Advances in Brachytherapy Dose Calculations, Part I

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Head of Medical Physics Research, CHU de Québec
Disclosures

• I hold a research contract on advanced dose calculation from Elekta/Nucletron

• I am the Chair 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. Explains in practical terms the recommendations of TG186
Acknowledgements

TG-186
Luc Beaulieu, CHU de Quebec (Chair)
Äsa Carlsson-Tedgren, Li University
Jean-François Carrier, CHU de Montreal
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Firas Mourtada, Christiana Care
Mark Rivard, Tufts University
Rowan Thomson, Carleton University
Frank Verhaegen, Maastro Clinic
Todd Wareing, Transpire inc
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WG-MBDCA
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Frank Verhaegen, Maastro Clinic
Contents

• Introduction: moving beyond TG43

• Advances in brachytherapy dose calculations

• Challenges and research topics

• Recommendations from AAPM/ESTRO/ABG Task Group 186
• Introduction: moving beyond TG43
• Advances in brachytherapy dose calculations
• Challenges and research topics
• Recommendations from AAPM/ESTRO/ABG Task Group 186
Brachytherapy is state-of-the-art

- Exquisite dose distribution and intensity modulation
- Dose deposition better than proton
- Real-time image guidance and dose guidance
- Addition of robotic brachytherapy
- Possibility of shielding, directional source, multiple isotope/energie tx
Brachytherapy versus Photon and Proton External Beam Therapy
...but dose calculation is not
TG43 has served us well!

- Is still!
- Worldwide uniformity
- Well-define process for source parameters
- Source specific
- Fast
- Dose optimization (IP)
G43-based TPS can fail to accurately calculate dose

- air ≠ water?
- tissue ≠ water?
- contrast?
- source superposition?
- source shielding?
- radiation scatter?

From Rivard
One size does not fit all!
Brachytherapy is a mature treatment modality that has benefited from technological advances. Treatment planning has advanced from simple lookup tables to complex, computer-based dose-calculating algorithms. The current approach is based on the AAPM TG-43 formalism with recent advances in acquiring single-source dose distributions. However, this formalism has clinically relevant limitations for calculating patient dose. Dose-calculation algorithms are being developed based on Monte Carlo methods, collapsed cone, and the linear Boltzmann transport equation. In addition to improved dose-calculation tools, planning systems and brachytherapy treatment planning will account for material heterogeneities, scatter conditions, radiobiology, and image guidance. The AAPM, ESTRO, and other professional societies are coordinating clinical integration of these advancements. This Vision 20/20 article provides insight on these endeavors.

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>
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<td>XXX</td>
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<td>low</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
<td>XXX</td>
</tr>
</tbody>
</table>

Importance of the Physics: Water vs Tissues

< 100 keV large differences
Impact of tissue composition: 192Ir

Low energy = large effect

Afsharpour et al., PMB 2010
Importance of the Physics: Attenuation by Metals

From NIST website
Fig. 1. Flexible, eight-channel intracavitary applicator for use in high-dose-rate $^{192}$Ir endorectal brachytherapy (Nucletron, Veenendaal, The Netherlands).

Fig. 2. Axial and coronal views of Monte Carlo (solid lines) and Task Group 43 (dashed lines) isodose distributions for high-dose-rate $^{192}$Ir endorectal brachytherapy patients treated (a,b) with tungsten shielding, (c,d) with lead shielding, and (e,f) without shielding. The clinical target volume is outlined in pink, and the white structure around applicator is the endocavitary balloon injected with contrast solution.
Eye plaques

Scatter conditions
...Contrast and Air
...Contrast and Air

• Effect of contracts agent – Kassas et al, Med Phys 31
  ✓ -1% to -6% effect relative to TG-43

• Effect of air cavity – Richardson et al, Med Phys 37
  ✓ 0% to +9% effect relative to TG-43
I-125+prostate: JF Carrier et al., IJROBP 2007

\[ \approx 4\% \downarrow \]

\[ \approx 3\% \downarrow \]
How Important in the clinic?

<table>
<thead>
<tr>
<th>Site / Application</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shielded Applicators</td>
<td>Huge</td>
</tr>
<tr>
<td>Eye plaque</td>
<td>-10 to -30% (TG129)</td>
</tr>
<tr>
<td>Breast Brachy</td>
<td>-5% to -40%</td>
</tr>
<tr>
<td>Prostate Brachy</td>
<td>-2 to -15% on D90</td>
</tr>
<tr>
<td>GYN</td>
<td>Depends on applicators</td>
</tr>
</tbody>
</table>
Accurate dose calculation should be a priority

- Effect can be large (> 10%)

- The dose-outcomes, tolerance doses, prescription doses will probably need to be revisited
  - e.g. $^{192}\text{Ir}$ breast skin tolerance dose

- Possibility of better tx approaches
## Rule of tumb

<table>
<thead>
<tr>
<th>Energy Range</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{192}\text{Ir}$</td>
<td>Scatter condition</td>
</tr>
<tr>
<td></td>
<td>Shielding (applicator related)</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>
Contents

• Introduction: moving beyond TG43

• Advances in brachytherapy dose calculations

• Challenges and research topics

• Recommendations from AAPM/ESTRO/ABG Task Group 186
### Alternatives to TG43

**Table I.** Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were usable 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>LAQUE SIMULATOR</td>
<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>
</tr>
<tr>
<td>Collapsed cone</td>
<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>
</tr>
<tr>
<td>RACHYDOSE</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>
<tr>
<td>ICPI</td>
<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>
<td>2005</td>
</tr>
<tr>
<td>MCPI</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>
</tr>
<tr>
<td>DEANT4/DICOM-RT</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>
</tr>
<tr>
<td>Scatter correction</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>
</tr>
<tr>
<td>Hybrid TG-43:MC</td>
<td>Transpire/Varian&lt;sup&gt;i&lt;/sup&gt;</td>
<td>$^{192}$Ir photons</td>
<td>Y</td>
<td>Y</td>
<td>2009</td>
</tr>
</tbody>
</table>
Brachytherapy Dose Calculation Methods

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

TG43  PSS  CCC  GBBS  MC  Physics Content

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

Current STD:
Full scatter water medium

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

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

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

Only commercial MDBCA. Solves numerically transport equations. Full heterogeneities.
BT Dose Calc.

TG43  PSS  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

Outline of the brachy-CC MBDCA

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

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

Brachy-CC MBDCA

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
Implementation in OncentraBrachy

CC figures from Bob van Veelen, Nucletron BV
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>
<thead>
<tr>
<th>Technique</th>
<th>Speed-up</th>
</tr>
</thead>
<tbody>
<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>

Monte Carlo Dose Calculations: Brachy

- Can be relatively fast
  - About 25 sec for a seed implant dosimetry (BrachyDose)
  - < 1 sec per dwell-position (MC on GPU)

- No commercial packages for brachytherapy

- Like CC and Acuros®, too slow to be coupled to IP for dose optimization
Grid-Based Boltzmann Solver (GBBS)

- Deterministic approach of solving the linear Boltzmann transport equation

\[ \hat{\Omega} \cdot \nabla \psi^{\gamma} + \sigma_t^{\gamma} \psi^{\gamma} = Q^{\gamma(\text{ext})} + Q^{\gamma(\text{scat})} \]

\[ \hat{\Omega} \cdot \nabla \psi^{e} + \sigma_t^{e} \psi^{e} - \frac{\partial}{\partial E} S_R \psi^{e} = Q^{e(\text{ext})} + Q^{\text{scat}} \]
Grid-Based Boltzmann Solver (GBBS)

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

- Position: \( \vec{r} = (x, y, z) \)  
  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)
    - \( D_{prim} = K_{coll} \)
    - First scatter from primary: \( \text{Scerma} = D_{prim} \cdot \left( \frac{\mu - \mu_{en}}{u_{en}} \right) \)
    - Share this step with CCC

- 3D scatter integration through GBBS

- Source modeling done in Atilla® (Transpire Inc)
Speed: 40 sec to 12 min depending on complexity


More references on the algorithm, see e.g.: K. A. Gifford *et. al.* Med. Phys. 35, 2279-2285 (2008).
Contents

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## Factor-based vs Model-based

<table>
<thead>
<tr>
<th>INPUT</th>
<th>CALCULATION</th>
<th>OUTPUT</th>
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<tbody>
<tr>
<td><strong>TG43</strong></td>
<td>Source characterization</td>
<td>Superposition of data from source characterization</td>
</tr>
<tr>
<td>Source characterization</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Åsa Carlsson-Tedgren

<table>
<thead>
<tr>
<th>INPUT</th>
<th>CALCULATION</th>
<th>OUTPUT</th>
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</thead>
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<tr>
<td><strong>MBDC</strong></td>
<td>Source characterization</td>
<td>Model-Based Dose Calculation Algorithms</td>
</tr>
<tr>
<td>Source characterization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tissue/applicator information</td>
<td></td>
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</tbody>
</table>
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

$x$: 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) $D_{m,m}$

Medium

Scoring volume

(b) $D_{w,m}$

Medium

Water

Scoring volume

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
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 \(\Rightarrow\) 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!
Contents

• Introduction: moving beyond TG43
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Status of TG-186

- Report approved by
  - AAPM (BTSC, TPC)
  - ESTRO (BRAPHYQS, EIR)
  - ABS (Physics Committee)
  - ABG

- Report published in Medical Physics
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

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The charge of Task Group 186 (TG-186) is to provide guidance for early adopters of model-based dose calculation algorithms (MBDCAs) for brachytherapy (BT) dose calculations to ensure practice uniformity. Contrary to external beam radiotherapy, heterogeneity correction algorithms have only recently been made available to the BT community. Yet, BT dose calculation accuracy highly depends on scatter contributions and photoelectric effect cross-sections relative to water. In specific situations, differences between the current water-based BT dose calculation formalism (TG-43) and MBDCAs can lead to differences in calculated doses exceeding a factor of 10. MBDCAs raise three major issues that are not addressed in current guidance documents: (1) MBDCA calculated doses are sensitive to the dose specification medium, resulting in energy-dependent differences between dose calculated to water in a homogeneous water geometry (TG-43), dose calculated to the local medium in the heterogeneous medium, and the intermediate scenario of dose calculated to a small volume of water in the heterogeneous medium. (2) MBDCA doses are sensitive to voxel-by-voxel interaction cross sections. Neither conventional single-energy CT nor ICRU/ICRP tissue composition compilations provide useful guidance for the task of assigning interaction cross sections to each voxel. (3) Since each patient-source-applicator combination is unique, having reference data for each possible combination to benchmark MBDCAs is impractical. Hence, a new commissioning process is required. TG-186 addresses these issues through the literature review
Goals of the Recommendations

• Maintain inter-institution consistency

• Preserve high QC/QA standards

• Provide Guidance to:
  • Define for each voxel: material and density
  • Define guidelines for the dose scoring medium

• Will have to address retrospectively and prospectively dose-outcome relationships
Basic recommendations

• 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
Which dose to report?

• \( D_{m,m} \) is inherently computed by Model-based algorithms
• \( D_{m,m} \) must be reported along with TG43
• \( D_{w,m} \) can also be reported but method must be specified:
  • e.g. large cavity theory, small cavity theory
  • Could be energy and target size dependent (voxel, cells, …)
Recommendation - segmentation

Extract electron density from CT calibration (see TG53, TG66 ...)

– Use the density from CT for each voxel

– Use recommended tissue compositions
  • Organ-based (contoured) assignments
    – Prostate from Woodard et al, BJR 59 (1986) 1209-18
    – All others from ICRU-46 composition
  • From CT calibration: breast, adipose, muscle and bone
Recommendation - segmentation

If artifacts (e.g. from metals)

- Override the density using the recommended default organ/tissue density
- Assign tissue composition based on organ contours

<table>
<thead>
<tr>
<th>Tissue</th>
<th>% mass</th>
<th>Z &gt; 8</th>
<th>Mass density g cm⁻³</th>
</tr>
</thead>
<tbody>
<tr>
<td>bony tissue (Ref. 110)</td>
<td></td>
<td>Na(0.2), P(0.1), S(0.2), K(0.2)</td>
<td>1.04</td>
</tr>
<tr>
<td>fat adipose (Ref. 110)</td>
<td></td>
<td>Na(0.1), S(0.1), Cl(0.1)</td>
<td>0.95</td>
</tr>
<tr>
<td>fat gland (Ref. 110)</td>
<td></td>
<td>Na(0.1), P(0.1), S(0.2), Cl(0.1)</td>
<td>1.02</td>
</tr>
<tr>
<td>fat male soft tissue (Ref. 109)</td>
<td></td>
<td>Na(0.1), P(0.2), S(0.3), Cl(0.2), K(0.2)</td>
<td>1.03</td>
</tr>
<tr>
<td>fat female soft tissue (Ref. 109)</td>
<td></td>
<td>Na(0.1), P(0.2), S(0.2), Cl(0.1), K(0.2)</td>
<td>1.02</td>
</tr>
<tr>
<td>fat skin (Ref. 109)</td>
<td></td>
<td>Na(0.2), P(0.1), S(0.2), Cl(0.3), K(0.1)</td>
<td>1.09</td>
</tr>
<tr>
<td>cortical bone (Ref. 109)</td>
<td></td>
<td>Na (0.1), Mg (0.2), P (10.3), S (0.3), Ca(22.5)</td>
<td>1.92</td>
</tr>
<tr>
<td>eye lens (Ref. 109)</td>
<td></td>
<td>Na(0.1), P(0.1), S(0.3), Cl(0.1)</td>
<td>1.07</td>
</tr>
<tr>
<td>lung (inflated) (Ref. 109)</td>
<td></td>
<td>Na(0.2), P(0.2), S(0.3), Cl(0.3), K(0.2)</td>
<td>0.26</td>
</tr>
<tr>
<td>liver (Ref. 109)</td>
<td></td>
<td>Na(0.2), P(0.3), S(0.3), Cl(0.2), K(0.3)</td>
<td>1.06</td>
</tr>
<tr>
<td>heart (Ref. 109)</td>
<td></td>
<td>Na(0.1), P(0.2), S(0.2), Cl(0.2), K(0.3)</td>
<td>1.05</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td>Na(0.1), P(0.2), S(0.2), Cl(0.2), K(0.3)</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Recommendation - segmentation

If no CT (US and MRI)

- Use contoured organs with recommended tissue compositions
  - For $^{192}$Ir, water is a good approximation for soft tissues only.
  - Air, lung, bone, ... should be assigned correctly

- Use accurate source and applicators geometry and composition
Recommendation - Commissioning

- Two parts process

- Next presentation by Dr. Firas Mourtada
TG-186 Recommendations

• The full TG-186 report has a detailed rational supporting the various recommendations

• Following the recommendations should ensure uniformity of implementation across centers

• NOTE: there is one MBDCA commercial system and it is for $^{192}$Ir only at this time.
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
Merci!

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