Clinical Impact of Novel Brachytherapy Dose Calculation Algorithms

AAPM DVC, May 15, 2015

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Disclosure

• Member of AAPM TG-186
• Member of AAPM Working Group - WGMBDCA
Learning Objectives

• Describe the dosimetric uncertainty in modern brachytherapy.

• Review the AAPM TG-186 and WGMBDCA guidelines to commission modern dose calculation engines.

• Identify factors requiring standardization to achieve dosimetric consistency among clinics.
Acknowledgements

TG-186
- Luc Beaulieu, CHU de Quebec (Chair)
- Äsa Carlsson-Tedgren, Li University
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- Mark Rivard, Tufts University
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- Frank Verhaegen, Maastro Clinic
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- Ron Sloboda, Cross Cancer Institute
- Rowan Thomson, Carleton University
- Frank Verhaegen, Maastro Clinic
### Common Past/Present Radionuclides in Brachytherapy (LDR/HDR)

<table>
<thead>
<tr>
<th>Radionuclides</th>
<th>$T_{1/2}$</th>
<th>$E_{avg}$(KeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>1,622 y</td>
<td>830</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>5.26 y</td>
<td>1,250</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>30 y</td>
<td>662</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>74.1 d</td>
<td>380</td>
</tr>
<tr>
<td>$^{198}$Au</td>
<td>2.7 d</td>
<td>410</td>
</tr>
<tr>
<td>$^{131}$Cs</td>
<td>~10 d</td>
<td>29</td>
</tr>
<tr>
<td>$^{125}$I</td>
<td>~60 d</td>
<td>28</td>
</tr>
<tr>
<td>$^{103}$Pd</td>
<td>~17 d</td>
<td>22</td>
</tr>
</tbody>
</table>

F. Mourtada, Ph.D.
New BT Sources

- How sensitive is dosimetry for novel radionuclides and eBT to material heterogeneities (and general differences with TG-43)?

Slide from Rivard

From Multiple Sources/Manual Loading to a Single Source/Afterloading

Ra-226 Tubes (manual) → Cs-137 Tubes (manual) → Cs-137 Pellet LDR (afterloading) → Ir-192 PDR/HDR (afterloading)
HDR/PDR Remote Afterloader

HDR: 10 Ci
PDR: 1-2 Ci

F. Mourtada, Ph.D.
ICBT- Gynecology

- Intracavitary: Places radioactive sources within a body cavity (cervical cancer)
- LDR (temporary, 48hrs) or HDR (temporary, minutes)
Recently Introduced Applicators
CT/MR (HDR/PDR Afterloader)

- Utrecht Interstitial Fletcher
- Fletcher Shielded
- Interstitial Ring

Shielded ovoids
Interstitial Examples

- Interstitial
  - Permanent
    - GU - prostate (I-125, Pd-103, Cs-131)
    - GYN - pelvic side wall (Au-198)
    - GI - rectum (Au-198)
CLINICAL APPLICATION TO APBI (ACCELERATED PARTIAL BREAST IRRADIATION)
Surface (Topical)

Places the radioactive sources on top of the area to be treated (choroidal melanoma)

Temporary: ~72hrs (LDR)

A custom-made radiation plaque. On the left is the inside of a plaque with the radiation seeds. On the right is the gold coating on the outside of the plaque.
Skin Surface Applicators
Ir-192 HDR

Freiburg Flap
Leipbzig (shielded)
Brachytherapy Dose Calculation (i.e. since 1995)

- TG43 formalism is the standard methodology for dose calculation.
- TG43 was created primarily for interstitial low energy brachytherapy purposes.
- Dose calculation is done assuming material is uniform water phantom.

\[
\frac{\dot{D}(r, \theta)}{\omega(r)} = S_K \cdot \Lambda \cdot \frac{G_L(r, \theta)}{G_L(r_0, \theta_0)} \cdot g_L(r) \cdot F(r, \theta)
\]

- $\dot{D}(r, \theta)$: dose rate to water in water at point $P(r, \theta)$
- $S_K$: air kerma strength
- $\Lambda$: dose rate constant
- $g_L(r)$: radial dose function
- $G_L(r, \theta)$: geometry function (line source approximation)
- $F(r, \theta)$: 2D anisotropy function

History

- 1995 – TG43 (I-125, Pd-103)
  - Provided recommendations for dose calculation for low energy source dosimetry (E<50keV).
- 2004 – TG43U1
  - Clarifications, 1D vs 2D formalism, etc.
- 2007 – TG43U1S1
  - Increased number sources, etc.
- 2010 “Erratum” of TG43U1S1
Prior to TG-43:
Sievert Integral Source Geometry

**Fig. 1.**
Geometry of dose calculation for linear radium sources.
Consensus Data Sets

- Report gives recommendations on how to experimentally and theoretically obtain dosimetric parameters for sources.
  - Experimentally: detector type, volume averaging effects, phantom materials, energy response characterization, etc.
  - Theoretically (MC): Cut off thresholds, good practice guidelines (e.g. # of histories)

• Uncertainty analysis
Clinical Source Registry Available

• 3 current source registries available
  – IROC- Houston (RPC)
  – Carlton University (CAN)
  – ESTRO
Low-Energy Brachytherapy Sources - examples

- Amersham Health model 3702 source
- NASI model MED3631-A/M or MED3633 source
- Source Tech Medical STM1251 seed
- IsoAid Advantage
- Bebig model 2301 source
- Imagyn model IS-2501 source
- Mentor Frosteaseed
- Implant Sciences 3500

Axxent electronic BT source: 27 keV
TG-43 Protocol
Phantom Size Requirement

• TG43 has recommendations for “along and away” dose rate tables to distances far away from the source (e.g. 5cm for I-125)

• Requires phantom sizes in MC calculations to be large enough to give full scatter at large distances (10+ cm for HEB)
  – Radius of 40 cm recommended.
Advantages of TG43

• An analytic, uniform approach standardizes dose calculation worldwide.

• Simple to implement into the TPS and 2nd calculation spreadsheet for a clinical physicist
Limitations of TG43

• Assumes a water medium with superpositions of single source positions.
  – No inter-source attenuation effects
  – Full scatter conditions
    • Most low energy applications have full scatter e.g. prostate implants
  – No variable tissue composition
    • More of an issue for low energy sources than for high energy sources
Limitations of TG43, cont

• High energy brachytherapy sources suffer more from effects of the scatter conditions than low energy brachytherapy sources.
  – Applications can range from deep (gyn) to shallow (skin).

• Neglects applicator shielding effects for treatments such as shielded ovoids or cylinders.
  – Incorrect correlation of doses reported with toxicities
TG43 has served us well!

- Is still!
- Worldwide uniformity
- Well-define process for source parameters
- Source specific
- Fast
- Dose optimization (IP)
Dose Calculation for Photon-Emitting Brachytherapy Sources with Average Energy Higher than 50 keV: Full Report of the AAPM and ESTRO

Report of the

High Energy Brachytherapy Source Dosimetry (HEBD) Working Group

August 2012
TG-229 Report Contains

1. Review the construction and available published dosimetry data for high-energy $^{192}\text{Ir}$, $^{137}\text{Cs}$, and $^{60}\text{Co}$ sources.

2. Perform a critical review of the existing TG-43U1 formalism applied to HEB.

3. Develop a complete consensus dataset to support clinical planning for each source model.

4. Develop guidelines on the use of computational and experimental dosimetry of high-energy brachytherapy sources.
TG43-based TPS can fail to accurately calculate dose

• Dose perturbations due to contrast medium and air pockets
• Effect of patient tissue inhomogeneities
• What is the impact on
  – PTV
  – Skin
  – Chest wall/ribs

Rivard, “Brachytherapy Dose Calculation Formalism Dataset Evaluation, and treatment planning system Implementation (AAPMSS 2009)
One size does not fit all!
### Sensitivity of Anatomic Sites to Dosimetric Limitations of Current Planning Systems

<table>
<thead>
<tr>
<th>anatomic site</th>
<th>photon energy</th>
<th>absorbed dose</th>
<th>attenuation</th>
<th>shielding</th>
<th>scattering</th>
<th>beta/kerma dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>prostate</td>
<td>high</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
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<tr>
<td>breast</td>
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<td>XXX</td>
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<td>low</td>
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<td>XXX</td>
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<td>GYN</td>
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<tr>
<td>skin</td>
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<td>XXX</td>
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<td></td>
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<td>XXX</td>
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<td>low</td>
<td></td>
<td></td>
<td></td>
<td>XXX</td>
<td>XXX</td>
</tr>
</tbody>
</table>

Importance of the Physics: Water vs Tissues

Mass Energy-Absorption Coefficients Relative to Water as a function of Energy

TG-186

< 100 keV large differences
Tissue composition impact is minimal (Ir-192)

But- Effect of Phantom Size

Scattered Photon Contribution in Brachy

A. K. Carlsson and A. Ahnesjo, Med Phys 27(10), 2000
### Physics « Rule of Thumb »

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Effect</th>
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<tbody>
<tr>
<td>$^{192}\text{Ir}$</td>
<td>Scatter condition</td>
</tr>
<tr>
<td>$^{103}\text{Pd}/\  ^{125}\text{I}/\  \text{eBx}$</td>
<td>Absorbed dose ($\mu_{\text{en}}/\rho$)</td>
</tr>
<tr>
<td></td>
<td>Attenuation ($\mu/\rho$)</td>
</tr>
<tr>
<td></td>
<td>Shielding (applicator, source)</td>
</tr>
</tbody>
</table>
# Alternatives to TG43

Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010

## Table I. Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were useable in brachytherapy treatment planning systems as of 12 May 2010.

<table>
<thead>
<tr>
<th>MBDCA system</th>
<th>Sponsor(s)</th>
<th>Radiation type</th>
<th>Clinical use</th>
<th>FDA/CE mark status</th>
<th>Release date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLAQUE SIMULATOR</td>
<td>Astrahan(^a)</td>
<td>$^{125}$I + $^{103}$Pd photons</td>
<td>Y</td>
<td>N</td>
<td>1990</td>
</tr>
<tr>
<td>Collapsed cone</td>
<td>Ahnesjö, Russell, and Carlsson(^b)</td>
<td>$^{192}$Ir photons</td>
<td>N</td>
<td>N</td>
<td>1996</td>
</tr>
<tr>
<td>BRACHYDOSE</td>
<td>Yegin, Taylor, and Rogers(^c)</td>
<td>0.01–10 MeV photons</td>
<td>N</td>
<td>N</td>
<td>2004</td>
</tr>
<tr>
<td>MCI</td>
<td>Chibani and Williamson(^d)</td>
<td>$^{125}$I + $^{103}$Pd photons</td>
<td>N</td>
<td>N</td>
<td>2005</td>
</tr>
<tr>
<td>GEANT4/DICOM-RT</td>
<td>Carrier et al.(^e)</td>
<td>Any</td>
<td>N</td>
<td>N</td>
<td>2007</td>
</tr>
<tr>
<td>Scatter correction</td>
<td>Poon and Verhaegen(^f)</td>
<td>$^{192}$Ir photons</td>
<td>N</td>
<td>N</td>
<td>2008</td>
</tr>
<tr>
<td>Hybrid TG-43:MC</td>
<td>Price and Mourtada(^g) and Rivard et al.(^h)</td>
<td>Any</td>
<td>Y</td>
<td>Y</td>
<td>2009</td>
</tr>
<tr>
<td>ACUROS</td>
<td>Transpire/Varian(^i)</td>
<td>$^{192}$Ir photons</td>
<td>Y</td>
<td>Y</td>
<td>2009</td>
</tr>
</tbody>
</table>
Brachytherapy Dose Calculation Methods

Model-Based Dose Calculation: MBDCA

Analytical / Factor-based

TG43, PSS, CCC, GBBS, MC

Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010
Current STD: Full scatter in water medium

Implicit particle transport: Heterogeneity, accurate to 1st scatter. GPU friendly

Gold STD for source characterization and other applications

No particle transport. No heterogeneity, shields. Primary can be used in more complex dose engine

Solves numerically transport equations. Full heterogeneity.
Grid-Based Boltzmann Solver (GBBS)

\[ \hat{\Omega} \cdot \vec{\nabla} \Psi(\hat{r}, E, \hat{\Omega}) + \sigma_t(\hat{r}, E) \Psi(\hat{r}, E, \hat{\Omega}) = Q^{\text{scat}}(\hat{r}, E, \hat{\Omega}) + Q^{\text{ex}}(\hat{r}, E, \hat{\Omega}) \]

- **Position:** \( \hat{r} = (x, y, z) \)  
  mesh position discretization (finite elements)
- **Energy:** \( E \)  
  Energy bins (cross section)
- **Direction:** \( \hat{\Omega} = (\theta, \phi) \)  
  Angular discretization

« multi-group discrete ordinates grid-based …»

2D: Daskalov et al (2002), Med Phys 29, p.113-124  
GBBS Benchmarks for $^{137}$Cs Pellets

Dosimetric accuracy of a deterministic radiation transport based $^{192}$Ir brachytherapy treatment planning system. Part III, Comparison to Monte Carlo simulation in voxelized anatomical computational models

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(Received 26 July 2012; revised 15 November 2012; accepted for publication 16 November 2012; published 18 December 2012)
MBDCA Calculation Speed…

- Can be relatively fast
  - Can be done within a few minutes
  - < 1 sec per dwell-position (MC on GPU)

- BUT, MC (CPU-based), CC and AcurosBV® are all too slow to be coupled to IP for dose optimization
TG-186 Report

Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

1. Recommendations to MBDCA early-adopters to evaluate:
   • phantom size effect
   • inter-seed attenuation
   • material heterogeneities within the body
   • interface and shielded applicators

2. Commissioning process to maintain inter-institutional consistency

3. Patient-related input data

4. Research is needed on:
   • tissue composition standards
   • segmentation methods
   • CT artifact removal

Approved by
ESTRO (EIR, ACROP)
AAPM (BTSC, TPC)
ABS (Phys Cmte, BoD)
ABG (Australia)

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A generic high-dose rate $^{192}\text{Ir}$ brachytherapy source for evaluation of model-based dose calculations beyond the TG-43 formalism

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Heterogeneity-corrected vs -uncorrected critical structure maximum point doses in breast balloon brachytherapy

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Department of Radiation Oncology, Cancer Institute of New Jersey, Robert Wood Johnson Medical School, University of Medicine and Dentistry of New Jersey, New

- 20 patients – 15 Contura + 5 Savi
- Linear relationship indicates predictability
Balloon-Based Accelerated Partial Breast Irradiation With Contura™: Comparison Between Conventional TG-43 and Brachyvision Acuros™ Dose Calculation Methods

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<table>
<thead>
<tr>
<th></th>
<th>TG-43</th>
<th>Acuros™</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTV_eval D95 (cGy)</td>
<td>322.7</td>
<td>311.9</td>
<td>(3.4 ± 0.5) %</td>
</tr>
<tr>
<td>PTV_eval D1 (cGy)</td>
<td>816.4</td>
<td>806.6</td>
<td>(1.2 ± 0.6) %</td>
</tr>
<tr>
<td>PTV_eval D_min (cGy)</td>
<td>238.4</td>
<td>254.1</td>
<td>(-7.1 ± 7.1) %</td>
</tr>
<tr>
<td>PTV_eval V150 (cm³)</td>
<td>26.5</td>
<td>24.0</td>
<td>(9.2 ± 1.3) %</td>
</tr>
<tr>
<td>Skin D_max (cGy)</td>
<td>439.0</td>
<td>420.1</td>
<td>(4.6 ± 1.2) %</td>
</tr>
<tr>
<td>Skin D_mean (cGy)</td>
<td>242.8</td>
<td>226.6</td>
<td>(6.7 ± 0.6) %</td>
</tr>
<tr>
<td>Skin D_skin_pt (cGy)</td>
<td>297.1</td>
<td>278.1</td>
<td>(6.7 ± 1.7) %</td>
</tr>
</tbody>
</table>

5 Contura patients
• 30 patients evaluated $\text{Skin}_{\text{max}}$, $\text{Rib}_{\text{max}}$, D90, V100, V150, V200

• Variety of applicators including interstitial
  • Results for interstitial were within 3% or 3cc

• Balloon based:
  • $\text{Skin}_{\text{max}}$ – 8% including >10% if only using central lumen/single dwell
  • $\text{Rib}_{\text{max}}$ - 5% on average
  • Target coverage less (3.5% – 8%)
  • Larger balloons had greater differences in V100, etc.
ABS 2015 Conclusions-APBI

• TG43 for APBI—impact
  – If you are using high levels of contrast – your overall dose is decreased
  – Skin dose is decreased ~ 4-10%
  – Dose to ribs is decreased ~ 5 -7%
  – Dose coverage is probably slightly reduced

• New methods of dose calculation are promising and show we have gains to be made in accuracy
Fletcher CT/MR Shielded Applicator Set
MDACC Clinical Outcomes (n=12)

• Enrolled on prospective protocol of image based brachytherapy

• PDR brachytherapy with Fletcher CT/MR Shielded Applicator

Dose Distribution at Ovoids

TG43 (no shields)                  TG186 (shields modeled)

200
150
100
50%
Dose Distribution at Ovoids

TG43 (no shields)                 TG186 (shields modeled)
Dose Distribution at Ovoids

TG43 (no shields)                   TG186 (shields modeled)
Dose Distribution at Ovoids

TG43 (no shields)                      TG186 (shields modeled)

200  150  100  50%
Dose Difference at Ovoids

1780
1190
790
595
395
100 cGy
DVH Analysis
% Reduction

- **Rectum: Mean (Range)**
  - D2cc  15% (5-22)
  - D1cc  15% (4-22)
  - D0.1cc  13% (3-22)

- **Bladder**
  - D2cc  6% (3-12)
  - D1cc  6% (3-11)
  - D0.1cc  6% (1-11)

- **Sigmoid**
  - D2cc  2% (1-14)
  - D1cc  2% (1-13)
  - D0.1cc  2% (1-12)
ABS2015 Conclusions-GYN

• The new brachy dose calculation algorithms provide more accurate dose distributions for GYN brachytherapy than the standard TG-43.

• Unshielded GYN CT/MR applicators impact is within +/-5%

• Shielded GYN Applicator significantly reduces dose to rectum, bladder, and sigmoid (up to 25%)
Conclusions

• With the recent introduction of heterogeneity correction algorithms for brachytherapy, the Medical Physics community is still unclear on how to commission and implement these into clinical practice.

• Recently-published AAPM TG-186 report discusses important issues for clinical implementation of these algorithms.