Advances in Brachytherapy Dose Calculations, Part II

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Disclosures

• I am a member of the AAPM/ESTRO/ABG Working Group on Model-based Dose Calculation Algorithms. Our WG is working with all brachytherapy TPS vendors.
Learning Objectives

1. Identify key clinical applications needing advanced dose calculation in brachytherapy.
2. Provide an overview of the alternatives to TG43
3. Explain in practical terms the recommendations of TG186
4. Identify relevant commissioning processes for safe clinical integration.
5. Provide practical clinical examples using a commercially available system
Section V of TG-186 Motivations

• No practical guidance on the commissioning for clinical use for MBDCA for Brachytherapy

• There is a need to establish uniform commissioning procedures for various MBDCA vendors and across institutions

• Not to forget the current guidelines ...
Brachytherapy TPS Commission Process

- AAPM TG-40: Comprehensive QA for Radiation Oncology
- AAPM TG-43: Dosimetry of Interstitial Brachytherapy sources
- AAPM TG-53: Quality Assurance for Clinical Radiotherapy Treatment Planning
- AAPM TG-59: High Dose-rate Brachytherapy Treatment Delivery
- AAPM TG-56: Code of Practice of Brachytherapy Physics
- AAPM TG-64: Permanent Prostate Seed Implant Brachytherapy

Two General Categories

Commission tasks broken down into two general categories:
- Non-dosimetric tests
- Dosimetric tests
“Non-dosimetric” Tests

- Image Input tests (CT, MR, PET, film)
- 3D anatomical structure input test
- Contour tests
- Image use and display test
- Accurate transfer to afterloader TCU
- Computer storage and database backup

“Dosimetric Tests”

- Dose calculation methodology/algorithm tests
- Dose display tests
- DVH tests
- Source strength decay
- Source localization tools
- Impact of grid size
- Etc.
### Ex1: Oncentra Single mHDR source Test (TG43)

**Table:**

<table>
<thead>
<tr>
<th>Name</th>
<th>Norm.</th>
<th>X (mm)</th>
<th>Y (mm)</th>
<th>Z (mm)</th>
<th>Abs. Dose (cGy)</th>
<th>OCB</th>
<th>Plato</th>
<th>(OCB-Plato)/Plato</th>
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### Ex2: Oncentra two mHDR sources Test (TG43)

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<th>Y (mm)</th>
<th>Z (mm)</th>
<th>Abs. Dose (cGy)</th>
<th>OCB</th>
<th>Plato</th>
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</table>
Dose algorithm tests beyond TG-43

• MC, CC or GBBS implementation as MBDCA involve compromises between computational speed and sufficient accuracy

• Must be carefully benchmarked against analog MC or experiment to ensure sufficiently accurate dose prediction within the intended domain

M. Rivard et al. (Vision 20/20), Med. Phys. 27, 2645-2658 (2010)

Basic recommendations of TG-186

• Previous TPS QA/QC process still valid

• Maintains TG43 dose prescriptions
  • Unless societal recommendation otherwise

• Model-based dose calculations should be performed in parallel with TG43
  • Radiation transport using the most accurate tissue medium compositions available
TG-186 Commission Tests Required

• AAPM/ESTRO recommend minimum standards to evaluate conditions similar to those of clinical brachytherapy practice based on established TG-43 formalism

• Two levels of commissioning tests that should be performed in addition to standard TPS QC/QA

Commission level I

• A direct comparison in reference-sized homogenous water to AAPM TG-43 consensus data: Water sphere with proper radius

• A first step since these parameters describe the spatial dose distribution due to the physical source model without significant consideration of the surrounding environment
High-Energy Brachytherapy Sources-examples

From Rivard

Low-Energy Brachytherapy Sources- examples

From Rivard
Level I Pass/Fail Criteria:

- As recommended in the 2004 AAPM TG-43U* report: 2.0% dose tolerance should be used for agreement with AAPM consensus TG-43 dosimetry parameters
- Deviations > 2.0% should be carefully examined. Clinical impact understood and documented before clinical use

*Med. Phys. 31 (3), 2004

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Example 1:
Mikell and Mourtada reported on the dose distributions of a HDR $^{192}$Ir source in a homogeneous water geometry calculated using BrachyVision (BV) TPS (BrachyVision v8.8, Varian Medical Systems, Palo Alto, CA) with the MBDCA-based Acuros® system. The percent dose difference ($\%\Delta D$) of GBBS was determined for three cases:

1. published TG-43 data;
2. MCNPX simulations of the model VS2000 HDR $^{192}$Ir source centered in a spherical water phantom of radius $R = 15$ cm, and
3. output from a TG-43-based TPS using vendor supplied $F(r, b)$ tables.

Dose differences >20% between Acuros® and TG-43-based dosimetry near the source delivery cable were observed. This was attributed to Acuros® using a 0.1 cm long delivery cable, while the TG-43-based TPS algorithm used data based on a 15 cm long cable. While these dose differences were large near the cable, the impact on clinical outcomes was negligible with dose differences of less than 3% reported.

*Med Phys, 37(9): 4733-43, 2010*
Ir-192 VS-2000 Model in BrachyVision TPS
Monte Carlo dosimetry of a new $^{192}$Ir high dose rate brachytherapy source

A. Angelopoulos, A. Baras, and L. Sakellou
Nuclear and Particle Physics Section, Physics Department, University of Athens, Panepistimiopolis Zia, 157 71 Athens, Greece

P. Kazarinos and P. Sandinos
Department of Radiology, Medical School, University of Athens, Evangelism Hospital, 7r Vas. Sofias Avenue, 111 28 Athens, Greece and Medical Physics Department, Evgenio Hospital, Kifissias Avenue, 24 Epanokampos, Marousi, 151 22 Athens, Greece

Level I:
Radial dose function
$g(r)$ check
For BV 8.9 Acuros

Note 1: The published clinical TG43 data for VS2000 source assumes a 15cm long NiTi cable.

Note 2: VS2000 source is modeled with 1mm of NiTi cable in BV-Acuros

Med Phys, 37(9): 4733-43, 2010
F(r,theta) reference points: Acuros vs. published TG43

Acuros Anisotropy vs published TG43 (reference points)

BV-Acuros vs. MCNPX Monte Carlo

Med Phys, 37(9): 4733-43, 2010
Abs. Dose Diff: 1mm cable vs. 15cm cable

Acuros Radial Dose Function $g(r)$*

$g(r)$: larger differences near source.

*BrachyVision v8.8 with GBBS (Acuros 1.3.1)
g(r) resolved!  -defined catheter length matters!

<table>
<thead>
<tr>
<th>Regionaway (θ≥10deg)</th>
<th>BV-TG43 vs MCNPX(15cm cable)</th>
<th>BV-Acuros vs MCNPX(1mm cable)</th>
<th>MCNPX(1mm) vs MCNPX(15cm)</th>
<th>BV-Acuros vs BV-TG43</th>
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<td>0.3</td>
<td>0</td>
<td>0</td>
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<td>1σ</td>
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<td>0.4</td>
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<th>Regionnear (θ&lt;10deg)</th>
<th>BV-TG43 vs MCNPX(15cm cable)</th>
<th>BV-Acuros vs MCNPX(1mm cable)</th>
<th>MCNPX(1mm) vs MCNPX(15cm)</th>
<th>BV-Acuros vs BV-TG43</th>
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<td>1.0</td>
<td>5.6</td>
<td>6.6</td>
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<td>1σ</td>
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<tr>
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Level II- Commissioning of MBDC algorithms

- Comparisons of the 3D dose distributions calculated with the clinical MBDCA-based TPS
- Verified against virtual phantoms, applicator, and source loading mimicking clinical scenarios
**Seed/Applicator Model Accuracy Requirements**

- Patient CT grids (>1 mm voxel) are not adequate for accurate modeling on the spatial scale of brachytherapy sources and applicators.
- MBDCA vendors should use analytic modeling schemes or recursively specify meshes with 1–10 $\mu$m spatial resolution.
- Vendors to disclose their geometry, material assignments, and manufacturing tolerances to both end users and TPS vendors (if responsible for data entry and maintenance).

TG-186 Section IV-B

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**If TPS Applicator Library provided**

- Will ease the verification task.
- Vendor must provide visualization or reporting tools to end user to verify the correctness of each included applicator and source model against independent design specifications.
- In addition, TPS vendors must disclose sufficient information regarding the model or recursive mesh generation to allow verification of the spatial resolution requirement specified in recommendation (2) in TG-186 Section IV-B
Which Test Cases to Pick?

- It is not reasonable to validate MBDCA implementation for all possible combinations of source-applicator-geometry
- Pick scenarios relevant to your clinic
- Creation of an official Registry should help early adopters for efficient work
- Developers of new test cases are strongly encouraged to share their validation geometries through the Registry.
- AAPM Working Group with international membership is developing a few registry cases

TG-186 Section IV.B: Applicators

- “It is the responsibility of the end-user clinical physicist to confirm that MBDCA dose predictions are based upon sufficiently accurate and spatially resolved applicator and source models, including correct material assignments, to avoid clinically significant dose-delivery error prior to implementing the dose algorithm in the clinic.”
Example: Solid Applicator Models in BV

A large number of Varian’s applicators have been modeled and are supplied as part of the BrachyVision standard package.
Applicator Geometry & Composition Verification

BV TPS
Applicator
Library-
Solid Model
part #: AL07334001

In house MC model derived from physical verification and vendor CAD

Brachytherapy 10 (3): S36, 2011

Results – CT/MR ovoid geometry
Results - CT/MR ovoid dosimetry

part #: AL07334001
Impact of Heterogeneity-Based Dose Calculation Using a Deterministic Grid-Based Boltzmann Equation Solver for Intracavitary Brachytherapy

Justin K. Mikell, B.S., ** Ann H. Klopp, M.D., Ph.D., ** Graciela M.N. Gonzalez, M.P.H., ** Kelly D. Kisting, M.S., ** Michael J. Price, Ph.D., ** Paula A. Berner, B.S., ** Patricia J. Effel, M.D., ** and Firas Mourtada, Ph.D., **

Departments of **Radiation Physics, **Radiation Oncology, **Kratskiewicz, **Radiation Physics – Radiation Cone, and **Experimental Diagnostic Imaging, the University of Texas MD Anderson Cancer Center, Houston, Texas; University of Texas Graduate School of Biomedical Sciences at Houston, Houston, Texas; **Department of Physics and Astronomy, Louisiana State University and Agricultural and Mechanical College, Baton Rouge, Louisiana; and **Department of Radiation Oncology, Helen F. Graham Cancer Center, Newark, Delaware.

Summary

This study investigated the use of a grid-based Boltzmann solver (GBBS) for cervical cancer patients treated with embedded CT/MR applicators. The GBBS was found to have minimal impact on clinical dosimetric parameters for these patients. GBBS differences from standard TG-43 dose estimates were modest due to source, boundary, and applicator model differences. CT- and MR-based mapping of rectal and bladder contrast did not impact clinical dosimetry. Rectal dose parameters may be affected by incorrectly mapping packing material.

Purposes: To investigate the dosimetric impact of the heterogeneity dose calculation Ansara (Therapix Inc., Gil Harbor, WA), a grid-based Boltzmann equation solver (GBBS), for Brachytherapy in a cohort of cervical cancer patients.

Methods and Materials: The impact of heterogeneities was retrospectively assessed in treatment plans for 26 patients who had previously received 192Ir intracavitary brachytherapy for cervical cancer with computed tomography (CT) and magnetic resonance imaging (MRI) compatible applicators and an embedded CT/MR applicator. The GBBS models sources, patient boundaries, applicators, and tissue heterogeneities. Multiple GBBS calculations were performed with and without total pelvic applicators, with and without overlaying the patient volume to 1 cm^2 seed mesh, and with and without overlaying CT us in breast volumes were 225 g/cm^3. Impact of source and boundary modeling, applicator, tissue heterogeneities, and sensitivity of CT-based CT/mapping of contrast were derived from the multiple calculations. American Association of Physicists in Medicine Task Group 51 (TG-51) guidelines and the GBBS were compared for the following clinical dosimetric parameters: Mean point A and B. International Commission on Radiological Units and Measurements (ICRU) report 90. rectal and bladder points, relative and relative risk constant, and standard deviation.

Results: Points A and B, R50 and R100, ICRU, and ICRU risk constant were within 5% of TG-43 for all GBBS calculations. The source and boundary and applicator account for most of the differences between the GBBS and TG-43 guidelines. The D_{100%} between (in = 3) D_{100%} and GBBS (in = 1) and ICRU score (in = 6) had differences of <5% from TG-43 for the worst case intracavitary mapping of contrast to bone. Clinical dosimetric parameters were within 5% of TG-43 when rectal and bladder contrast were mapped to bone and radiopaque packing was not overlaid.

Conclusions: The GBBS has minimal impact on clinical parameters for this cohort of patients with unmodified applicators. The incorrect mapping of rectal and bladder contrast does not have a significant impact on clinical parameters. Rectal parameters may be sensitive to the mapping of radiopaque packing. © 2012 Elsevier Inc.
Spatial distributions of the 3 factors contributing to differences between GBBS and TG-43:

1. **source & boundary factor**
   - % difference
     - 10.0
     - 7.0
     - 4.0
     - 3.0
     - 2.0
     - -2.0
     - -3.0
     - -4.0
     - -7.0
     - -10.0

2. **applicator factor**

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. bone.
Top row: combination of all three factors: source/boundary + applicator + heterogeneity

Bottom row: Contribution of the heterogeneity only. From left to right, the GBBS with solid applicator with contrast overridden to muscle $D(Y,N,M,M)$, contrast not overridden $D(Y,N,N,N)$, or contrast overridden to bone $D(Y,N,B,B)$. 

ICRU Rectal Point Dose Impact of GBBS relative to TG-43
Example for Registry Case

BV v8.8
Shielded GYN Cylinder
(Part # GM11004380)/ 180° shield

General Workflow for a Registry Case

a. Download test case plan from online Registry
b. Import DICOM test case
c. Run TG-43 based tests
   • Removes errors not related to MBDCA!
d. Run MBDCA based tests “Clinical Site-specific”
e. Reference CT scanner calibration data
f. Select scoring medium
Virtual CT Object (IDL DICOM Creator) + Solid Applicator from TPS Library

Import Virtual Phantom into your TPS
TG43 Run to Check Case Setup

Radioactive source
- Total air kerma strength: 1773.44 cGy cm²
- Total treatment time: 2214.80 s
- Total Curie seconds: 1680.10
- Calibration date: 8/1/2000 12:00:00 AM
- Calibration activity mCi: 107.53 mCi
- Calibration activity Ci: 15.75 Ci
- Calibration strength: 40700.00 cGy cm²/h
- Treatment activity mCi: 759.58 mCi
- Treatment activity Ci: 0.79Ci
- Treatment strength: 288.60 cGy cm²/h
- Treatment date: 5/10/2010 12:00:00 AM
- Hairline: 73.83

Sources Positions

TG43 Run to Check Case Setup

Applicators
- Dwell times are displayed for a single fraction

<table>
<thead>
<tr>
<th>Applicator Id</th>
<th>Source Id</th>
<th>Source Model</th>
<th>Density</th>
<th>Treatment Strength</th>
<th>Treatment Activity mCi</th>
<th>Neighboring (cm)</th>
<th>Channel total dwell time</th>
</tr>
</thead>
<tbody>
<tr>
<td>probe</td>
<td>V5 l=192 (5mm)</td>
<td>288.60 cGy cm²/h</td>
<td>759.58 mCi</td>
<td>288.60 cGy cm²/h</td>
<td>759.58 mCi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Position (cm) | Dwell time (s) | Coordinates (cm,0,0) |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>150.00</td>
<td>459.40</td>
<td>(-0.05, 0.0, 1.00)</td>
</tr>
<tr>
<td>140.00</td>
<td>174.10</td>
<td>(-0.05, 0.0, 1.30)</td>
</tr>
<tr>
<td>130.00</td>
<td>239.80</td>
<td>(-0.05, 0.1, 1.30)</td>
</tr>
<tr>
<td>120.00</td>
<td>180.70</td>
<td>(-0.05, 0.2, 1.30)</td>
</tr>
<tr>
<td>110.00</td>
<td>188.00</td>
<td>(-0.05, 0.3, 1.30)</td>
</tr>
<tr>
<td>100.00</td>
<td>307.30</td>
<td>(-0.05, 0.3, 1.60)</td>
</tr>
<tr>
<td>90.00</td>
<td>185.40</td>
<td>(-0.05, 0.4, 1.60)</td>
</tr>
<tr>
<td>80.00</td>
<td>491.60</td>
<td>(-0.05, 0.4, 2.00)</td>
</tr>
</tbody>
</table>

Ref Data Set

Site TPS TG43 Results

Passed Setup Check: 100% agreement
Ready now to run the Acuros test!

- Copy as New Plan - MBDCA
- Reference CT Calibration
- Select dose scoring medium type
- Check plan input
- Run MBDCA
- Plan Eval Pass?
  - NO
    - TPS Manual
    - Other Commission activity per TG-63
  - YES
    - Generate Commission Report
- Check Material Assigned
- Match?
  - YES
  - FINISH
  - NO
Sagittal plane: points

<table>
<thead>
<tr>
<th>Point</th>
<th>Dose (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.25</td>
</tr>
<tr>
<td>P2</td>
<td>6.0</td>
</tr>
<tr>
<td>P1-sup</td>
<td>0.26</td>
</tr>
<tr>
<td>P2-sup</td>
<td>5.88</td>
</tr>
<tr>
<td>P1-inf</td>
<td>0.25</td>
</tr>
<tr>
<td>P2-inf</td>
<td>5.83</td>
</tr>
<tr>
<td>P3</td>
<td>1.77</td>
</tr>
</tbody>
</table>

✓ Acuros: Check Reference Points Doses

| Reference Points | Fractionation | 3D-coordinates | | |
|------------------|---------------|----------------|---------|
|                  | Id |   X     |   Y     |   Z     | Total Dose |
| P1               | P1 | -0.65 cm | 1.05 cm | 2.33 cm | 0.248 Gy   |
| P1               | P2 | -0.65 cm | -0.95 cm| 2.33 cm | 0.600 Gy   |
| P1               | P1-Sup | -0.65 cm | 1.05 cm | 1.00 cm | 0.263 Gy   |
| P1               | P2-Sup | -0.65 cm | -0.95 cm| 1.00 cm | 5.876 Gy   |
| P1               | P1-inf | -0.65 cm | 1.05 cm | 3.66 cm | 0.296 Gy   |
| P1               | P2-inf | -0.65 cm | -0.95 cm| 3.66 cm | 5.931 Gy   |
| P1               | P3   | -0.65 cm | 0.05 cm | -1.10 cm| 1.768 Gy   |

✓ Acuros: Check DVH

<table>
<thead>
<tr>
<th>Dosimetric Quality Parameters</th>
<th>Structure</th>
<th>Id</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectum</td>
<td>D0.1cc</td>
<td></td>
<td>D0.1cc: 0.61 Gy (10.12%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D1.0cc</td>
<td></td>
<td>D1.0cc: 0.51 Gy (8.54%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D2.0cc</td>
<td></td>
<td>D2.0cc: 0.46 Gy (7.69%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D3.0cc</td>
<td></td>
<td>D3.0cc: 0.37 Gy (6.23%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D10.0cc</td>
<td></td>
<td>D10.0cc: 0.29 Gy (4.68%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D50.0cc</td>
<td></td>
<td>D50.0cc: 0.00 Gy (0.00%)</td>
</tr>
<tr>
<td>Rectum</td>
<td>D90</td>
<td></td>
<td>D90: 0.23 Gy (3.86%)</td>
</tr>
</tbody>
</table>
Use BV Plan Evaluation Tools

Need more analysis tools—like gamma index analysis

Level II Pass/Fail Criteria:

- What dose accuracy tolerance is required?
- Gamma-index as a first step, similar to IMRT.

  Stock et al. "Interpretation and evaluation of the $\gamma$ index and the $\gamma$ index angle for the verification of IMRT hybrid plans," PMB 50, 2005

- Site-specific tolerance needed
- Further research required, but use your common sense to clinical is important
Registry for Level II

AAPM/ESTRO/ABG working group to tackle this issue

Luc Beaulieu (chair), Frank-André Siebert (vice-chair)
Facundo Ballaster, Åsa Carlsson-Tedgren, Annette Haworth, Goeff Ibbott, Firas Mourtada, Panagiotis Papagiannis, Mark J Rivard, Ron Sloboda, Rowan Thomson and Frank Verhaegen.

Strategy: Registry of validated cases with reference doses calculations.

We will try to involved the vendor as much as possible to make the cases compatible with all TPS.

Summary & Recommendations

• Commission your brachy TPS for clinical tasks related to your clinic

• Direct comparison to reference plan having heterogeneous conditions is mandatory

• Specific virtual phantoms mimicking the clinical scenarios should be independently verified against benchmarks
Acknowledgements

TG-186
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Rowan Thomson, Carleton University
Frank Verhaegen, Maastro Clinic
Todd Wareing, Transpire inc
Jeff Williamson, VCU

WG-MBDCA
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Ron Sloboda, Cross Cancer Institute
Rowan Thomson, Carleton University
Frank Verhaegen, Maastro Clinic