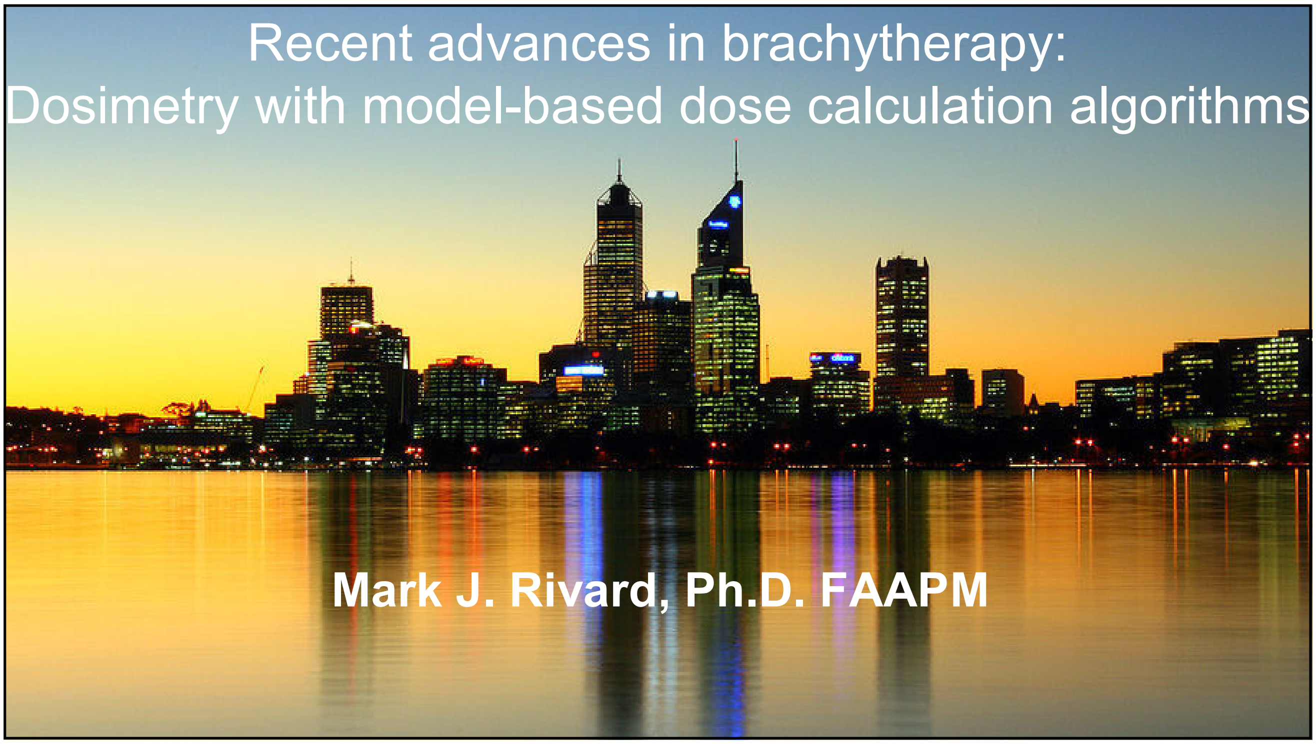


Disclosure

Research equipment and software have been provided by Elekta Brachytherapy and Varian Medical Systems.

Dr. Rivard serves as a consultant to CivaTech Oncology and a minor stakeholder for Advanced Radiation Therapy, LLC

Learning Objectives

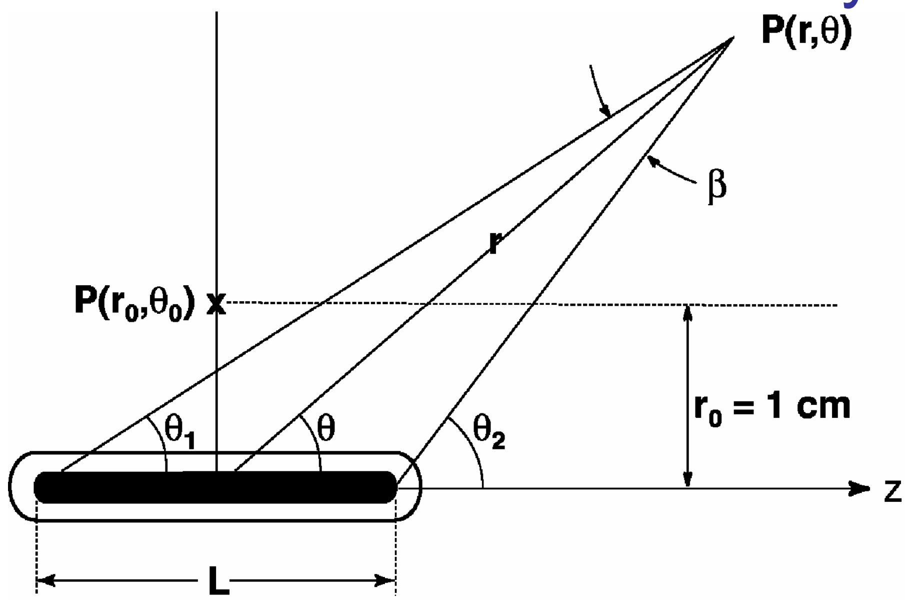
- current state-of-the-art of MBDCAs for BT dosimetry
- MBDCAs for dosimetry of directional-modulated sources and intensity-modulated BT

TG-43U1 BT Dosimetry Formalism (2D)

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta)$$

$\dot{D}(r,\theta)$	dose rate to water in water at point $P(r,\theta)$
S_K	air kerma strength
Λ	dose rate constant
$g_L(r)$	radial dose function
$G_L(r,\theta)$	geometry function (line source approximation)
$F(r,\theta)$	2D anisotropy function

BT Dose Calculation Geometry

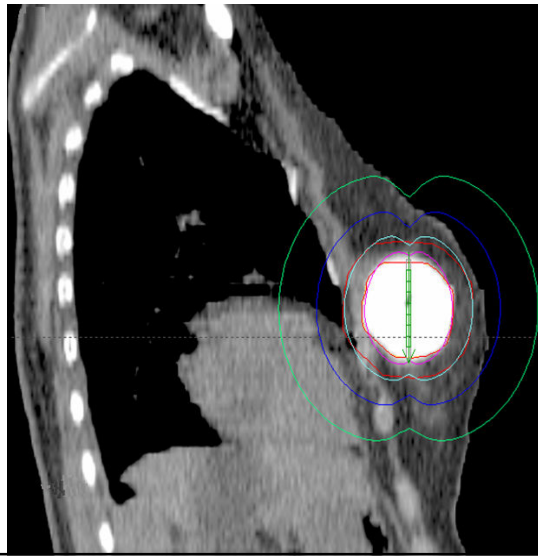


Rivard *et al.*, *Med. Phys*. 31, 633-674 (2004)

Example Dosimetry Parameter Dataset

1	r [cm]	$g_L(r)$	$g_P(r)$	r [cm]	phi(r)		F(r,8)	0	10	20	30	40	50	60	70	80
2	0.10	0.990	0.582	0.25	1.164		0.05							1.067	0.996	0.985
3	0.25	1.021	0.889	0.5	0.973		0.075					1.050	1.006	0.994	0.996	0.996
4	0.50	1.030	0.998	1.0	0.933		0.1				1.046	0.996	0.990	0.993	0.988	0.999
5	1.00	1.000	1.000	1.5	0.931		0.15			1.039	0.978	0.958	0.977	0.988	0.987	0.996
6	1.50	0.943	0.949	2.0	0.931		0.2		0.987	0.921	0.940	0.960	0.975	0.984	0.988	0.997
7	2.00	0.872	0.879	2.5	0.932		0.25	0.494	0.574	0.785	0.899	0.943	0.967	0.986	0.995	1.000
8	2.50	0.795	0.803	3.0	0.934		0.5	0.610	0.513	0.679	0.808	0.892	0.944	0.974	0.990	0.997
9	3.00	0.717	0.724	3.5	0.935		1	0.580	0.561	0.705	0.813	0.885	0.933	0.967	0.987	0.997
10	3.50	0.643	0.650	4.0	0.937		2	0.652	0.626	0.743	0.830	0.893	0.934	0.967	0.987	0.997
11	4.00	0.573	0.579	4.5	0.938		5	0.690	0.700	0.789	0.854	0.905	0.941	0.968	0.986	0.996
12	4.50	0.508	0.513	5.0	0.938		10	0.709	0.742	0.815	0.872	0.912	0.947	0.972	0.990	0.997
13	5.00	0.448	0.453	6.0	0.939											
14	6.00	0.347	0.351	7.0	0.942		Λ =	1.011								
15	7.00	0.265	0.268	10.0	0.948		L = 3.7 mm or 0.37 cm									
16	8.00	0.201	0.203													
17	9.00	0.151	0.153													
18	10.00	0.114	0.115													

Conventional TPS Fails to Accurately Calculate Brachytherapy Dose



air ≠ water?

tissue ≠ water?

contrast impact?

source superposition?

source shielding?

radiation scatter?

TG-43 Formalism: Liquid Water

tissue is not water-equivalent
variable/dynamic scattering conditions
no account for source/applicator shielding
TG-43 formalism to serve as future QA method

Brachytherapy Dose Calculation Methods

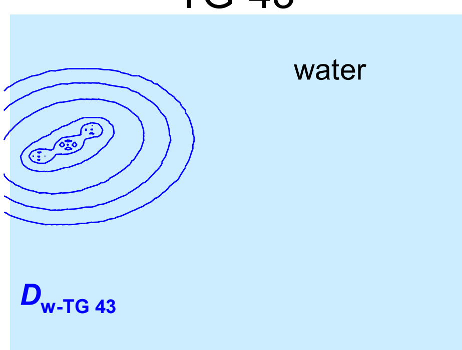
	INPUT		"CALCULATION"		OUTPUT
TG-43	source characterization	⇨	superposition of single-source data	⇨	$D_{W:TG\text{-}43}$

	INPUT		CALCULATION		OUTPUT
MBDCA	source characterization	⇨	Monte Carlo GBBS Collapsed Cone	⇨	$D_{M,M}$ $D_{W,M}$
	tissue+applicator information	⇨			

courtesy Å. Carlsson Tedgren

Dose is Calculated

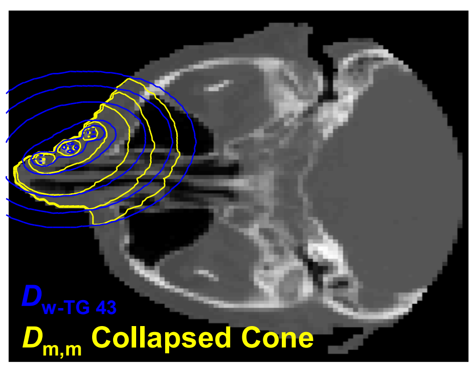
TG-43



superposition of single-source water-doses

imaging: localize dose onto anatomy

MBDCA



dose is *calculated* using imaging for tissue information

courtesy Å. Carlsson Tedgren

BT Dose Calculation Methods

Method	Characteristics	Remarks
Monte Carlo	explicit particle transport simulation + accurate – noisy dose distributions	standard source characterization and research tool, clinical use under development
analytic solvers	solves transport equations deterministic methods + accurate – discretization effects	standard tool in Nuc engin, clinical implementation (GBBS) only for HDR ^{192}Ir
scatter kernel methods ***Collapsed Cone based on PSS data***	implicit particle transport + accurate – discretization effects – small systematic errors	potenital for parallel hardware, e.g. GPU, clinical use under development
TG-43 hybrid methods	+ much more accurate than TG-43 + fast, available with current TPS – highest accuracy not obtained	can sevrve as dose engine within optimization loops, sensitive geometry assumptions
Parameterization of Primary and Scatter Separation (PSS) data	no particle transport + fast, robust radial extrapolation – neglect effects from shields, finite patient, heterogeneties	same source data as advanced algorithms
TG-43	no particle transport + fast, familiar, permits hand calcs – neglect effects from shields, finite patient, heterogeneties	current clinical workhorse

model based

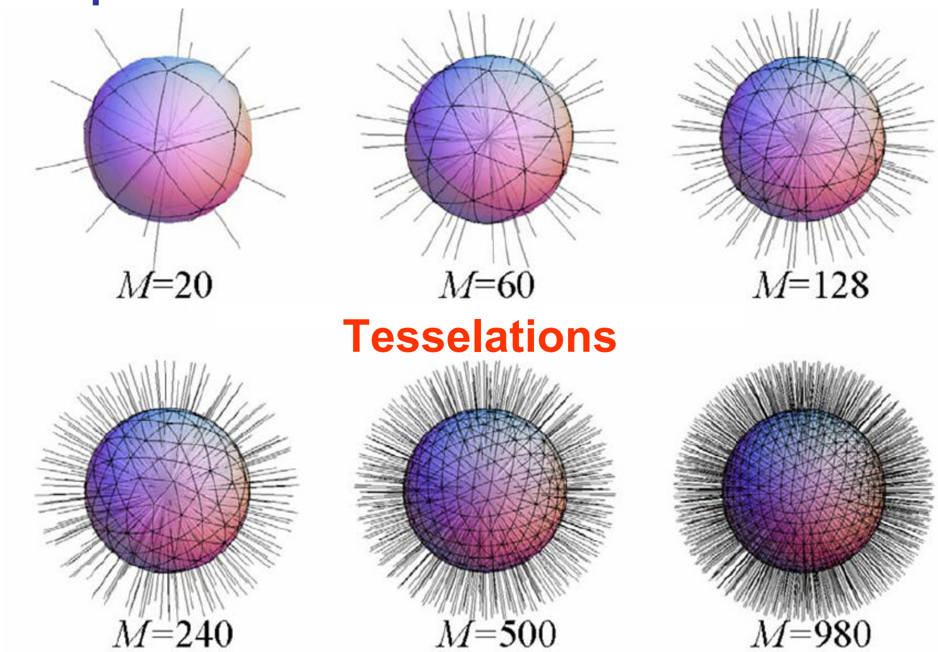
factor based

explicit physics modeling

Relevance of MBDCA Influence

- HDR ^{192}Ir breast tissues (–10% to –30%), bone (+5% to +10%)
- HDR eBT breast tissues (–10% to –70%), bone (+25% to +800%)
- HDR ^{192}Ir GYN tissues (–3% to –10%) much lower with shielding
- HDR ^{192}Ir prostate tissues (–3% to –10%)
- LDR ^{125}I prostate tissues (–5% to –10%) much lower with Ca
- LDR ^{125}I eye plaque tissues (–10% to –92%), bone (+15% to +500%)

Collapsed Cone Scatter Tesellations



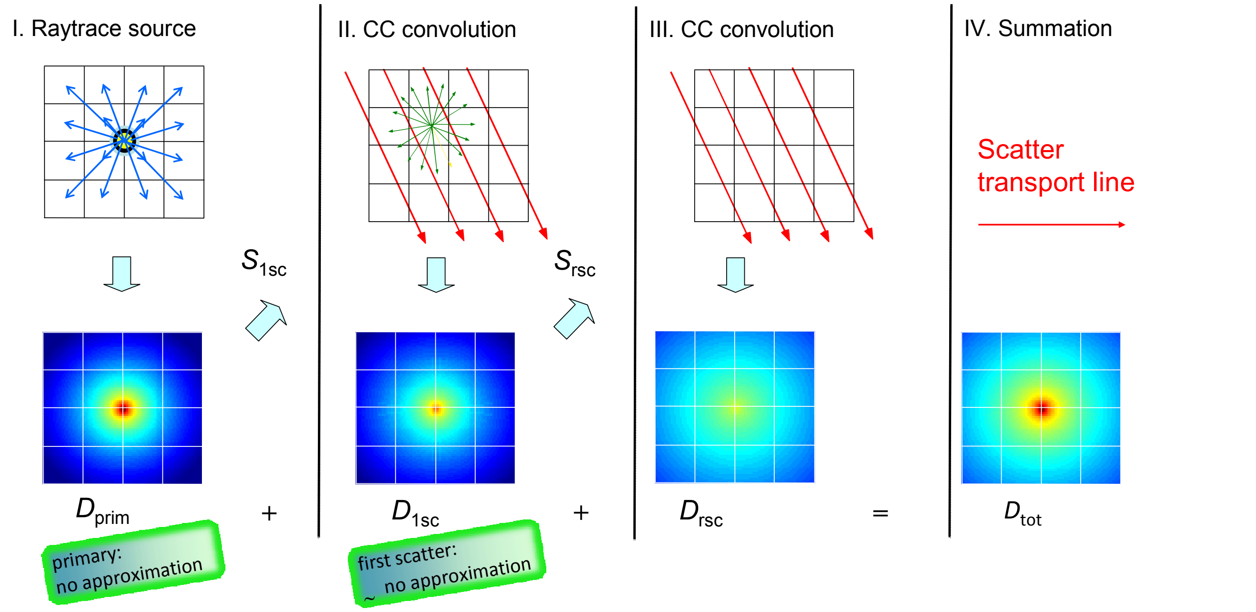
Advanced Collapsed Cone Engine: ACE

- Implementation only for ^{192}Ir
  1. CPE assumption : D_{prim} ➔ K_{coll}
     - Primary dose analytical (from fluence)
     - Ray-tracing with scaling (heterogeneities!)
     - Some correction factors (volume, anisotropy, …)
  2. First scatter from primary : $S_{1c} = \left(\frac{\mu - \mu_{en}}{\mu_{en}} \right) D_{prim}$
  3. Multiple scatter components from D_{1sc}.
     - Exponential parametrization of MC point kernels

Russell & Ahnesjö 1996 PMB 41; Carlsson & Ahnesjö 2000 Med Phys 27;
Carlsson & Ahnesjö 2000 PMB 45; Carlsson & Ahnesjö. 2003 Med Phys 30;
Russell et al 2005 Med Phys 32; Carlsson Tedgren & Ahnesjö 2008 Med Phys 35.

courtesy Firas Mourtada

Outline of ACE



(Åsa K. Carlsson & Anders Ahnesjö, 2000)

courtesy Firas Mourtada

Linear Boltzmann Transport Equation

In this section, we describe the general methods used in Attila™ for neutral particle transport. The methods used for charged particle transport will be described in a future article. Attila™ solves three-dimensional linear Boltzmann transport equation, the governing equation for radiation transport[1]. For volume, V, with surface, δV, the linear Boltzmann transport equation, along with vacuum boundary conditions, is given by:

$$\hat{\Omega}\cdot\vec{\nabla}\Psi(\vec{r},E,\hat{\Omega})+\sigma_t(\vec{r},E)\Psi(\vec{r},E,\hat{\Omega}) = Q^{scat}(\vec{r},E,\hat{\Omega})+Q^{ex}(\vec{r},E,\hat{\Omega}),\ \vec{r}\in V \quad (1a)$$

$$\Psi(\vec{r},E,\hat{\Omega})=0,\ \vec{r}\in\delta V,\ \hat{\Omega}\cdot\vec{n}<0. \quad (1b)$$

Here $\Psi(\vec{r},E,\hat{\Omega})$ is the angular flux at position, $\vec{r}=(x,y,z)$, energy, E, direction, $\hat{\Omega}=(\mu,\eta,\xi)$, and $\vec{n}$ is the normal vector to surface δV. The first term on the left hand side of Eq. (1) is termed the streaming operator. The second term on the left hand side of Eq. (1a) is termed the collision operator, where $\sigma_t(\vec{r},E)$ is the macroscopic total cross section. The right had side of Eq. (1a) includes the source terms, where $Q^{scat}(\vec{r},E,\hat{\Omega})$ is the scattering source and $Q^{ex}(\vec{r},E,\hat{\Omega})$ is the extraneous source. The scattering source is explicitly given as:

$$Q^{scat}(\vec{r},E,\bar{\Omega})=\int_0^\infty dE'\int_{4\pi}\sigma_s(\vec{r},E'\to E,\hat{\Omega}\cdot\hat{\Omega}')\Psi(\vec{r},E',\hat{\Omega}')d\hat{\Omega}', \quad (2)$$

courtesy Firas Mourtada

Grid-Based Boltzmann Solver (GBBS)

- Deterministic approach solving the linear Boltzmann transport equation

$$\underbrace{\hat{\Omega}\cdot\vec{\nabla}\psi^{\gamma}}_{\text{Streaming operator}} + \underbrace{\sigma_t^{\gamma}\psi^{\gamma}}_{\text{Collision operator}} = \underbrace{Q^{\gamma(ext)} + Q^{\gamma(scat)}}_{\text{Sources}}$$

$$\underbrace{\hat{\Omega}\cdot\vec{\nabla}\psi^{e}}_{\text{Streaming operator}} + \underbrace{\sigma_t^{e}\psi^{e}}_{\text{Collision operator}} - \underbrace{\frac{\partial}{\partial E} s_R \psi^{e}}_{\text{CSDA operator}} = \underbrace{Q^{e(ext)} + Q^{scat}}_{\text{Sources}}$$

courtesy Firas Mourtada

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 discretization (finite elements)
- Energy: E Energy bins (cross section)
- Direction: $\hat{\Omega} = (\theta,\phi)$ Angular discretization

« multi-group discrete ordinates»

2D: Daskalov et al, Med Phys 29 (2002)
3D: Gifford et al, Phys Med Biol 53 (2006)

courtesy Luc Beaulieu

Grid-Based Boltzmann Solver (GBBS)

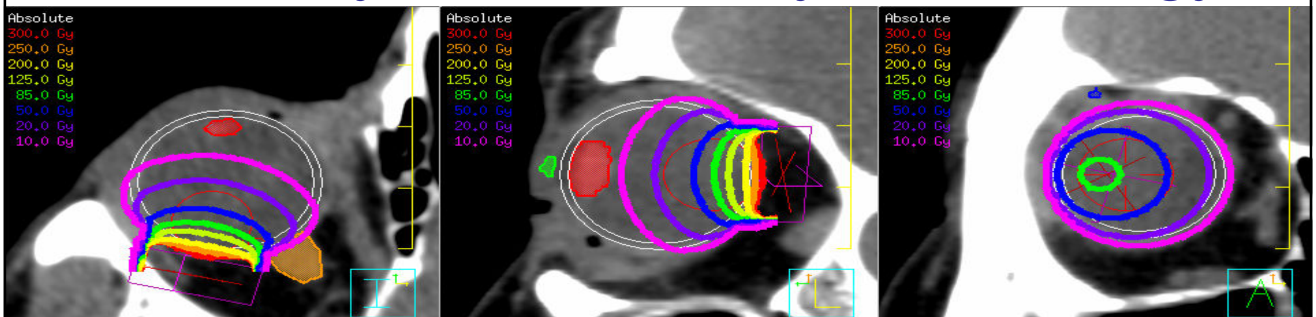
- Varian BV-Acuros® implementation:
  - CPE assumption : Primary dose analytical (ray-tracing with scaling)
    - $D_{prim} = K_{coll}$
    - First scatter from primary:
      Scerma = Dprim•((μ-μ_{en})/u_{en})
    - <u>Share this step with CCC</u>
  - 3D scatter integration through GBBS
  - Source modeling done in Atilla® (Transpire Inc)

courtesy Luc Beaulieu

TG-43 Hybrid Methods

- use on FDA/CE approved TG-43-based BT TPS
- no 3D dose kernel entry (yet)
- only for rigid applicators/sources
- clinical applications for TG-43 hybrid approach
  - –vaginal cylinder (HDR ^{192}Ir)
  - –skin applicators – Leipzig and Valencia (HDR ^{192}Ir)
  - –eye plaques (LDR ^{103}Pd, ^{125}I, ^{131}Cs)
  - –AccuBoost breast BT boost/APBI (HDR ^{192}Ir)
  - –CivaSheet (LDR ^{103}Pd) directional source

TG-43 Hybrid Dosimetry: Low Energy



Medical Physics

An approach to using conventional brachytherapy software for clinical treatment planning of complex, Monte Carlo-based brachytherapy dose distributions

Mark Rivard,[1] Chris Melhus,[1] Domingo Granero,[2] Jose Perez-Calatayud,[2] Facundo Ballester[3]

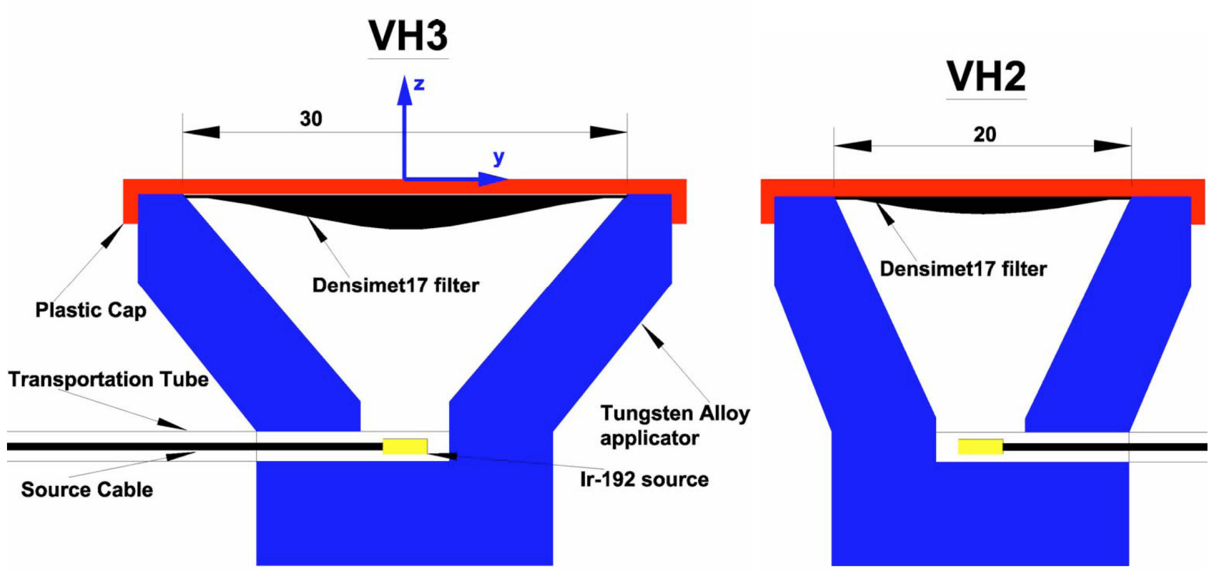
[1]*Department of Radiation Oncology, Tufts Medical Center, Boston, Massachusetts 02111*

[2]*Radiation Oncology Department, ''La Fe'' University Hospital, Valencia, Spain*

[3]*Department of Atomic, Molecular, and Nuclear Physics, University of Valencia, Spain*

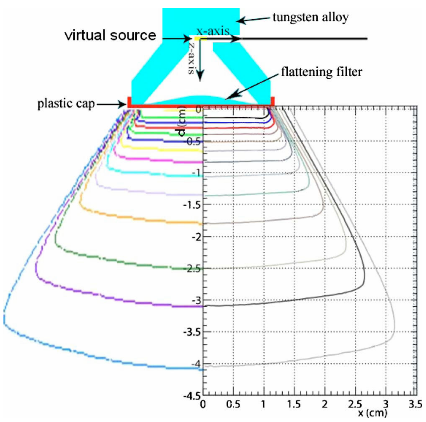
Med. Phys. 36, 1968-1975 (2009)

Valencia Skin Applicators

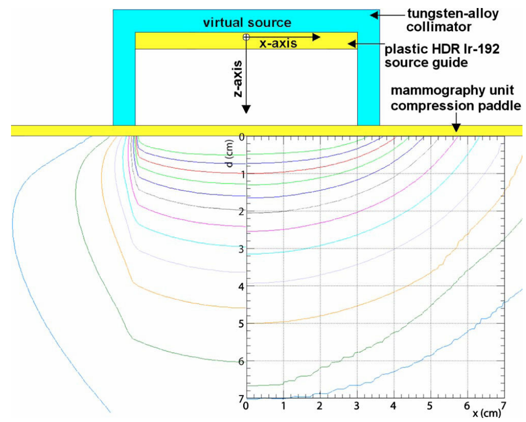


TG-43 Hybrid Dosimetry: High-Energy

Account for scatter/attenuation, shielding, media



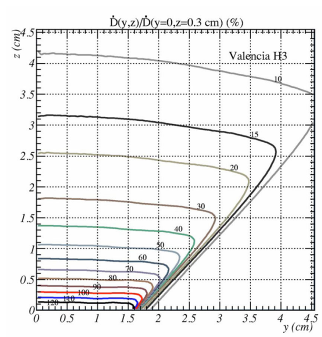
Valencia skin applicator

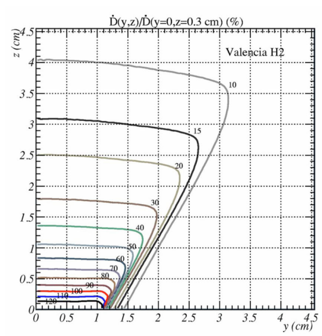


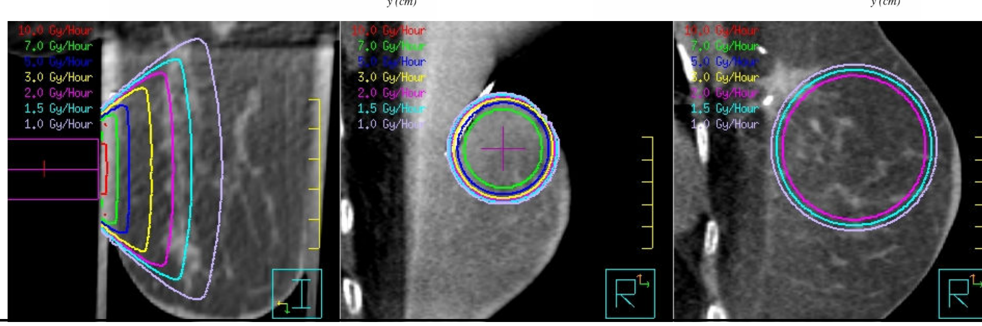
AccuBoost breast applicator

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

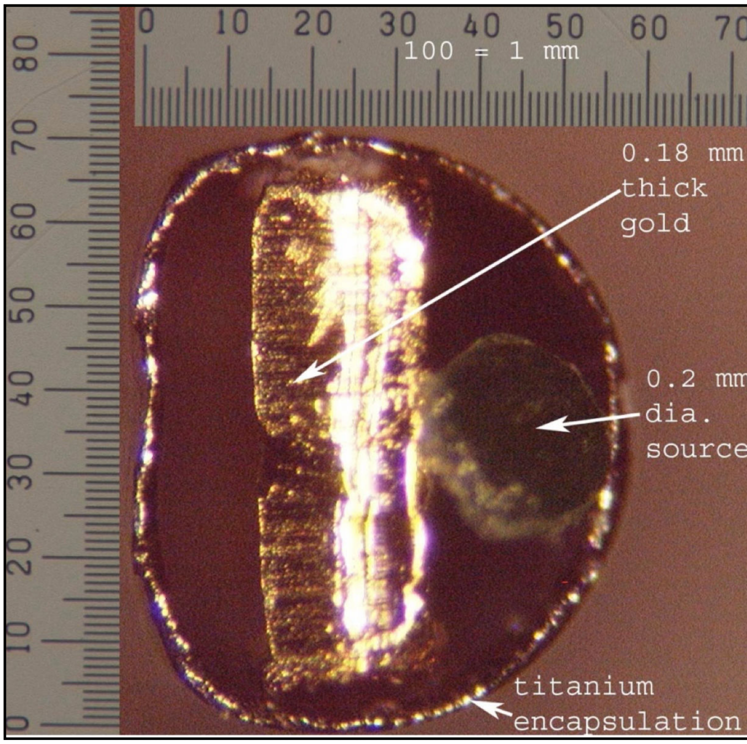
Valencia Applicator Dose Distributions

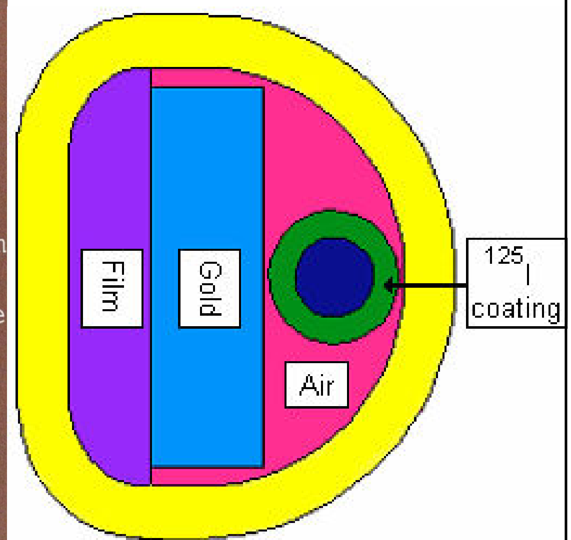






LDR ^{125}I directional source

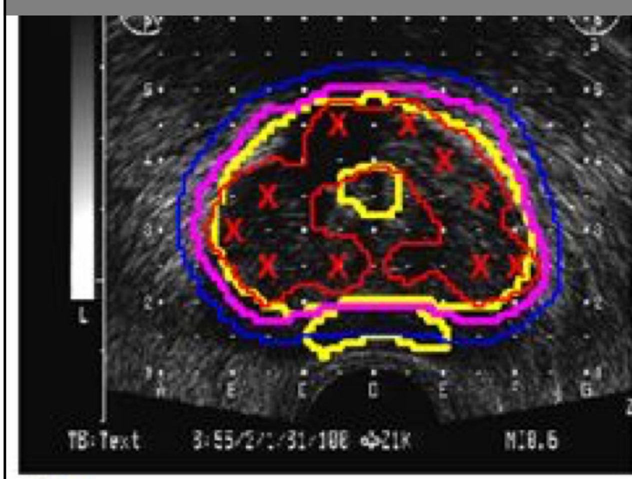


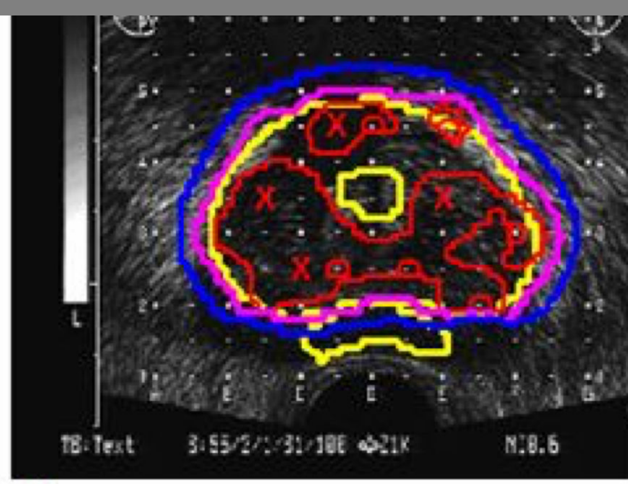


Lin et al. Med Phys 35, 240-247 (2008)

Prostate Plan Comparison

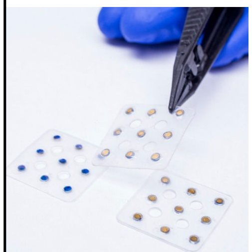
conventional seeds	directional seeds

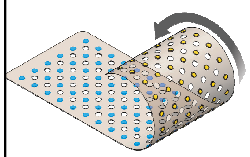


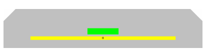


courtesy Bruce Thomadsen

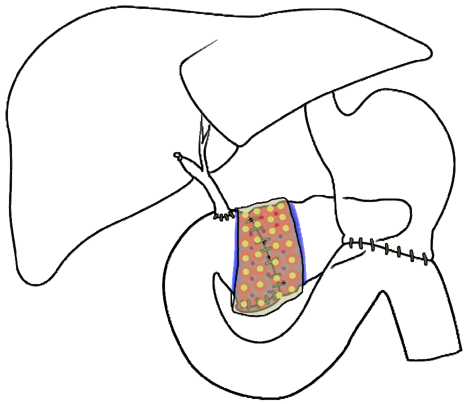
CivaSheet Description

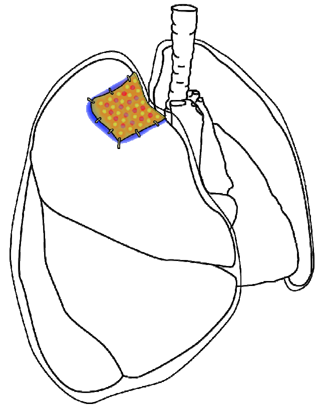






2.5 mm diam.

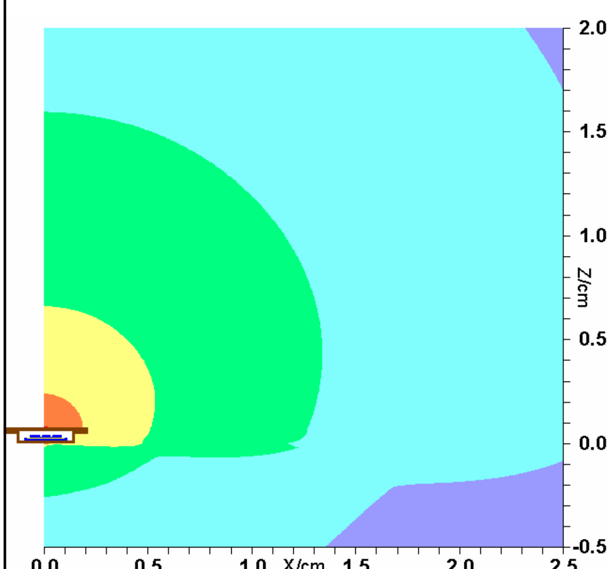




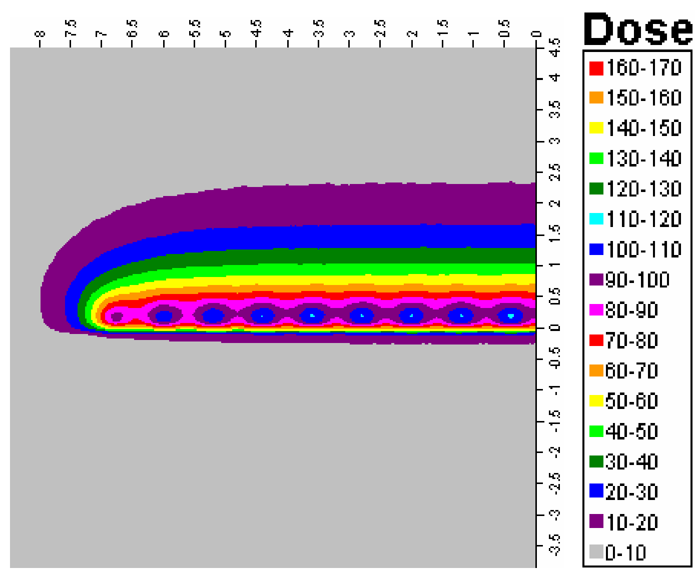
- flexible brachytherapy device containing ^{103}Pd
- directional radiation: front-side collimation, back-side shielding

courtesy Graeme O'Connell

CivaSheet LDR ^{103}Pd Shielded Source

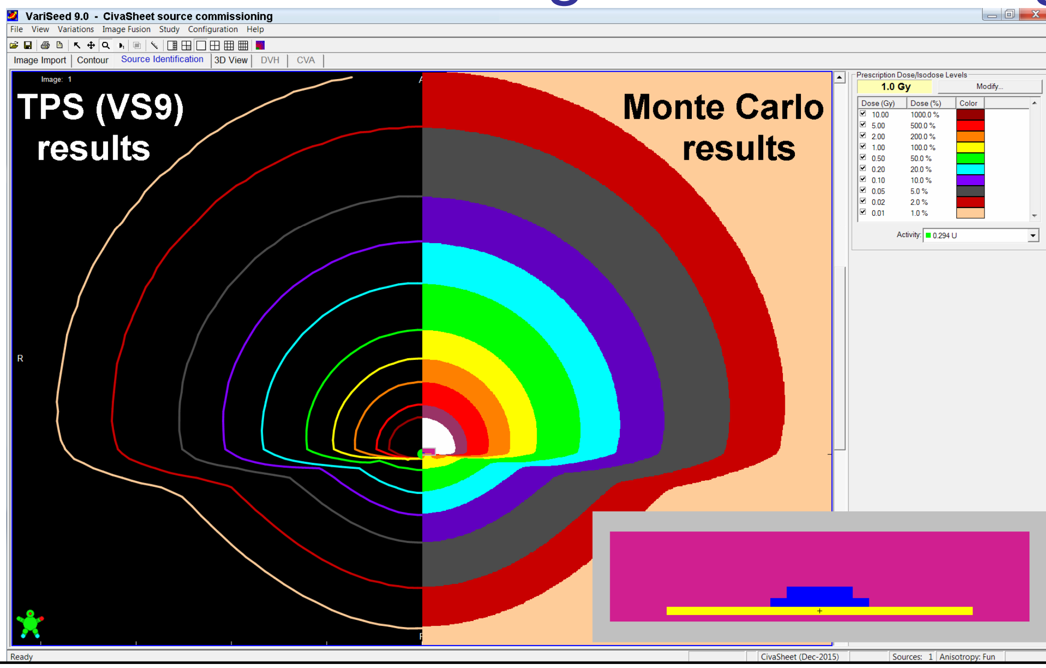


individual CivaDot

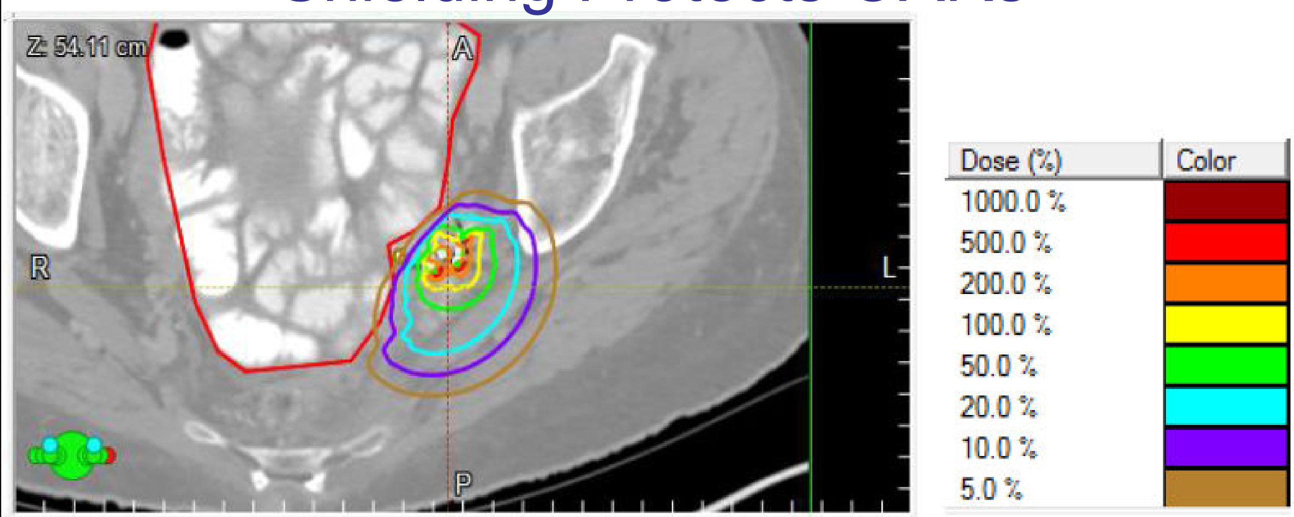


CivaSheet

Treatment Planning Commissioning

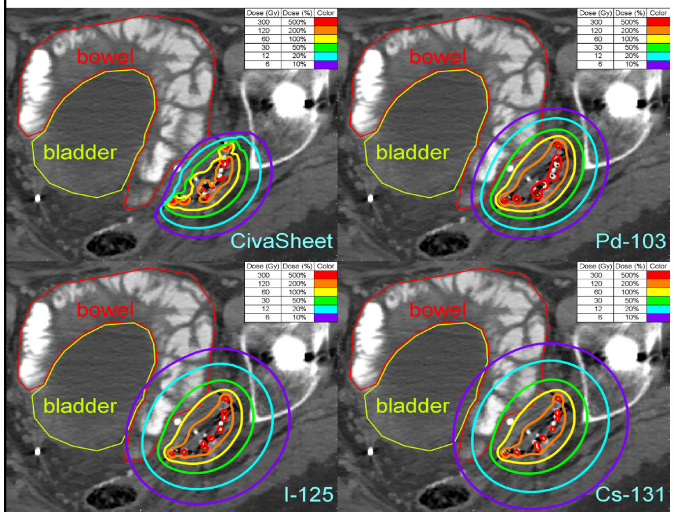


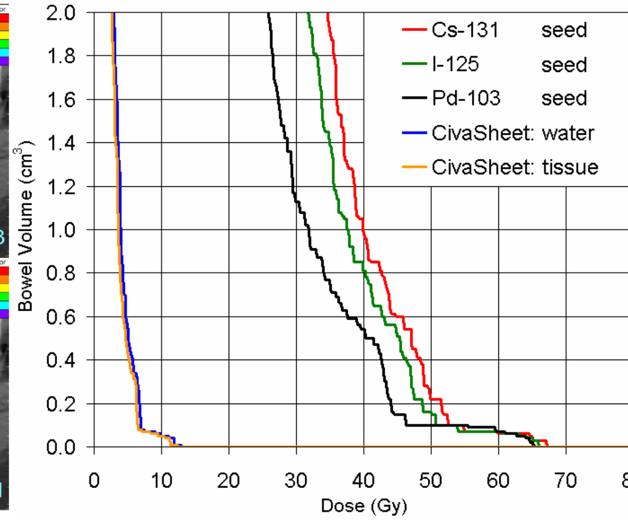
Shielding Protects OARs



post-op treatment planning results from a patient treated with CivaSheet

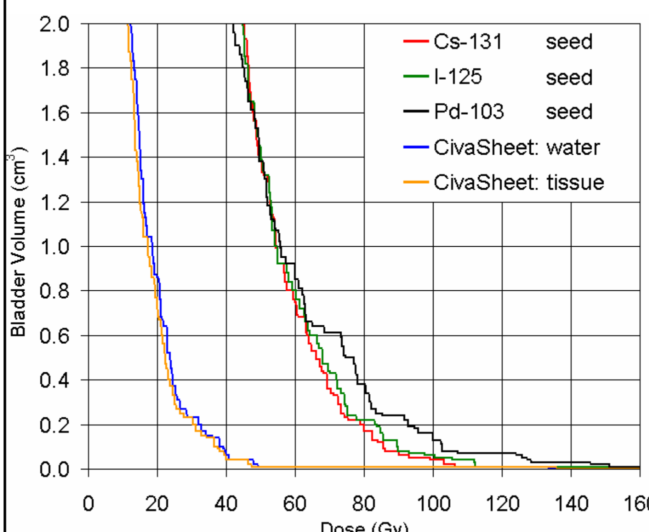
Isodose Comparison: LDR Seeds



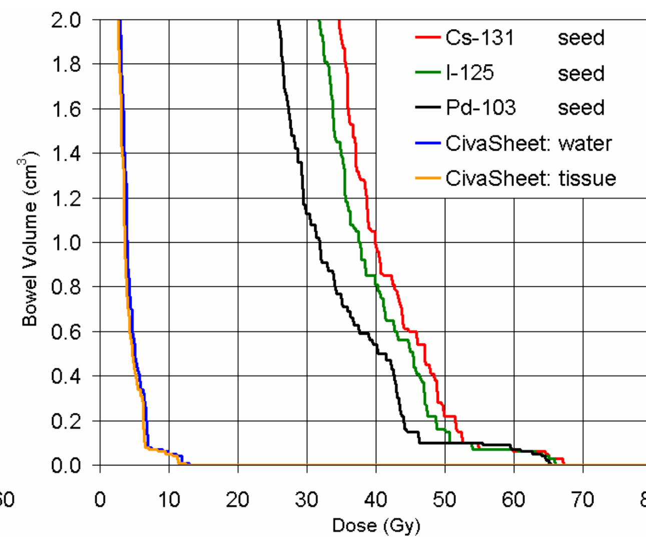


bowel DVH
reduced by *factor of 7*

Bladder DVH



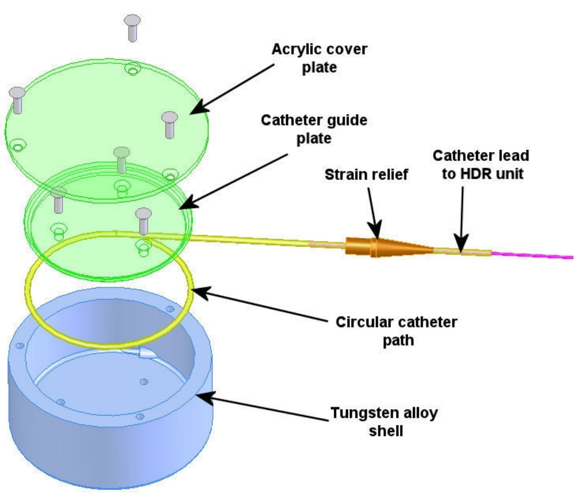
Bowel DVH

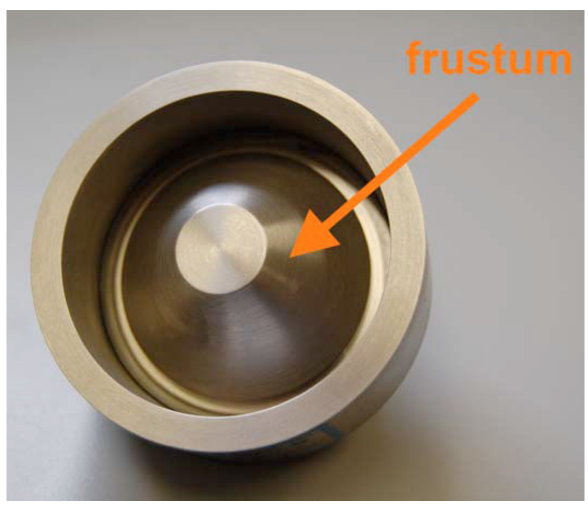


AccuBoost Applicators

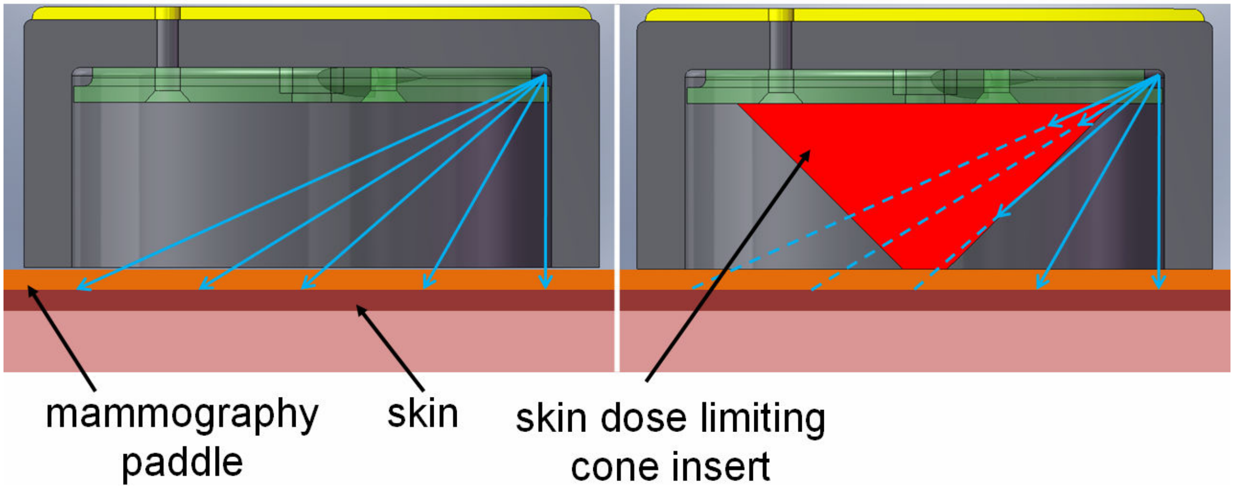
Yang, Melhus, Sioshansi, and Rivard, Med. Phys. 38, 1519-1525 (2011)

Applicator: Exploded View



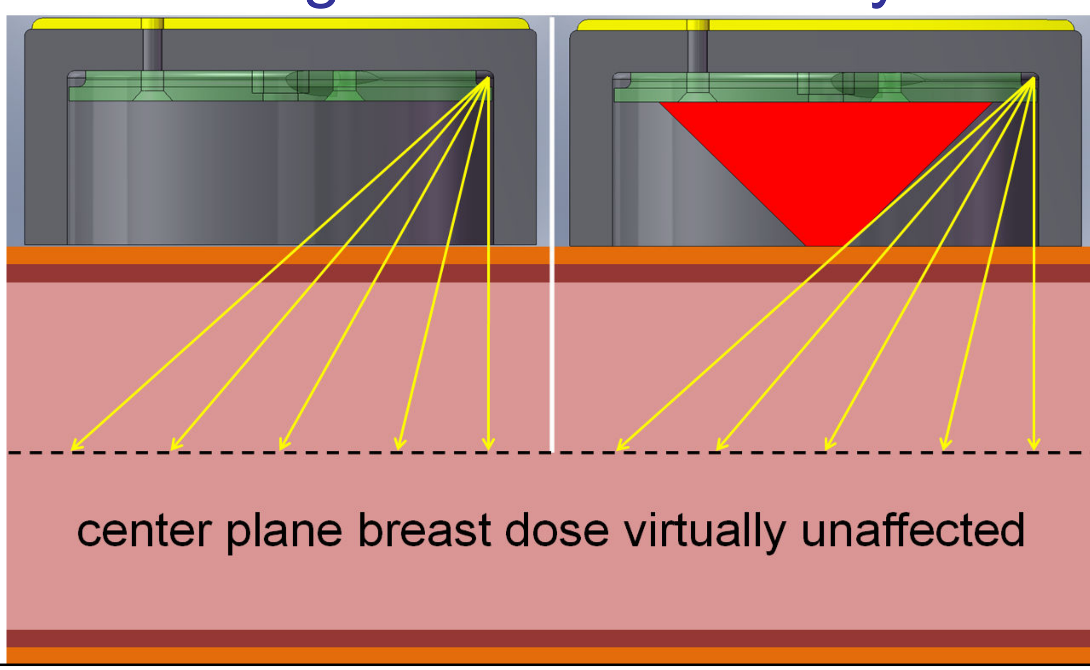


Dose Sparing of Skin

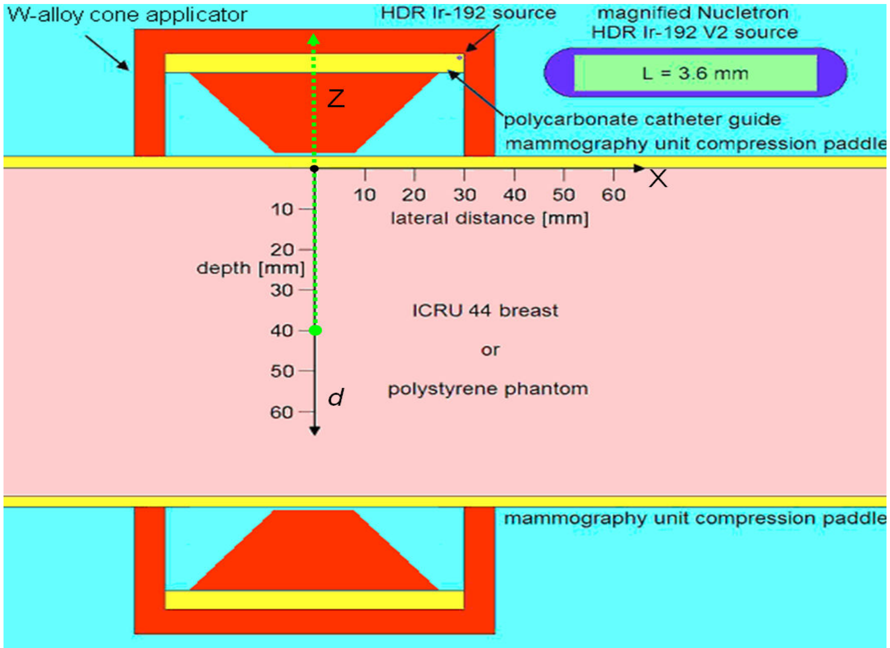


skin dose reduced to all points in
skin volume on opposing sides of the breast

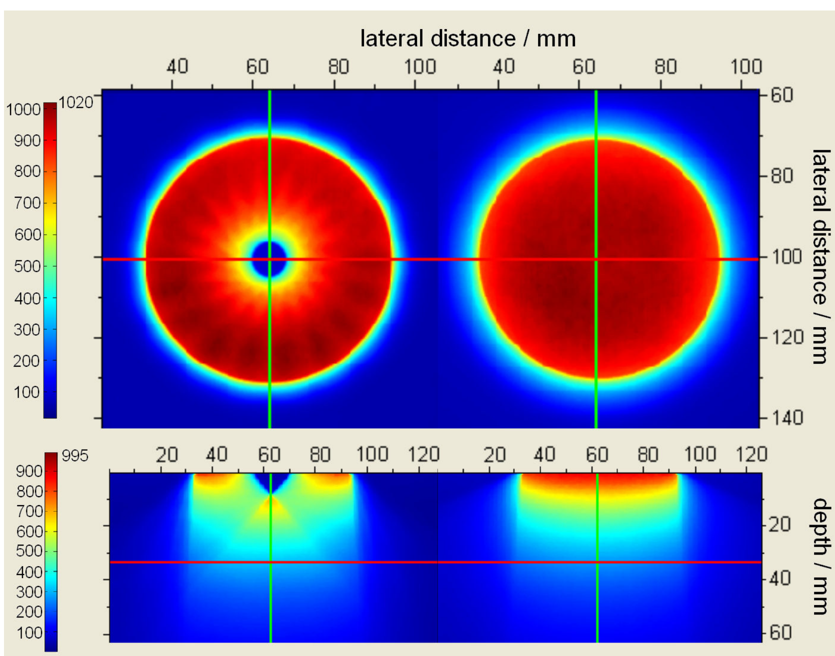
Target Dose Uniformity



Monte Carlo Simulation Geometry

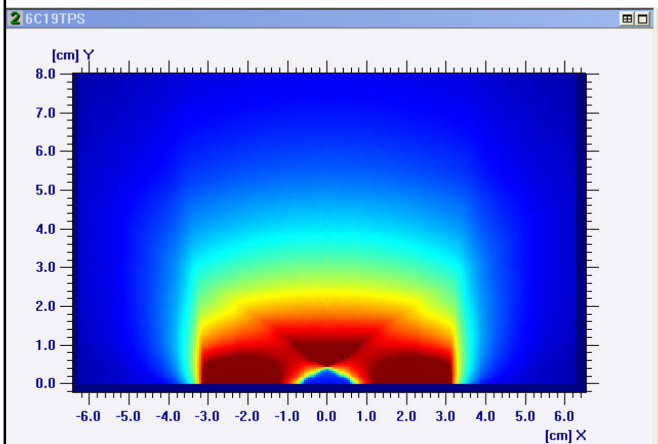


Measured Dose Distributions

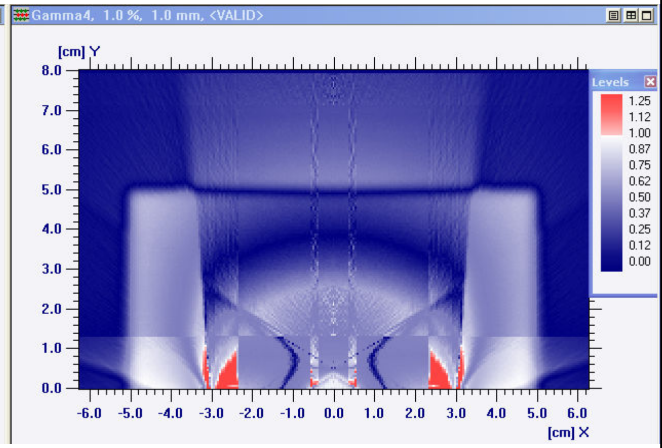


Need New TPS Evaluation Criteria

consider gamma-index analysis: distance-to-agreement (meaning?)

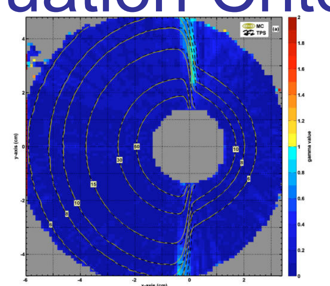


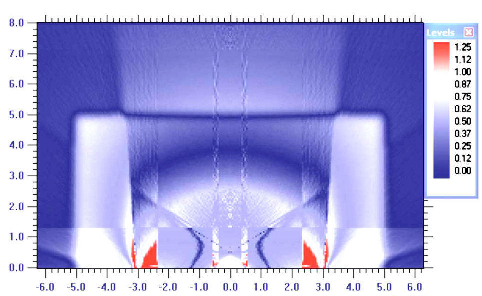
Yang et al., Med. Phys. 38, 1519-1525 (2011)

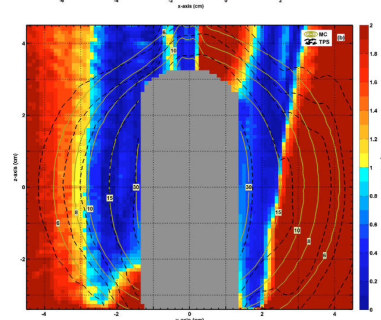


Yang & Rivard, Med. Phys. 37, 5665-5671 (2010)

Need New TPS Evaluation Criteria





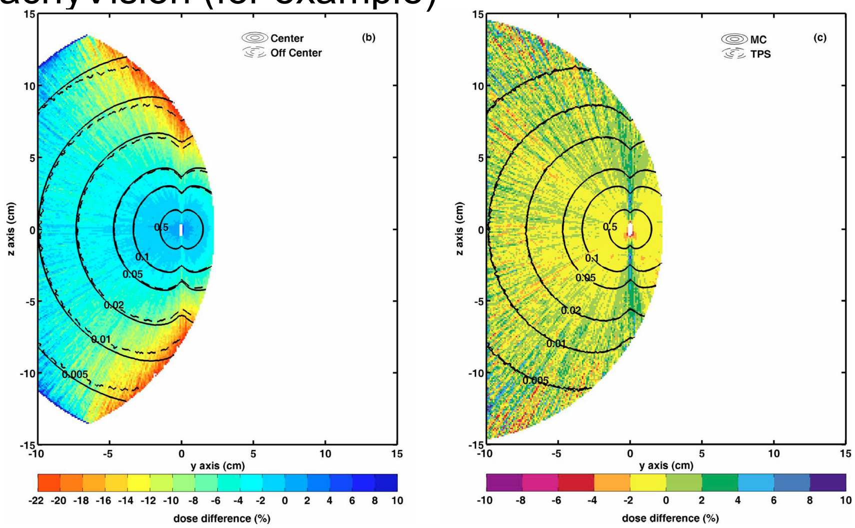


1% and 1 mm
Yang *et al.*, *Med. Phys.* (2011)

5% and 2 mm
Petrokokkinos *et al.*, *Med. Phys.* (2011)

Need Standardized MBDCA Benchmarks

- excellent reference HDR ^{192}Ir benchmark
  - –Acuros BrachyVision (for example)



Zourari *et al.*, *Med. Phys.* 37, 649-661 (2010)

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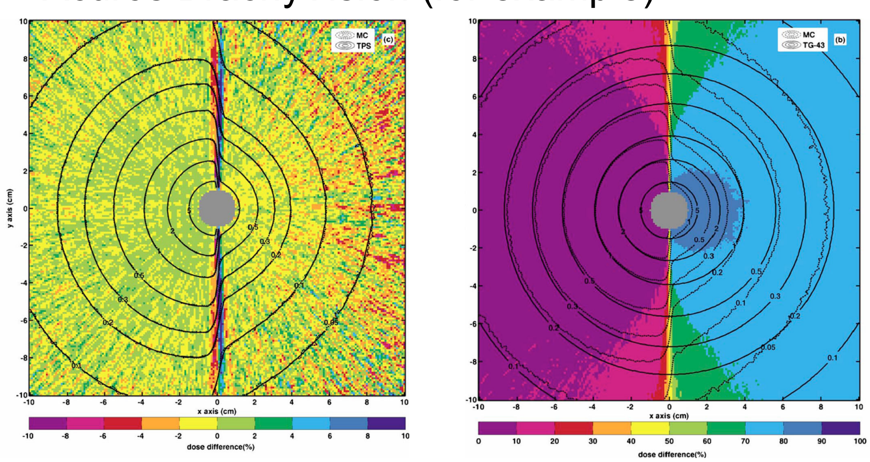
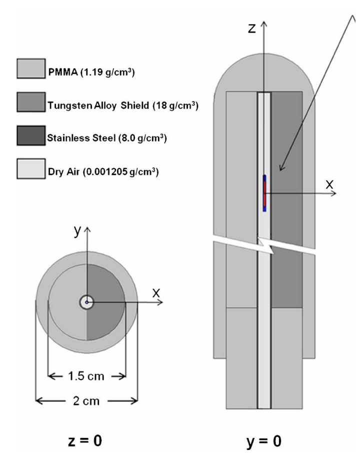
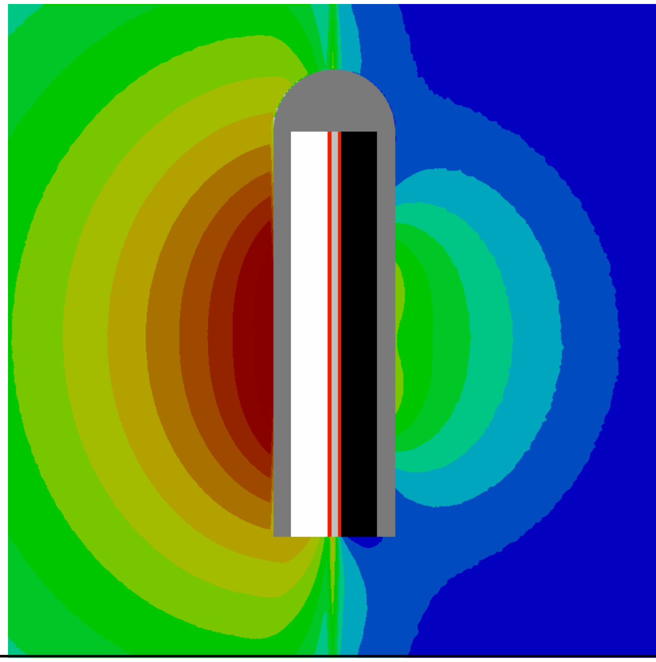




Petrokokkinos *et al.*, *Med. Phys.* 38, 1981-1992 (2011)

HDR ^{192}Ir source (1 dwell) Shielded Cylinder



courtesy Yunzhi Ma

Summary

- several choices available for advanced BT dose calcs
- MBDCAs are helpful for conventional source dosimetry, and required for dosimetry of directional modulated sources and intensity-modulated BT
- field is advancing through enhanced infrastructure, practice standardization, and image-guided BT