Overview of "Update of AAPM Task Group No. 43 Report - A Revised AAPM Protocol for Interstitial Brachytherapy Dose Calculations"

Jeffrey F. Williamson, Ph.D.

On behalf of Report Authors

Mark Rivard, Bert Coursey, Larry DeWerd, William Hanson Saiful Huq, Geoffrey Ibbott, Michael Mitch, Ravinder Nath, Jeff Williamson

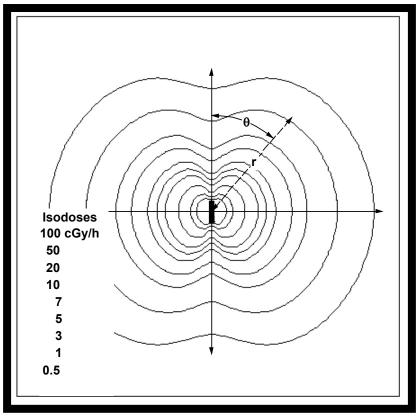
VCU Radiation Oncology Physics

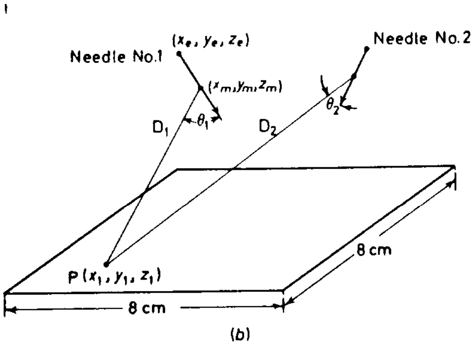
Virginia Commonwealth University

Outline

- **Motivation of a revised TG-43**
- **Report organization & goals**
- **Revised TG-43 Content review**
  - **Calibration standards and dose estimation technology: review and report recommendations**
  - **Modified TG-43 formalism**
  - **Data merging and analysis strategy**
  - **Clinical implementation issues**
- **Learning Objectives**
  - **Understand basic concepts and issues in low-energy source dosimetry**
  - **Understand TG-43 formalism and important recommendations; and major differences between 1995 and 2003 editions**

Single-Source Dose Distributions
Superposition Model



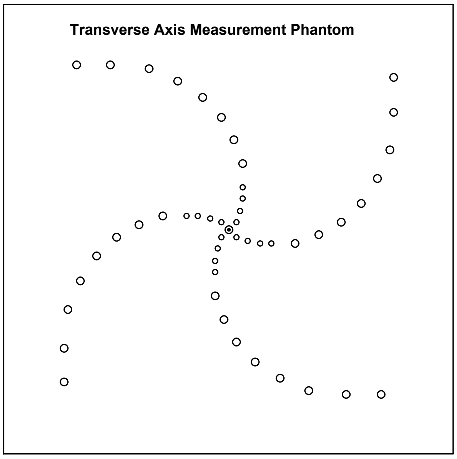


Current dose calculation paradigm: for each source type, a single source dose array used to estimate the contribution of each source, based on coordinates in patient, to each point of interest

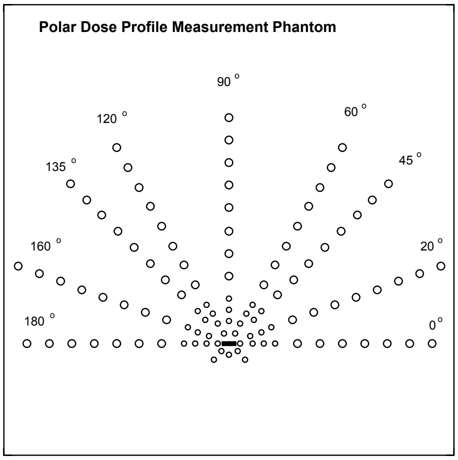
Basic Elements of TG-43 Dose-Calculation ‘Algorithm’

- **For each source, a discrete grid of measured or Monte Carlo dose rates is required**
- **A set of standard dose ratios (Λ, $F(r,\theta)$, $g(r)$, $\varphi_{an}(r)$) are defined to represent measured dose-rate distribution in compact form**
- **A standard approach for interpolating between table entries to get dose rate at an arbitrary point (r,θ)**

Starting Point: discrete grid of dose rates measured by TLD or calculated by Monte Carlo



Transverse Axis Measurement Phantom



Polar Dose Profile Measurement Phantom

Why do we need a new TG 43 report?

- Report originated and written by AAPM Low-energy Interstitial Brachytherapy Dosimetry SC (LIBD) of RTC
  - The number of seed models has increased from 3 in 1999 to approximately 20 in 2003.
    - » 1995 report limited to 6711, 6702 and Model 200 Pd.
    - » Data is old and needs to be supplanted by new
  - Correct errors/inconsistencies in old formalism and definitions
  - Present up-to-date consensus dosimetry sets for 8 seed models
  - Provide guidance and standards for MC and TLD investigators
  - Consolidate recent LIBD guidance in single report

Revised TG-43 Contents

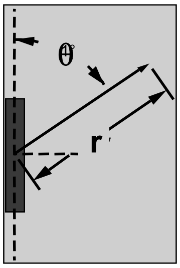
- III: updated spectral and half-life data for ^{125}I &^{103}Pd
- IV: History of 1985 (Loftus) and 1999 (WAFAC) calibration standards
  - Revised S_K definition
- V: Revised 2-D and 1-D dose calculation formalisms
- VI: Consensus data sets for clinical implementation
  - Procedure for comparing and merging multiple TLD and MC data sets from literature
  - Tables of TG-43 parameters

Revised TG-43 Contents: cont'd

- VI: Consensus data sets for clinical implementation
  - Sources covered by this report (LIBD compliant as of 7/01)
    - Amersham-Health model 6702 and 6711 ^{125}I sources
    - Best Industries model 2301 ^{125}I source
    - North American Scientific Inc. model MED3631-A/M ^{125}I source
    - Bebig model I25.SO6 ^{125}I source
    - Imagyn Medical Technologies Inc. *isostar* model IS-12501 ^{125}I source
    - Theragenics model 200 ^{103}Pd source
    - North American Scientific Inc. model MED3633 ^{103}Pd source

Revised TG-43 Contents: cont'd

- VII: Recommendations for estimation and tabulation of dosimetry parameters
  - Minimum standards: angular/distance range and resolution
  - Guidelines for TLD dosimetry
  - Guidelines for Monte Carlo dosimetry
- VIII: Clinical implementation
  - Acceptance testing and commissioning
  - Guidelines for calibration and traceability
- Appendices
  - Extrapolation to large and small distances
  - Use of apparent activity
  - Anisotropy constant



AAPM Revised 2-D Formalism

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(1\ \mathrm{cm},\pi/2)} \cdot F(r,\theta) \cdot g_L(r)$$

$$\text{for } x = L \quad G_L(r,\theta) = \begin{cases} \dfrac{\beta}{Lr\sin\theta} & \text{if } \theta \neq 0^\circ \\ \left(r^2 - L^2/4\right)^{-1} & \text{if } \theta = 0^\circ \end{cases}$$

line-source approximation

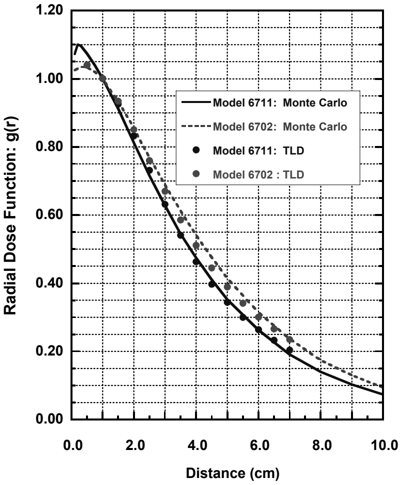
$$\text{for } x = P \quad G_P(r,\theta) = r^{-2}$$

point-source approximation

Where L = effective active length of source

Task Group 43 2-D Radial Dose Function: $g_X(r)$

- $g_X(r)$ = dimensionless radial dose function Describes transverse-axis dose Fall-off
- G_X-Factor suppresses dose variation due to inverse square-law fall-off

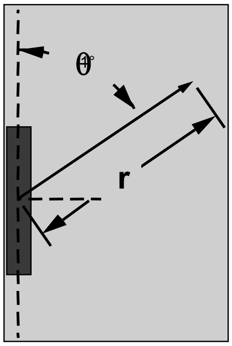


$$g_X(r) = \frac{\dot{D}(r,\pi/2)\cdot G_X(1\ \mathrm{cm},\pi/2)}{\dot{D}(1\ \mathrm{cm},\pi/2)\cdot G_X(r,\pi/2)}$$

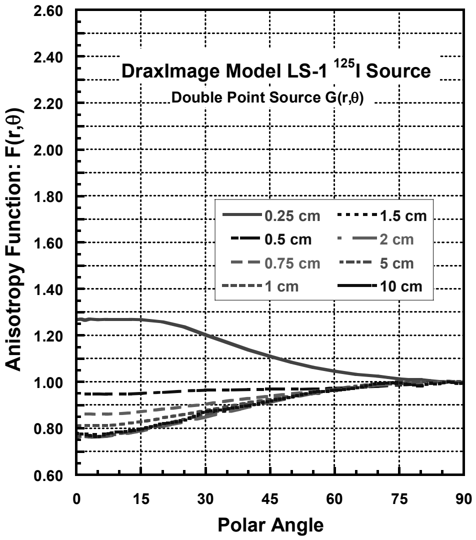
$$g_P(r) = \frac{\dot{D}(r,\pi/2)}{\dot{D}(1\ \mathrm{cm},\pi/2)}\cdot\left(\frac{r}{1\ \mathrm{cm}}\right)^2$$

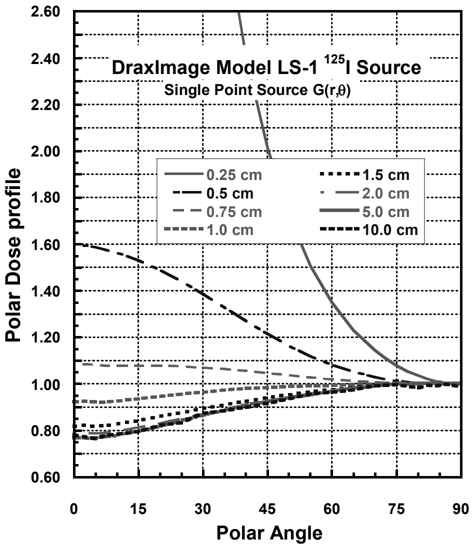
Task Group 43 2-D Anisotropy Function: $F(r,\theta)$

- $F(r,\theta)$ = dimensionless anisotropy function
  - Describes angular dose variation at fixed distance
  - G suppresses inverse-square dose variation
  - Only Line-source G recommended



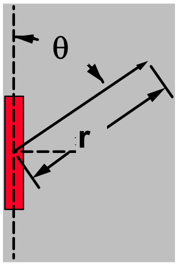
$$F(r,\theta) = \frac{\dot{D}(r,\theta)\cdot G_L(r,\pi/2)}{\dot{D}(r,\pi/2)\cdot G_L(r,\theta)}$$





Revised TG 43 1-D Formalism

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_X(r,\pi/2)}{G_X(1\ \mathrm{cm},\pi/2)} \cdot g_X(r) \cdot \phi_{an}(r)$$



- $\phi_{an}(r)$ is 1-D anisotropy function

$$\phi_{an}(r) = \frac{\int_0^{\pi} \dot{D}(r,\theta) \cdot \sin\theta \cdot d\theta}{2 \cdot \dot{D}(r,\pi/2)}$$

TG 43 Update: Two possible 1D Models

- End user's RTP system MUST use the Geometry function used to extract the TG-43 quantities from raw data
  - P = Point Source (Acceptable option)

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{1\ \text{cm}}{r} \right)^2 \cdot g_P(r) \cdot \phi_{an}(r)$$

  - L = Line Source (Recommended option)

$$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r, \pi/2)}{G_L(1\ \text{cm}, \pi/2)} \cdot g_L(r) \cdot \phi_{an}(r)$$

TG-43 Dose-Calculation 'Algorithm'

- TG-43 starts with a discrete grid of measured or Monte Carlo dose rates
- $F(r,\theta)$, $g(r)$, and $\varphi_{an}(r)$ table entries correspond to measurement/MC points
- What does RTP do at arbitrary point (r,θ)?:
  - Finds $g(r_1)$ and $g(r_2)$, etc. at nearest neighbor points
  - Calculates $g(r)$, etc., by bi-linear interpolation

$$g(r) = \left[g(r_2) - g(r_1) \right] \left[\frac{r - r_1}{r_2 - r_1} \right] + g(r_1)$$

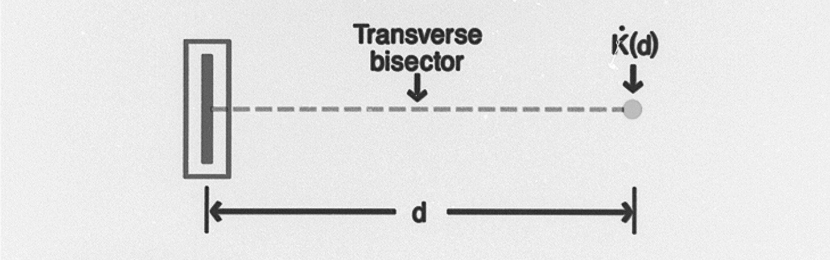
  - Calculate exact $G(r,\theta)$ and obtain $D(r,\theta)$ from TG-43 equation

TG 43 Updated Formalism

- Extrapolation to large and small distances outside table entries addressed
- Anisotropy constant discarded

  Trick RTP system by using: $g'(r) \Rightarrow g_X(r) \cdot \phi_{an}(r)$
- Rationale: Geometry function recommendations
  - Any G, if consistently applied, will always reproduce exactly the measured data
  - More accurate G $\Rightarrow$ more accurate interpolation between table entries
  - G_L is a good compromise between simplicity and accuracy
  - More complex G acceptable but not included in report

Revised Definition of Air-Kerma Strength

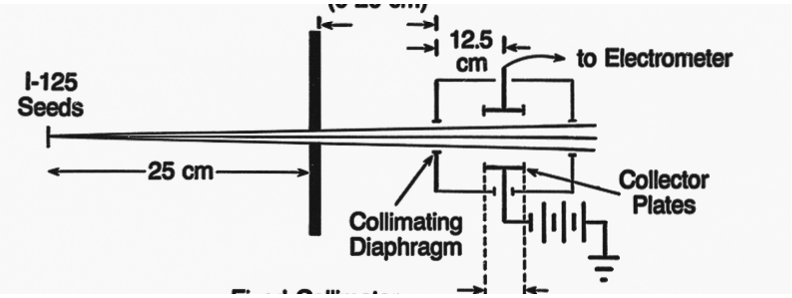


$$S_K = \dot{K}_\delta(d)\,d^2 \;[\mu Gy \cdot m^2 \cdot h^{-1} = cGy \cdot cm^2 \cdot h^{-1} = U]$$

$\dot{K}_\delta(d)$ is air-kerma rate in vacuo due to photons of energy $> \delta$ (~ 5 keV), $d \gg L$

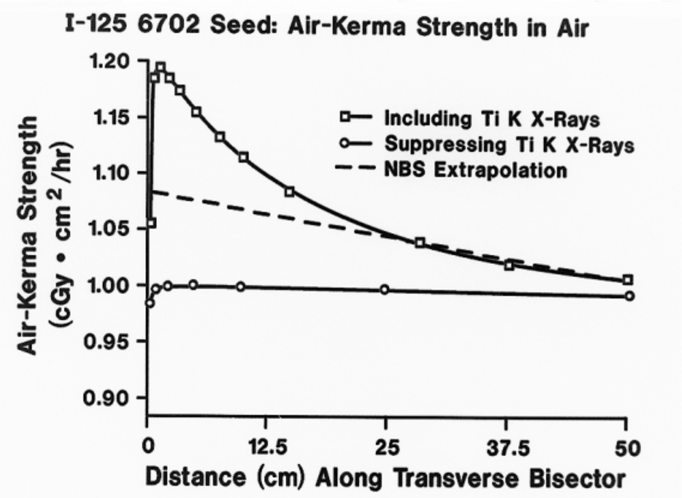
Cutoff designed to exclude low-energy contaminant radiation

Ritz Free-Air Chamber
NIST 1985 S_K Standard for ^{125}I Seeds



- Implemented in 1985 for 6711 and 6702 seeds; difficult to extend to new seed models
- No filtering of Ti K x rays (4.5 keV)
- Small volume ⇒ only seed plaques measurable

Influence of Ti K-edge X-rays on S_K measurements
NIST 1985 S_K Standard for ^{125}I Seeds
J. Williamson, Monte Carlo Calculations 1988

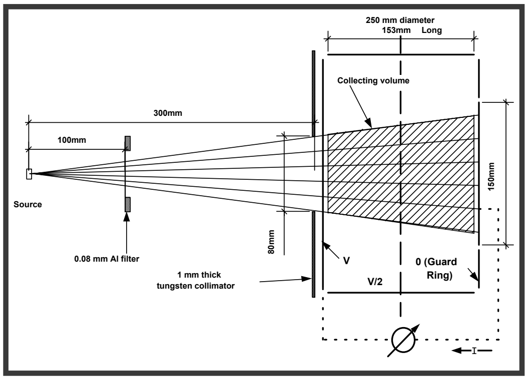


‘WAFAC:’ Wide Angle Free-Air Chamber

U.S. NIST Primary Standard for Low-Energy Seeds

Rotating Seed Holder

Wide-angle Free-Air Chamber $S_{K,N99}$



for same seed and radiation output

$$\frac{S_{K,N99}}{S_{K,N85}} = 0.897$$

- **Large volume ⇒ single seeds measurable**
- **Extended to all ^{125}I and ^{103}Pd models**
- **Ti characteristic x-rays filtered out**
- **Implemented 1999**

TG-43 Formalism: original = revised Λ

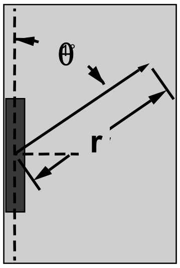
$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(1\ \mathrm{cm},\pi/2)} \cdot F(r,\theta) \cdot g_L(r)$$

- S_K is Air-Kerma Strength

  1 U = 1 Unit of Air-kerma strength

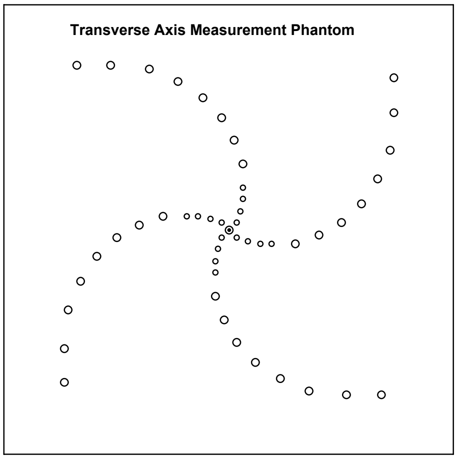
  = 1 μGy•m^2•h^{-1} = 1 cGy•cm^2•h^{-1}

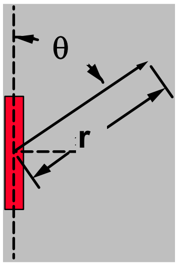
- Λ =Dose-Rate Constant in cGy•h^{-1}•U^{-1}



$$\Lambda = \frac{\dot{D}(1\ \mathrm{cm},\pi/2)}{S_K}$$

Solid "water substitute" Phantoms for TLD Dosimetry



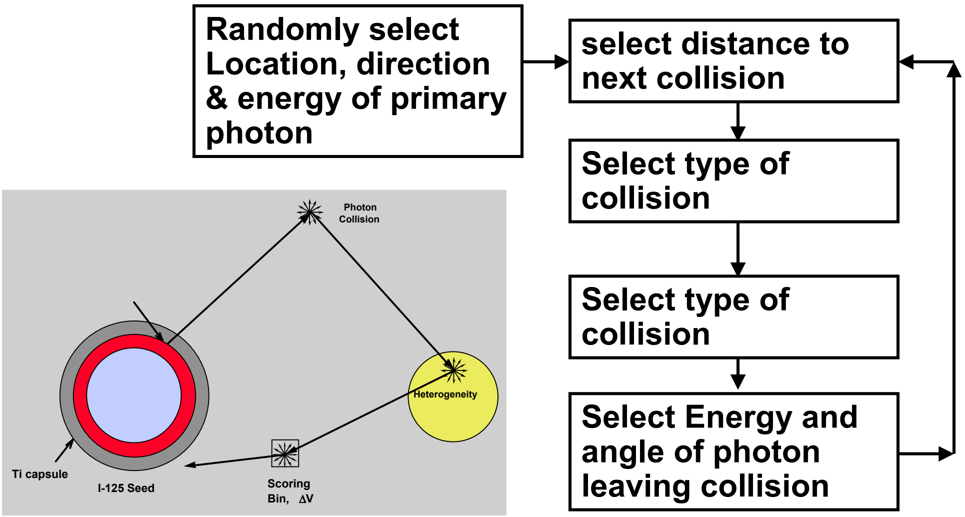


$$\Lambda = \frac{\dot{D}_{wat}\ \text{at} \begin{cases} r = 1\ \mathrm{cm} \\ \theta = \pi/2 \end{cases}}{S_{K,N99}}$$

where $\dot{D}_{wat}$ = TLD measurement

$S_{K,N99}$ = NIST measurement

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

Calculation of TG-43 Parameters by MCPT

MCPT calculates per disintegration within source:

- Dose to medium, $\Delta D_{med}(r)$, near source in phantom geometry
- Air-kerma strength, ΔS_K, in free-air geometry

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

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

WAFAC Simulation Method

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

where ΔE_{ab}^{x} = Energy absorbed/disintegration in WAFAC volume of length x

$d = 38$ cm = seed-to-WAFAC volume center

$$\left. k_{att} = \frac{(\Delta S_K)_{extr}}{k_{inv} \cdot \left(\Delta K \cdot d^2\right)_{WFC}} \right\} \text{for a point source} = \begin{cases} 1.032 & \text{Pd-103} \\ 1.023 & \text{I-125} \end{cases}$$

$$k_{inv} = \text{inverse-square correction} = \frac{\int_A \Phi(\ell) \cdot dA}{\Phi(d) \cdot A} = 1.0089$$

General Recommendations

- Measure/calculate dose-rates with sufficient resolution and range
  - RDF: 0.5 cm to 5 cm (Pd-103) – 7 cm (I-125)
  - $F(r,\theta)$: for r =1, 2, 3, 5 and 7 cm (I-125 only) at 10° intervals
  - Report active length, L, used
  - Perform rigorous uncertainty analysis
- Appropriate tools
  - TLD-100/diode accepted for relative, TLD for absolute
    - » Other detectors: require extensive & published benchmarking
  - Well characterized MC code: EGS-4, MCNP, PTRAN
    - » New users/features/codes: reproduce published benchmarks

Recommendations for TLD dosimetry

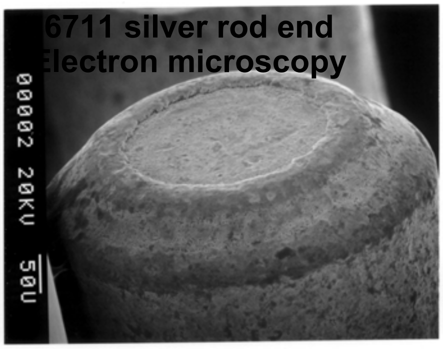
- For DRC: ≈ 15 measurements on 8-10 seeds, 1 with directly traceable NIST calibration
  - 1-σ statistics < 5%, 1-σ systematic < 7%
  - Calibrate TLD’s against external beam, not a brachytherapy source
  - Make sure E(d) matches experiment wrt calibration technique, displacement/attenuation corrections, measurement medium
  - Correct for non-water equivalence of phantom: Solid Water may require chemical analysis
  - Recommended standards of methodology description for published papers

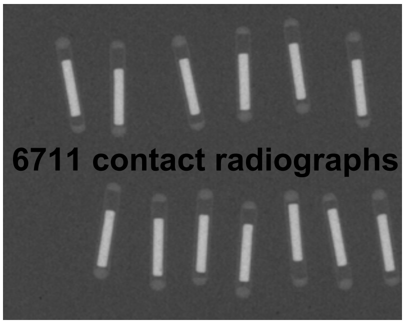
---

Recommendations for Monte Carlo Dosimetry

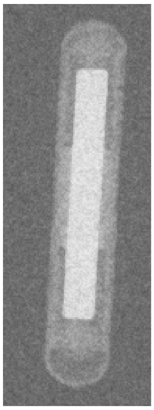
- Monte Carlo Code recommendations
  - Physics model: electron binding corrections, coherent scattering and characteristic x-ray production. Electron transport unnecessary
  - NIST PHOTEX or equivalent cross-section library
  - 1-s statistical uncertainty <2%, volume-averaging <1%
  - Calculate dose rates in 30 cm diameter liquid water sphere
- Other precautions
  - transverse-plane anisotropy ⇒ Simulate WAFAC aperture
  - Carefully validate geometric model through mechanical and radiological measurements. Perform parametric studies to assess component motion, uncertainties, etc.

Geometric Model Validation

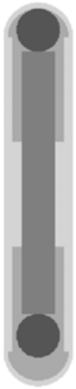




DraxImage I-125 Seed



Contact Radiograph



Final Model

Data Merging Procedures: Λ

- **2-25 papers available documenting dosimetry for each source model. Candidate datasets identified**
  - **MC: NIST PHOTEX equivalent cross sections, normalization to $S_{K,N99}$ standard, and simulation of WAFAC geometry for "sharp edges" phenomenon**
  - **TLD: prefer recent studies based on $S_{K,N99}$.**
  - **All data: corrected to $S_{K,N99}$ standard, for CY-2000 WAFAC measurement errors, solid-to-liquid water corrections**
  - **All data corrected to consistent active length, L**

$$\Lambda_{con} = {}^{1}\!/_{2}\left[\bar{\Lambda}_{exp} + \bar{\Lambda}_{MC}\right]$$

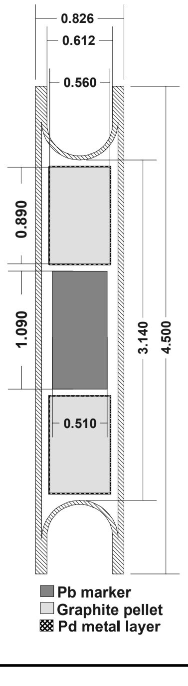
where $\bar{\Lambda}_{X}$ = mean of candidate exp or MC values

Data Merging: $g(r)$, $F(r,\theta)$ & $\varphi_{an}(r)$

- Transform different candidate datasets to same L
- Graphically compare different datasets
- If discrepancies < experimental error, accept as consensus, dataset with maximum range, resolution and smoothness
  - For $g(r)$ and $F(r,\theta)$, usually MC data accepted
  - For $g(r)$, discrepancies < 5% for $r < 5$ cm
  - $F(r,\theta)$, discrepancies < 10%, & < 5% for $\theta > 30°$
- $\varphi_{an}(r)$: calculate dose from consensus $F(r,\theta)$ and integrate wrt to $d\Omega$
- If discrepancies > experimental error, more elaborate merging strategies needed

---

Example: Theragenics Model 200 Pd-103 Source



- Sole product 1987-1999
- All Pd-103 products depend on Mod 200 History for dose prescription
- Two variants : “Heavy” and “Light” seeds
  - <1994 = Heavy Seed: reactor-produced 20 μm Pd layer on carbon pellet
  - >1994 = Light Seed: accelerator-produced 2 μm layer
- No S_K standard until 1999: Vendor A_{app} “standard” 1988-1999

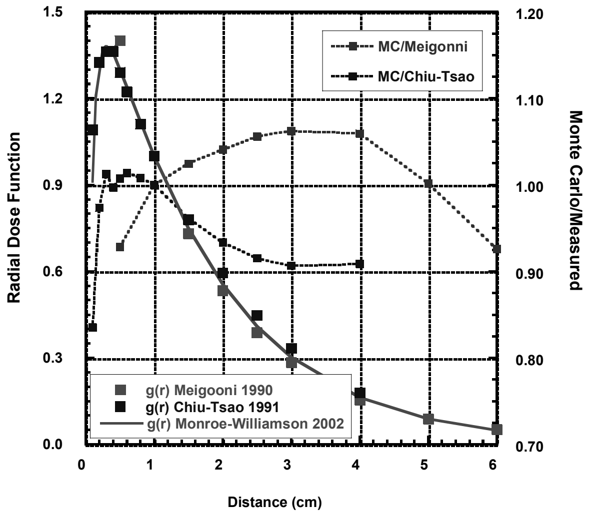
Model 200: Consensus Λ

- **Candidate datasets**
  - **MC: Monroe & Williamson: *Med. Phys.*, 29:609-621, 2002**
  - **TLD: Nath et al. Med Phys 27 (4), 655-658, 2000**

$$\Lambda_{con} = \frac{1}{2}\left[\Lambda_{Nath,TLD} \cdot \left(S_{K,N99} : \frac{x=99}{x=00}\right) + \Lambda_{JFW,MC}\right]$$

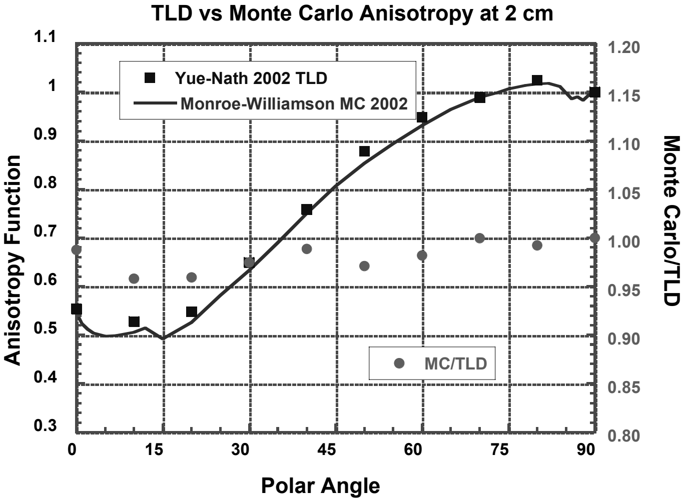
$$= \frac{1}{2}\left[\quad 0.65 \quad \cdot \quad 1.053 \quad + \quad 0.691 \quad\right] = 0.687$$

Model 200 Pd-103: radial dose function



- **No "light seed" TLD**
- **Compare Meigooni 90 & Chiu-Tsao 91 TLD to Monroe 02 Monte Carlo**
- **Monte Carlo: little difference between light and heavy seeds**
- **Monroe g(r) is consensus dataset**

Model 200: MC vs TLD anisotropy at 2 cm



- Agreement within 5%
- φ_{an}(1 cm) = 0.859 (TLD)

  0.855 (MC) vs

  0.90 TG-43
- Use Monroe TLD data (from 0.25 to 7 cm) as consensus data

Revised Dose-Rate Constants

Source	1995 TG-43 $\Lambda_{95D,N85S}$ $S_{K,N85}$	2000 LIBD Guidance $\Lambda_{95D,N99S}$ $S_{K,N99}$	Revised TG-43 $\Lambda_{03D,N99S}$ $S_{K,N99}$
Model 6711 I-125	0.88	0.981	0.964
Model 6702 I-125	0.93	1.037	1.036
NAS 3631 A/S I-125	0.93 (Wallace 1998)	1.037	1.02
Model 200 Pd-103	0.74 $S_{K,T88}$	0.665	0.686

Conclusions and Future Work

- A major TG-43 revision is approaching approval
  - Revised dosimetry parameters for 8 seed models
  - Updated dose calculation formalism
  - Guidance for future reference-quality dosimetry
- Future activities of LIBD
  - Consensus data for remaining low energy sources
  - Revised prescribed-to-administered dose ratios for Pd-103
  - Consensus data for HDR and LDR Ir-192 sources
  - Dose-calculation guidance for Cs-137 sources
  - Procedures for vendor and end-user calibration procedures