Purpose

Present summary of:
- AAPM TG-43U1 brachytherapy dosimetry protocol,
- future supplements, and
- possible future projects.

2004 AAPM TG-43U1 Report

- high level perspective of brachytherapy in U.S.
- dosimetry formalism and clinical datasets
- revised dosimetry formalism
  - 2-D, 1-D, and air kerma strength definition
- consensus data formulation
- clinical implementation recommendations
- clarify interpolation / extrapolation methods
- recommendations to dosimetry investigators
  - experimental measurements & Monte Carlo calculations
- formalism errata and published comments

Full Disclosure

Dr. Rivard has received research funds from the following brachytherapy source manufacturers:
- Implant Sciences Corporation
- IsoRay Medical, Inc.
- Mentor Corporation
- North American Scientific
- Nucletron Corporation
- Theragenics Corporation
- Xoft, Inc.

other Working Group members may also serve as manufacturer consultants - see AAPM COI website
**Brachytherapy Background**

1898: Marie Curie discovered radioactivity (\(^{210}\)Po), and later \(^{226}\)Ra.

1903: awarded Nobel Prize, same year that Alexander Graham Bell proposed brachytherapy.

\(^{226}\)Ra brachytherapy dominated for next 60 years.

Post-1950s reactor development produced man-made radionuclides: \(^{60}\)Co, \(^{137}\)Cs, \(^{192}\)Ir, \(^{198}\)Au, etc.

Currently wide variety of source manufacturers, radionuclides, and brachytherapy source types.

---

**Permanent LDR Brachytherapy**

CT and radiograph of clinical LDR \(^{125}\)I implant.

---

**AAPM Committee Structure 101**

AAPM BoD

Science Council

Imaging

Therapy

Radiation Safety

Therapy Research

Calibrations

Quality Assurance

Therapy Imaging

Treatment Planning

Treatment Delivery

Brachytherapy

LIBC LEBD HEBD EBM BSR

Butler Rivard Li Thomadsen Ibott

ASTRO, ABS, ESTRO, NRC, FDA, etc

---

**Brachytherapy Data Coordination**

Patients

Clinics

Vendors

AAPM

RPC / NIST / ADCLs
Purpose of the Revised Protocol

The goals of the revised protocol (TG-43U1) were:

(a) provide a revised definition of air-kerma strength;

(b) eliminate apparent activity for specification of source strength;

(c) eliminate the anisotropy constant in favor of the distance dependent 1-D anisotropy function;

(d) provide guidance on extrapolating tabulated TG-43 parameters to longer and shorter distances; and

(e) eliminate minor inconsistencies and omissions in the original protocol and its implementation.
\[ \dot{D}(r, \theta) = S_K \cdot A \cdot \frac{G_L(r, \theta)}{G_L(r_0, \theta_0)} \cdot \Lambda \cdot F(r, \theta) \]

- \( \dot{D}(r, \theta) \): dose rate to water at point \( P(r, \theta) \)
- \( S_K \): air kerma strength
- \( \Lambda \): dose rate constant
- \( g_r(r) \): radial dose function
- \( G_L(r, \theta) \): geometry function (line source approximation)
- \( F(r, \theta) \): 2-D anisotropy function
Revised AAPM TG-43
Brachytherapy Dosimetry Formalism (1-D)

\[ \hat{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r, \theta_0)}{G_L(r_0, \theta_0)} \cdot g_L(r) \cdot \phi_{an}(r) \]

\( \hat{D}(r) \)   dose rate to water at point P(r)
\( S_K \)   air kerma strength
\( \Lambda \)   dose rate constant
\( g_L(r) \)   radial dose function
\( G_L(r, \theta_0) \)   geometry function (line source approximation)
\( \phi_{an}(r) \)   1-D anisotropy function

Revised Air Kerma Strength Definition

\[ S_K \equiv \tilde{K}_\delta(d) \cdot d^2 \]

\( S_K \)   air kerma strength
\( \tilde{K}_\delta(d) \)   air kerma rate in vacuo at specification point d with energy cutoff \( \delta \) typically 5 keV

- low-energy photon cutoff now included, and
- measurement conditions are now specified

### Consensus Dataset Formulation Methodology

- comparisons of all candidate datasets
- average \( MC \Lambda \) and average \( EXP \Lambda \) from literature

\[ CON \Lambda = \frac{(MC \Lambda + EXP \Lambda)}{2} \]

- \( g(r) \) and \( F(r, \theta) \) candidate datasets transformed using common \( L \), possibly with \( L_{eff} = \Delta S \times N \)
- \( g(r) \) and \( F(r, \theta) \) typically taken from Monte Carlo
- \( \phi_{an}(r) \) calculated from consensus \( F(r, \theta) \) dataset
- final results tabulated with common mesh

### Comparison of 1-D Formalisms

**BAD**

\[ \hat{D}(r) = S_K \cdot \Lambda \cdot \left( \frac{r_0}{r} \right)^2 \cdot g_L(r) \cdot \phi_{an}(r) \]

**BAD**

\[ \hat{D}(r) = S_K \cdot A \cdot \left( \frac{r_0}{r} \right)^2 \cdot g_L(r) \cdot \phi_{an}(r) \]

**GOOD**

\[ \hat{D}(r) = S_K \cdot A \cdot \left( \frac{r_0}{r} \right)^2 \cdot g_P(r) \cdot \phi_{an}(r) \]

**BEST**

\[ \hat{D}(r) = S_K \cdot A \cdot \frac{G_L(r, \theta_0)}{G_L(r_0, \theta_0)} \cdot g_L(r) \cdot \phi_{an}(r) \]
Consensus Dataset Formulation Methodology

- Literature review of experimental methods & Monte Carlo dosimetry characterization of 8 brachytherapy seeds (2004 AAPM TG-43U1)
  - Amersham / Oncura model 6733 125I
  - DraxImage model LS-1 125I
  - Implant Science model 3500 125I
  - IBT 125I 1L 125I
  - IsoAid model IA 125I
  - Mentor model SL-125/SH-125.S06 125I
  - SourceTech Medical STM1251 125I
  - Best Medical model 2335 103Pd

- Literature review of experimental methods & Monte Carlo dosimetry results for 8 brachytherapy seeds:
  - Amersham Health models 6702 and 6711 125I
  - Bebig/Theragenics Corporation model I25.S06 125I
  - Best Industries model 2301 125I
  - Imagyn Medical Technologies model IS-12501 125I
  - North American Scientific model MED3631-A/M 125I
  - Theragenics Corporation model 200 103Pd
  - North American Scientific model MED3633 103Pd

Clinical Implementation Recommendations

- know your Bx TxP algorithm, deal with limitations
- acceptance testing and commissioning
  - follow AAPM TG-40, TG-53, & TG-56 recommendations
  - compare/validate with Eq.(10) reference dose rates

<table>
<thead>
<tr>
<th>Distance (cm)</th>
<th>Amersham</th>
<th>Amersham</th>
<th>Besig</th>
<th>Best</th>
<th>Imagyn</th>
<th>Theragenics</th>
<th>North American Scientific</th>
<th>North American Scientific</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.519</td>
<td>0.537</td>
<td>0.73</td>
<td>0.77</td>
<td>0.78</td>
<td>0.84</td>
<td>0.89</td>
<td>0.87</td>
</tr>
<tr>
<td>1.0</td>
<td>0.605</td>
<td>0.611</td>
<td>0.84</td>
<td>0.86</td>
<td>0.89</td>
<td>0.93</td>
<td>0.97</td>
<td>0.95</td>
</tr>
<tr>
<td>2.0</td>
<td>0.713</td>
<td>0.718</td>
<td>0.97</td>
<td>0.99</td>
<td>1.01</td>
<td>1.05</td>
<td>1.08</td>
<td>1.06</td>
</tr>
<tr>
<td>3.0</td>
<td>0.846</td>
<td>0.858</td>
<td>1.10</td>
<td>1.11</td>
<td>1.13</td>
<td>1.17</td>
<td>1.19</td>
<td>1.17</td>
</tr>
<tr>
<td>4.0</td>
<td>1.003</td>
<td>1.014</td>
<td>1.24</td>
<td>1.25</td>
<td>1.27</td>
<td>1.31</td>
<td>1.33</td>
<td>1.31</td>
</tr>
<tr>
<td>5.0</td>
<td>1.179</td>
<td>1.191</td>
<td>1.42</td>
<td>1.43</td>
<td>1.45</td>
<td>1.48</td>
<td>1.50</td>
<td>1.48</td>
</tr>
<tr>
<td>6.0</td>
<td>1.382</td>
<td>1.394</td>
<td>1.63</td>
<td>1.64</td>
<td>1.66</td>
<td>1.69</td>
<td>1.71</td>
<td>1.70</td>
</tr>
<tr>
<td>7.0</td>
<td>1.607</td>
<td>1.619</td>
<td>1.85</td>
<td>1.86</td>
<td>1.88</td>
<td>1.91</td>
<td>1.93</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Correction of Errors and Inconsistencies

- g(r) presented for dimensionless units, consistency with investigator g(r), and 5th order polynomial
- explicit contraindication for erroneous 1-D equation
  \[ \dot{D}(r) = S_k \cdot \frac{G_p(r, \theta)}{G_p(r_0, \theta_0)} \cdot g_L (r) \cdot \phi_{\text{aniso}}(r) \]
- goodbye A_{app} and anisotropy constant
- methodology to extrapolate dose calculations for large and small distances

- well chamber ADCL calibrations, NIST traceability
Removal of Previously Defined Terms

- apparent activity: $A_{app}$
  - choice of $(\Gamma_\delta)$ may lead to dosimetric errors
  - AAPM solely specifies $S_k$ for calibration standard

- anisotropy constant: $\phi_{an}$
  - not able to accurately reproduce dosimetry data $r < 1$ cm
  - changes may be made to minimize error, but can lead to significant errors under specific circumstances

Reference Data

- NIST-specified source spectra, half-lives, $\rho$ and atomic composition for both air and water

<table>
<thead>
<tr>
<th>Radius (cm)</th>
<th>% Air dose (cm$^2 \cdot$ cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100.00</td>
</tr>
<tr>
<td>5</td>
<td>95.65</td>
</tr>
<tr>
<td>10</td>
<td>91.35</td>
</tr>
<tr>
<td>15</td>
<td>87.05</td>
</tr>
<tr>
<td>20</td>
<td>82.75</td>
</tr>
<tr>
<td>25</td>
<td>78.45</td>
</tr>
<tr>
<td>30</td>
<td>74.15</td>
</tr>
</tbody>
</table>

Need for Uncertainty Analyses

- TABLE: Table of uncertainties for various sources and compositions using TLDs and Monte Carlo methods for radiation transport calculations. Type A and B uncertainties correspond to statistical and systematic uncertainties, respectively. All values provided are for 1 cm.

I-125 g(r), Variable $\rho$ and Composition

- Graph: Graph of radial dose function, g(r), for I-125 at various $\rho$ values.
Need for Extrapolation Methodology

- Experimental measurement descriptors
  - Description of internal and external source geometry
  - Source irradiation geometry, orientation, irradiation timeline
  - Detector calibration technique & energy response function, $E(r)$
  - Radiation detector and readout system
  - Measurement phantom
  - Phantom dimensions and use of backscatter
  - Estimation volume averaging effect at all detector positions
  - Number of repeated readings with standard deviation, number of sources
  - NIST $S_p$ value and uncertainty for measured source
  - Uncertainty analysis section (statistical and systematic)
Recommendations to Dosimetry Investigators

- Monte Carlo recommended good practices
  - primary calculations in 30 cm diameter liquid water phantom, with at least 5 cm of backscatter material
  - use sufficient histories to limit statistical uncertainty
  - modern cross-section libraries should be used
  - Volume averaging effects should be limited to < 1 %
  - model $k(\theta)$ as a function of polar angle for $s_K$ simulation
  - mechanical mobility of internal source structures

- Monte Carlo calculation descriptors
  - radiation transport code, version, and major options
  - cross-section library name, version, and customizations
  - manner in which dose-to-water and air-kerma strength are calculated (i.e., tally used)
  - source geometry, phantom geometry, and sampling space
  - composition and mass density of materials in the source
  - composition and mass density of materials in the phantom
  - physical distribution of radioisotope within the source
  - uncertainty analysis section (statistical and systematic)

Publication of Dosimetry Results

- unofficial Medical Physics Seed Policy (2001) limiting publication of basic dosimetry parameters to a Technical Note
- focus more on new science versus mundane data
- other scientific journals are receptive to publish
- do not reiterate TG-43U1 formalism, established methods, and citeable literature towards KISS
- TG-43U1 Independence Policy
  - authors should minimize conflict-of-interest with vendors
  - measurements & calculations should be gathered independently and not be dependent upon each other

Errata and Literature Comments

- Medical Physics (August 2002) letter-to-the-editor (Jerry Meli) and AAPM response to justify retention of line-source geometry functions
- erratum in Medical Physics (December 2004) primarily to address typos
- Medical Physics (June 2005) letter-to-the-editor (Ali Meigooni et al.) and AAPM response to clarify the geometry function and Eq. (5) $\text{Leff} = \Delta S \times N$
- $U = \mu \text{Gy.m}^2.\text{h}^{-1}$ or $\text{cGy.cm}^2.\text{h}^{-1}$
Deposition characterics

similar dose rates to 10 Ci HDR $^{192}$Ir over region of interest

Free Air Attix Ionization Chamber

Free Air Attix Chamber Schematic
Conclusion

- need to supplement consensus data from the AAPM TG-43U1 (2004) report
- consensus datasets for 8+8 brachytherapy sources are provided for consistent clinical use
- guidance provided to physicists and RTP software vendors for interpolation / extrapolation methods
- draft report is under review at AAPM, results to be published in Medical Physics
- forthcoming supplement for additional sources
- need to advance the field through better algorithms