wide Angle Free-Air Chamber
- Source
- 0.08 mm Al filter
- 1 mm thick tungsten collimator
- Collecting volume
- 0 (Guard Ring)
- V
- V/2
- 250 mm diameter
- 153 mm Long
- 300 mm
WAFAC Simulation Method

\[ \Delta S_K = \frac{(\Delta E_{153}^{ab} - \Delta E_{11}^{ab}) \cdot d^2}{\rho_{air} \cdot (V_{153} - V_{11})} \cdot k_{inv} \cdot k_{att} \]

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

\[ d = 38 \text{ cm} = \text{seed-to-WAFAC volume center} \]

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

for a point source = \( \{1.025 \quad \text{Pd-103} \}
\]

\( \{1.013 \quad \text{I-125} \) \]

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Investigator</th>
<th>$\Lambda_{xxD,N99S}$</th>
<th>TLD</th>
<th>MC Extrap.</th>
<th>MC WAFAC</th>
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<tbody>
<tr>
<td><strong>Point</strong></td>
<td>This work</td>
<td>____</td>
<td>0.683</td>
<td>0.683</td>
<td></td>
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<tr>
<td><strong>Model 200</strong></td>
<td>This work</td>
<td>___</td>
<td>0.797</td>
<td>0.691</td>
<td></td>
</tr>
<tr>
<td>(light)</td>
<td>Nath 2000</td>
<td>0.684</td>
<td>0.65</td>
<td>0.691</td>
<td></td>
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<tr>
<td></td>
<td>ICWG 1989</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Model 200</strong></td>
<td>This work</td>
<td>______</td>
<td>0.744</td>
<td>0.694</td>
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<tr>
<td>(heavy)</td>
<td>ICWG 1989</td>
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<td><strong>NAS MED 3633</strong></td>
<td>Li Wallace 1998</td>
<td>0.693</td>
<td>0.677</td>
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<td></td>
<td></td>
<td>0.68</td>
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</table>

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*Note: The table shows the dose-rate constants for different sources and models, with TLD, MC Extrap., and MC WAFAC values listed for comparison.*
Monte Carlo vs. TLD: $^{125}$I Seeds

- 14 Seed models, 38 Candidate datasets

![Graph showing dose-rate ratios vs. distance for Monte Carlo vs. experimental data. The x-axis represents distance in cm, and the y-axis represents the ratio of Monte Carlo to experimental dose rates.]
Monte Carlo/TLD Dose Rates: $^{125}$I Seeds
Monte Carlo/TLD Dose Rates: $^{125}\text{I}$ Seeds
### Table 2: Uncertainties for $^{125}\text{I}$ transverse-axis TLD and Monte Carlo dose estimation

<table>
<thead>
<tr>
<th>Component</th>
<th>1 cm distance</th>
<th>5 cm distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%$\sigma_y$</td>
<td>Type</td>
</tr>
<tr>
<td>Repetitive TLD measurements</td>
<td>4%</td>
<td>A</td>
</tr>
<tr>
<td>TLD calibration (including Linac calibration)</td>
<td>3%</td>
<td>A+B</td>
</tr>
<tr>
<td>Solid-to-liquid water conversion</td>
<td>2%</td>
<td>B</td>
</tr>
<tr>
<td>Seed and TLD positioning errors (Δd = 100 µm)</td>
<td>2%</td>
<td>B</td>
</tr>
<tr>
<td>Energy-response correction</td>
<td>5%</td>
<td>B</td>
</tr>
<tr>
<td>ADCL $S_K$ measurement + transfer</td>
<td>2%</td>
<td>B</td>
</tr>
<tr>
<td><strong>Total combined uncertainty</strong></td>
<td>7.9%</td>
<td></td>
</tr>
</tbody>
</table>

#### Uncertainties for Monte Carlo estimates $\hat{D}_{\text{wat}}(\vec{r}) / S_k$ for $^{125}\text{I}$ in liquid water

<table>
<thead>
<tr>
<th>Component</th>
<th>1 cm distance</th>
<th>5 cm distance</th>
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<tbody>
<tr>
<td>Statistics</td>
<td>0.3%</td>
<td>1.0%</td>
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<tr>
<td>Photo ionization cross-sections (Δσ_{PE} = 2.3%)</td>
<td>1.5%</td>
<td>4.5%</td>
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<tr>
<td>Seed geometry</td>
<td>2%</td>
<td>2%</td>
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<tr>
<td>Source energy spectrum</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td><strong>Total combined uncertainty</strong></td>
<td>2.5%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>
Monte Carlo vs TLD

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

• Monte Carlo Pros and Cons
  – Artifact free and low uncertainty
  – Garbage in-Garbage out
    » Seed geometry errors
    » Will not anticipate contaminant radionuclides etc., $S_K$ errors
  – Does not model detector signal formation
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
  - Measurement: Confirm assumptions underlying Monte Carlo model

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