• Research and Relevance of Brachytherapy
Dose Calculation Advancements: Advances in brachytherapy dose calculation

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<td>Astrahan&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(^{125})I + (^{103})Pd photons</td>
<td>Y</td>
<td>N</td>
<td>1990</td>
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<td>Ahnesjö, Russell, and Carlsson&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(^{192})Ir photons</td>
<td>N</td>
<td>N</td>
<td>1996</td>
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<td>Brachydose</td>
<td>Yegin, Taylor, and Rogers&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.01–10 MeV photons</td>
<td>N</td>
<td>N</td>
<td>2004</td>
</tr>
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<td>Chibani and Williamson&lt;sup&gt;d&lt;/sup&gt;</td>
<td>(^{125})I + (^{103})Pd photons</td>
<td>N</td>
<td>N</td>
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<tr>
<td>GEANT4/DICOM-RT</td>
<td>Carrier et al.&lt;sup&gt;e&lt;/sup&gt;</td>
<td>Any</td>
<td>N</td>
<td>N</td>
<td>2007</td>
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<tr>
<td>Scatter correction</td>
<td>Poon and Verhaegen&lt;sup&gt;f&lt;/sup&gt;</td>
<td>(^{192})Ir photons</td>
<td>N</td>
<td>N</td>
<td>2008</td>
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<td>Hybrid TG-43:MC</td>
<td>Price and Mourtada&lt;sup&gt;g&lt;/sup&gt; and Rivard et al.&lt;sup&gt;h&lt;/sup&gt;</td>
<td>Any</td>
<td>Y</td>
<td>Y</td>
<td>2009</td>
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<tr>
<td>ACUROS</td>
<td>Transpire/Variante&lt;sup&gt;i&lt;/sup&gt;</td>
<td>(^{192})Ir photons</td>
<td>Y</td>
<td>Y</td>
<td>2009</td>
</tr>
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</table>

Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010
Brachytherapy Dose Calculation Methods

Analytical / Factor-based Model-Based Dose Calculation: MBDCA

TG43  PSS  CCC  GBBS  MC

Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010
BT Dose Calc.

Current STD: Full scatter water medium

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

Explicit particle transport simulation. Gold STD for source characterization and other applications

TG43

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

PSS

Only commercial MDBCA. Solves numerically transport equations. Full heterogeneity.

CCC

GBBS

MC
TG-43 Hybrid Approaches for High-Energy

- Use on FDA-approved TG-43-based Bx TPS

- Use MC to derived TG43-like parameters using the shielded applicator composition
  - No 3D dose kernel entry

- Only for rigid, cylindrical applicators (symmetry)

- Clinical applications for TG-43 hybrid approach
  - vaginal cylinder
  - skin applicators (Leipzig, Valencia)
  - AccuBoost breast brachytherapy boost/APBI

CCC MBDC for Brachytherapy

I. Raytrace source

Primary source rays
Material info

II. CC convolution

Scatter transport line
First-scatter kernel
Material info
First scerma $S_{1sc}$

III. CC convolution

Scatter transport line
Residual-scatter kernel
Material info
Second scerma $S_{2sc}$

IV. Summation

$D_{\text{prim}} + D_{1sc} + D_{rsc} = D_{\text{tot}}$

I. TG43

Superposition of single-source water-dose imaging in TG43: localise dose - anatomy

II. MBDCA

Information on tissue, etc composition from images or elsewhere

From Åsa Carlsson-Tedgren
CCC in Oncentra TPS (Elekta)

CC figures from Bob van Veelen, Nucletron BV/Elekta
Grid-Based Boltzmann Solver (GBBS)

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

- 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
Grid-Based Boltzmann Solver (GBBS)

- Varian BV-Acuros® implementation: **only commercial MBDCA solution at this time**
  - CPE assumption: Primary dose analytical (ray-tracing with scaling)
    - \( D_{\text{prim}} = K_{\text{coll}} \)
    - First scatter from primary: \( \text{Scerma} = D_{\text{prim}} \cdot ( (\mu - \mu_{\text{en}})/u_{\text{en}}) \)
    - **Share this step with CCC**

- 3D scatter integration through GBBS

- Source modeling done in Atilla® (Transpire Inc)
137Cs Attila Benchmarks

Monte Carlo simulations

• Mimics the discrete particle, statistical nature of ionization radiation

• "Golden standard" for dose calculations
  o TG43 parameters
  o Primary Scatter Separation

• Model complex geometries

• Derive information not accessible in measurements

DWO Rogers, Review paper, PMB 51 (2006);
TG43-U1 by Rivard et al., Med Phys 2004;
Monte Carlo Dose Calculations: Brachy

- General Purpose
  - EGSnrc
  - MCNP (5,X)
  - Penelope
  - Geant4

- Brachytherapy specific
  - ALGEBRA (Afsharpour et al., (2012), PMB)
## MC speed up techniques

<table>
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<tr>
<th>Technique</th>
<th>Speed-up</th>
</tr>
</thead>
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<tr>
<td>CPE, only photons</td>
<td>20 -70%&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Track length estimator</td>
<td>Factor 20-30&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>Phase space (source)</td>
<td>30-40%&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Photon recycling</td>
<td>30-40%&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Correlated sampling</td>
<td>Factor 40-60&lt;sup&gt;3&lt;/sup&gt;</td>
</tr>
<tr>
<td>MC on GPU</td>
<td>Sub second&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

MBDCA Calculation Speed…

• Can be relatively fast
  o About 25 sec for a seed implant dosimetry (BrachyDose)
  o < 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
# Factor-based vs Model-based

## TG43

<table>
<thead>
<tr>
<th>INPUT</th>
<th>CALCULATION</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source characterization</td>
<td>Superposition of data from source characterization</td>
<td>$D_{w-TG43}$</td>
</tr>
</tbody>
</table>

## MBDC

<table>
<thead>
<tr>
<th>INPUT</th>
<th>CALCULATION</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source characterization</td>
<td>Model-Based Dose Calculation Algorithms</td>
<td>$D_{m,m}$</td>
</tr>
<tr>
<td>Tissue/applicator info</td>
<td></td>
<td>$D_{w,m}$</td>
</tr>
</tbody>
</table>

From Åsa Carlsson-Tedgren
Three main areas identified as critical

1. Definition of the scoring medium
2. Cross section assignments (segmentation)
3. Specific commissioning process
1. Definition of the scoring medium

\[ D_{x,y} \]

\( x \): dose specification medium

\( y \): radiation transport medium

\( x,y \): Local medium (m) or water (w)

FROM: G Landry, Med Phys 2011
Which best correlate to cell doses or outcomes?

(a) $D_{m,m}$

(b) $D_{w,m}$

or

???
2- Cross section assignments (segmentation)

MDBCA requires assignment of interaction cross section on a voxel-by-voxel basis.

In EBRT one only needs electron densities $\rho_e$ (e$^-$/cm$^3$) from CT scan.

In BT (energy range 10-400 keV) the interaction probabilities depend not only on $\rho_e$ but also strongly on atomic number $Z$. 

![Diagram showing the variation of interaction probabilities with atomic number Z and photon energy $h\nu$.](image)
2- Cross section assignments

Accurate tissue segmentation, sources and applicators needed: identification \((\rho_e, Z_{\text{eff}})\)

- e.g. in breast: adipose and glandular tissue have significantly different \((\rho_e, Z_{\text{eff}})\); dose will be different

If this step is not accurate ➔ incorrect dose

- Influences dosimetry and dose outcome studies
- Influences dose to organs at risk
2- Cross section assignments

Requirements from vendors

• Accurate geometry (information accessible to users for commissioning)

• Responsible for providing accurate composition of seeds, applicators and shields.

• To provide a way for the manufacturers (of the above) or alternatively the end users to input such information into the TPS

• Poke your favorite vendor, this will be critical
3- Specific commissioning process

MBDCA specific tasks

- Currently, only careful comparison to Monte Carlo with or w/o experimental measurements can fully test the advanced features of these codes

  - This is not sustainable for the clinical physicists
Why moving away from TG43?

Large effects are not taken into account
  • Much more important than in EBRT
  • Impact on prescription, dose to OARs, ...

Uncertainties are expected to be, in most cases smaller than moving away from water-only geometries
  • But strong guidance needed!
Recent Publication about use of Acuros with Shielded Colpostats

• Report the dosimetric impact of colpostats with shields in a cohort of cervical cancer patients (n=24) treated with HDR, retrospectively

Mikell et al, Brachytherapy, 2013 (in press)
### Table 2
Percent difference \((100 \times [\text{GBBS}(Y, \text{CT}) - \text{TG43}]/\text{TG43})\) for clinical dosimetric parameters

<table>
<thead>
<tr>
<th>Dosimetric parameter</th>
<th>(n)</th>
<th>Mean (%)</th>
<th>SD (%)</th>
<th>Median (%)</th>
<th>Range ([\text{min, max}]) (%)</th>
<th>(p)-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point A Lt</td>
<td>24</td>
<td>-2.54</td>
<td>0.53</td>
<td>-2.57</td>
<td>[-3.80, -1.22]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Point A Rt</td>
<td>24</td>
<td>-2.56</td>
<td>0.45</td>
<td>-2.55</td>
<td>[-3.34, -1.22]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Point B Lt</td>
<td>24</td>
<td>-1.50</td>
<td>1.00</td>
<td>-1.55</td>
<td>[-3.25, 1.09]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Point B Rt</td>
<td>24</td>
<td>-1.56</td>
<td>0.92</td>
<td>-1.51</td>
<td>[-3.62, 0.44]</td>
<td>&lt;0.001</td>
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<tr>
<td>3 o’clock</td>
<td>24</td>
<td>-2.60</td>
<td>0.53</td>
<td>-2.71</td>
<td>[-3.68, -1.42]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>9 o’clock</td>
<td>24</td>
<td>-2.57</td>
<td>0.51</td>
<td>-2.54</td>
<td>[-3.41, -1.57]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ICRU rectum</td>
<td>24</td>
<td>-8.36</td>
<td>2.49</td>
<td>-8.23</td>
<td>[-14.07, -4.08]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D(_{2\text{cc}}) rectum</td>
<td>24</td>
<td>-6.22</td>
<td>2.59</td>
<td>-6.41</td>
<td>[-11.91, -0.75]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D(_{2\text{cc}}) sigmoid</td>
<td>21</td>
<td>-5.64</td>
<td>2.55</td>
<td>-4.83</td>
<td>[-9.27, -2.02]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ICRU bladder</td>
<td>24</td>
<td>-7.16</td>
<td>3.64</td>
<td>-7.45</td>
<td>[-15.74, -2.08]</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>D(_{2\text{cc}}) bladder</td>
<td>24</td>
<td>-3.42</td>
<td>1.85</td>
<td>-2.57</td>
<td>[-7.22, -1.12]</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

GBBS = grid-based Boltzmann solver; ICRU = International Commission on Radiation units; \(D_{2\text{cc}}\) = doses for the most exposed 2 cm\(^3\) of the bladder.
Clinical GYN HDR Example with Shielded Colpostats
Spatial distributions of the 3 factors contributing to differences between GBBS and TG-43:

(1) source and boundary,
(2) applicator,
(3) Heterogeneity*

*The contrast is overridden to
(1) muscle,
(2) no override,
(3) or bone.

Mikell et al IJROBP, 83(3), pp e414-e422, 2012
Conclusion

• Advanced dose calculation is a necessary step for better brachytherapy treatments

• Change in dose calculation standard is not new (e.g. lung EBRT)
  • Transition period
  • Revisiting dose-outcomes, dose prescription

• The future of brachytherapy is exciting