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

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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.

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TG-186

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Contents

- Advances in brachytherapy dose calculation
- Challenges and research topics
- Clinical Impact- initial findings

Alternatives to TG43

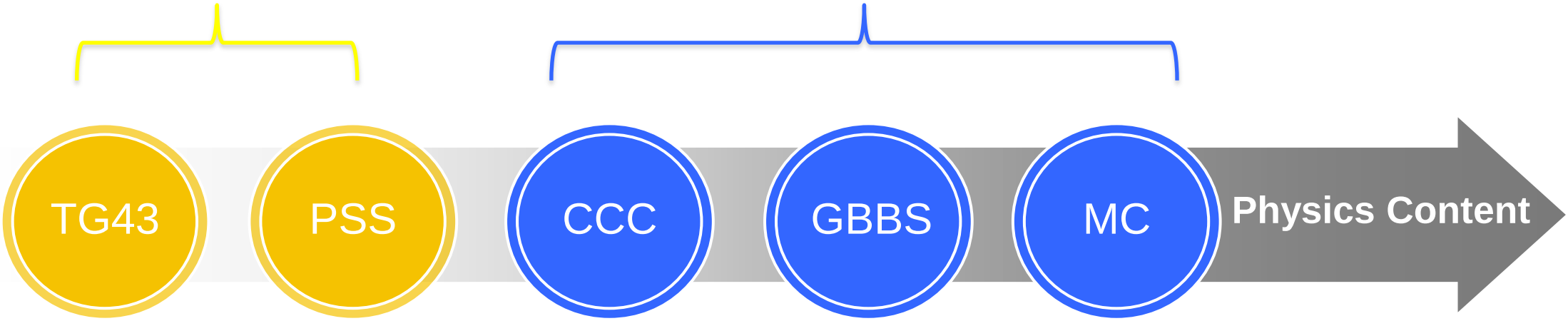
TABLE I. Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were useable in brachytherapy treatment planning systems as of 12 May 2010.

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
MCPI	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



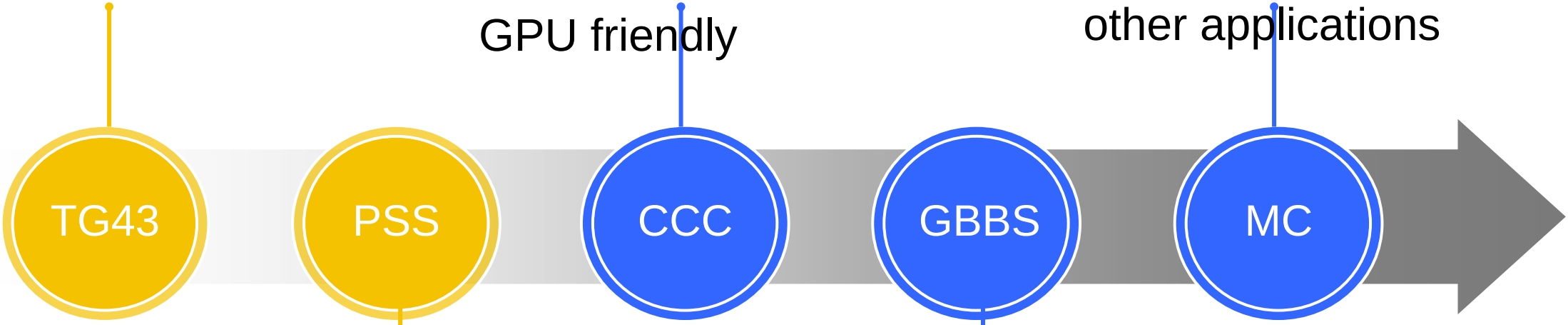
Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010

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 dose engine

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

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 (2009)

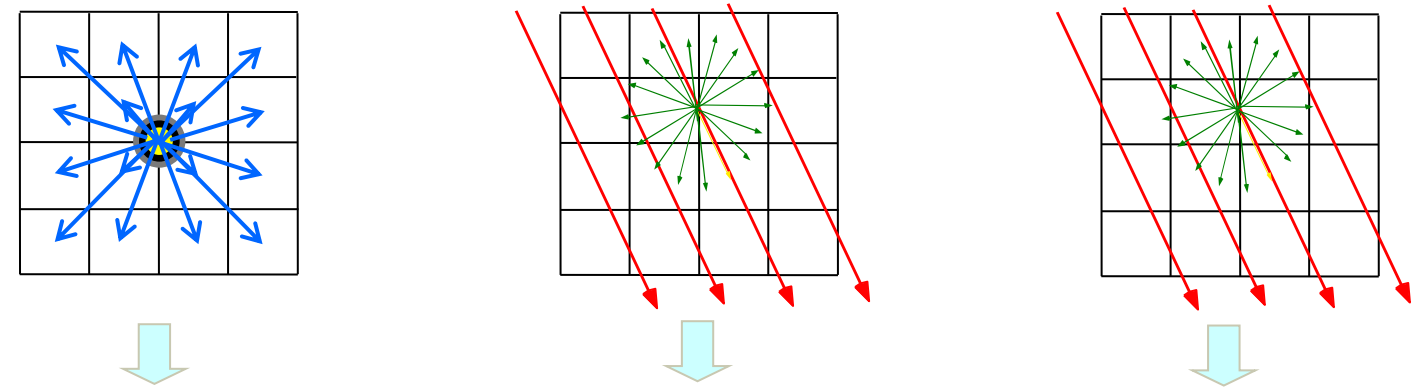
CCC MBDCA for Brachytherapy

I. Raytrace source | II. CC convolution | III. CC convolution | IV. Summation

Primary source rays
Material info

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

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

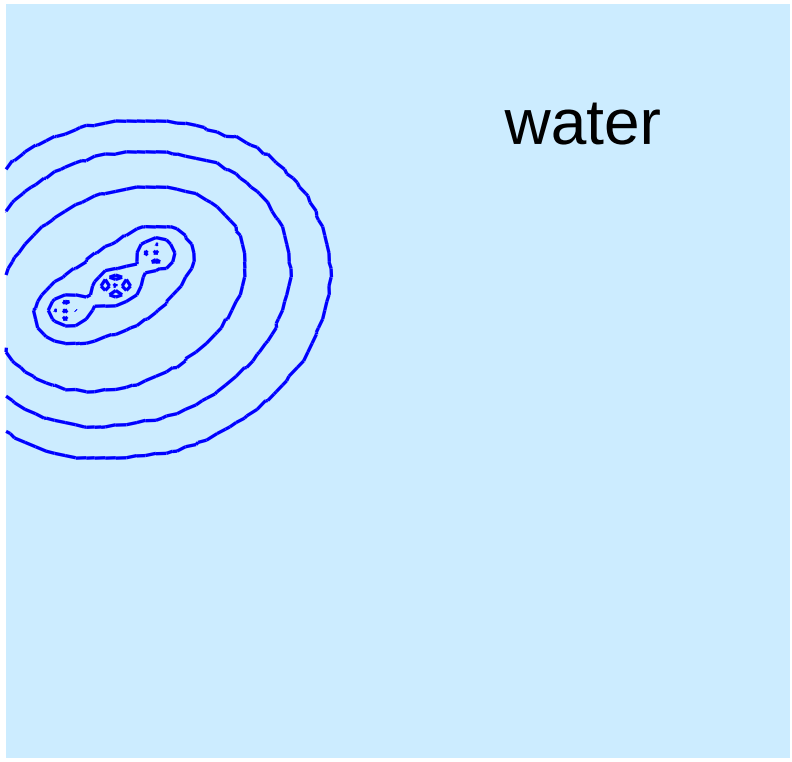


D_{prim} + D_{1sc} + D_{rsc} = D_{tot}

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

CCC MBDCA for Brachytherapy

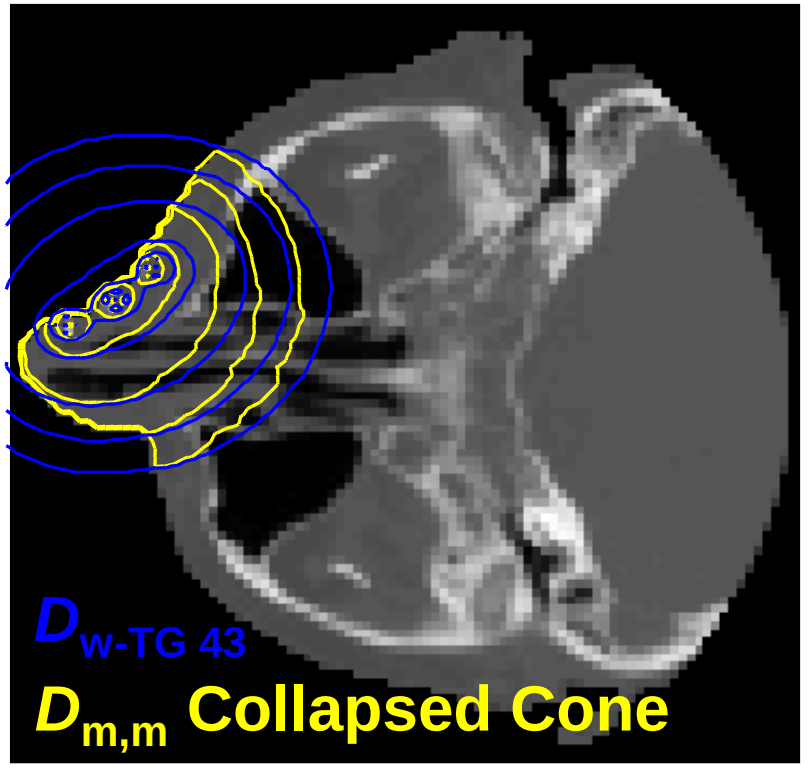
I. TG43



Superposition of sngle-source water-dose

Imaging in TG43: localise dose - anatomy

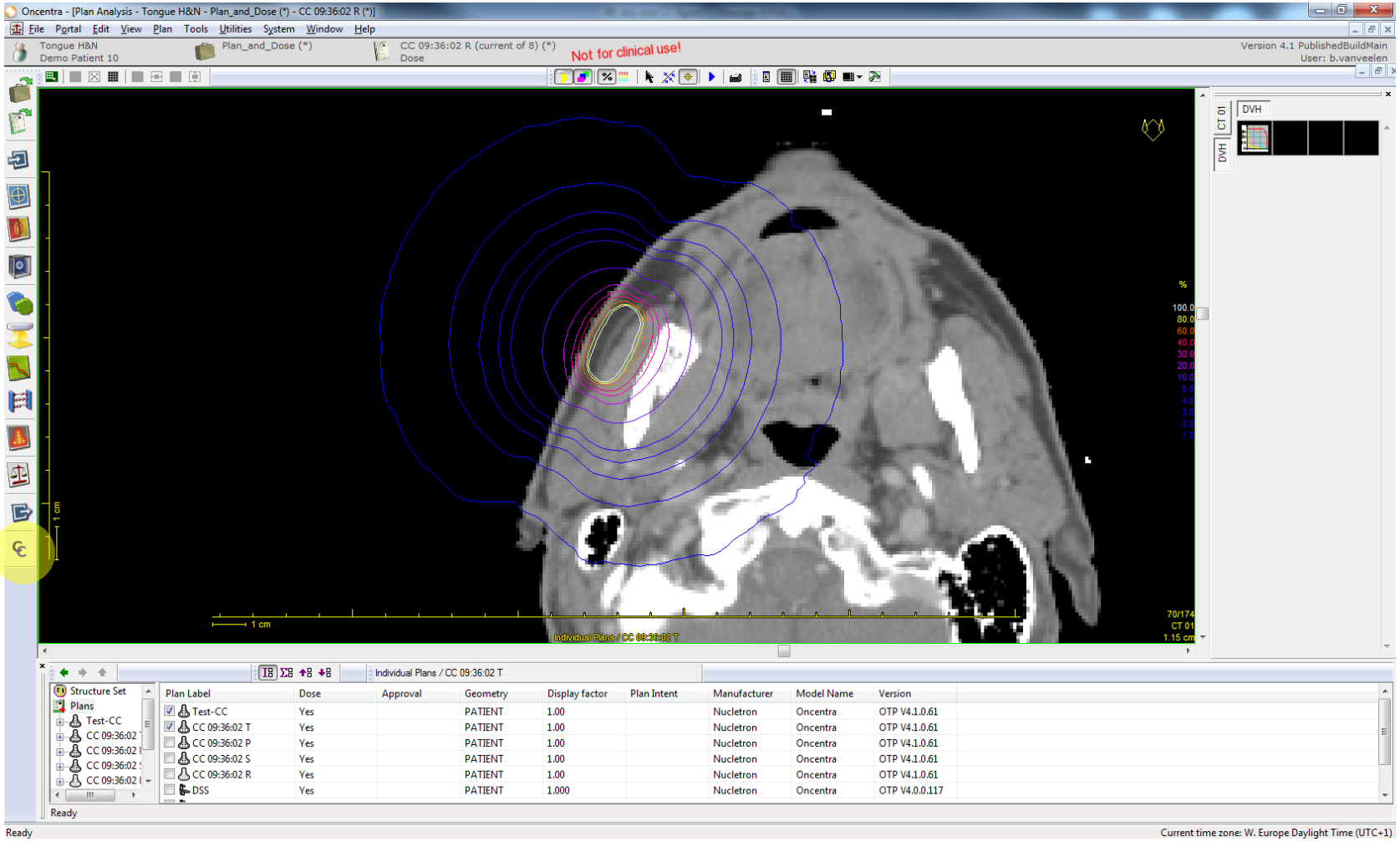
II. MBDCA



Information on tissue, etc composition from images or elsewhere

From Åsa Carlsson-Tedgren

CCC in Oncentra TPS (Elekta)



CC figures from Bob van Veelen, Nucletron BV/Elekta

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 … »

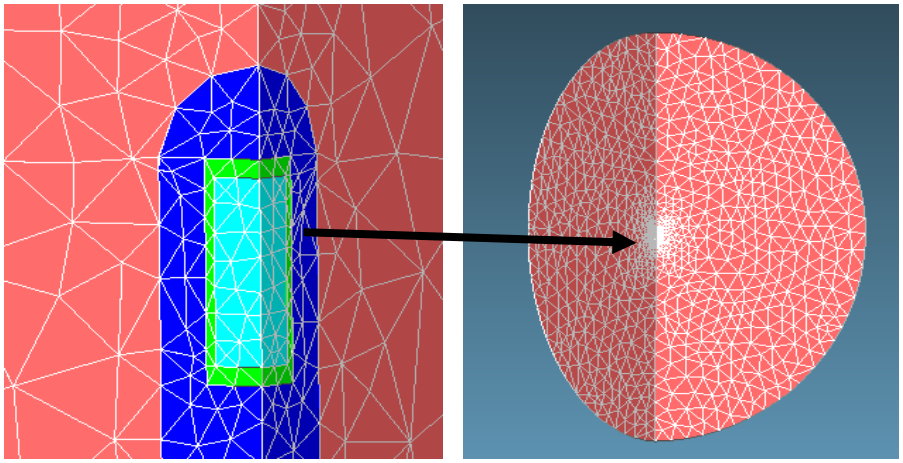
2D: Daskalov et al (2002), Med Phys 29, p.113-124
3D: Gifford et al (2006), Phys Med Biol vol 53, p 2253-2265

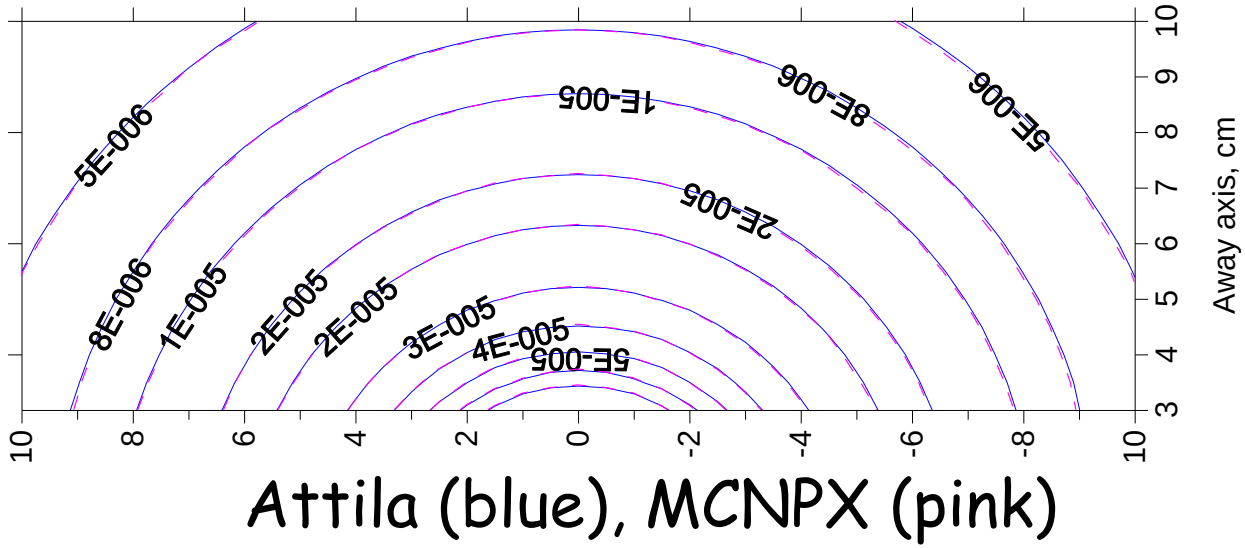
Grid-Based Boltzmann Solver (GBBS)

- 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)

^{192}Ir and ^{137}Cs Attila Benchmarks*

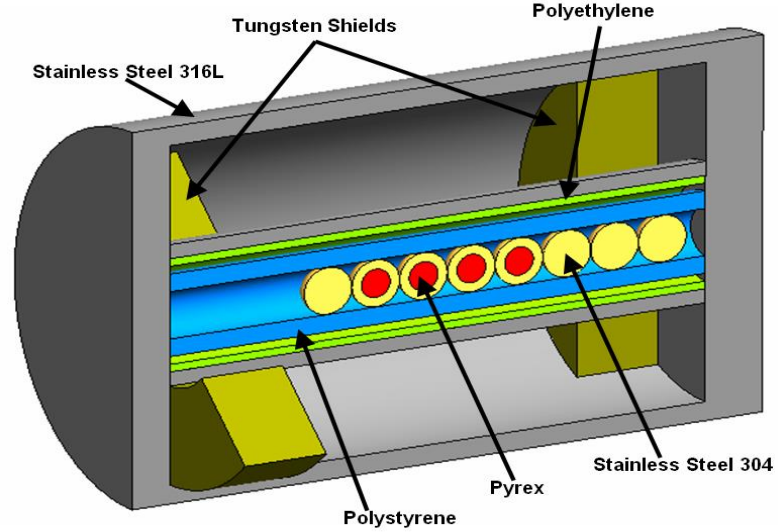
F. Mourtada, T. Wareing, J. Horton, J. McGhee, D. Barnett, G. Failla, R. Mohan, 'A Deterministic Dose Calculation Method with Analytic Ray Tracing for Brachytherapy Dose Calculations', *AAPM*, Pittsburgh, PA, 2004.

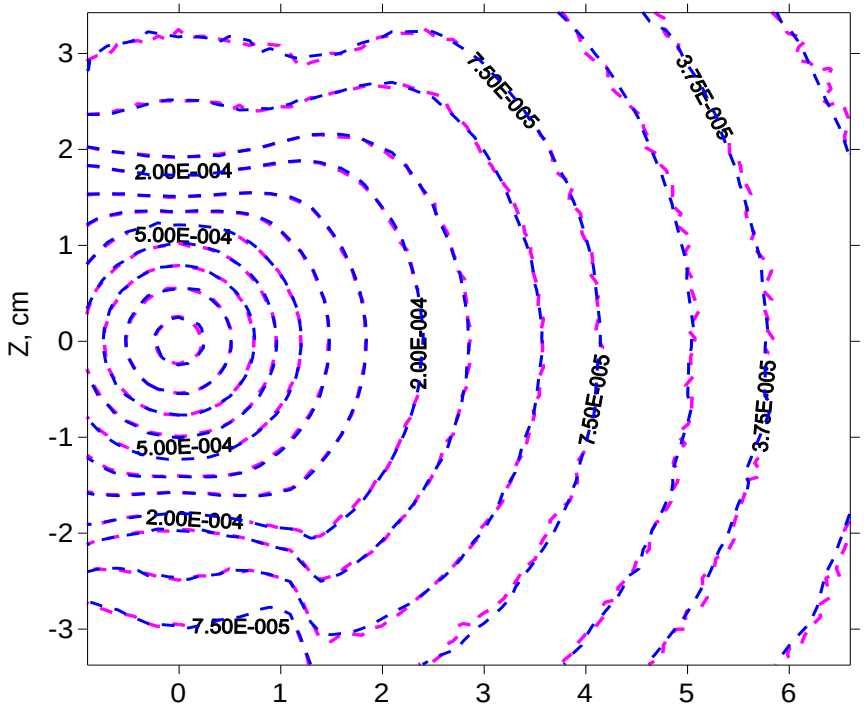




^{137}Cs Attila Benchmarks

F. Mourtada, T. Wareing, J. Horton, J. McGhee, D. Barnett, K. Gifford, G. Failla, R. Mohan, 'A Deterministic Dose Calculation Method Applied to the Dosimetry of Shielded Intracavitary Brachytherapy Applicators', *AAPM*, Pittsburgh, PA, 2004.

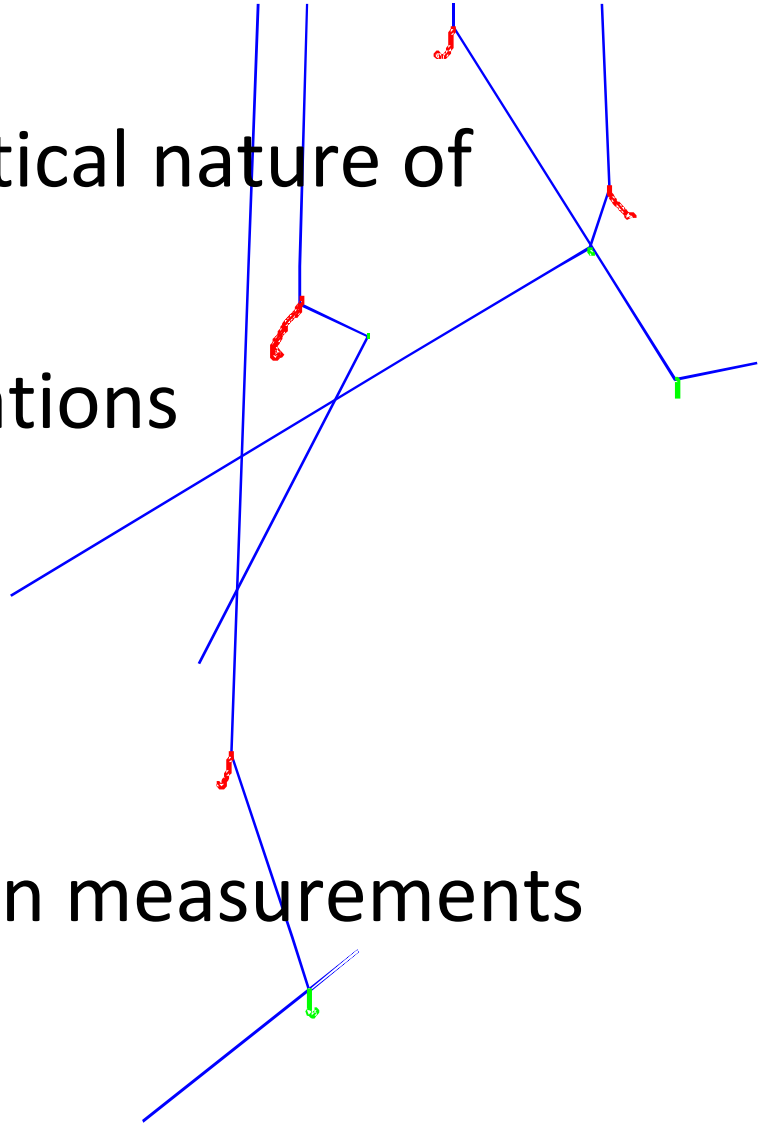




Attila (blue), MCNPX (pink)

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]

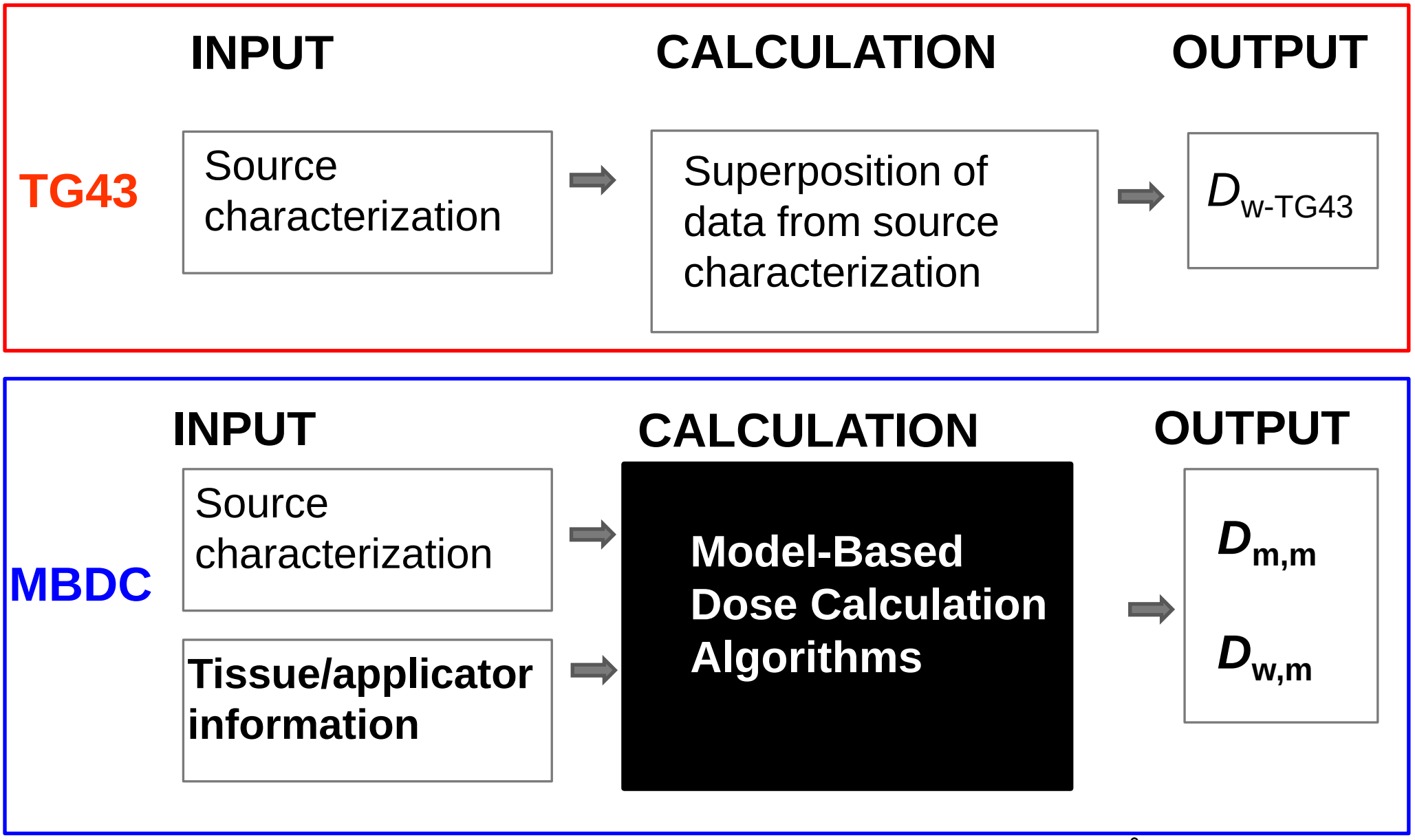
1) Williamson (1987) Med Phys p 567-576, Hedtjärn et al (2002) Phys Med Biol p 351-376, 2) Taylor et al (2007) Med Phys p 445-457, Chibani and Williamson (2005), 3) Sampson et al, Med Phys (2012). 4) S. Hissoiny et al, Med Phys 39 (2012).

MBDCA Calculation Speed…

- Can be relatively fast
  - About 25 sec for a seed implant dosimetry (BrachyDose)
  - < 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
  - BUT: D'Amours et al IJROBP 2011; Hossoiny et al, Med Phys 2012

Factor-based vs Model-based



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

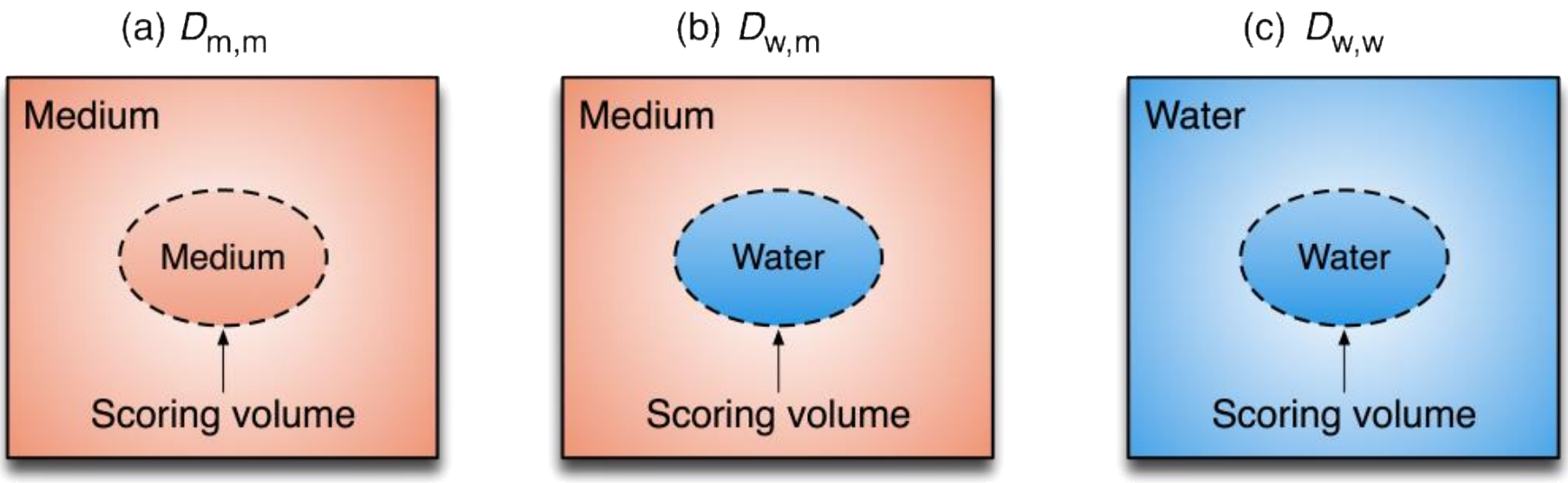
1. Definition of the scoring medium

$D_{x,y}$

x: dose specification medium

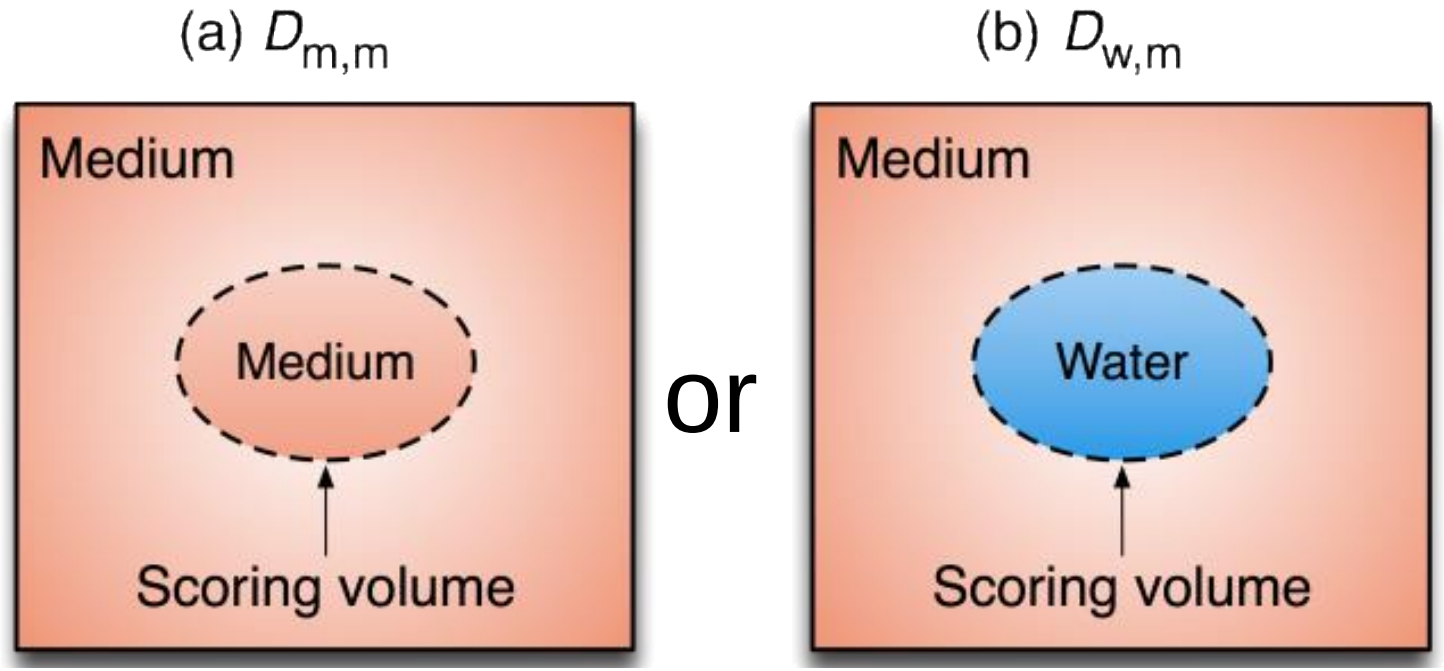
y: radiation transport medium

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



FROM: G Landry, Med Phys 2011

Which best correlate to cell doses or outcomes?



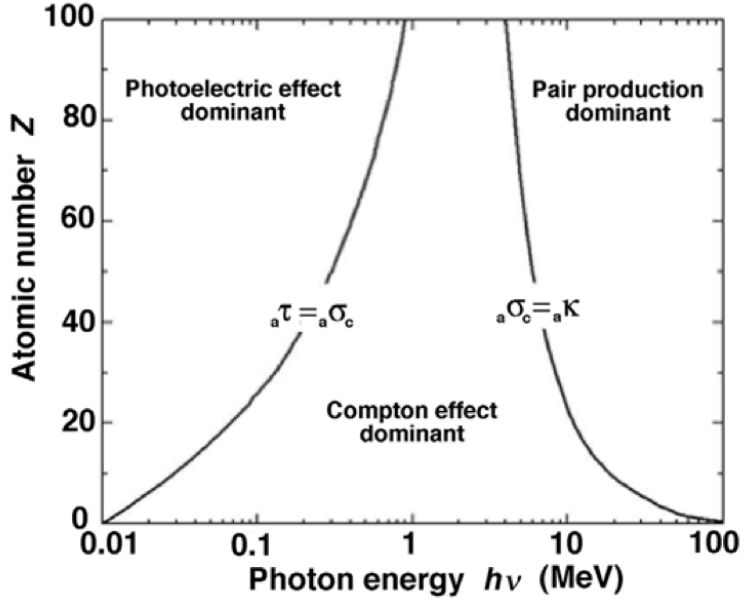
???

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!

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)

Clinical GYN HDR Example with Shielded Colpostats

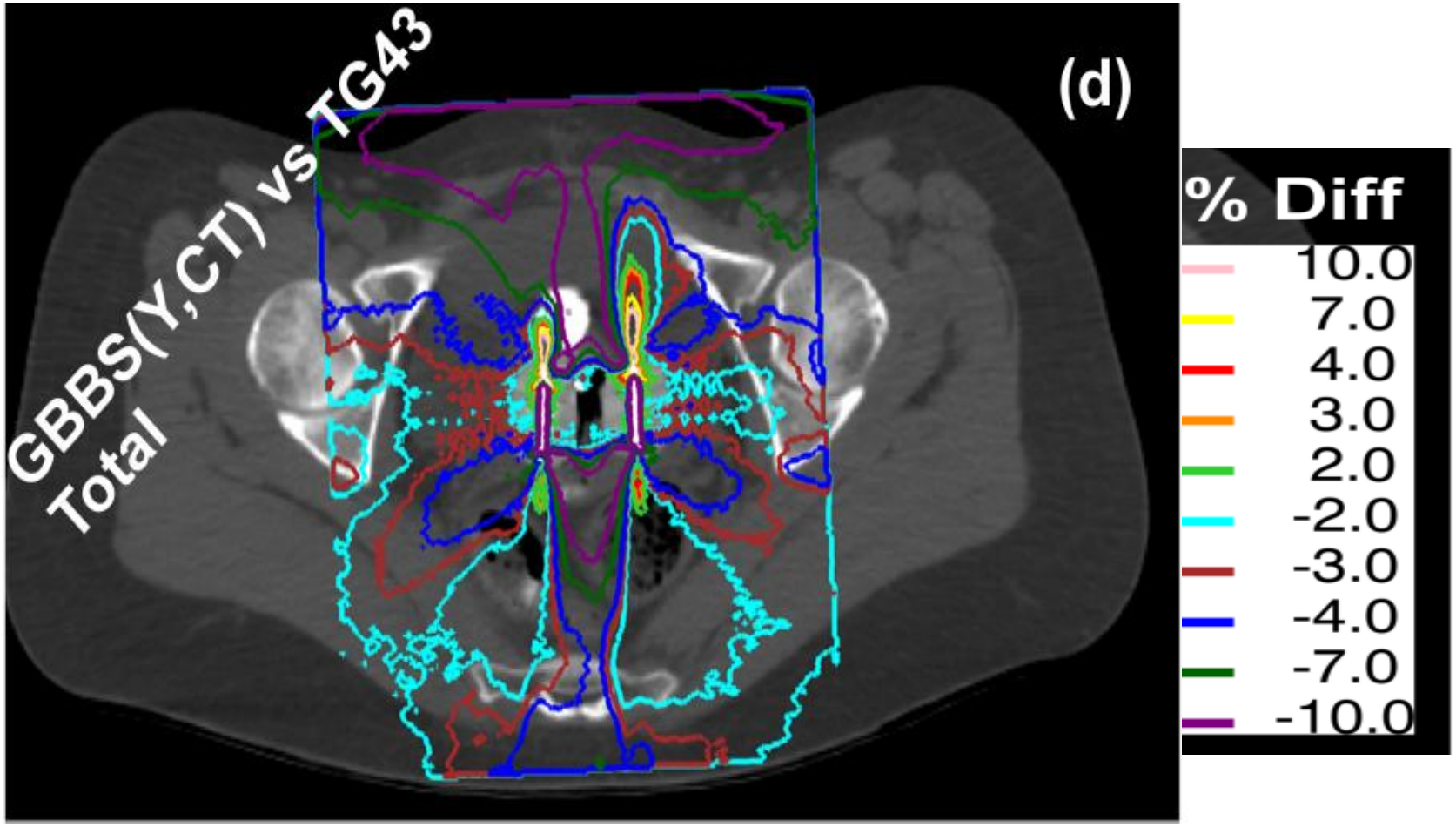
Table 2
Percent difference (100 × [GBBS(Y, CT) − TG43]/TG43) for clinical dosimetric parameters

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

GBBS = grid-based Boltzmann solver; ICRU = International Commission on Radiation units; D_{2cc} = doses for the most exposed 2 cm^3 of the bladder.

Mikell et al, Brachytherapy, 2013 (in press)

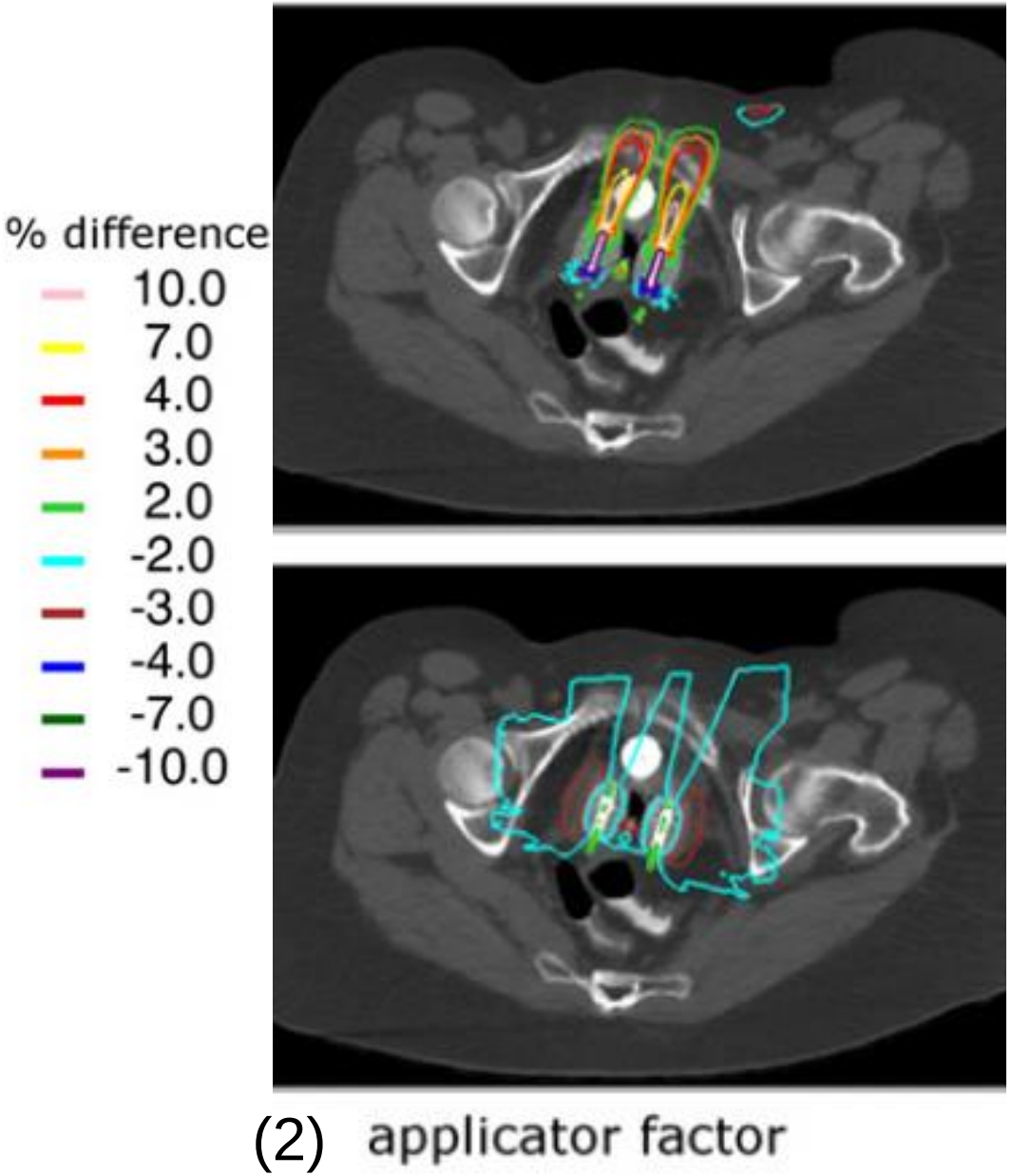
Clinical GYN HDR Example with Shielded Colpostats



Mikell et al, Brachytherapy, 2013 (in press)

CT/MR Colpostats

(1) source & boundary factor



(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) 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