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Advances in Brachytherapy Dose Calculations, Part I

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UNIVERSITÉ LAVAL

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
Steve Davis, McGill University
Firas Mourtada, Christiana Care
Mark Rivard, Tufts University
Rowan Thomson, Carleton University
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Todd Wareing, Transpire inc
Jeff Williamson, VCU

WG-MBDCA

Luc Beaulieu, CHU de Quebec (Chair)
Frank-André Siebert, UKSH (Vice-chair)
Facundo Ballaster, Valancia
Äsa Carlsson-Tedgren, Li University
Annette Haworth, Peter MacCallum CC
Goeffrey Ibbott, MD Anderson
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Panagiotis Papagiannis, Athens
Mark Rivard, Tufts University
Ron Sloboda, Cross Cancer Institute
Rowan Thomson, Carleton University
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

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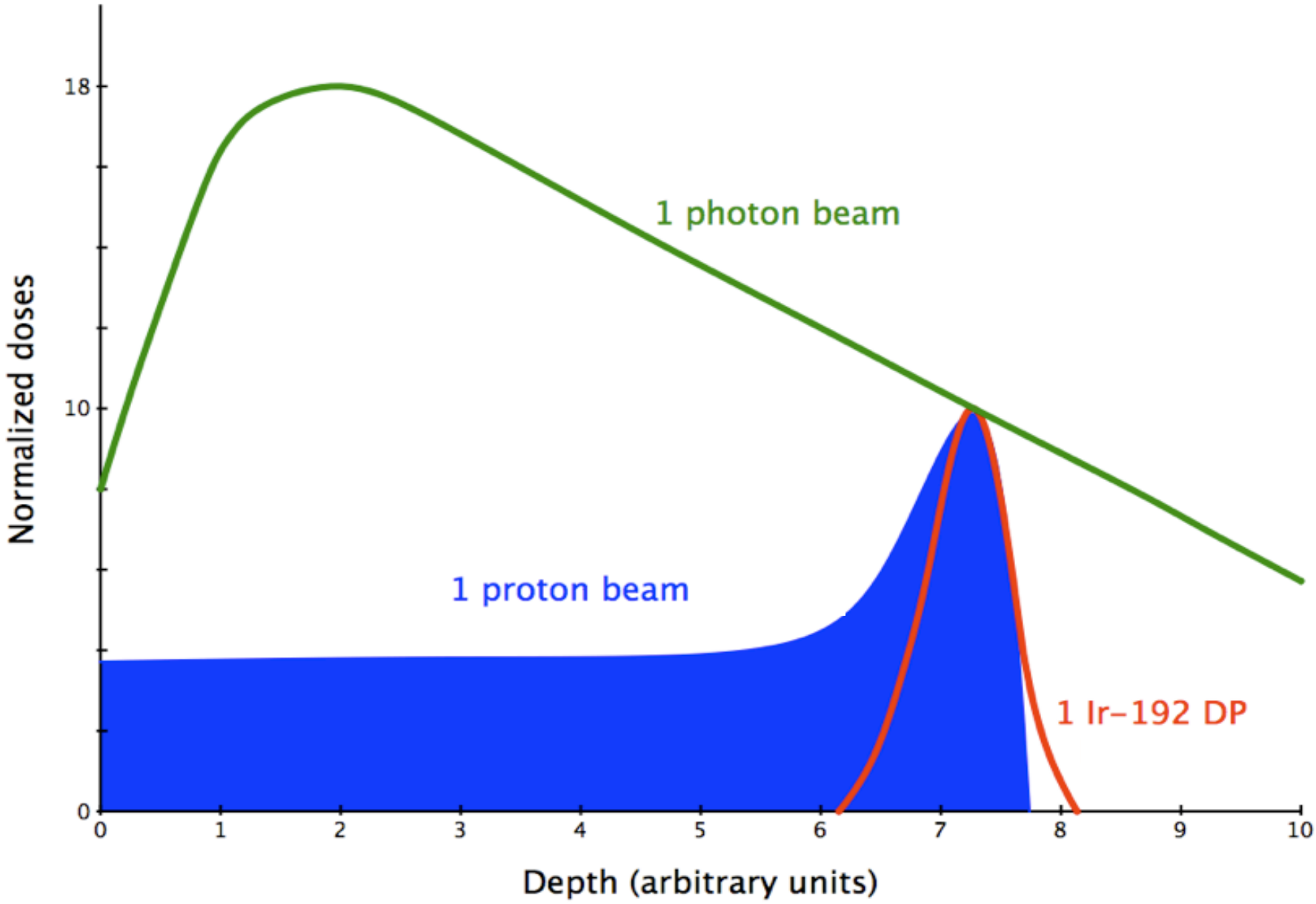
Brachytherapy is state-of-the-art

- 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

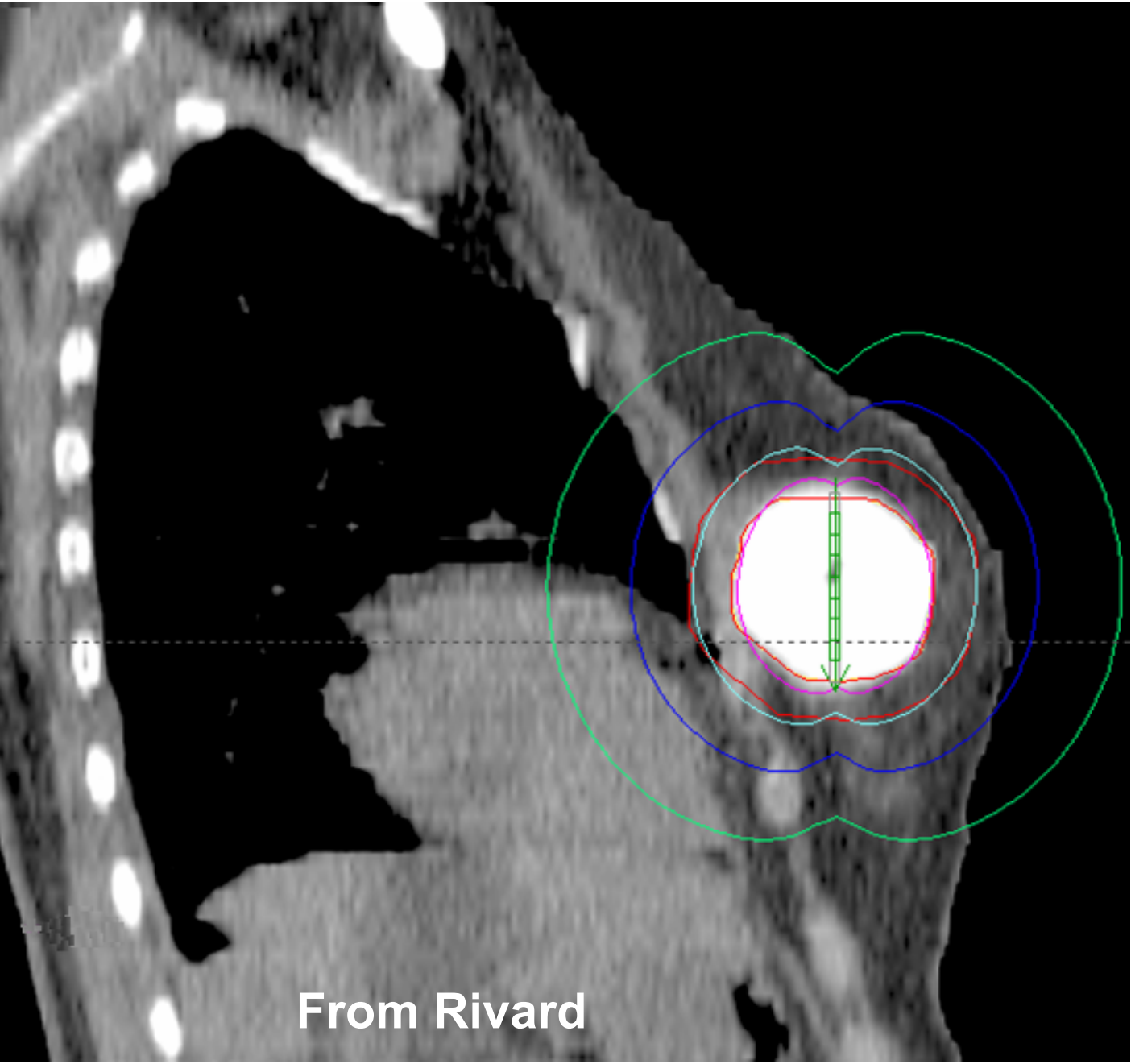


…but dose calculation is not

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?

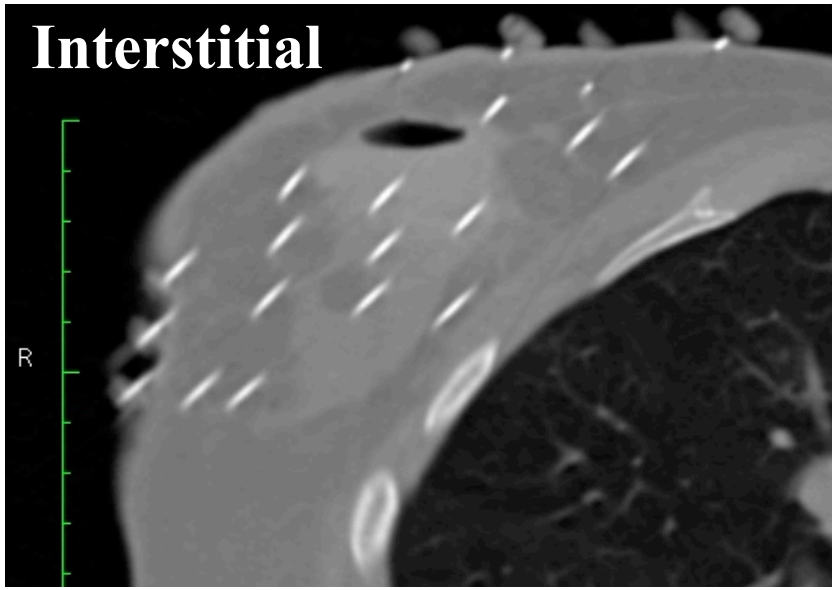
contrast?

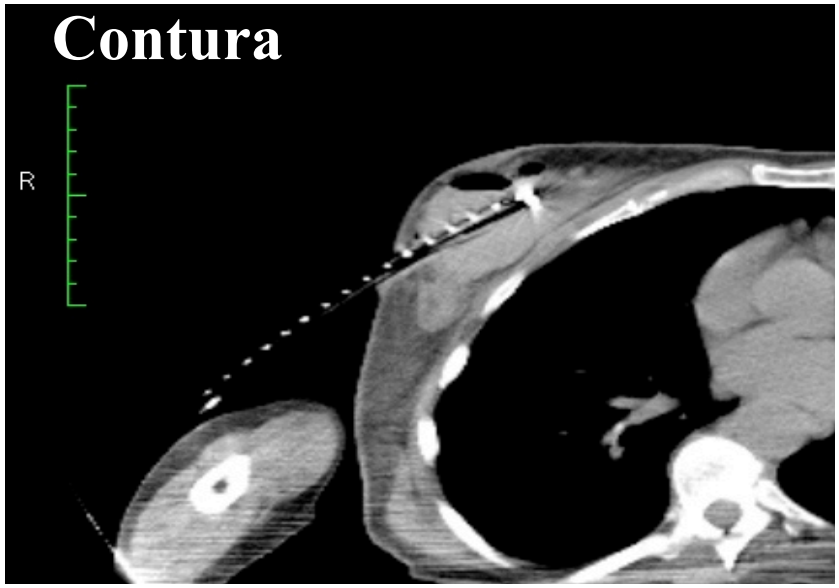
source superposition

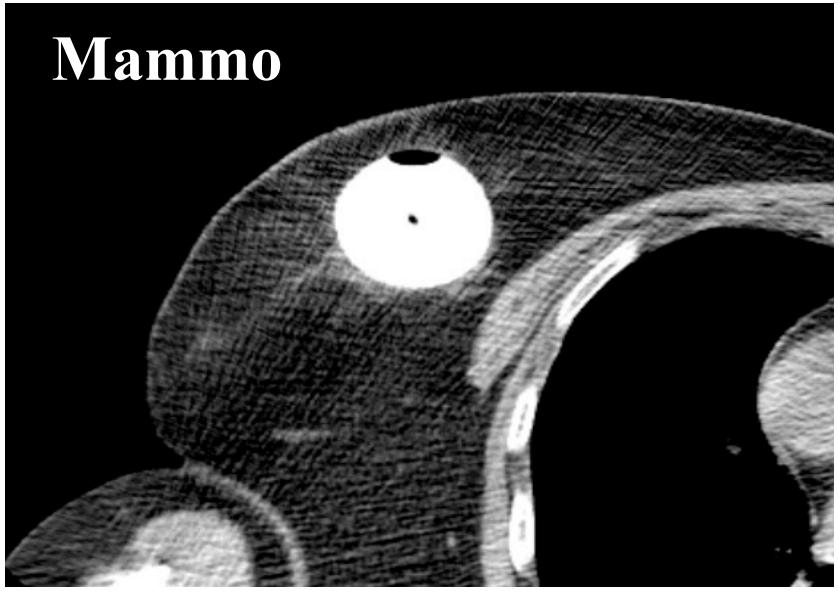
source shielding?

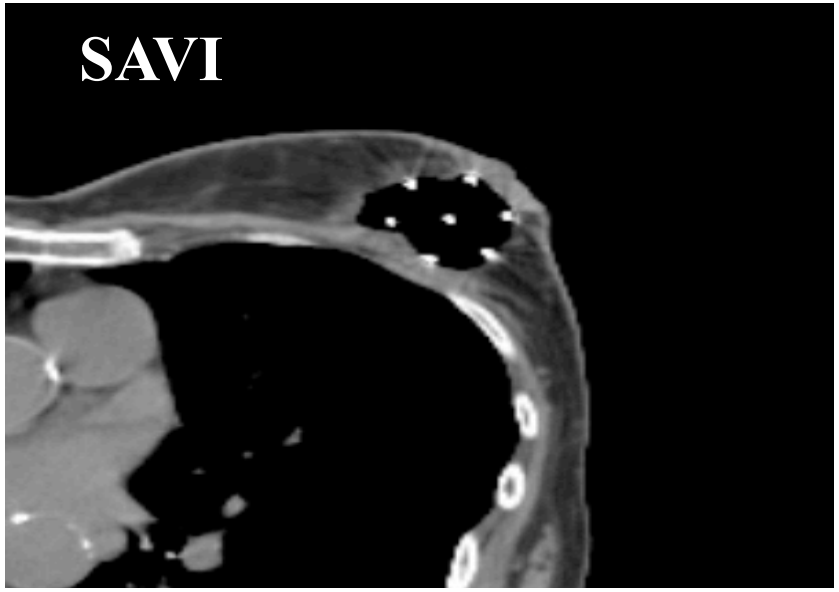
radiation scatter?

One size does not fit all!









Vision 20/20 Paper

Medical Physics

The evolution of brachytherapy treatment planning

Mark Rivard,[1] Jack L. M. Venselaar,[2] and Luc Beaulieu[3]
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[2]*Department of Medical Physics, Instituut Verbeeten, P.O. Box 90120, 5000 LA Tilburg, The Netherlands*
[3]*Département de Radio-Oncologie et Centre de Recherche en Cancérologie de l'Université Laval, Quebec*

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 calculation algorithms. The current approach is based on the AAPM TG-43 formalism with recen 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 treatmen 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.

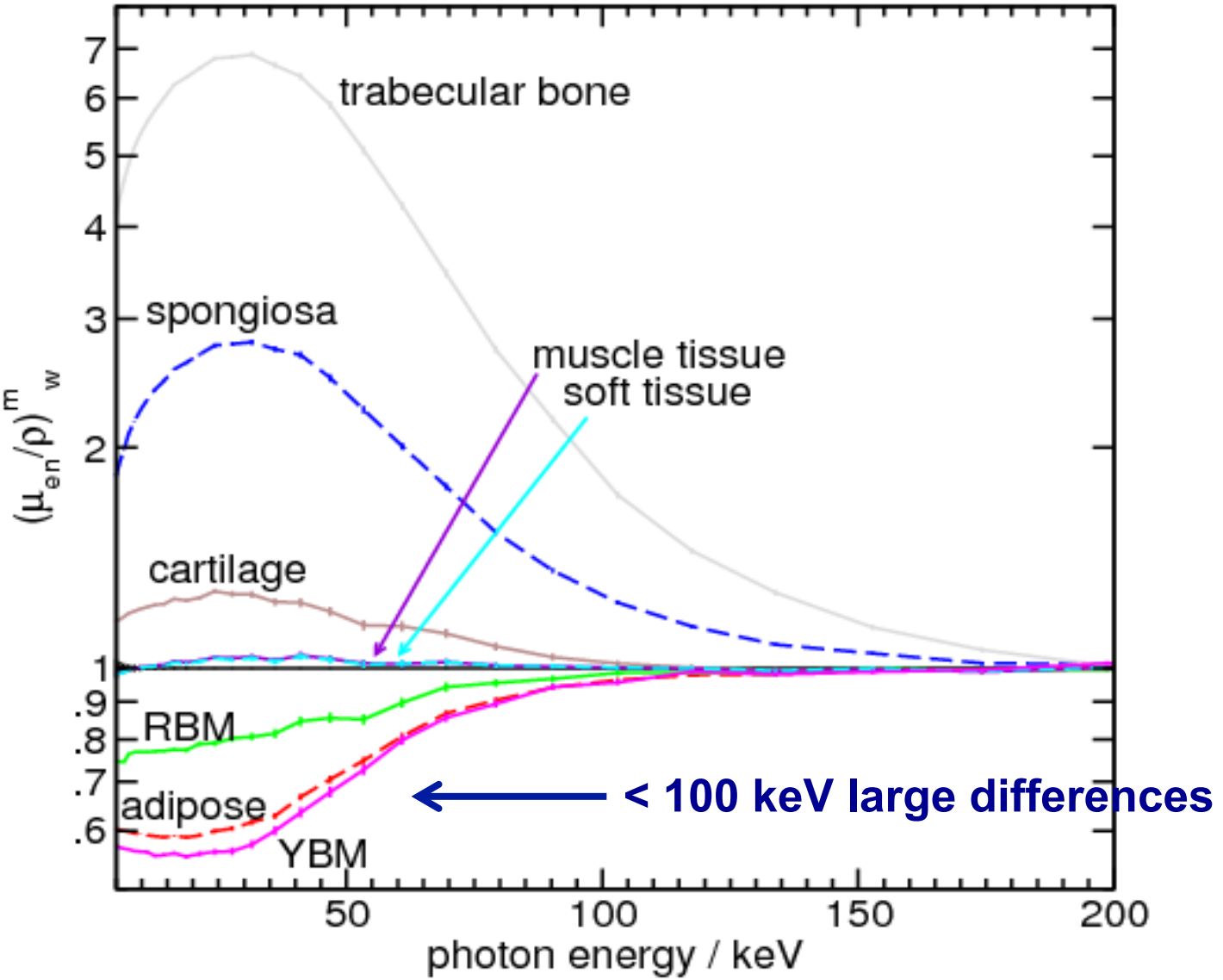
Med. Phys. 36, 2136-2153 (2009)

Sensitivity of Anatomic Sites to Dosimetric Limitations of Current Planning Systems

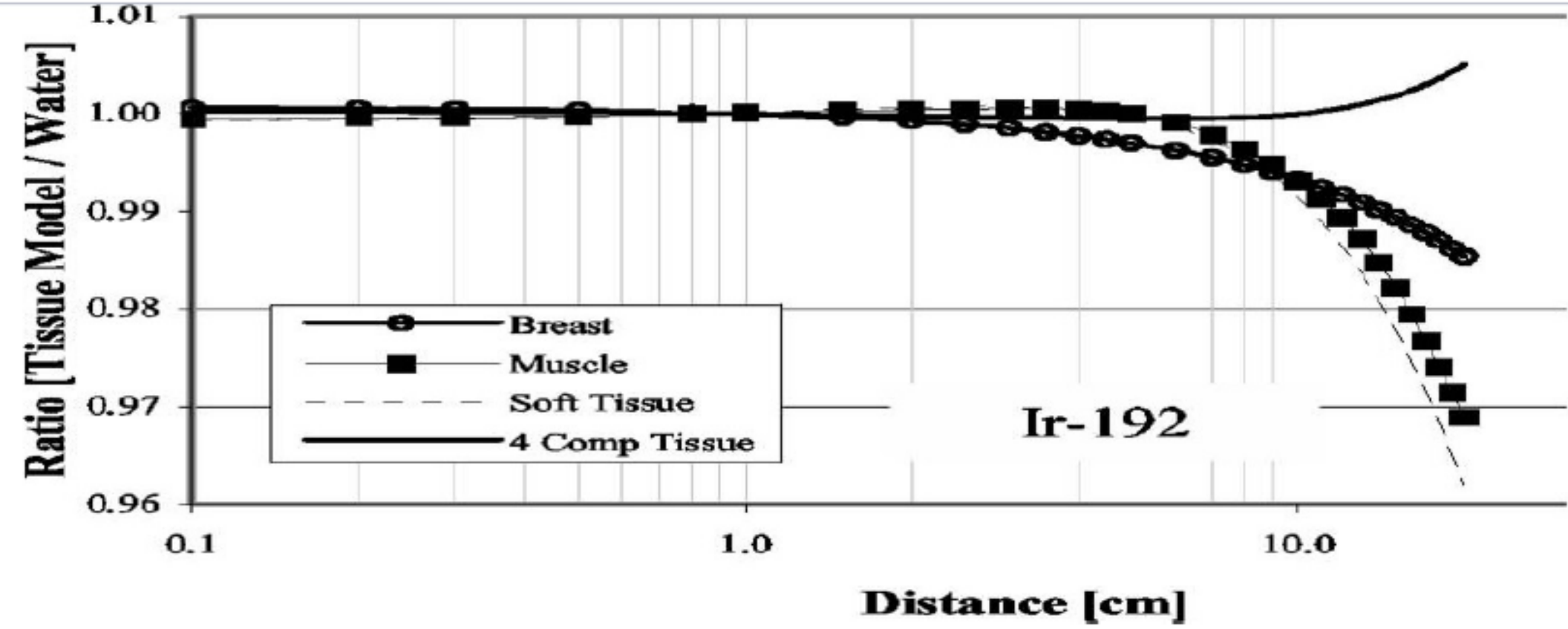
anatomic site	photon energy	absorbed dose	attenuation	shielding	scattering	beta/kerma dose
prostate	high					
	low	XXX	XXX	XXX		
breast	high				XXX	
	low	XXX	XXX	XXX		
GYN	high			XXX		
	low	XXX	XXX			
skin	high			XXX	XXX	
	low	XXX		XXX	XXX	
lung	high				XXX	XXX
	low	XXX	XXX		XXX	
penis	high				XXX	
	low	XXX			XXX	
eye	high			XXX	XXX	XXX
	low	XXX	XXX	XXX	XXX	

Rivard, Venselaar, Beaulieu, *Med Phys* 36, 2136-2153 (2009)

Importance of the Physics: Water vs Tissues

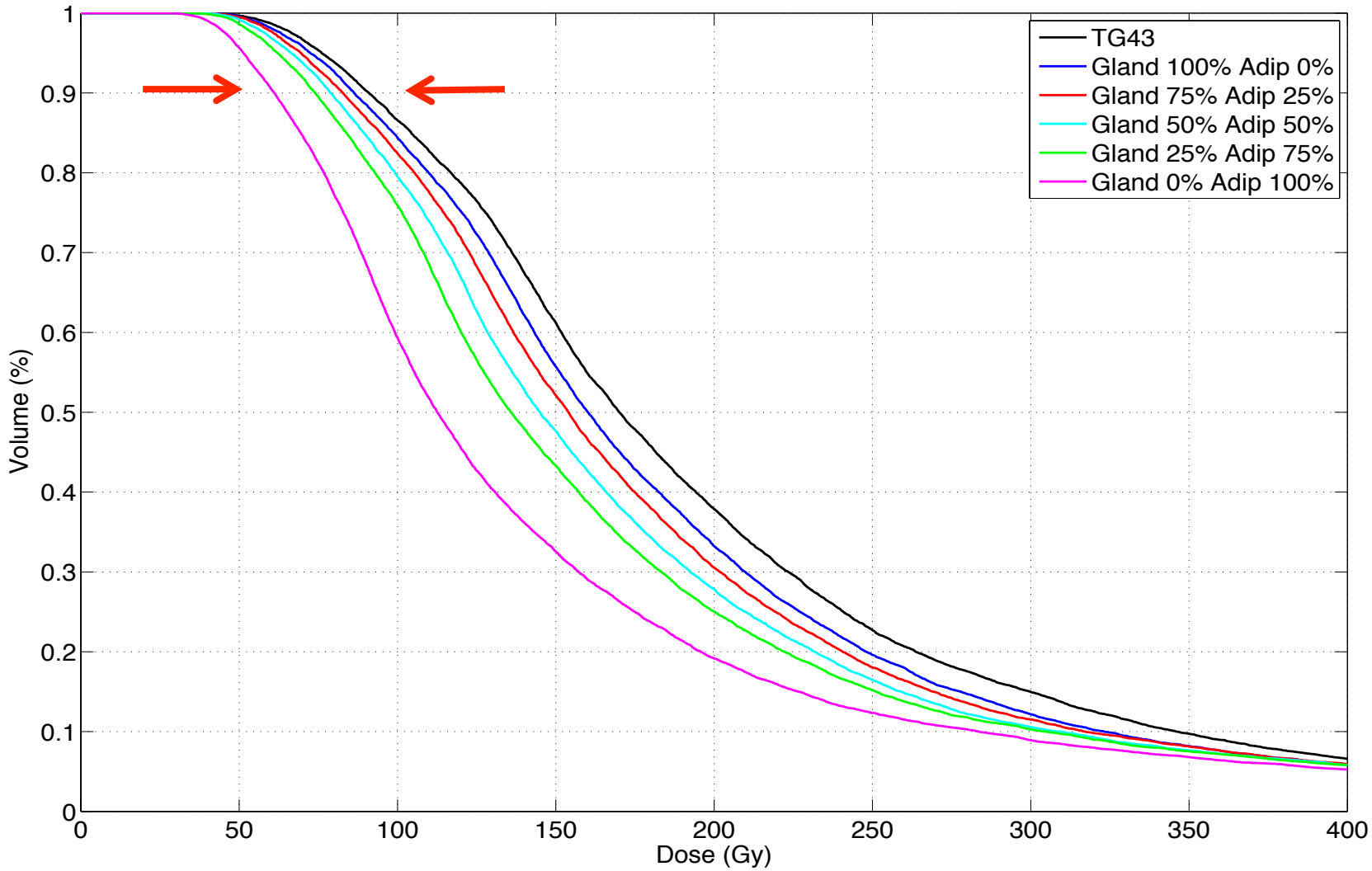


Impact of tissue composition: 192Ir



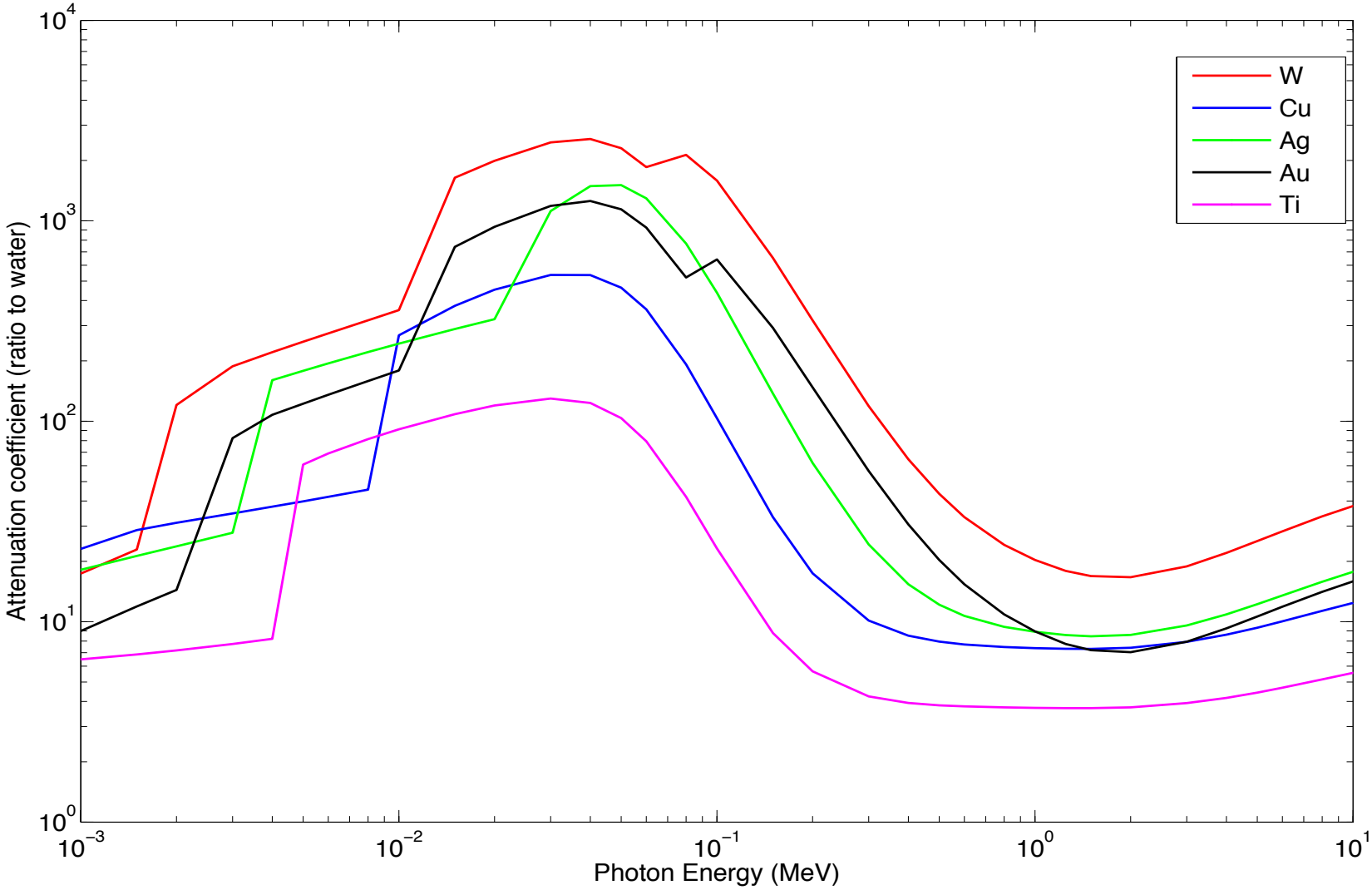
lhus C S, Rivard M J, « Approaches to calculating AAPM TG-43 brachytherapy dosimetry parameters for Cs-137, 2, Pd-103, and Yb-169 sources », Med. Phys., 33(6), 2006

Low energy = large effect



Afsharpour et al., PMB 2010

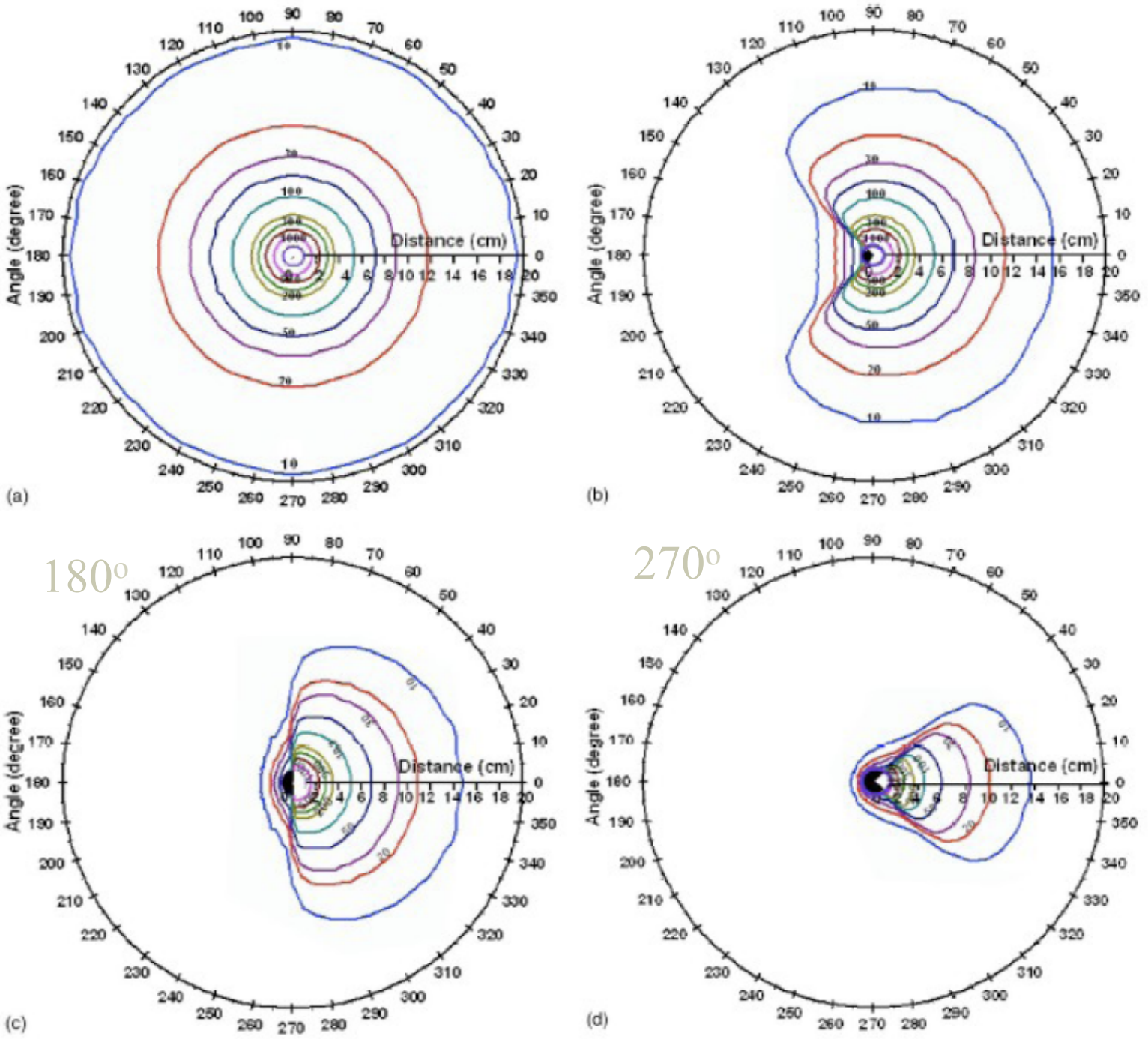
Importance of the Physics: Attenuation by Metal



From NIST website

TG43

90°



180°

270°

6 : Sureka C S, Aruna P, Ganesan S, « Computation of relative dose distribution and effective transmission around a shielded vaginal cylinder with Ir-192 HDR source using MCNP4B », Med. Phys., 44(6), 2006

Poon et al., IJROBP (2008)

ig. 1. Flexible, eight-channel intracavitary applicator for use in igh-dose-rate ^{192}Ir endorectal brachytherapy (Nucletron, Veenen-aal, The Netherlands).

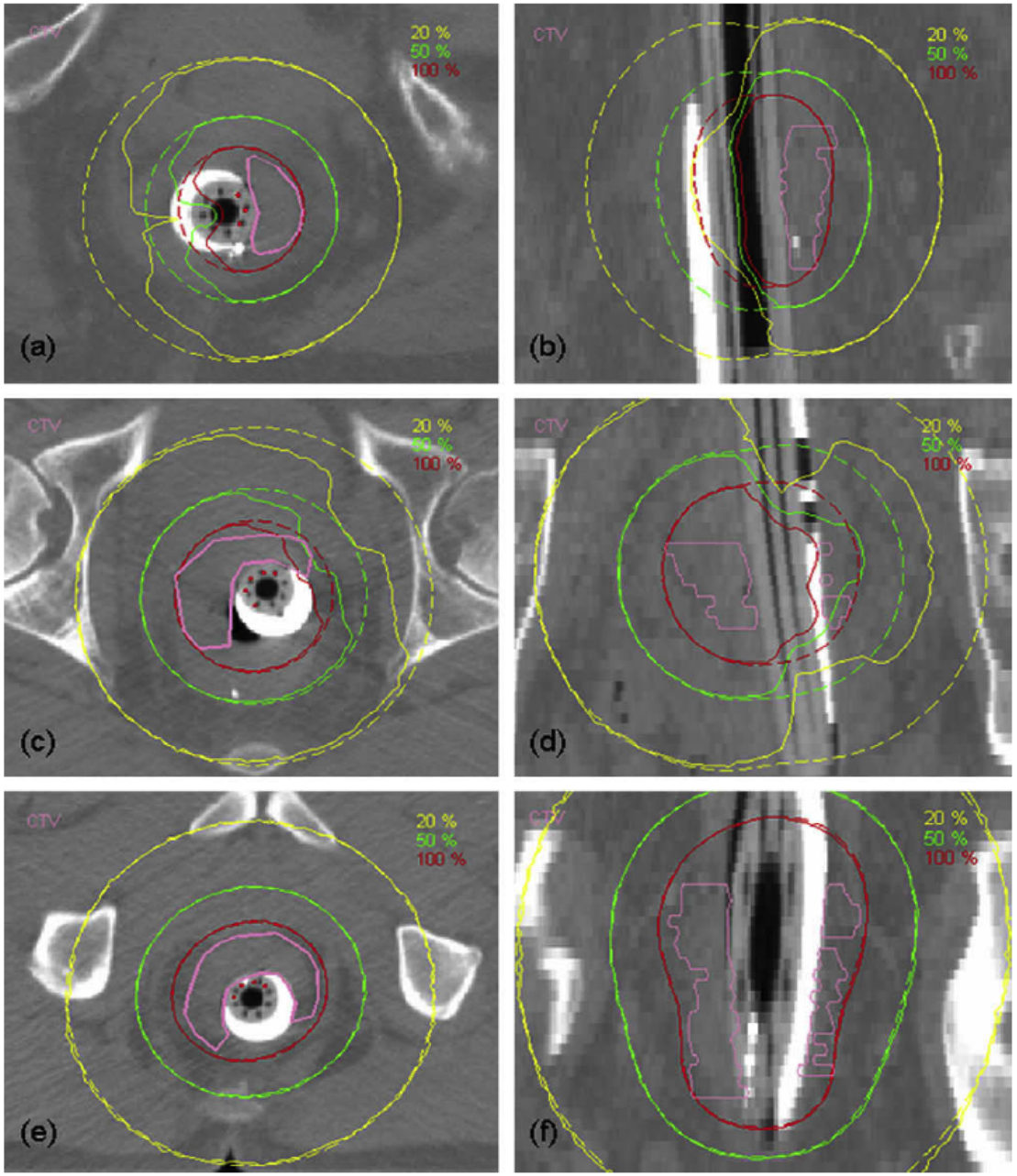
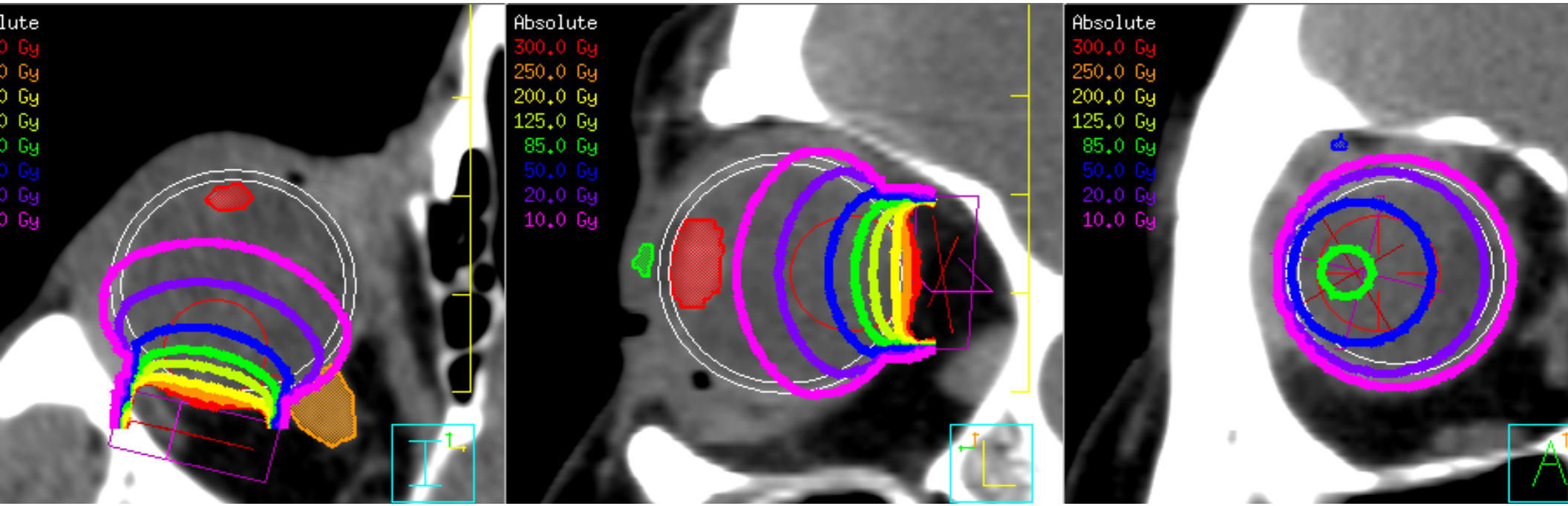


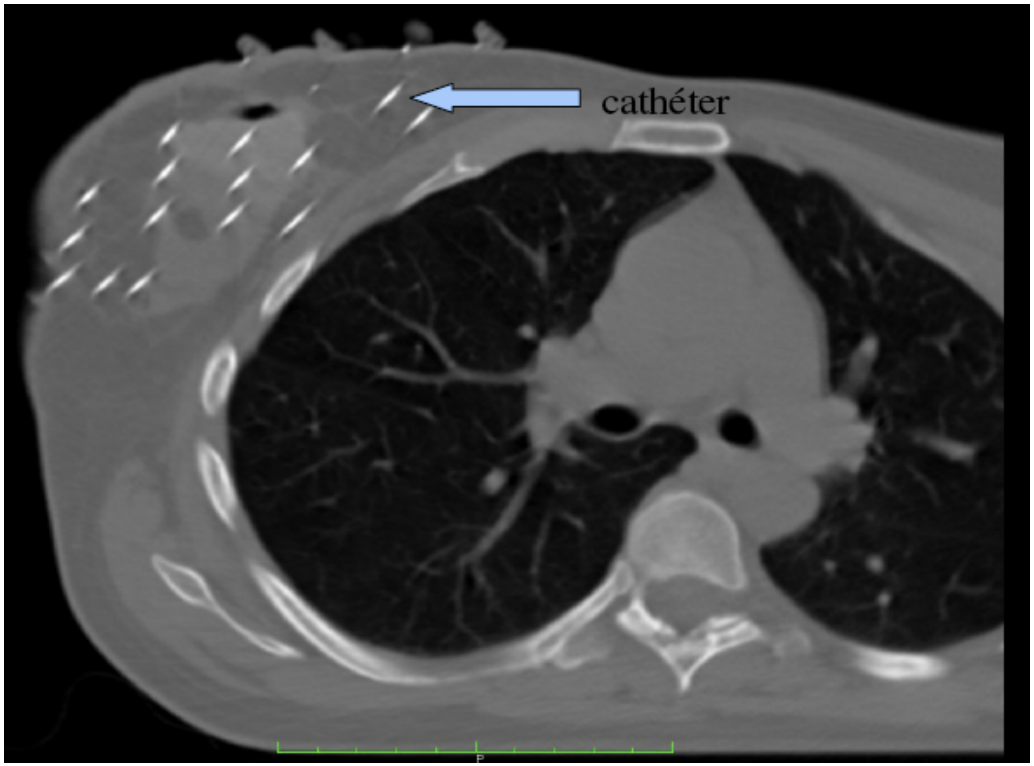
Fig. 2. Axial and coronal views of Monte Carlo (solid lines) and Task Group 43 (dashed lines) isodose distributions for high-dose-rate ^{192}Ir endorectal brachytherapy patients treated (a,b) with tungsten shielding, (c,d) with lead shielding, and (e,f) without shielding. The clinical target volume is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

Eye plaques

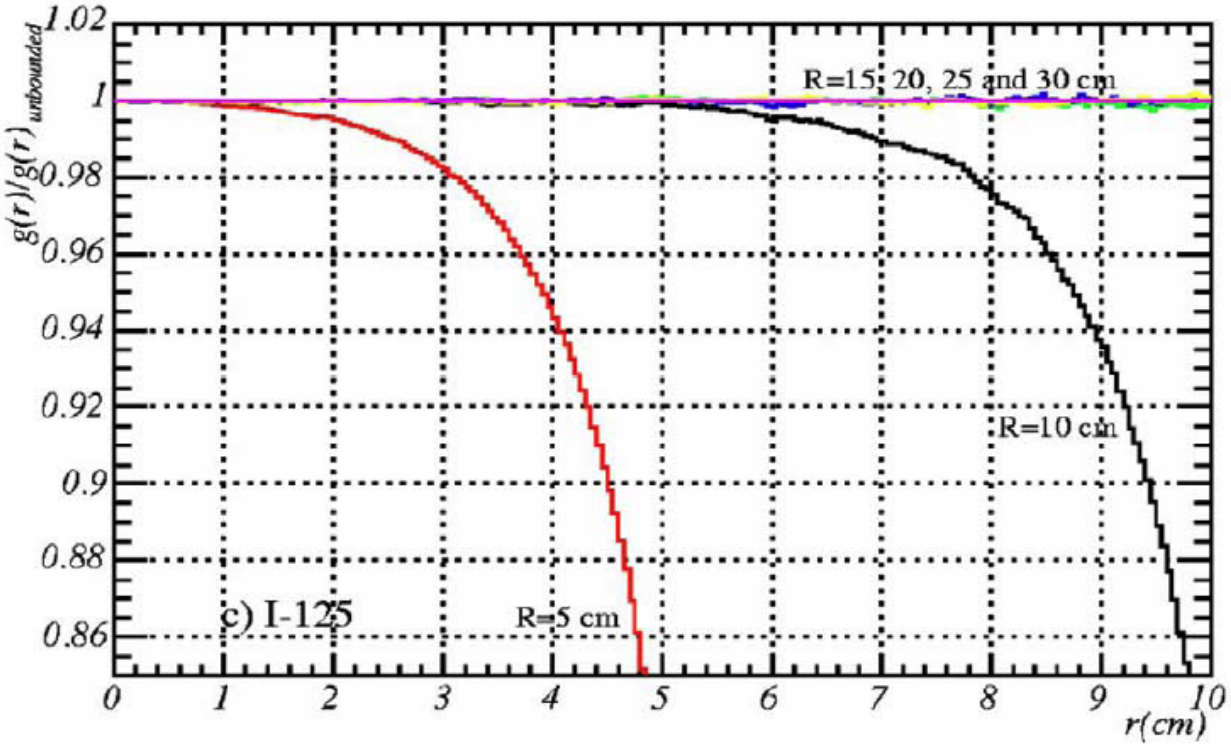


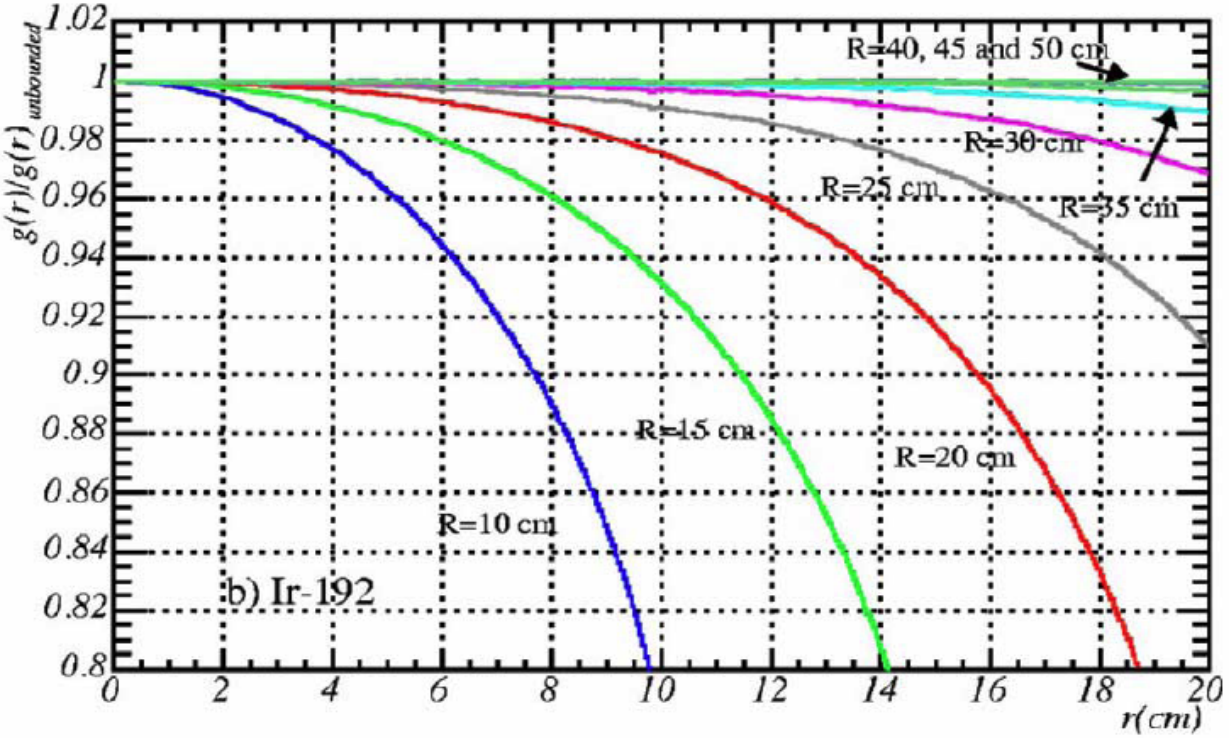
Rivard et al, Med. Phys. 36, 1968-1975 (2009)

Scatter conditions

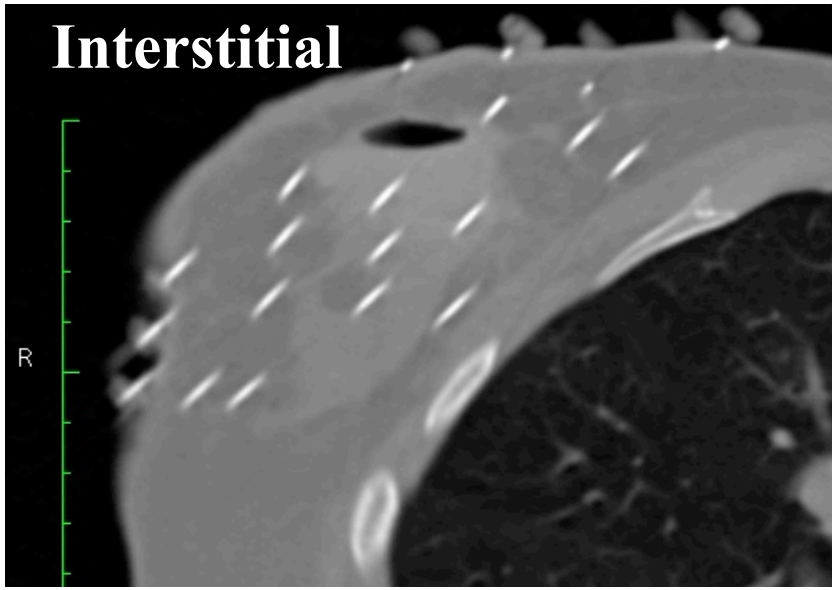


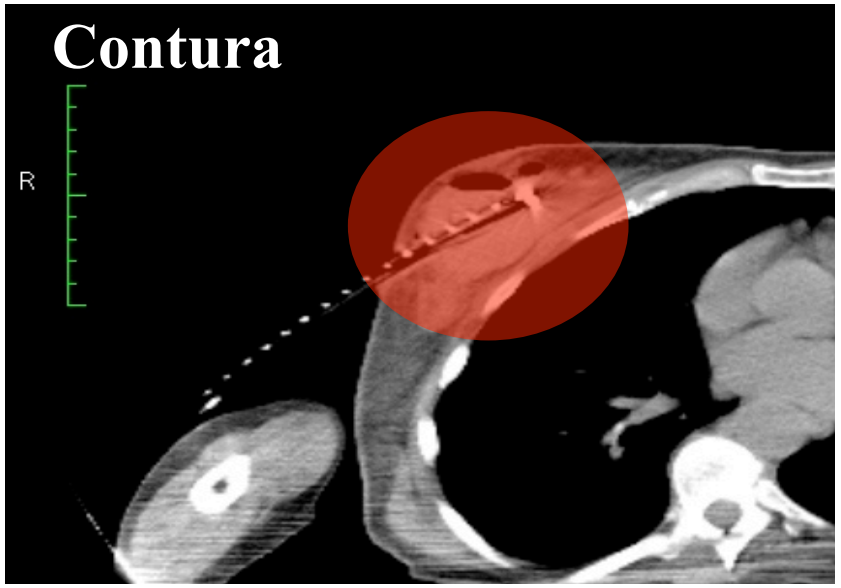
Perez-Calatayud, Granero, Ballester MedPhys (2004)

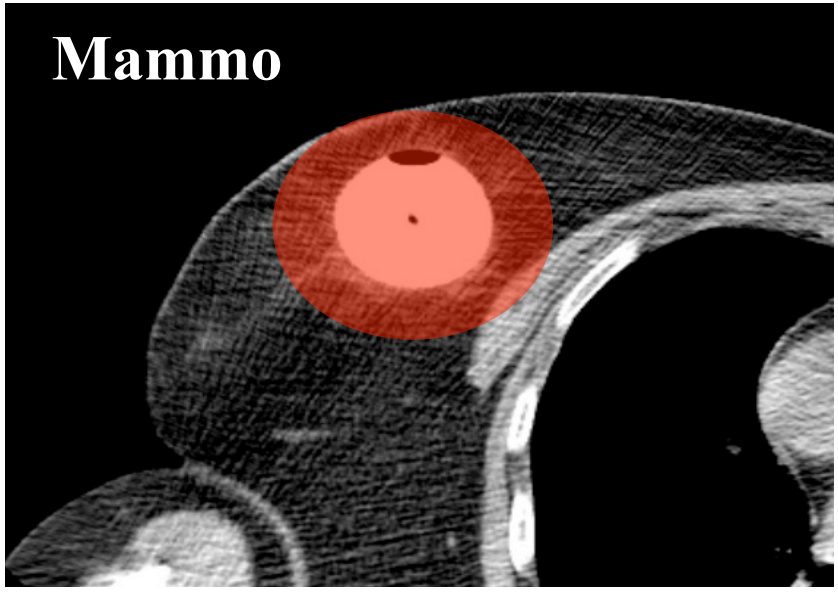


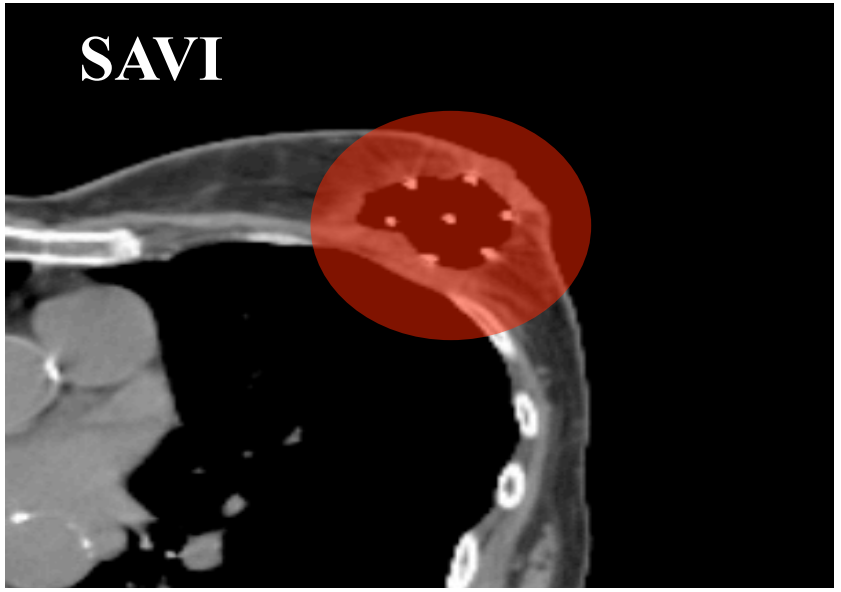


…Contrast and Air





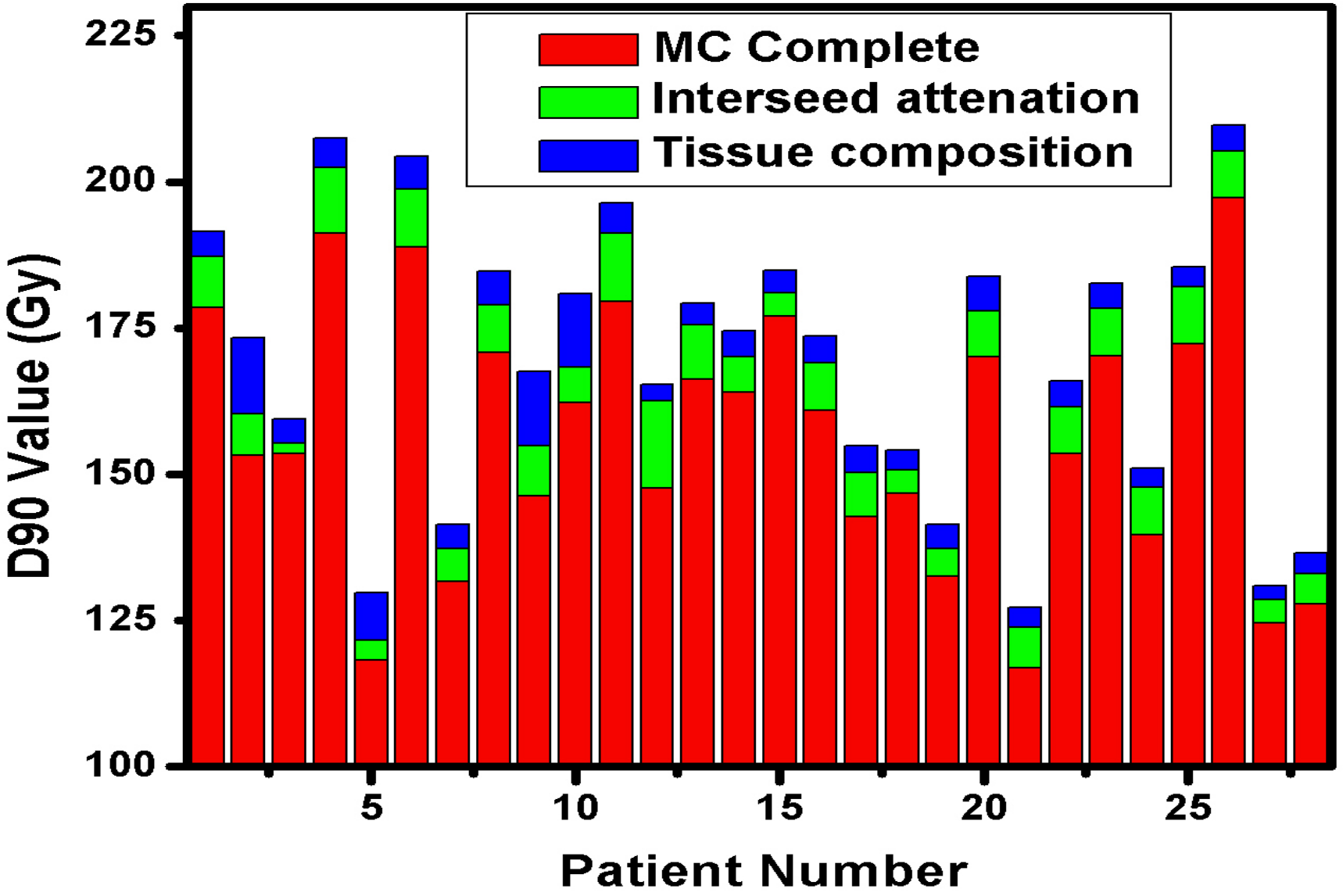




…Contrast and Air

- Effect of contrats 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



≈ 4% ↓

≈ 3% ↓

How Important in the clinic?

Site / Application	Importance
Shielded Applicators	Huge
Eye plaque	-10 to -30% (TG129)
Breast Brachy	-5% to -40%
Prostate Brachy	-2 to -15% on D90
GYN	Depends on applicators

Accurate dose calculation should be a priority

- Effect can be large (> 10%)
- The dose-outcomes, tolerence doses, prescription doses will probably need to be revisited
  - e.g. ^{192}Ir breast skin tolerance dose
- Possibility of better tx approaches

Rule of tumb

Energy Range	Effect
^{192}Ir	Scatter condition
	Shielding (applicator related)
$^{103}Pd/^{125}I$/eBx	Absorbed dose (μ_{en}/ρ)
	Attenuation (μ/ρ)
	Shielding (applicator, source)

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Alternatives to TG43

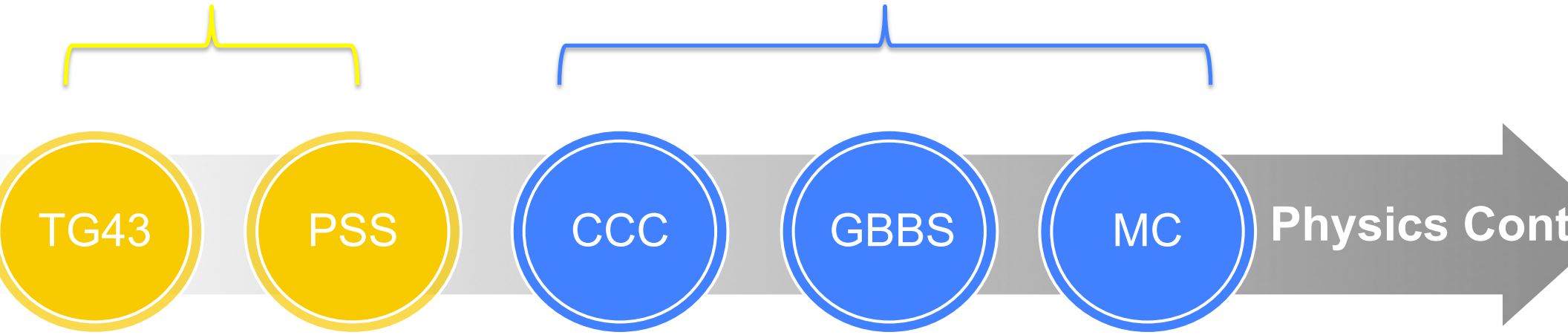
TABLE I. Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were useable in brachytherapy treatme planning systems as of 12 May 2010.

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

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

Brachytherapy Dose Calculation Methods

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



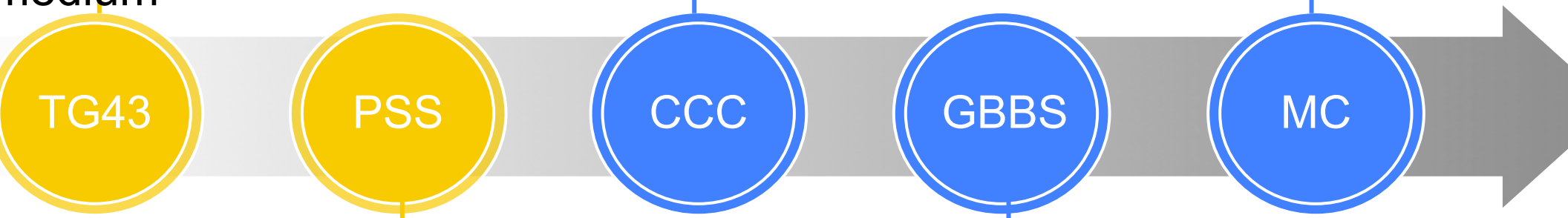
Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys

BT Dose Calc.

Current STD: Full scatter water medium

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

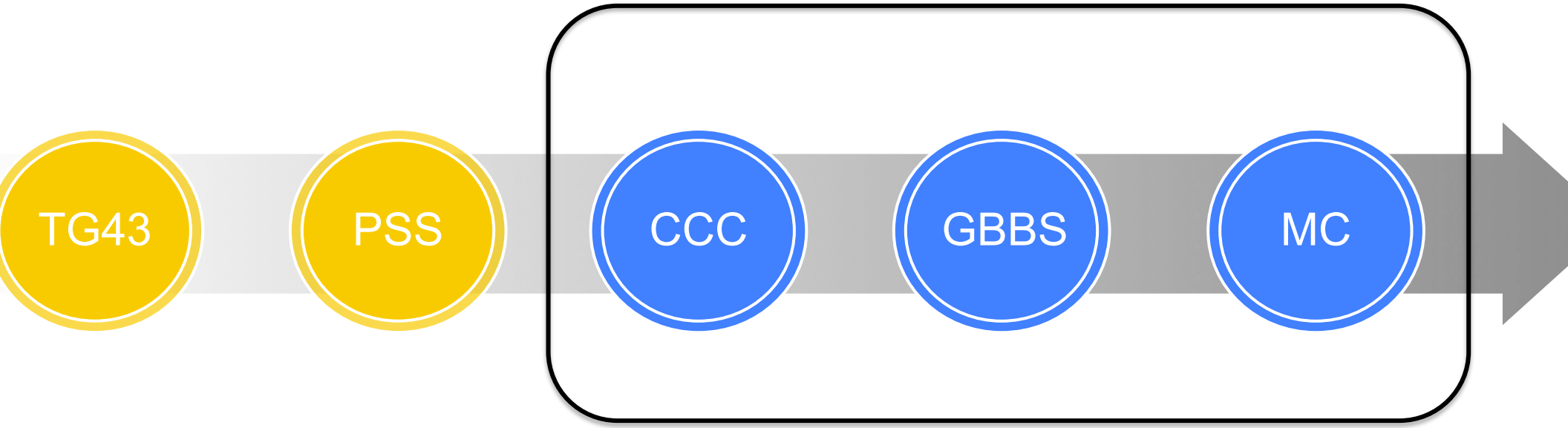
Explicit particle transport simulation. Gold STD for source characterization and other applications



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

Only commercial MDBCA. Solves numerically transport equtations. Full heteregoneities.

BT Dose Calc.



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

Rivard *et al*., MedPhys 36, 1968-1975 (200

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

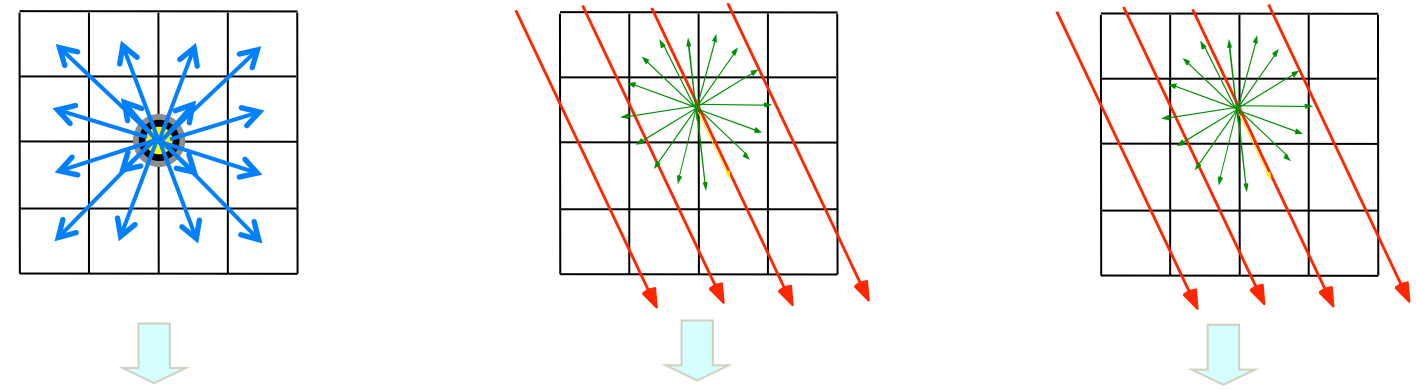
Scatter transport line

Residual-scatter kernel

Material info

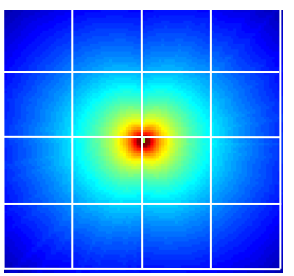
Second scerma S_{2sc}

IV. Summation



$S_{1sc} \overset{CPE}{\propto} D_{prim}$

$S_{2sc} \overset{CPE}{\propto} D_{1sc}$

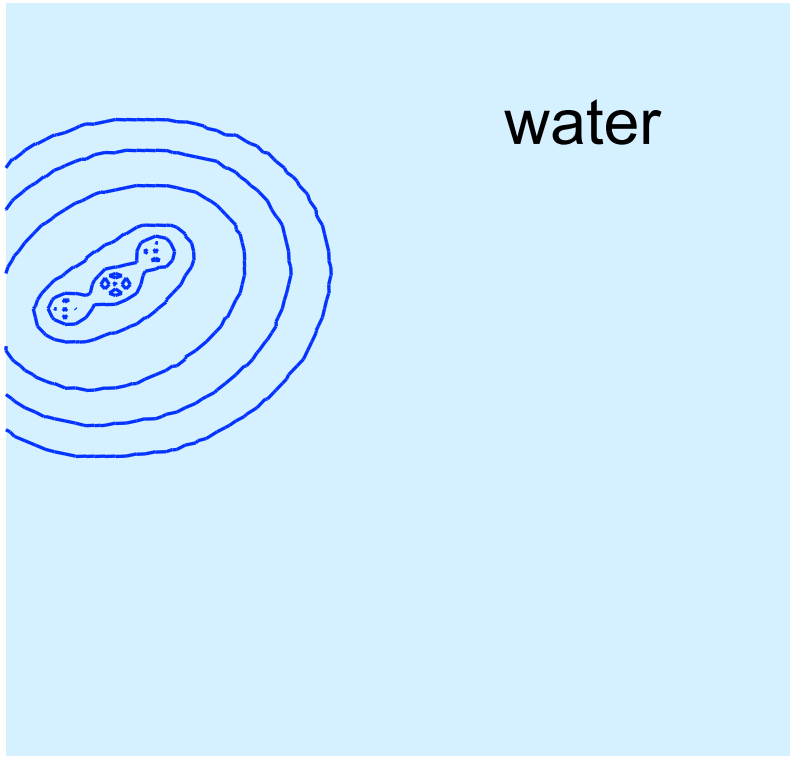


$D_{prim} + D_{1sc} + D_{rsc} = D_{tot}$

Details in Carlsson and Ahnesjö (2000) Med Phys p 2320-2332

Brachy-CC MBDCA

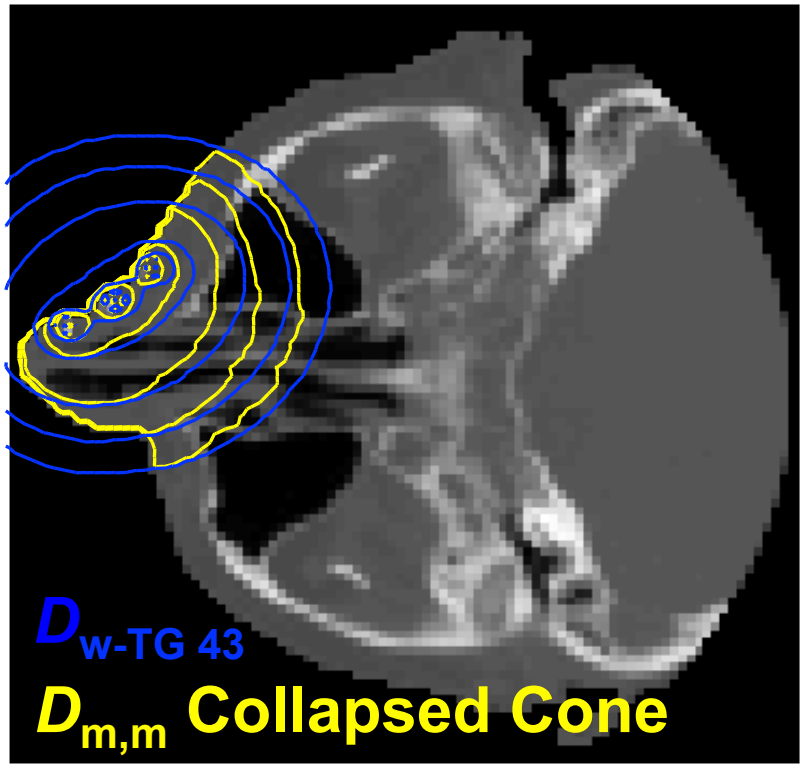
I. TG43



Superposition of sngle-source water-dose

Imaging in TG43: localise dose - anatomy

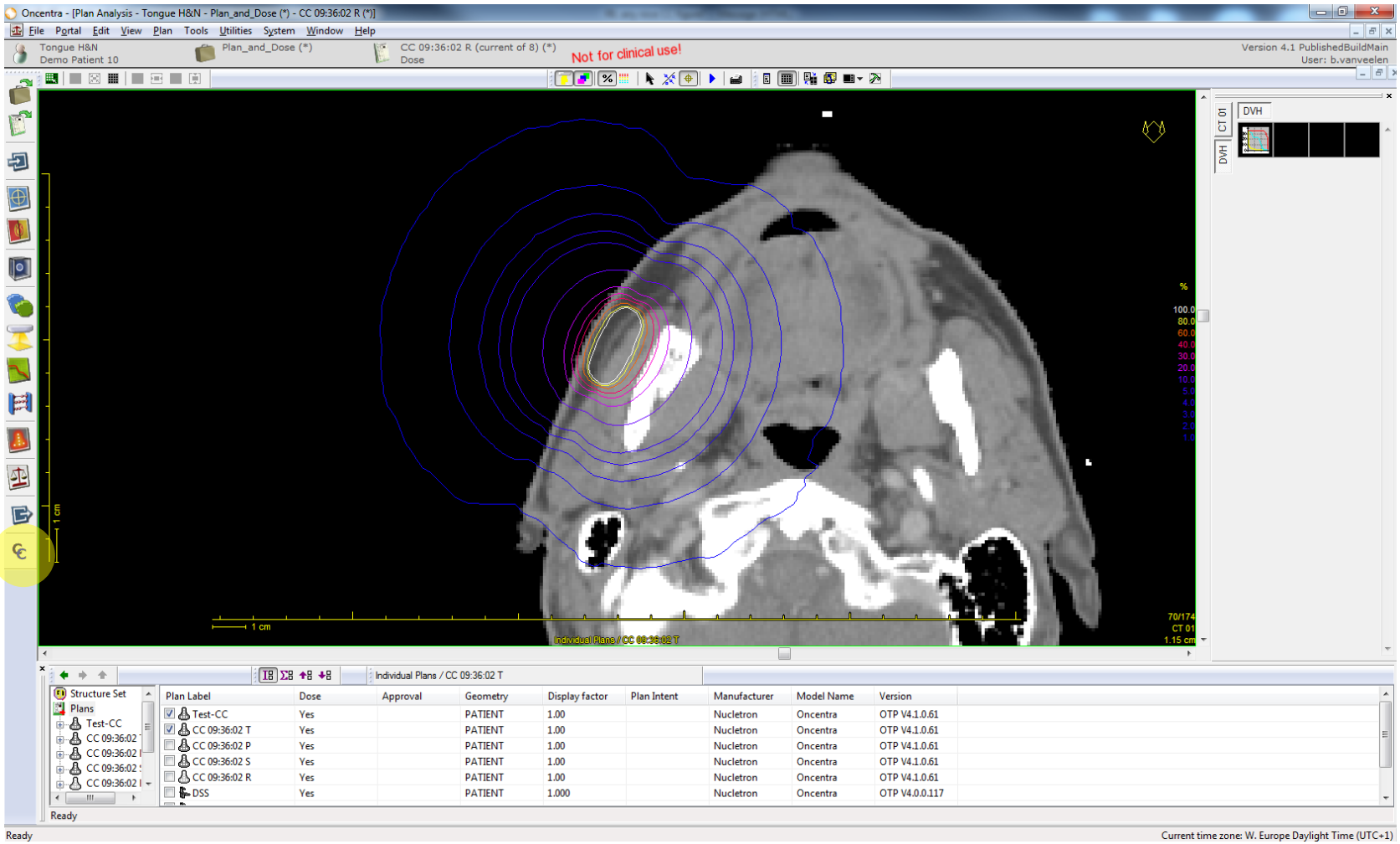
II. MBDCA



Information on tissue, etc composition from images or elsewhere

From Åsa Carlsson-Tedgre

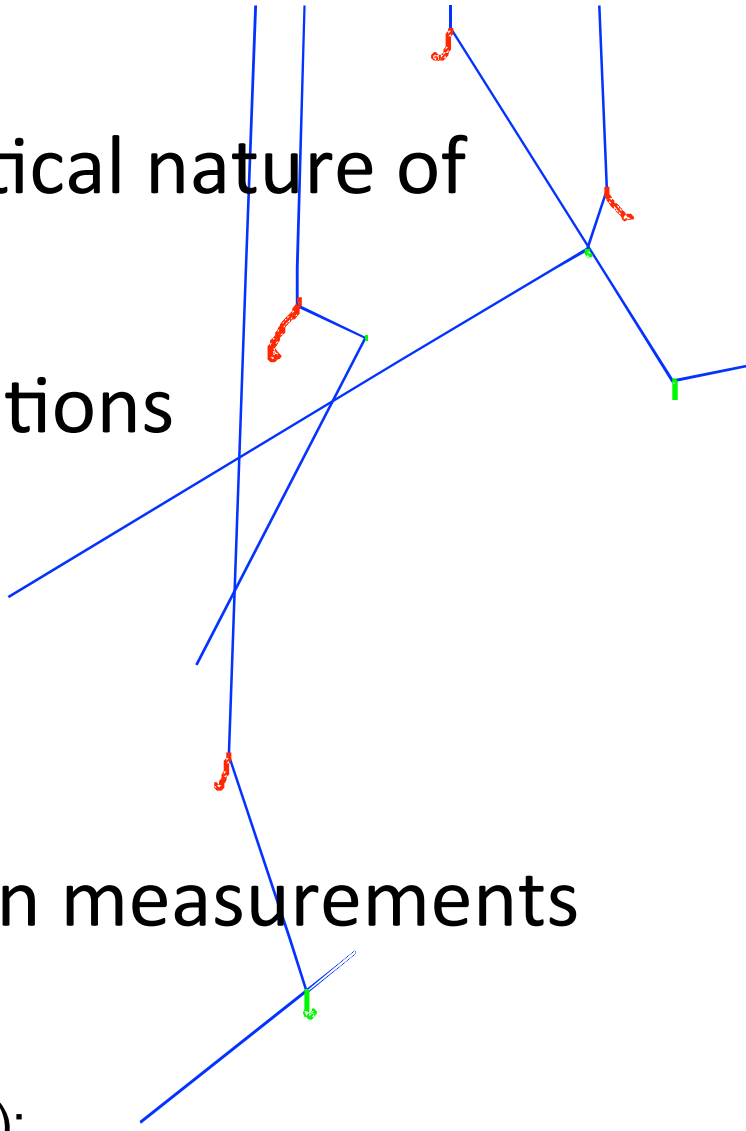
Implementation in OncentraBrachy



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
  - TG43 parameters
  - 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
  - MCPI – Seeds (Chibani and Williamson (2005) Med Phys 3688-3698)
  - BrachyDose - Seeds (Taylor et al (2007) Med Phys 445-457)
  - PTRAN CT (Williamson et al (1987) Med Phys p 567-576)
  - ALGEBRA (Afsharpour et al., (2012), PMB)

MC speed up techniques

Technique	Speed-up
CPE, only photons	20 -70%[1]
Track length estimator	Factor 20-30 [1]
Phase space (source)	30-40%[2]
Photon recycling	30-40%[2]
Correlated sampling	Factor 40-60 [3]
MC on GPU	Sub second [4]

1) Williamson (1987) Med Phys p 567-576, Hedtjärn et al (2002) Phys Med Biol p 351-376, 2) Taylor et al (2007) Med Phys p 445-457, Chibani and Williamson (2005), 3) Sampson et al, Med Phys (2012). 4) S. Hissoiny et al, Med Phys 39 (2012).

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
  - BUT: D'Amours et al IJROBP 2011; Hossoiny et al, Med Phys 2012

Grid-Based Boltzmann Solver (GBBS)

- Deterministic approach of solving the linear Boltzmann transport equation

$$\hat{\Omega}\cdot\vec{\nabla}\psi^{\gamma} + \sigma_t^{\gamma}\psi^{\gamma} = Q^{\gamma(ext)} + Q^{\gamma(scat)}$$

Streaming operator — Collision operator — Sources

$$\hat{\Omega}\cdot\vec{\nabla}\psi^{e} + \sigma_t^{e}\psi^{e} - \frac{\partial}{\partial E}s_R\psi^{e} = Q^{e(ext)} + Q^{scat}$$

Streaming operator — Collision operator — CSDA operator — Sources

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

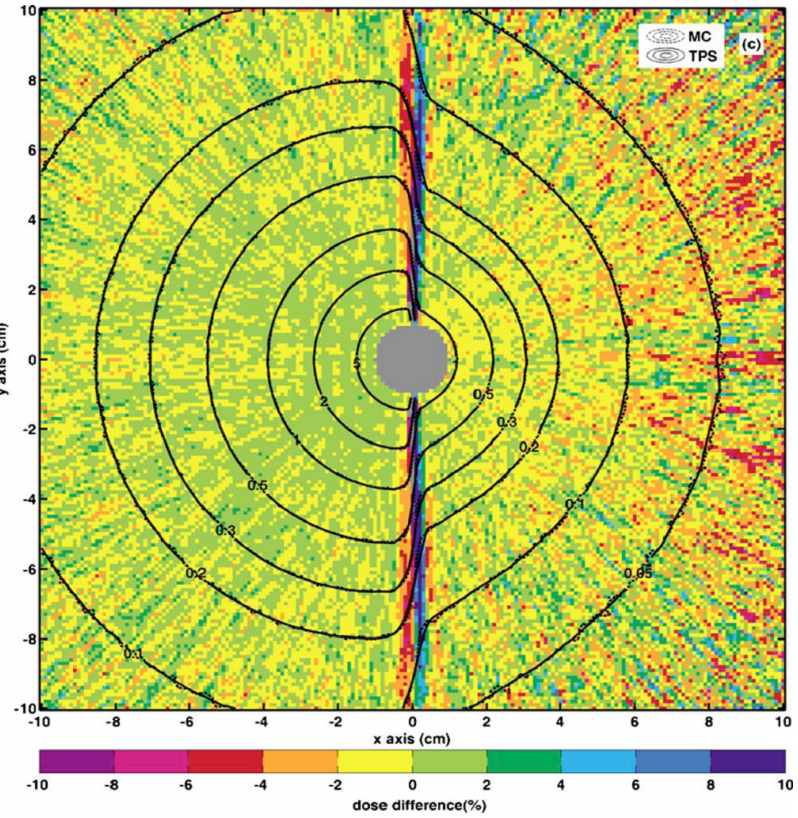
« multi-group discrete ordinates grid-based …»

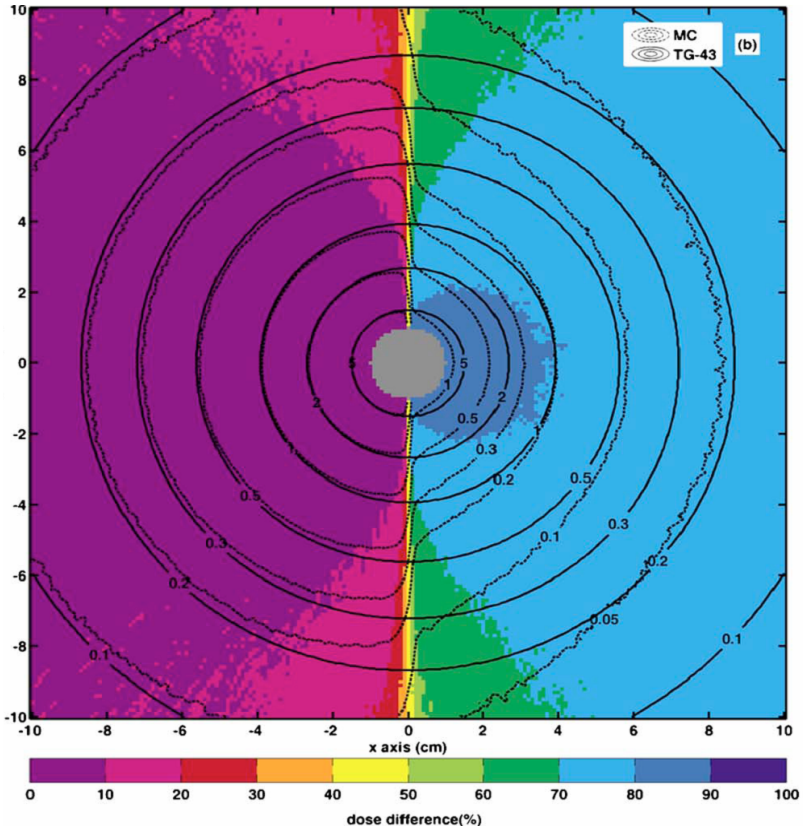
2D: Daskalov et al (2002), Med Phys 29, p.113-124
3D: Gifford et al (2006), Phys Med Biol vol 53, p 2253-226

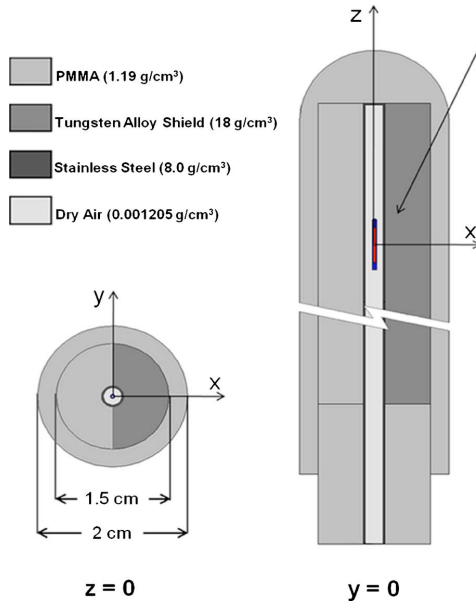
Grid-Based Boltzmann Solver (GBBS)

- 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 : Scerma = Dprim•$((\mu-\mu_{en})/u_{en})$
    - Share this step with CCC
  - 3D scatter integration through GBBS
  - Source modeling done in Atilla® (Transpire Inc)

Example







- Speed: 40 sec to 12 min depending on complexity

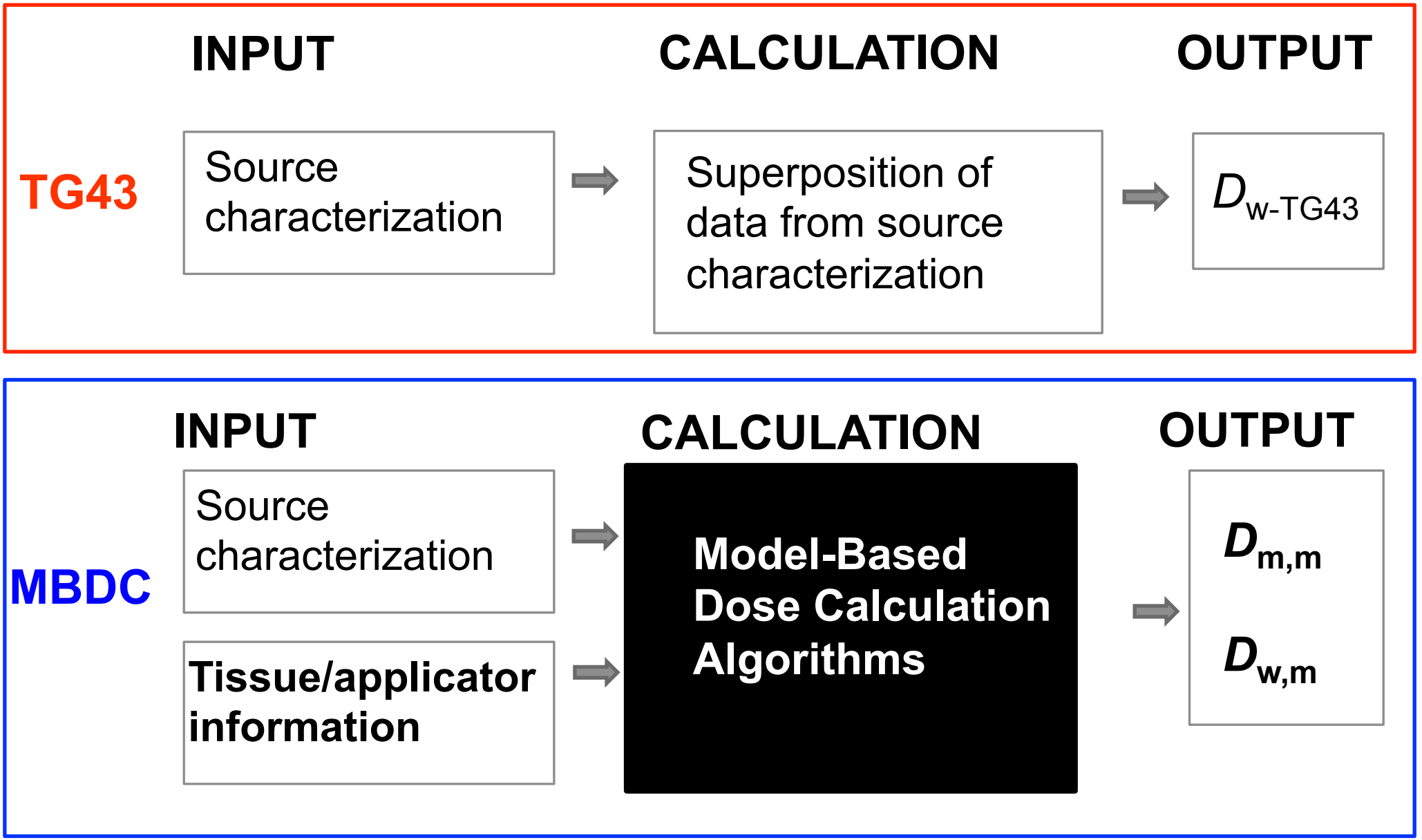
Figure from : L. Petrokokkinos *et. al.* Med. Phys. **38**, 1981-1992 (2011).

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

Contents

- Introduction: moving beyond TG43
- Advances in brachytherapy dose calculations
- Challenges and research topics
- Recommendations from AAPM/ESTRO/ABG Task Group 186

Factor-based vs Model-based



From Åsa Carlsson-Tedgre

Three main areas identified as critical

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

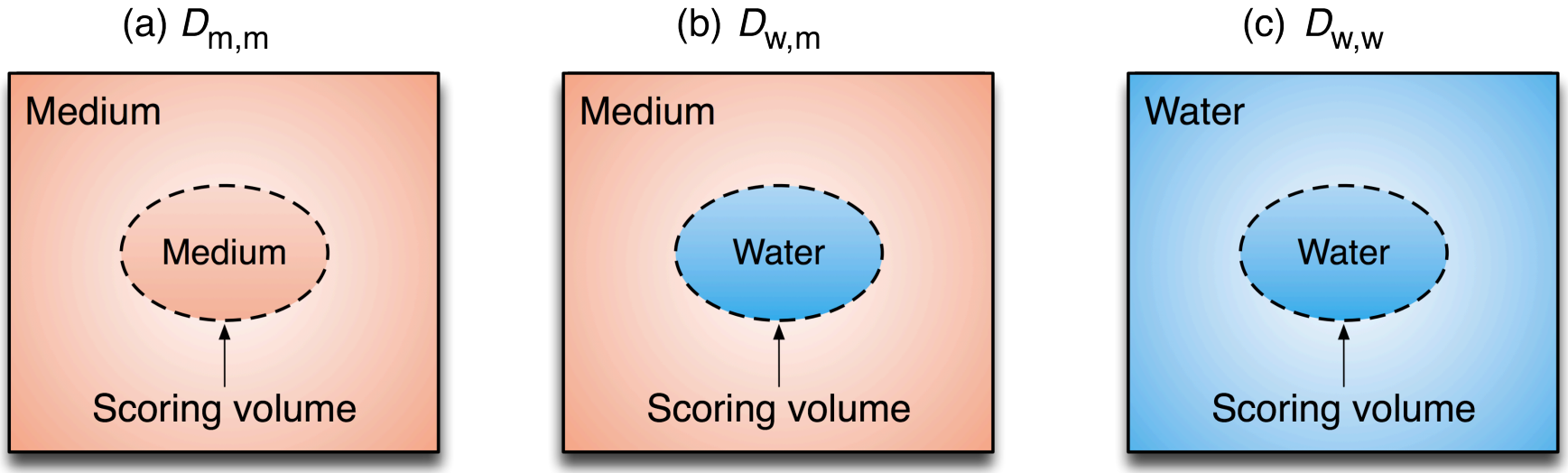
1. Definition of the scoring medium

$D_{x,y}$

x: dose specification medium

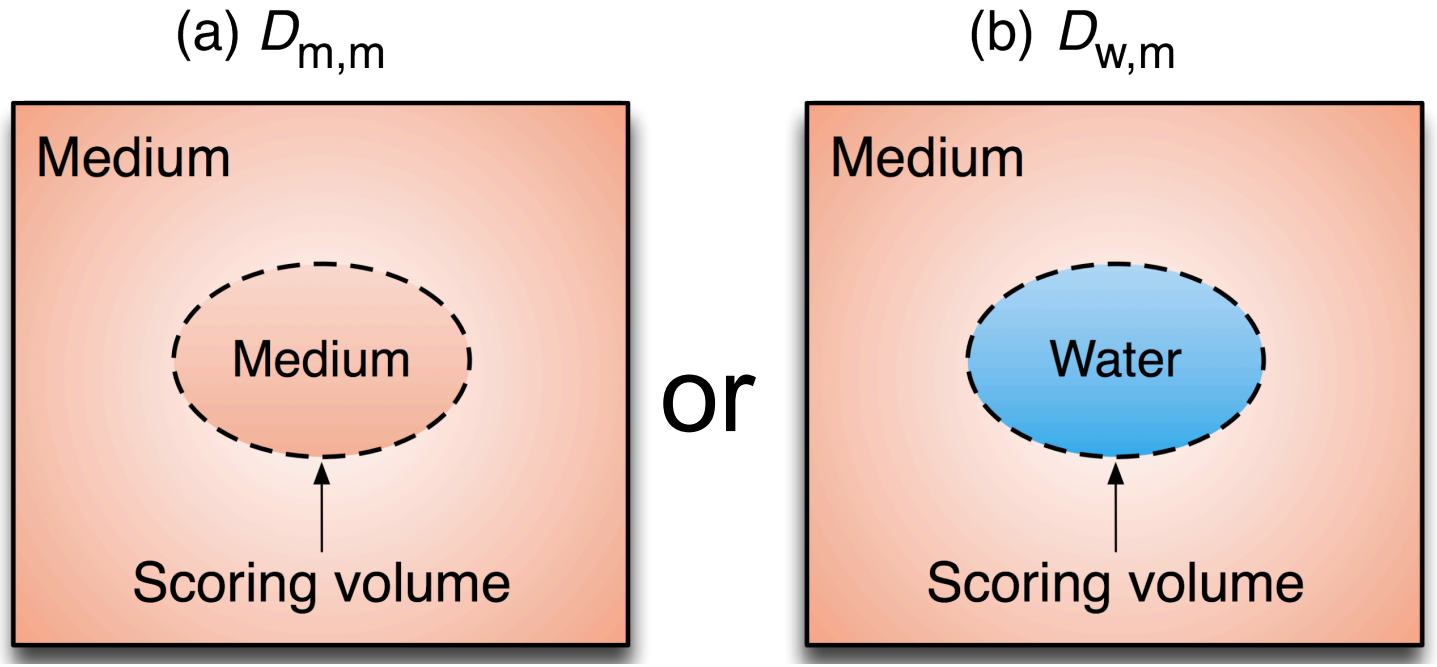
y: radiation transport medium

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



FROM: G Landry, Med Phys 2011

Which best correlate to cell doses or outcomes?

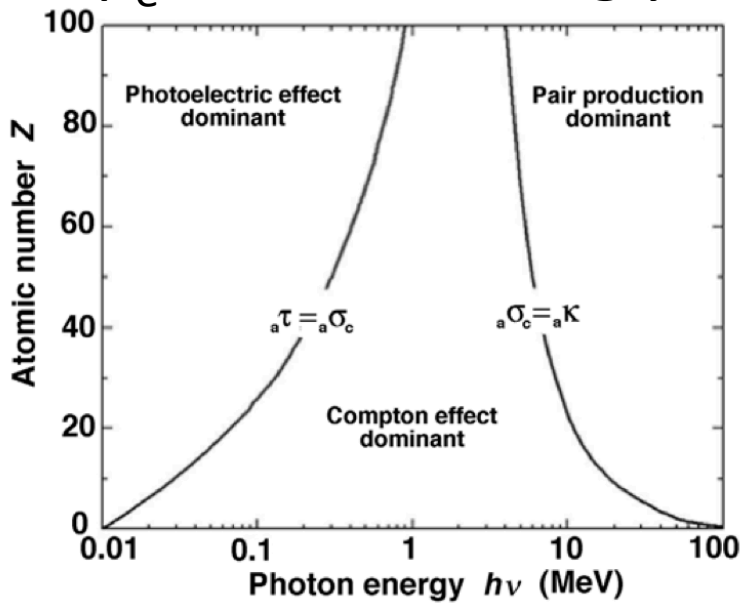


2- Cross section assignments (segmentation)

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

In EBRT one only needs electron densities ρ_e (e^-/cm^3) from CT scan

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



2- Cross section assignments

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

- e.g. in breast: adipose and glandular tissue have significantly different (ρ_e ,Z_{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!

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

  L. Beaulieu *et al*, Med Phys 39 (2012)

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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(Received 7 May 2012; revised 26 July 2012; accepted for publication 2 August 2012; published 25 September 2012)

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 is highly dependent on scatter conditions 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 by 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 voxel-by-voxel 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 an impractical strategy. Hence, a new commissioning process is required. TG-186 addresses in detail the above issues through the literature review

 0094-2405/2012/39(10)/6208/29/$30.00 © 2012 Am. Assoc. Phys. Med.

Goals of the Recommendations

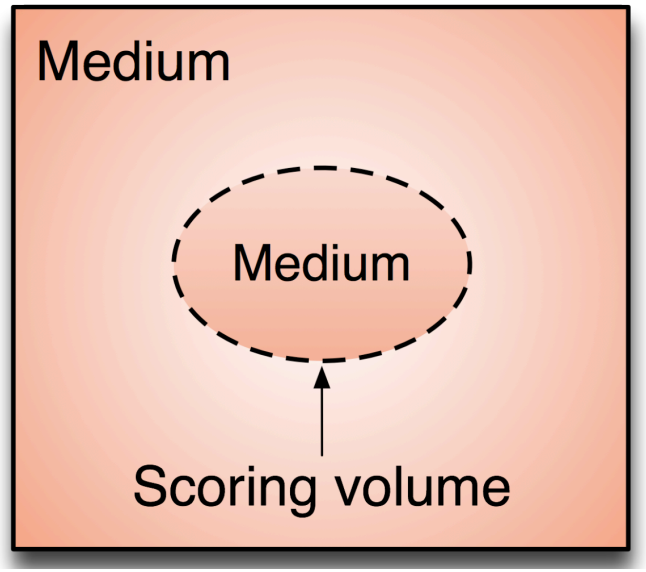
- Maintain inter-institution consistency
- Preserve high QC/QA standards
- Provide Guidance to:
  - Define for each voxel: material and density
  - Define guidelines for the dose scoring medium
- *Will have to address retrospectively and prospectively dose-outcome relationships*

Basic recommendations

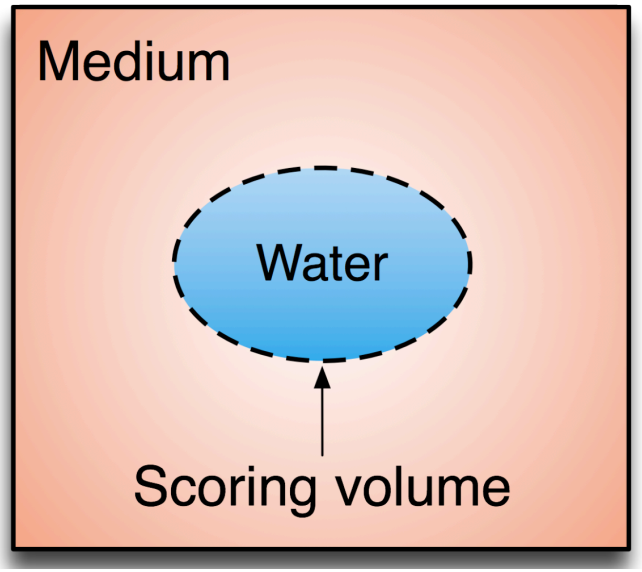
- Previous TPS QA/QC process still valid
- Maintains TG43 dose prescriptions
  - Unless societal recommendation otherwise
- Model-based dose calculations should be performed in parallel with TG43
  - Radiation transport using the most accurate tissue medium compositions available

Which dose to report?

#1: $D_{m,m}$



#2: $D_{w,m}$



- $D_{m,m}$ 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

BLE III. Material definitions. Water is given for comparison.

sue	% mass H	C	N	O	$Z > 8$	Mass densi g cm^{-3}
state (Ref. 110)	10.5	8.9	2.5	77.4	Na(0.2), P(0.1), S(0.2), K(0.2)	1.04
an adipose (Ref. 110)	11.4	59.8	0.7	27.8	Na(0.1), S(0.1), Cl(0.1)	0.95
an gland (Ref. 110)	10.6	33.2	3.0	52.7	Na(0.1), P(0.1), S(0.2), Cl(0.1)	1.02
an male soft tissue (Ref. 109)	10.5	25.6	2.7	60.2	Na(0.1), P(0.2), S(0.3), Cl(0.2), K(0.2)	1.03
an female soft tissue (Ref. 109)	10.6	31.5	2.4	54.7	Na(0.1), P(0.2), S(0.2), Cl(0.1), K(0.2)	1.02
an skin (Ref. 109)	10.0	20.4	4.2	64.5	Na(0.2), P(0.1), S(0.2), Cl(0.3), K(0.1)	1.09
tical bone (Ref. 109)	3.4	15.5	4.2	43.5	Na (0.1), Mg (0.2), P (10.3), S (0.3), Ca(22.5)	1.92
lens (Ref. 109)	9.6	19.5	5.7	64.6	Na(0.1), P(0.1), S(0.3), Cl(0.1)	1.07
g (inflated) (Ref. 109)	10.3	10.5	3.1	74.9	Na(0.2), P(0.2), S(0.3), Cl(0.3), K(0.2)	0.26
er (Ref. 109)	10.2	13.9	3.0	71.6	Na(0.2), P(0.3), S(0.3), Cl(0.2), K(0.3)	1.06
art (Ref. 109)	10.4	13.9	2.9	71.8	Na(0.1), P(0.2), S(0.2), Cl(0.2), K(0.3)	1.05
ter	11.2			88.8		1.00

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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