Course 3

Beyond TG-43 to Improve Brachytherapy Dosimetry

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COI Disclosure

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- Nucletron BV
- Varian Medical Systems
- Theragenics
- Transpire Inc.
- NIH/NCI R43 and R43 grants

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Learning Objectives / Purpose

- Explain current brachytherapy dose calculation formalism
- Current Brachytherapy TPS algorithm limitations
- Introduction to AAPM TG-186
- Some clinical implications

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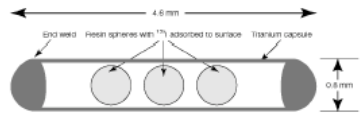
Brachytherapy Dosimetry Standard of Practice: AAPM Task Group No. 43

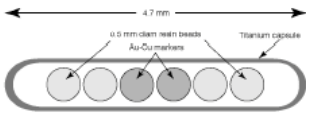
- TG-43 published in 1995
- More recently the 2004 TG-43U1 and 2007 TG-43U1S1 reports
  - recognized worldwide standards for
    - low-energy photon-emitting brachytherapy dosimetry,
    - HDR ^{192}Ir remote afterloading brachytherapy dosimetry.

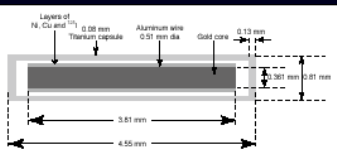
TG-43

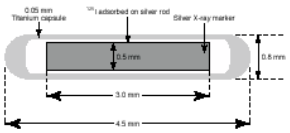
- In a modular fashion, dose deposition around one source in a finite radius of a water sphere.
- TPS uses pre-calculated dose distributions for given pattern of source placement and time.
- This method is fast, practical, and can be <u>consistent</u> in the clinic.

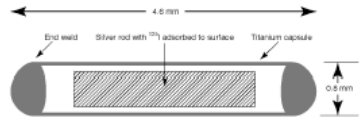
Low-Energy Brachytherapy Sources

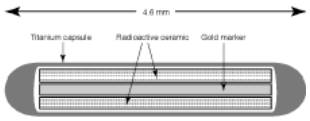

Amersham Health model 6702 source

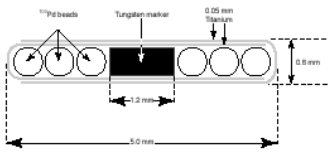

NASI model MED3631-A/M or MED3633 source

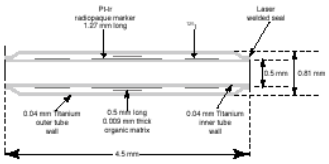

Source Tech Medical STM1251 seed

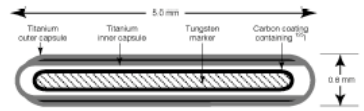

IsoAid Advantage

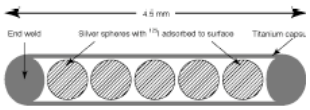

Amersham-Health model 6711 source


Bebig model I25.S06 source


Best Pd


International Brachytherapy InterSource


Best model 2301 source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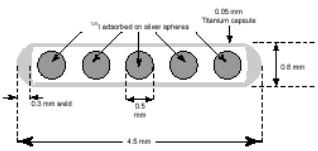
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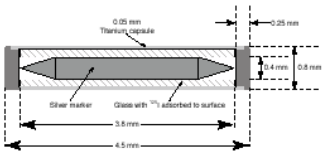
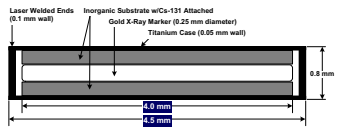
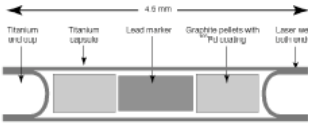
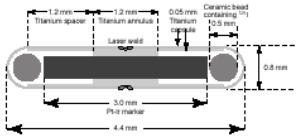
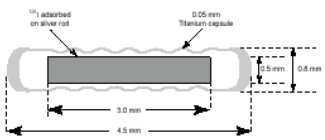

Implant Sciences 3500


IsoRay model CS-1 Rev2


Theragenics model 200 source


DraxImage LS-1


Amersham 6733

Courtesy of Mark Rivard

High-Energy Brachytherapy Sources

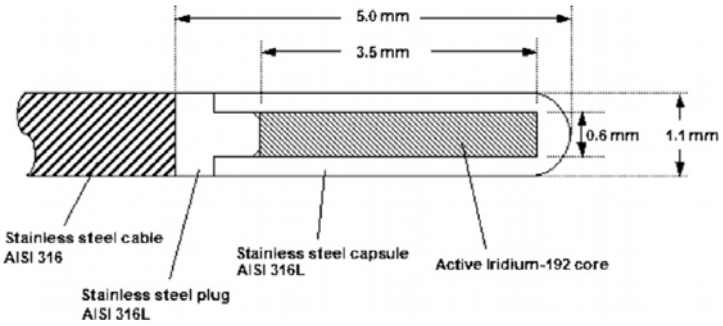
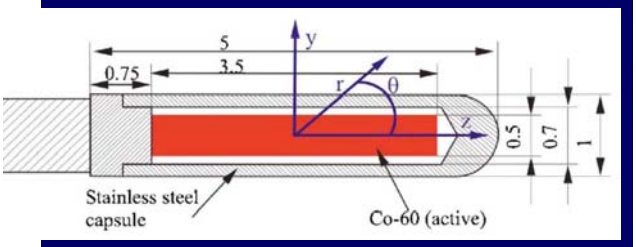


Figure 1. Schematic drawing of the Nucletron 'Classic' ^{192}Ir HDR brachytherapy source.



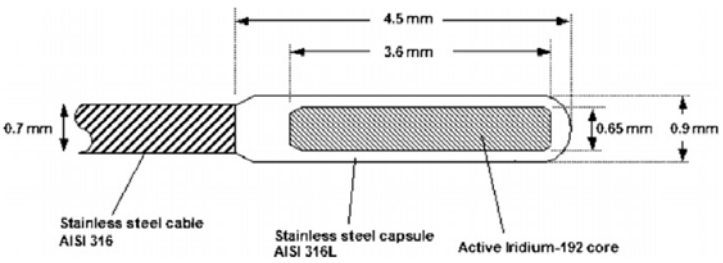
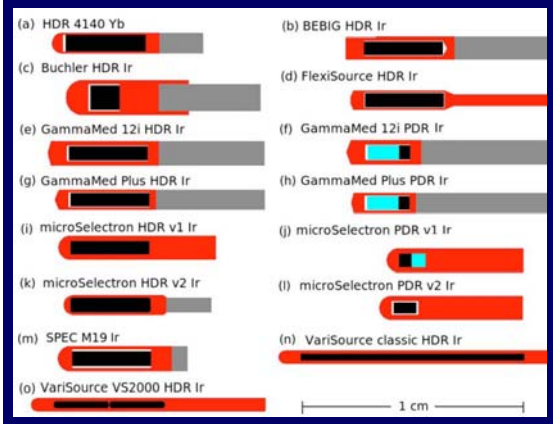
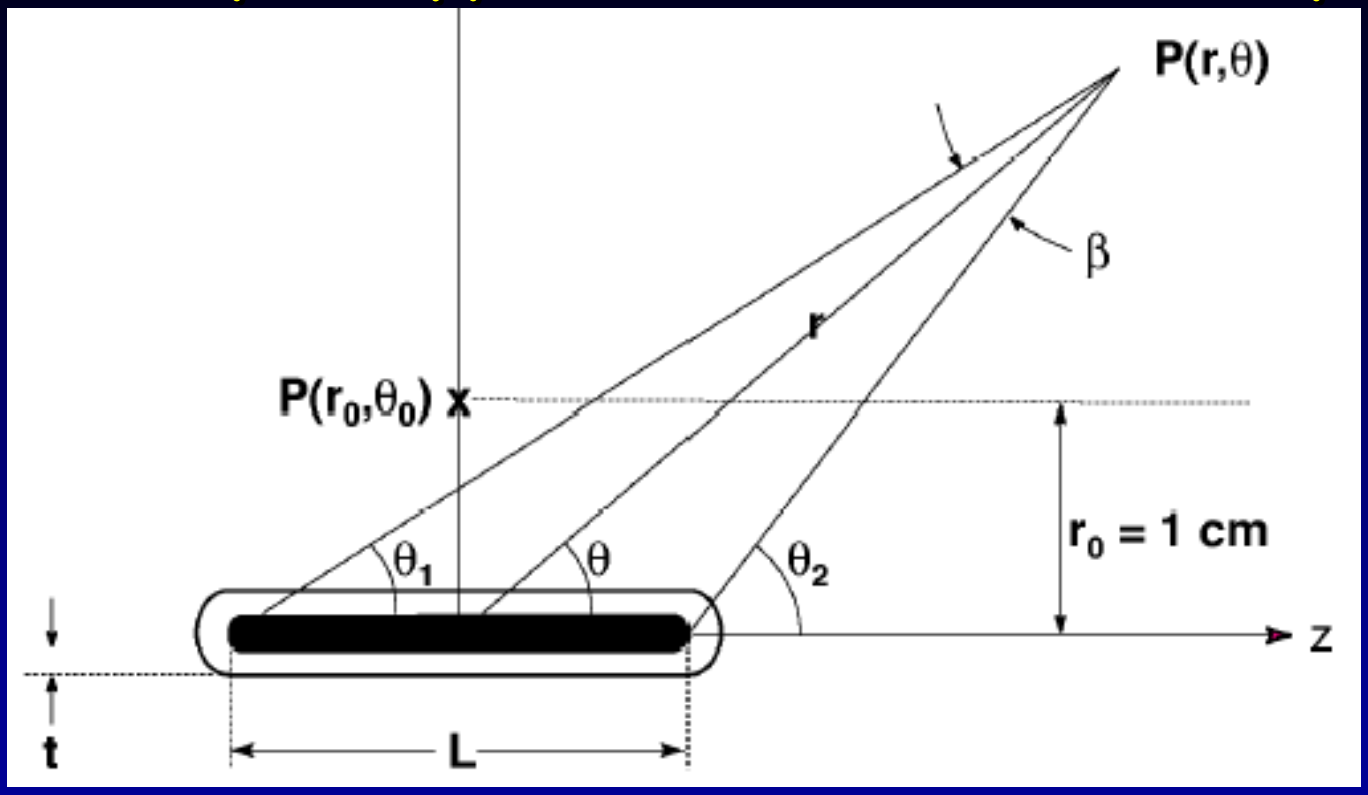


Figure 2. Schematic drawing of the Nucletron 'V2' ^{192}Ir HDR brachytherapy source.



Courtesy of Mark Rivard

Brachytherapy Dose Calculation Geometry



2004 AAPM TG-43U1 Brachytherapy Dosimetry Formalism (2D)

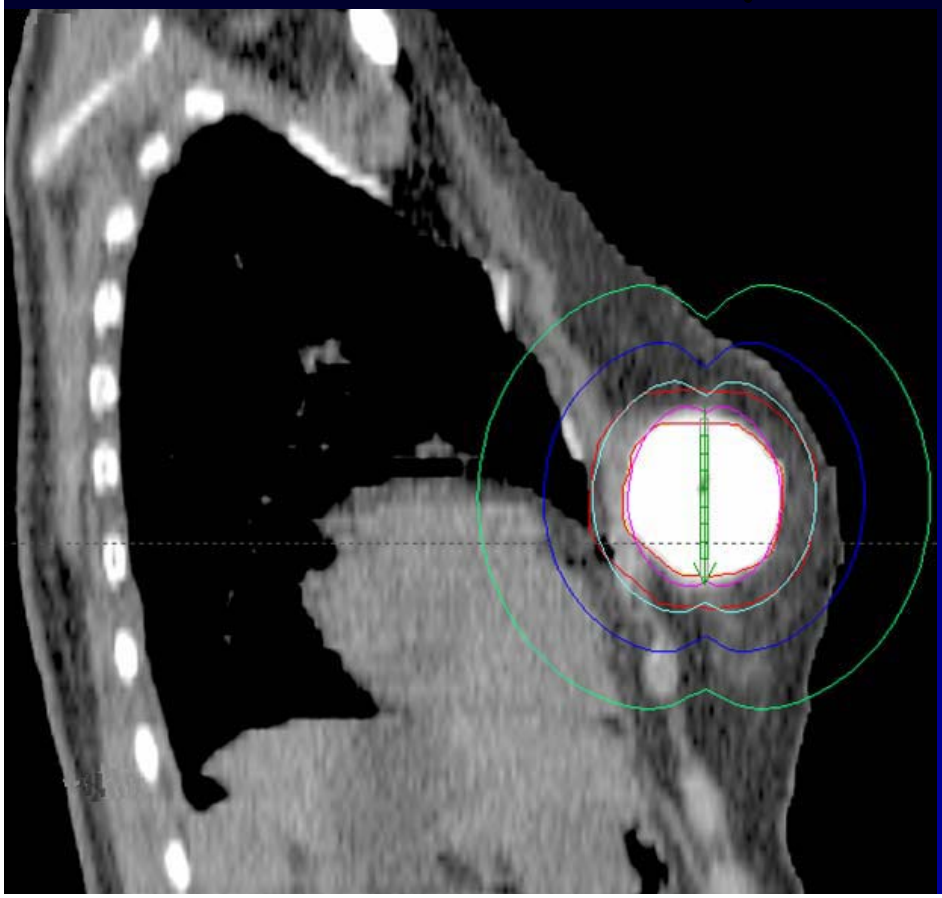
$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta)$$

$\dot{D}(r,\theta)$	dose rate to water in water at point P(r,θ)
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

The Paradigm Shift

- TG43 simplifications have been challenged by many publications over the past decade.
- New approaches based on fundamental physics processes or physics models such as the linear-Boltzmann transport equation are now applicable in a clinical setting.

Conventional TPS Fails to Accurately Calculate Brachytherapy Dose



air ≠ water?

tissue ≠ water?

contrast impact?

source superposition?

source shielding?

radiation scatter?

Courtesy of Mark Rivard

Ideally…

- A Brachytherapy treatment planning system should….
  - Account for the effects of the patient boundaries
    - (5-15%)
  - Account for the effect of applicator
    - reduction or enhancement or both
    - (5% to 50%)
  - Account for patient heterogeneities
    - (1-10% for Ir-192, 10-20% for Pd-103)
  - Fast and easily done in a busy clinic!!!
    - No cluster required to run
    - Workflow similar to current TPS

Scattered Photon Contribution in Brachy

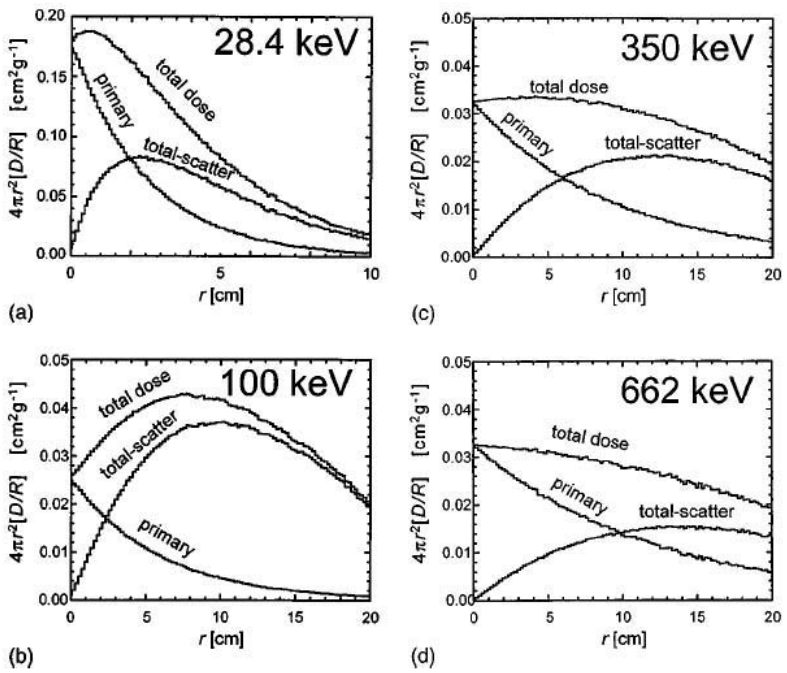
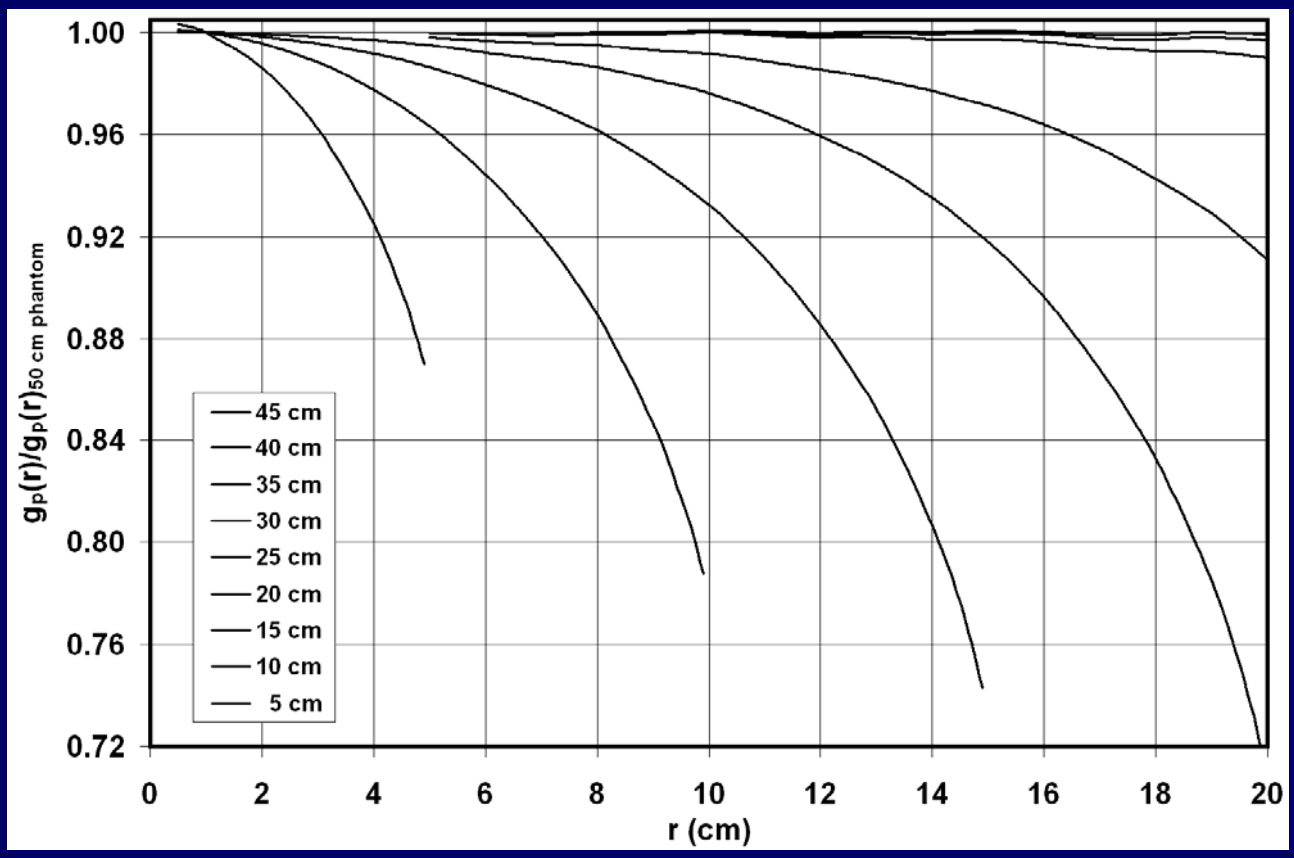


FIG. 1. Contributions of primary and scattered photons to total absorbed dose at the photon energies investigated in this work. (a) 28.4 keV, (b) 100 keV, (c) 350 keV, and (d) 662 keV. The calculations are for point sources inside cubic phantoms with side lengths of 20 cm at 28.4 keV and 40 cm at the higher energies. The dose distributions are derived by an extended version of EGS4 and multiplied by the distance squared and normalized to the primary photon energy.

A. K. Carlsson and A. Ahnesjo, Med Phys 27(10), 2000

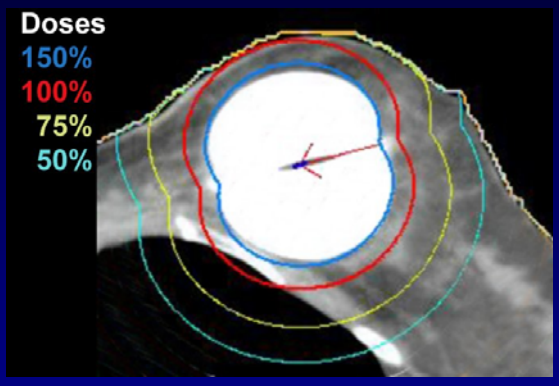
TG43 accurately account for scatter for a single source in water (R=15cm)

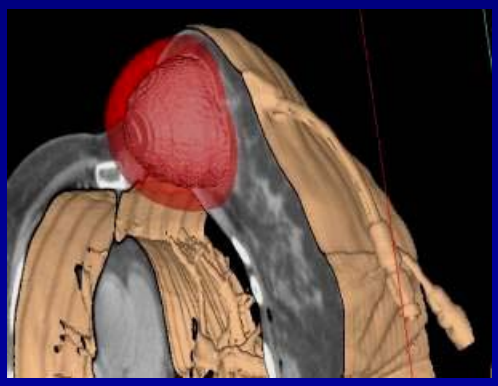
Phantom Size and ^{192}Ir Photon Scattering



Melhus and Rivard, *Med Phys* 33, 1729-1737 (2006)

Contrast Perturbation: Partial Breast Irradiation





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JOURNAL OF APPLIED CLINICAL MEDICAL PHYSICS, VOLUME 7, NUMBER 3, SUMMER 2006

Dose modification factors for ^{192}Ir high-dose-rate irradiation using Monte Carlo simulations

Bassel Kassas,[1] Firas Mourtada,[2] John L. Horton,[2] Richard G. Lane,[2] Thomas A. Buchholz,[3] and Eric A. Strom[3]

- MC simulations showed dose rate reductions at skin of
  - 9% for the smallest balloon and
  - 12% for the largest balloon
- Dose reduction at the breast–lung interface was
  - 6% for the smallest balloon
  - 9% for the largest balloon
- Dose reduction, therefore, warrants comparing plans with a correction for heterogeneity and plans that assume homogeneity.

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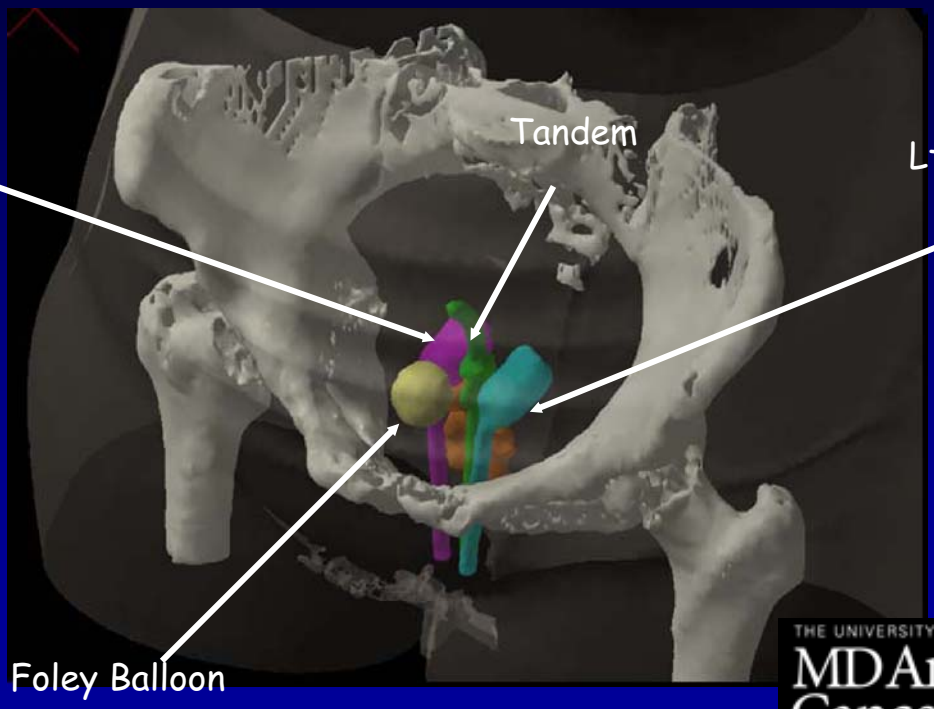
Intracavitary Brachytherapy Applicators Cervical Cancer Boost after EBRT (MDACC, Courtesy of Dr. Eifel)



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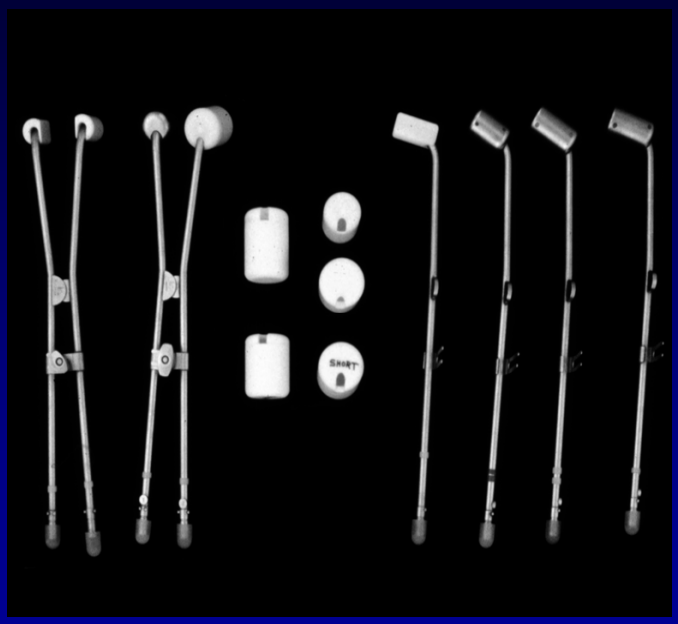
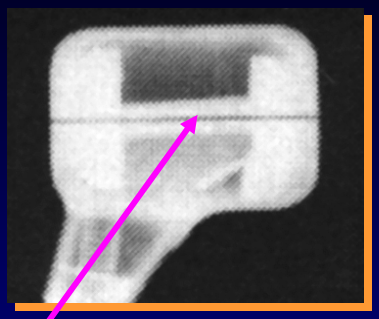
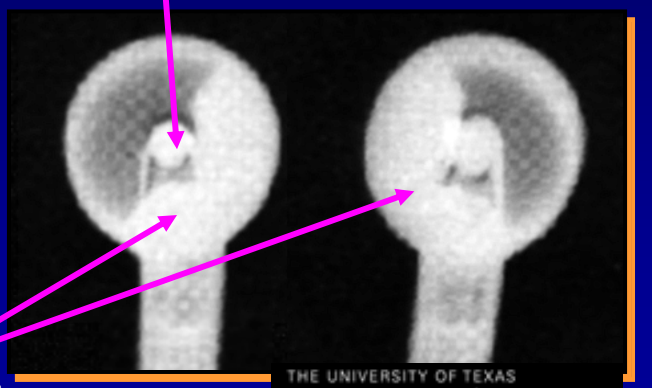
Fletcher-Suite-Delclos LDR Ovoid





Source on central axis



Tungsten Shields

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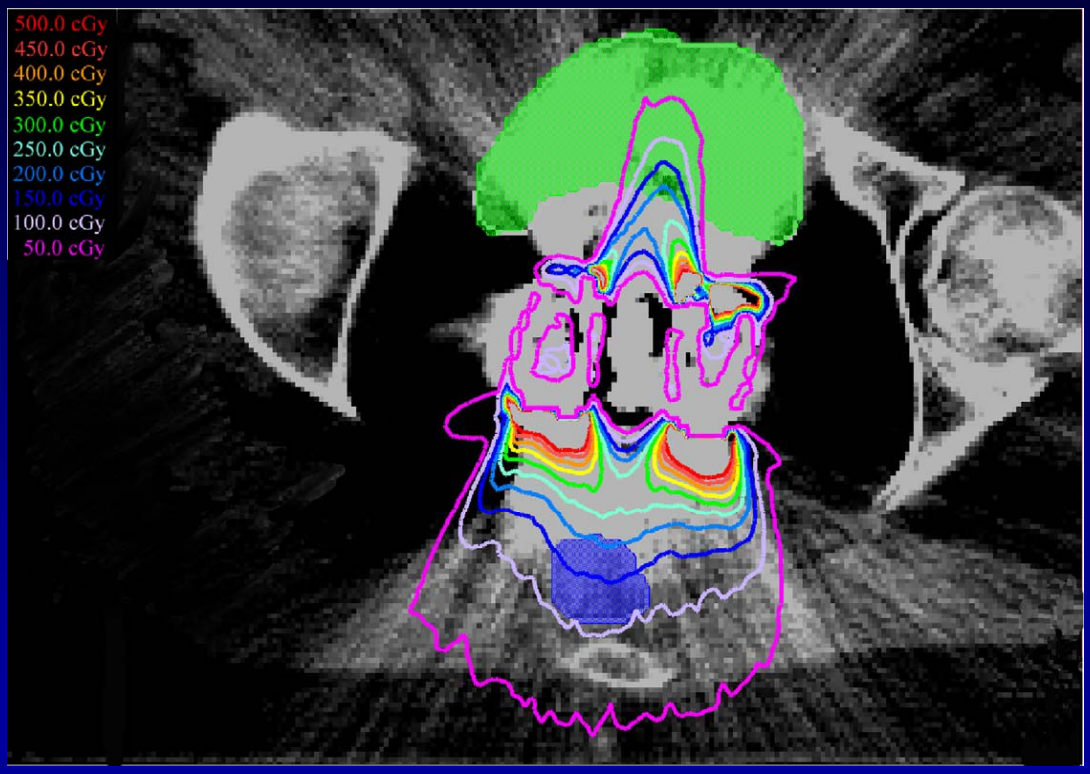
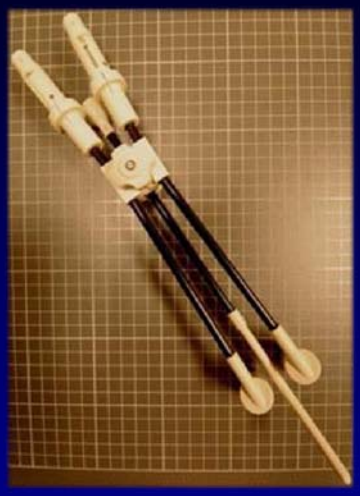
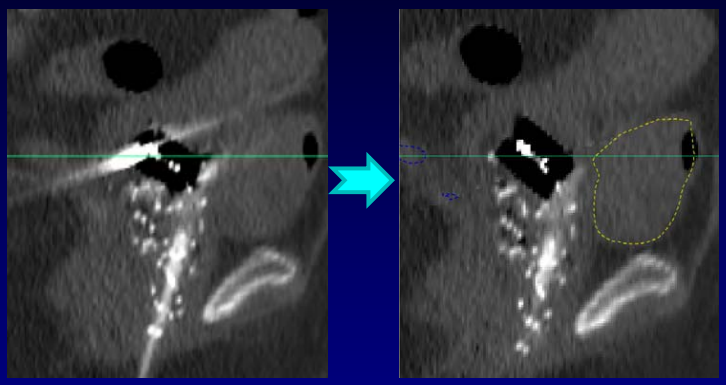
Absolute Dose Diff Plot (TG43-MC)



Need of New Brachy Applicators

Med Phys **36**(12): 5515-5524

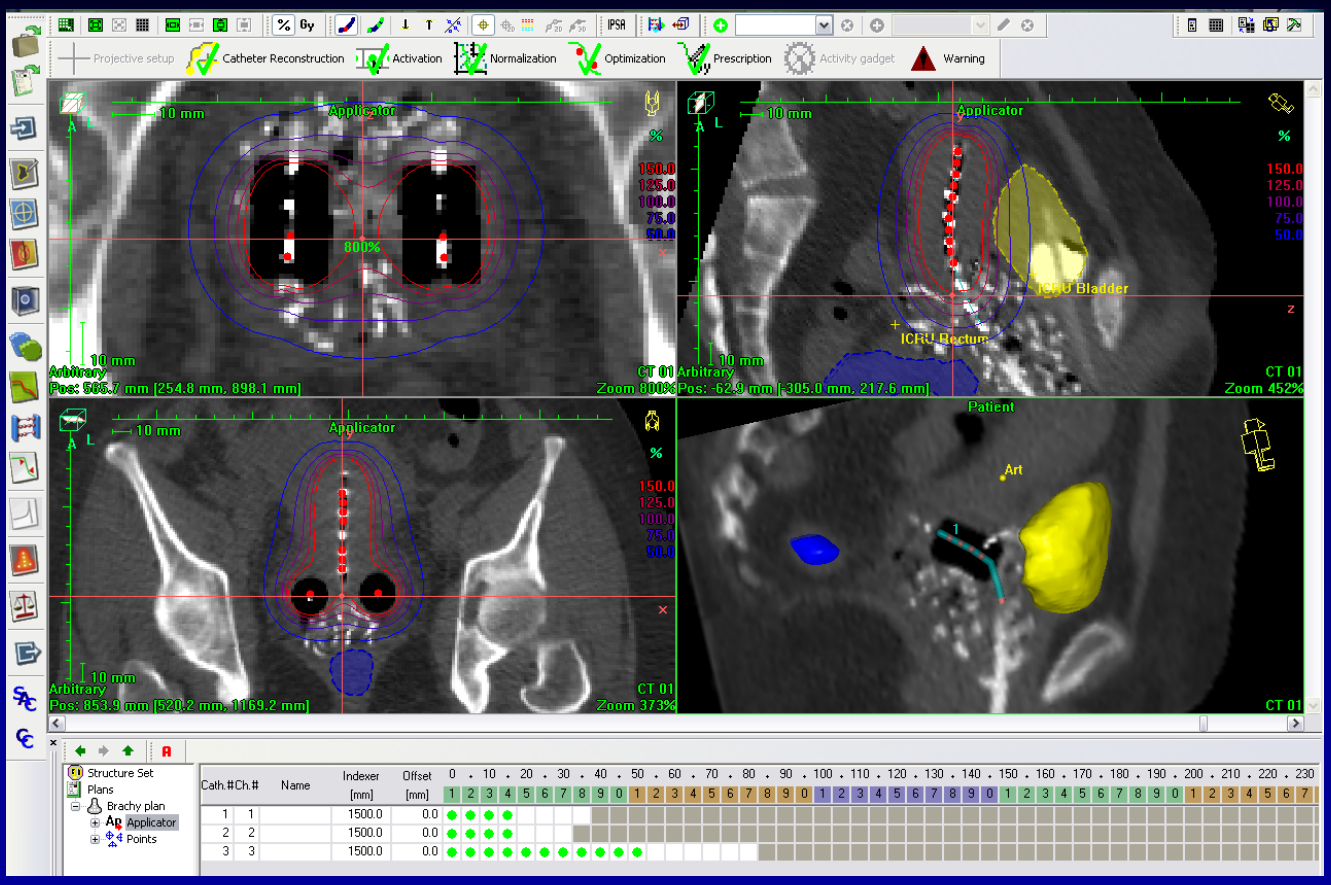




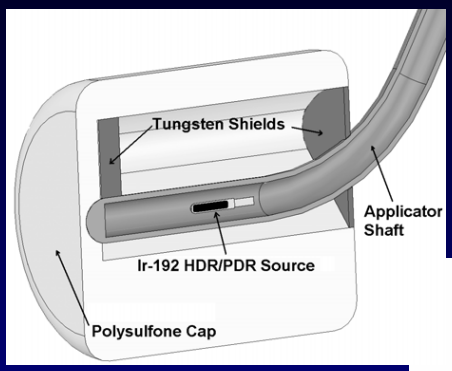
Static Shields Move Shields

CT imaging of ICBT applicators is problematic
- Metal artifacts due to Tungsten shields
- Attenuation robs algorithm of data necessary for detailed image reconstruction
  - Anatomical structures cannot be discerned
    - "Remove" shield Remove artifacts

No CT artifacts- next step is inverse planning

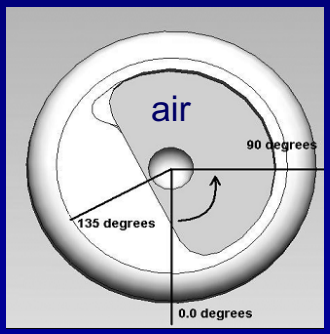


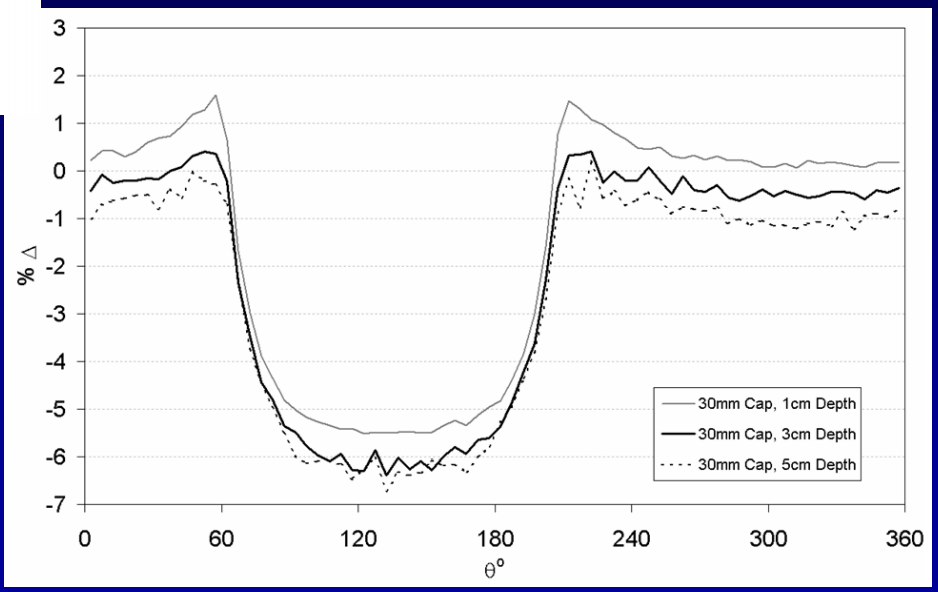
FW HDR/PDR Polysulfone Cap



MCNPX 2.5 simulations

% Δ is relative to Plato TG43 dose





J Appl Clin Med Phys. 2010 Jan 28;11(1):3146

Attenuation of intracavitary applicators in ^{192}Ir-HDR brachytherapy

Sung-Joon Ye,[a] Ivan A. Brezovich, Sui Shen, Jun Duan, Richard A. Popple, and Prem N. Pareek
Department of Radiation Oncology, University of Alabama School of Medicine, 1824 6th Avenue South, Birmingham, Alabama 35294

TABLE I. Elemental compositions and densities of the ^{192}Ir source and applicator components used in the Monte Carlo simulations.

Component	Material	Atomic composition	Density (g/cm^3)
Active wire	Iridium metal	1.0 Ir	22.42
Encapsulation	Stainless steel	[0.02 Si, 0.18 Cr	8.02
Uterine tube	Stainless steel	0.02 Mn, 0.67 Fe, 0.11 Ni]	8.02
Vaginal cylinder	Polysulfone	0.41 H, 0.5 C, 0.07 O, 0.02 S	1.40

Med. Phys. 31 (7), July 2004

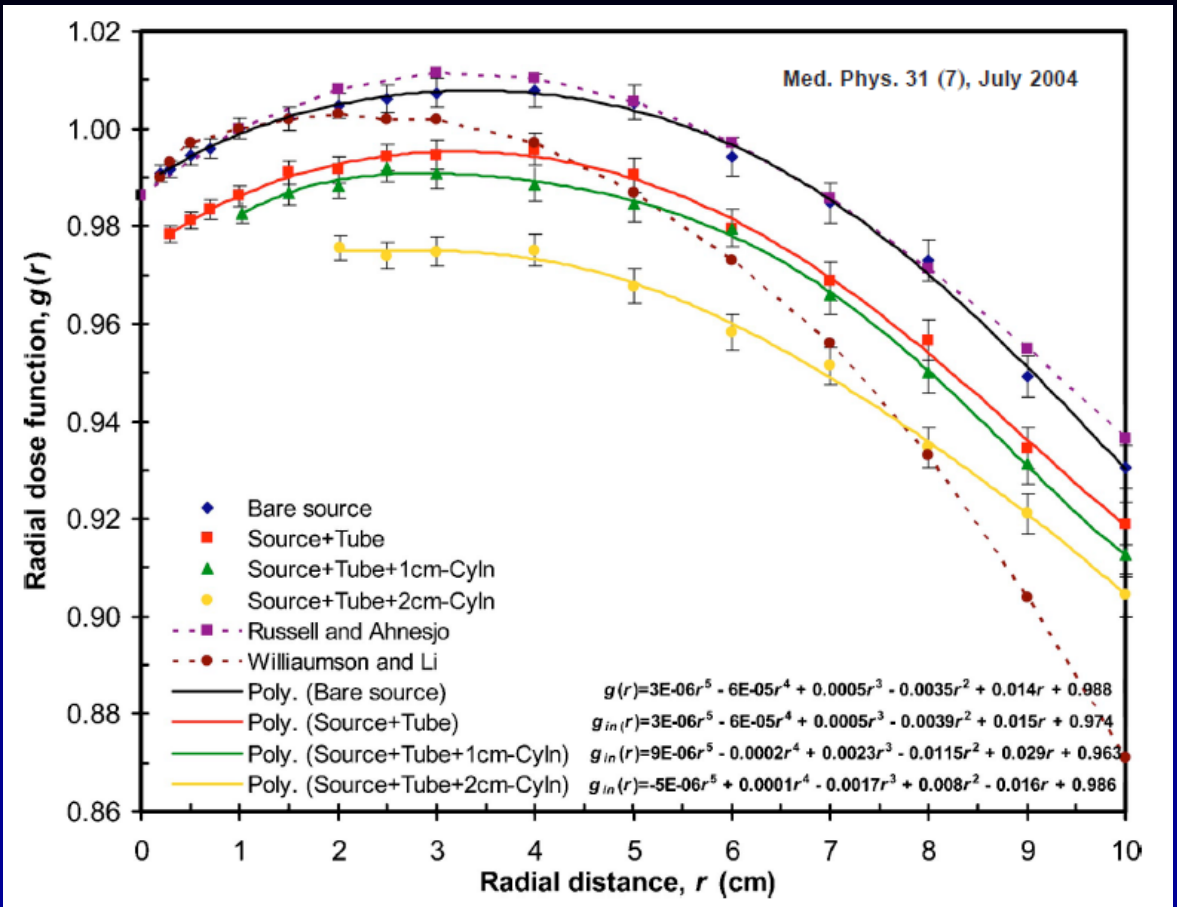


FIG. 5. Radial dose functions calculated for a bare source and a source embedded in various cylindrical applicators and their comparisons to published data. Fifth-order polynomial fittings to our calculated radial dose functions are also presented.

Recently Published Vision 20/20 Paper

The evolution of brachytherapy treatment planning

Mark Rivard,[1] Jack L. M. Venselaar,[2] and Luc Beaulieu[3]

[1]*Dept of Radiation Oncology, Tufts University School of Medicine, Boston, Massachusetts, USA*
[2]*Dept of Medical Physics, Instituut Verbeeten, P.O. Box 90120, 5000 LA Tilburg, The Netherlands*
[3]*Dépt de Radio-Oncologie et Centre de Recherche en Cancérologie de l'Université Laval, Quebec*

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
prostate	high				
	low	X	X	X	
breast	high				X
	low	X	X	X	
GYN	high			X	
	low	X	X		
skin	high			X	X
	low	X		X	X
lung	high				X
	low	X	X		X
penis	high				X
	low	X			X
eye	high			X	X
	low	X	X	X	X

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

2nd Recently Published Vision 20/20 Paper

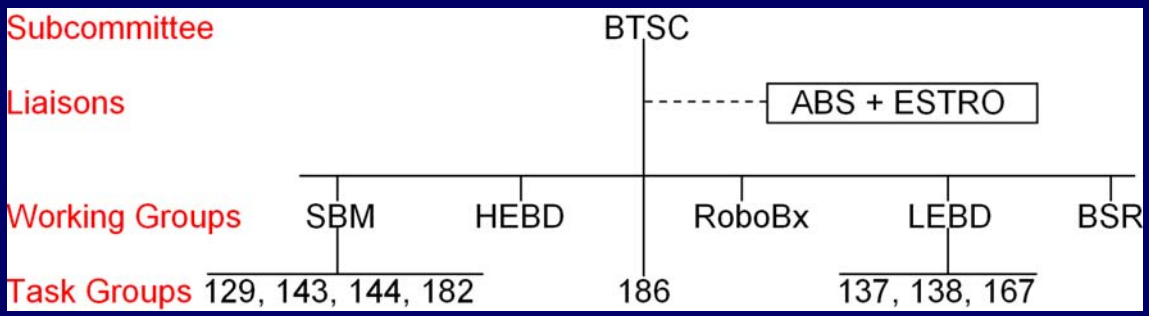
Enhancements to commissioning techniques and QA of brachytherapy treatment planning systems that use model-based dose calculation algorithms

Mark Rivard,[1] Luc Beaulieu,[2] and Firas Mourtada[3]
[1]Tufts University, Boston [2]Centre Hospitalier Universitaire de Québec [3]MD Anderson Cancer Center
Med. Phys. 37, 2645-2658 (2010)

Vision 20/20 Paper Insight

- Need of new QA standards to augment current societal recommendations
- Consideration of dose specification such as
  - Dose to medium in medium,
  - Collisional kerma to medium in medium, or
  - Collisional kerma to water in medium (Acuros)
- Infrastructure needed to uniformly introduce these new algorithms

Current AAPM Committee Structure



Chairs and Liaisons

Brachytherapy Subcommittee (BTSC), Mark Rivard

- Special Brachytherapy Modalities Working Group (SBM), Ravinder Nath
- High-Energy Brachytherapy Source Dosimetry Working Group (HEBD), Jose Perez-Calatayud
- Robotic Brachytherapy Working Group (RoboBx), Bruce Thomadsen and Yan Yu
- Low-Energy Brachytherapy Source Dosimetry Working Group (LEBD), Michael Mitch
- Brachytherapy Source Registry Working Group (BSR), Geoff Ibbott
  - TG-129 Eye Plaque Dosimetry, Sou-Tung Chiu-Tsao
  - TG-143 Dosimetry for Elongated Brachytherapy Sources, Ali Meigooni
  - TG-144 Dosimetry & QA Procedures for ^{90}Y Microsphere Brachy for Liver Cancer, Dezarn
  - TG-137 Prostate Cancer Dose Prescription Recommendations, Ravinder Nath
  - TG-138 Brachytherapy Dose Evaluation Uncertainties, Larry DeWerd
  - TG-167 Investigational Brachytherapy Source Recommendations, Ravinder Nath
  - TG-182 Electronic Brachytherapy Quality Management, Bruce Thomadsen
  - TG-186 Model-Based Dose Calculation Techniques for Advanced Dosimetry: Status and Clinical Requirements for Implementation Beyond AAPM TG-43, Luc Beaulieu
  - American Brachytherapy Society (ABS), Zoubir Ouhib
  - European Society for Therapeutic Radiology & Oncology (ESTRO), Jack Venselaar

TG186 Members

- Luc Beaulieu, Chair
- Åsa Carlsson Tedgren
- Jean-François Carrier
- Steve D. Davis
- Firas Mourtada
- Mark Rivard
- Rowan M. Thomson
- Frank Verhaegen
- Todd A Wareing (consultant)
- Jeffrey Williamson

Plan to Address Dosimetry Hurdles

TG-186 charged to review

- next-generation dose calculation algorithms
- studies evaluating advanced algorithms for
  - phantom size effect
  - inter-seed attenuation
  - material heterogeneities within the body
  - interface and shielded applicators
- commissioning issues
- patient-related input data
- potential clinical issue, risks, and limitations

Report of the AAPM Task Group No. 105: Issues associated with clinical implementation of Monte Carlo-based photon and electron external beam treatment planning

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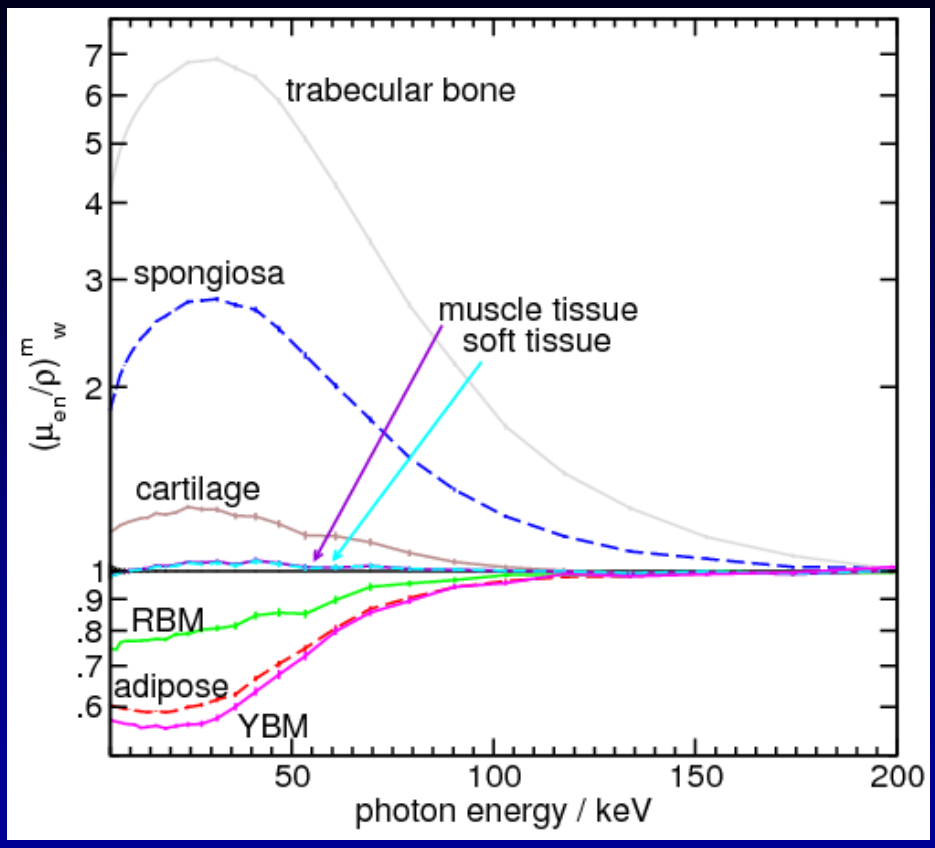
Med. Phys. 34 (12), December 2007

TG105 did not give much details, just review!

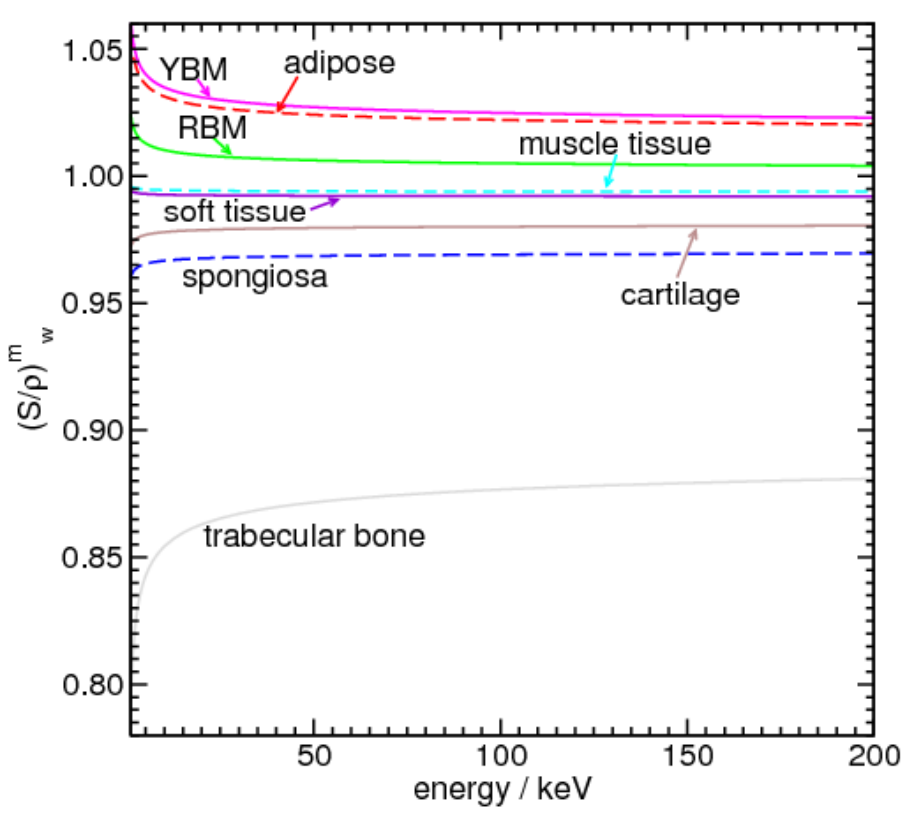
TG-186 Tasks

- CT imaging and patient modeling
  - Material characterization
  - CT segmentation
  - Dual energy CT and spectral CT
  - CT artifacts
- Dose scoring medium
  - Low/High energy
  - Methods to convert $D_{m,m}$ into $D_{w,m}$
- Commissioning of MBDC algorithms
  - Commission levels I & II
  - Define clinical workflow



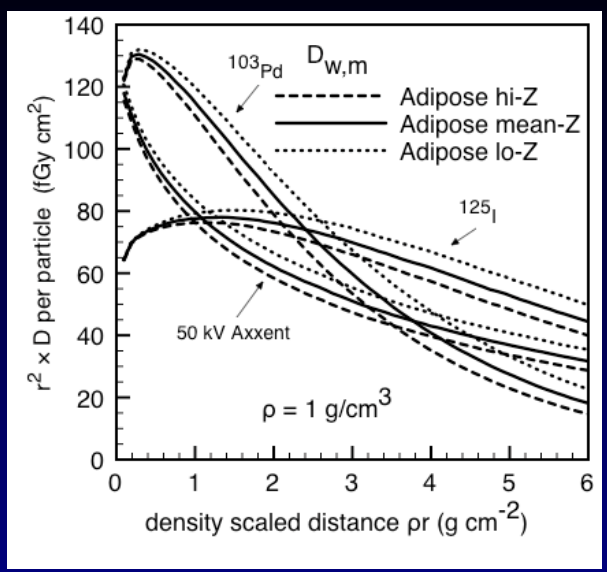
- Mass energy absorption coeff rel to H2O for 5 to 200 keV photons
- Atomic compositions and densities are those from ICRU Report 44 (1989) and ICRP Report 89 (2003).
- Composition of the RBM (YBM) is that for "active marrow" ("inactive marrow") (ICRP 2003).

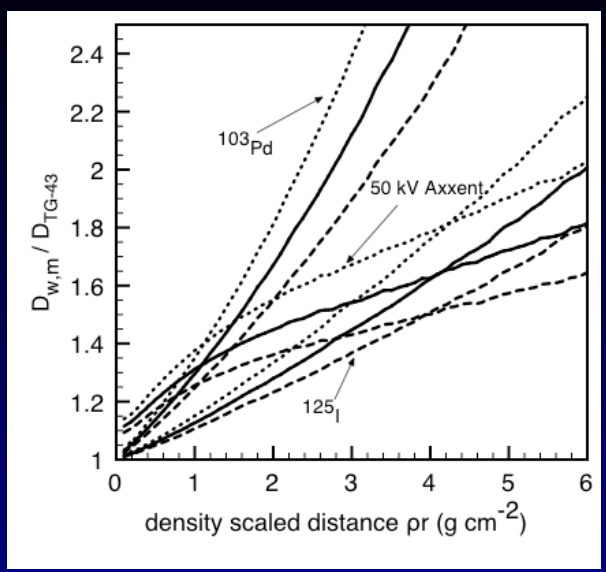
TG-186 report (pending) , calculated using EGSnrc "g" code



Unrestricted mass stopping power ratios for the materials indicated relative to those for water.

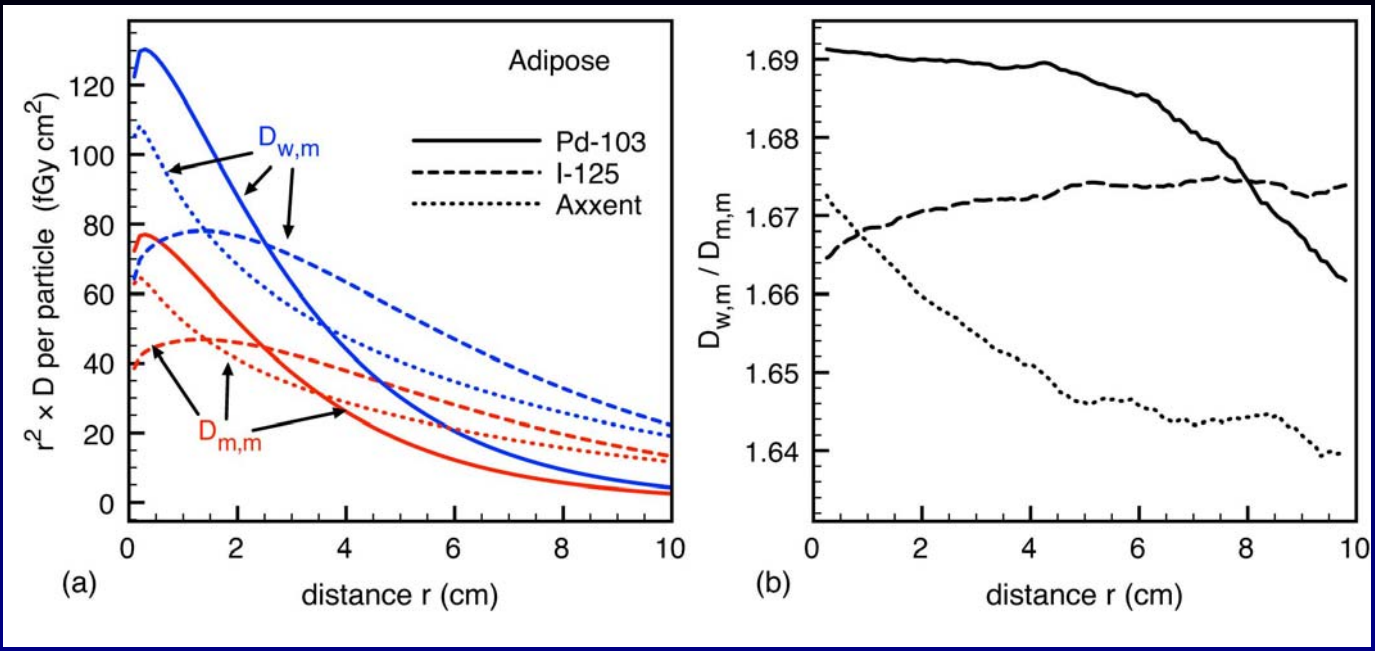
TG-186 report (pending) , calculated using EGSnrc "g" code





(a) Radial $D_{w,m}$ in three different compositions of adipose tissues corrected for the inverse square law for three different brachytherapy photon sources. (b) Ratio of $D_{w,m}$ to the dose obtained in water (D_{TG-43})

Landry, et al. (2010). "Sensitivity of low energy brachytherapy Monte Carlo dose calculations to uncertainties in human tissue composition. Med Phys, accepted



(a) Radial $D_{w,m}$ and $D_{m,m}$ in *Adipose mean-Z* corrected for the inverse square law for three different brachytherapy photon sources. (b) Ratio of $D_{w,m}$ to $D_{m,m}$ illustrating spatial variation in conversion factor.

Landry, et al. (2010). "Sensitivity of low energy brachytherapy Monte Carlo dose calculations to uncertainties in human tissue composition. Med Phys, accepted

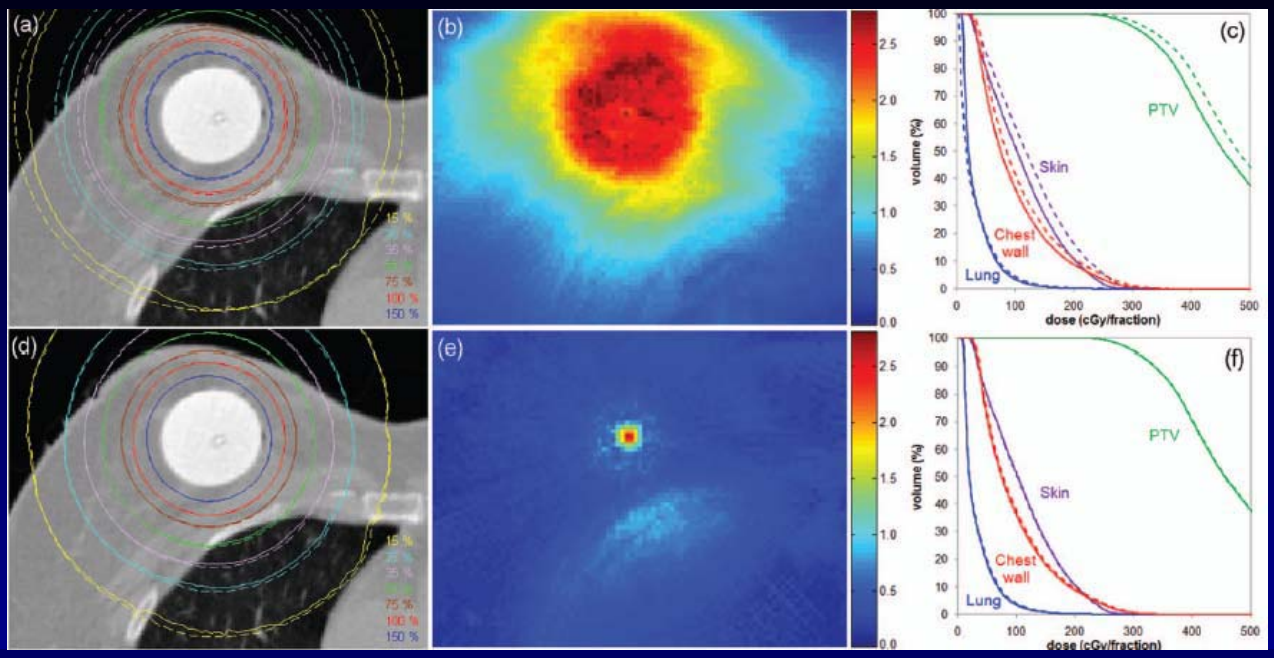
Methods beyond TG-43

- Ray-tracing with scaling
- Collapsed cone convolution algorithm
- Linear Boltzmann Transport Equation (LBTE) solvers
  - Monte Carlo
  - Deterministic GBBS

Methods beyond TG-43

- **Ray-tracing with scaling**
  - Rely on pre-calculated Monte Carlo dose kernels and/or empirical corrections to approximate specific scenarios
  - "effective attenuation" (1D, 2D, primary only), do not account for full 3D scatter conditions
  - have in common use of 1D ray-tracing with scaling for the primary dose but differs in approaches to treat the scatter dose

Breast Brachytherapy



Medical Physics

A CT-based analytical dose calculation method for HDR ^{192}Ir brachytherapy

Emily Poon[1] and Frank Verhaegen[2]

[1]Medical Physics Unit, McGill University, 1650 Cedar Avenue, Montreal, Quebec H3G 1A4, Canada

[2]Department of Radiation, University Hospital Maastricht, Maastricht 6229ET, The Netherlands

Methods beyond TG-43

- **Collapsed cone convolution (CCC)**
  - Point kernel superposition method
  - "collapsing" the transport of energy released onto cone axes for efficient ray tracing
  - Used in few external beam TPS
- **Brachy version of CCC (Carlsson and Ahnesjö 2000)**
  - utilizing brachy source specific data on the primary dose in water (MC pre-calculated)
- Further improvements in calc speed can be achieved via graphical processing units (GPUs)

Why not solve the LBTE?

- LBTE – Linear Boltzmann Transport Equation
- Approaches for solving the LBTE:
  - Stochastic (Monte Carlo)
    - Indirectly solves the LBTE by tracking a statistically significant number of random particles
      - central limit theorem
  - Deterministic (can also be referred to Grid Based Boltzmann Solvers – GBBS)
    - Directly solve the LBTE by discretizing the phase-space variables (space, angle, and energy)
    - *Attila and Acuros both deterministically solve the LBTE*

LBTE Fundamentals

- The LBTE is the governing equation for radiation transport:

$$\underbrace{\hat{\Omega}\cdot\vec{\nabla}\psi}_{\text{streaming}} + \underbrace{\sigma_t\psi}_{\text{collision}} = \underbrace{Q^{scat} + Q^{ext}}_{\text{sources}}$$

where,
Ψ = Angular photon fluence f(position, angle, and energy)

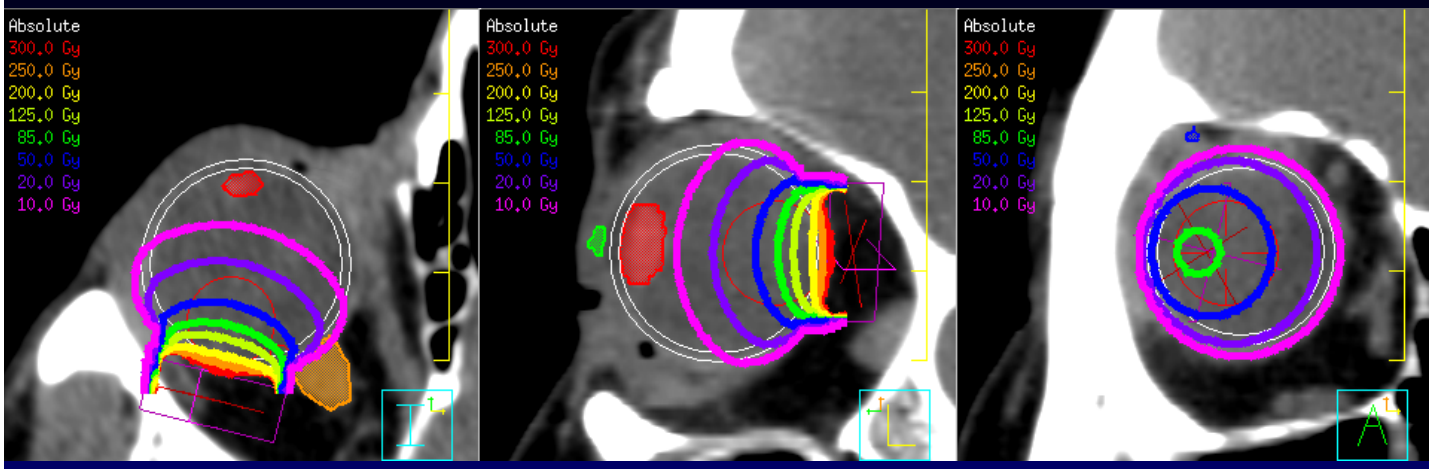
  - Represents a particle balance over a differential control volume:
    - Streaming + Collision = Scattering Source + Fixed brachy source
    - Particles conserved

PMB v51 (2006) 2253-2265

Monte Carlo

- MCNP, GEANT4, EGSnrc, etc
  - Well benchmarked for brachytherapy but not optimized for speed
- Accelerated approaches: non-analogue, correlated sampling, pre-calculated phase space
- Not commercially available

MCNP for Eye Plaque Dosimetry- with interface to Pinnacle TPS



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]
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[2]Radiation Oncology Dept, "La Fe" University Hospital, Valencia, Spain
[3]Dept of Atomic, Molecular, and Nuclear Physics, University of Valencia, Spain

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

Early Discrete Ordinates Methods (DOM) for Brachy

- Research in brachytherapy using 2-D DOM (DANTSYS)
  - Daskalov G, Baker R, Rogers D, Williamson J, "Dosimetric modeling of the microselectron HDR ^{192}Ir source by the multigroup discrete ordinates method", Med. Phys. 27(10), pp. 2307-2319, 2000.
  - Daskalov G, Baker R, Rogers D, Williamson, J, "Multigroup discrete ordinates modeling of ^{125}I 6702 seed dose distributions using a broad energy-group cross section representation", Med. Phys. 29(2), 113-124, 2002.
    - Suggested use of more advanced spatial and angular differencing techniques, along with spatially variable grids, may lead to significant efficiency gains

Determinsitic LBTE Solvers

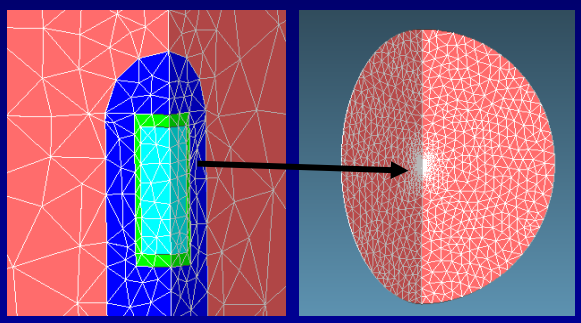
- Solves the LBTE by discretizing in space, angle and energy
  - Space: computational mesh
  - Angle: discrete-ordinates
  - Energy: multi-group form of the particle cross sections
- The term 'Discrete Ordinates' has commonly been used to refer to a class of solvers using discrete ordinates angular discretization

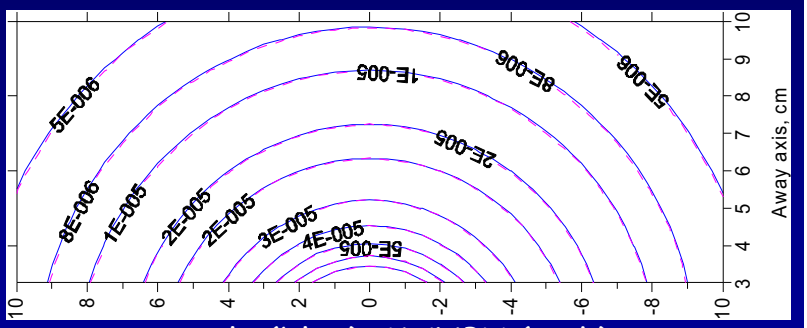
BV-Acuros GBBS

- Acuros™ developed specifically for accurate and rapid dose calculations for medical physics.
  - Integrated into BrachyVision as BV-Acuros (Varian Medical Systems)
- Solves the coupled LBTE for neutral particles on a locally adaptive Cartesian grid.
- An optimized rewrite of general purpose Attila©,
  - for comparable accuracy levels, it is roughly an order of magnitude faster than Attila

^{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.



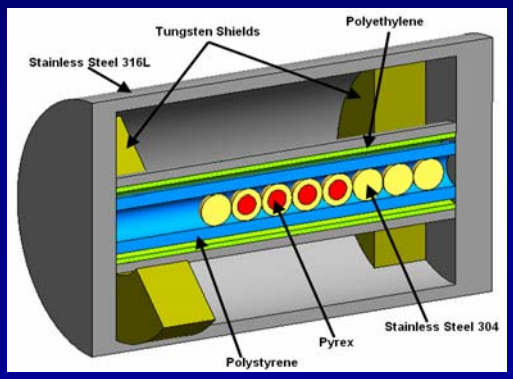


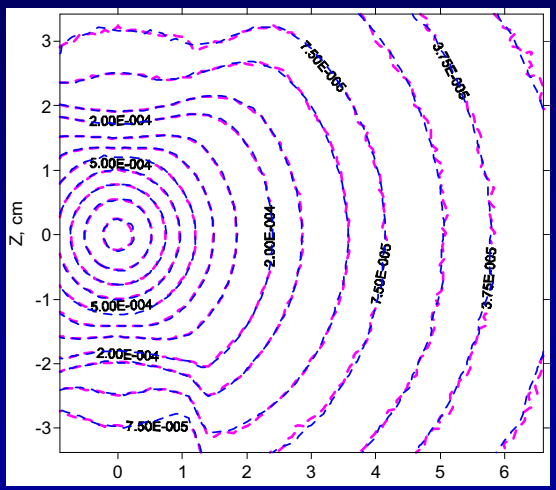
Attila (blue), MCNPX (pink)

*Partially Funded by Transpire Inc.

^{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)

Commissioning of MBDC algorithms

- Commissioning of brachytherapy TPS includes many tasks outlined in AAPM TG-40, TG-56, and TG-64
- TG-59: specifics provided on HDR ^{192}Ir systems
- TG-64: specifics provided on LDR permanent prostate brachytherapy
- TG-186 is tasked to establish guidelines for MBDC commission

Commissioning of MBDC algorithms

- For LE photon-emitting sources,
  - radiation scatter has minimal role.
  - tissue composition has a major role.
- For HE photon-emitting sources,
  - radiation scatter has major role.
  - tissue composition has minimal role (exception is dense applicators (> 2 $g.cm^{-3}$)
- For both energy regimes, any deviations between the MBDCA-based TPS results and the reference data should be documented, and the clinical significance understood

Commissioning of MBDC algorithms

- Commission level I
  - A direct comparison of the MBDCA-based TPS output in a reference-sized homogenous water to AAPM consensus data
  - helpful for physicists in transition using MBDCA-based TPS.
  - Comparing TG-43 dosimetry parameters is a necessary first step since these parameters describe the spatial dose distribution due to the physical source model without significant consideration of the surrounding environment

VS-2000 HDR source

Monte Carlo dosimetry of a new ^{192}Ir high dose rate brachytherapy source

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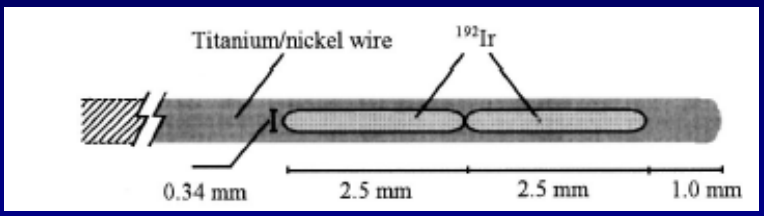
Nuclear and Particle Physics Section, Physics Department, University of Athens, Panepistimioupolis, Ilisia, 157 71 Athens, Greece

P. Karaiskos and P. Sandilos
Department of Radiology, Medical School, University of Athens, Areteion Hospital, 76 Vas. Sofias Avenue, 115 28 Athens, Greece and Medical Physics Department, Hygeia Hospital, Kiffisias Avenue, 24 Erythroy Stavrou, Marousi, 151 23 Athens, Greece



Med. Phys. 27 (11), November 2000

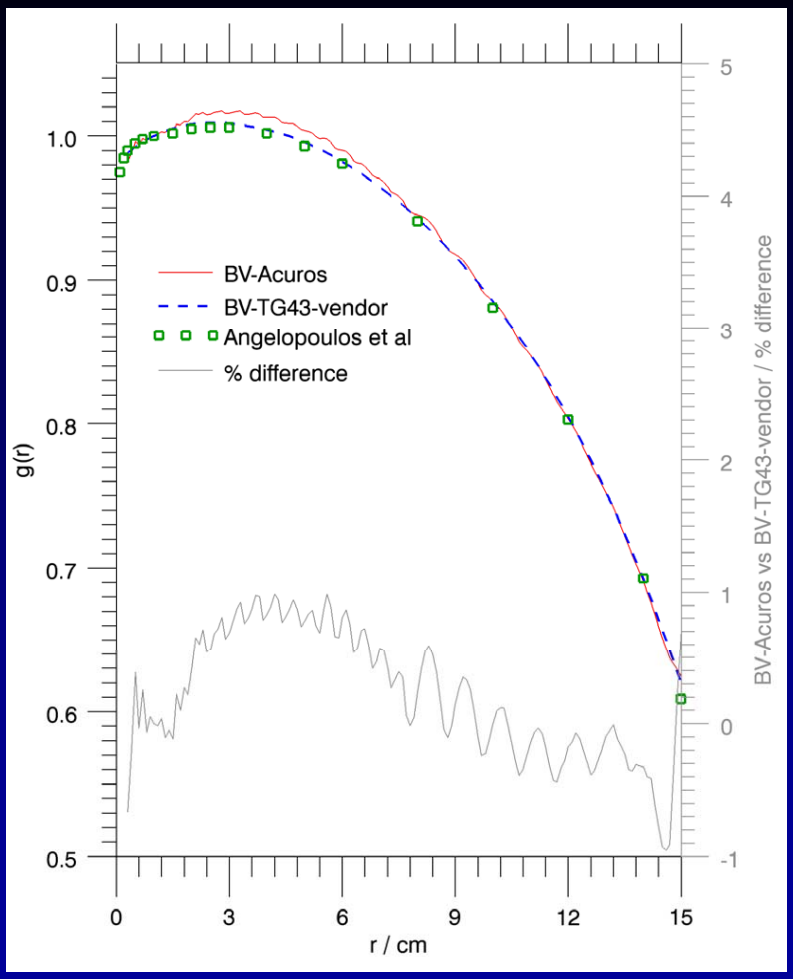
The published clinical TG43 data for VS-2000 source assumes a 15cm long NiTi cable.

The VS2000 is modeled with 1mm of NiTi cable in BV-Acuros

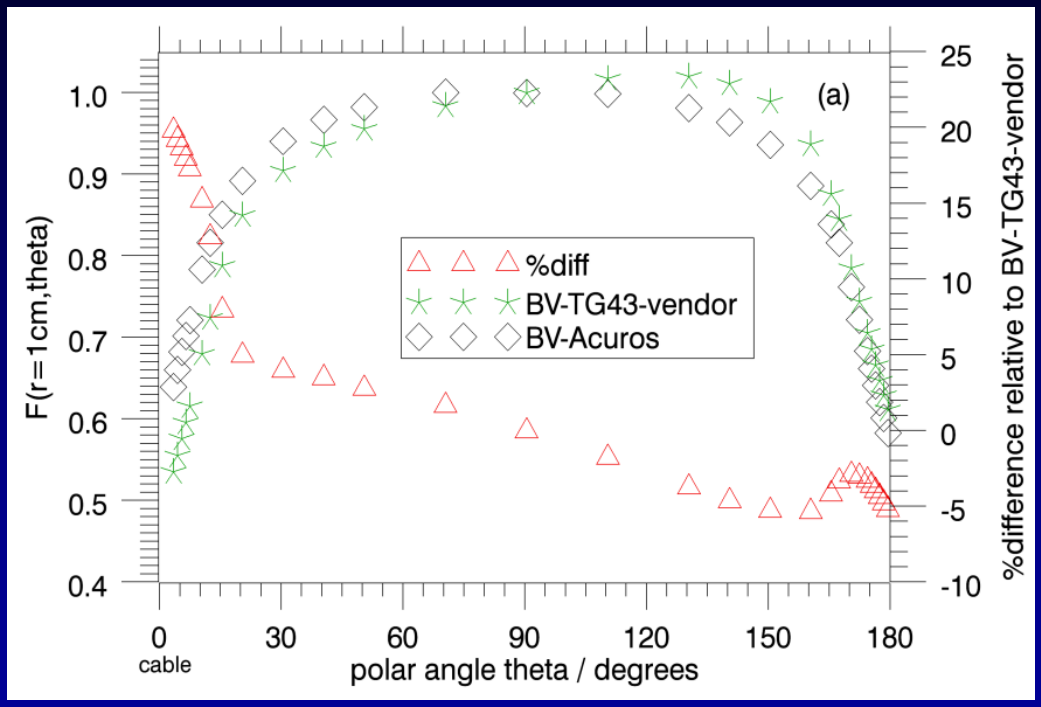
Level I:

- Radial dose function g(r) check For BV 8.9 Acuros

Mikell and Mourtada, Med Phys, Sept, 2010

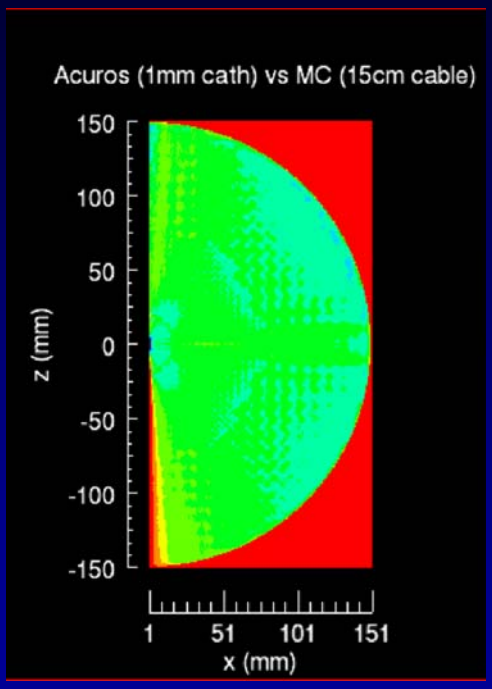


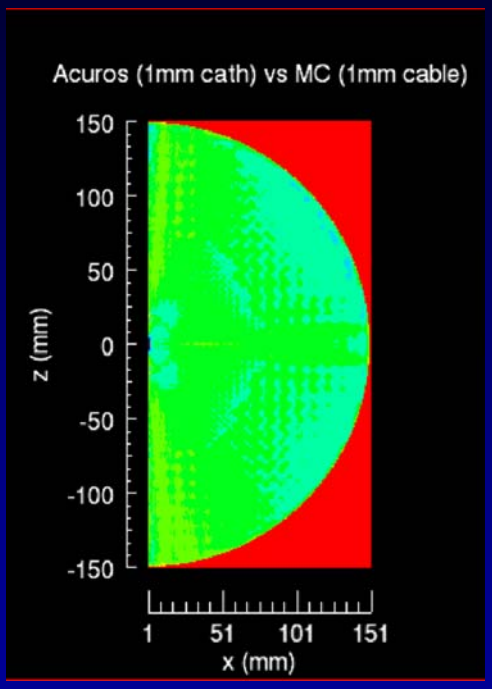
Level I Test: BV Acuros v 8.9

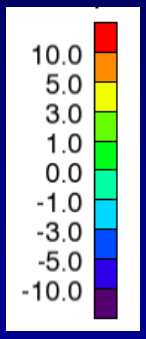


Mikell and Mourtada, Med Phys, Sept, 2010

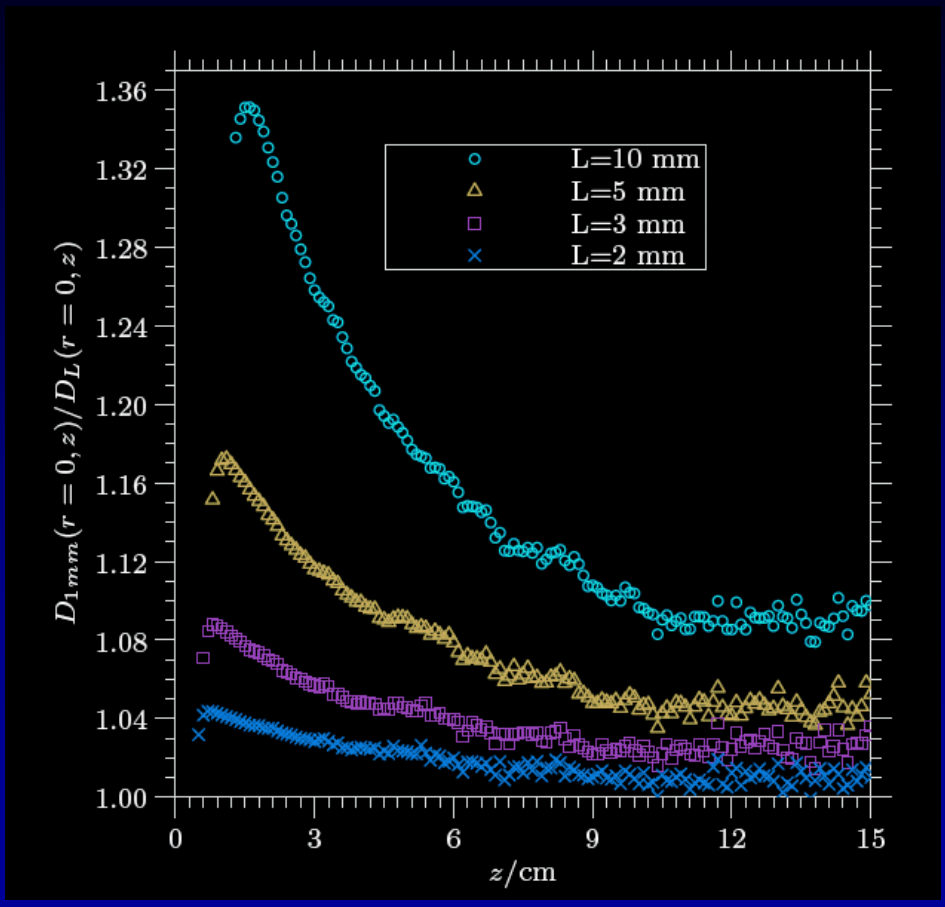
BV-Acuros(short cath) vs MCNPX







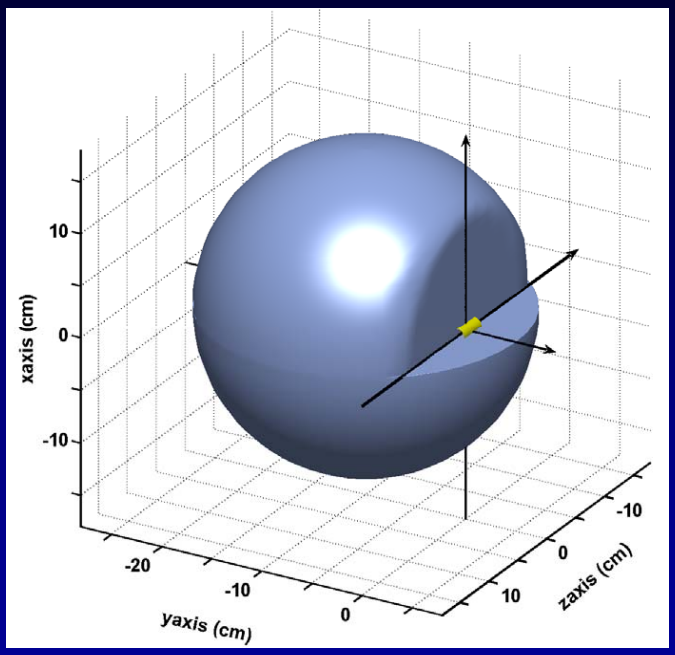
Ratio along cable: MC-1mm/MC-L



Commissioning of MBDC algorithms

- Commission level II
  - Comparisons of the 3D dose distributions calculated with the clinical MBDCA-based TPS should be independently verified against virtual phantoms mimicking clinical scenarios.
  - Direct comparison to a reference treatment plan having heterogeneous conditions is mandatory for physicists to commission MBDCA-based TPS.

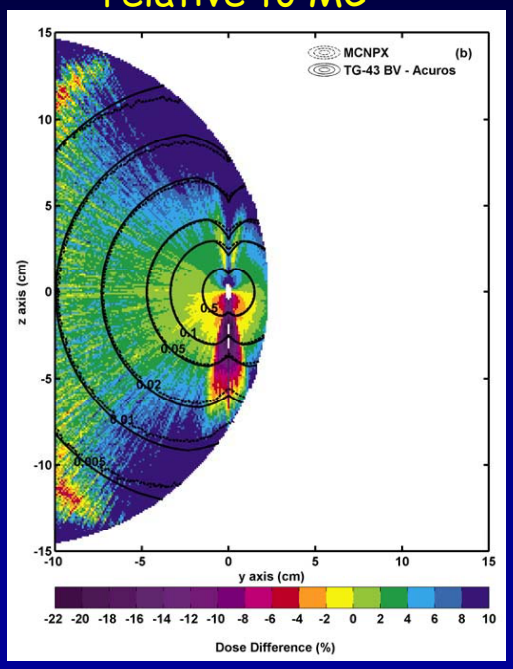
VS2000 HDR 12.5cm off the center of the R=15cm water sphere



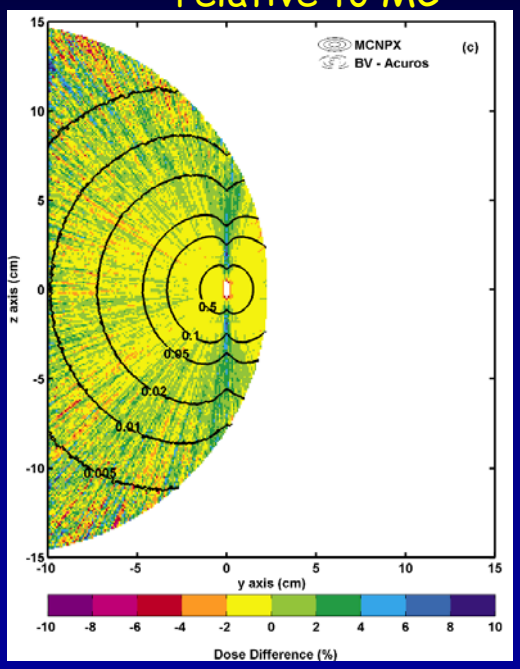
Medical Physics, Vol. 37, No. 2, pp. 649–661, February 2010

VS2000 HDR 12.5cm off the center of the R=15cm water sphere

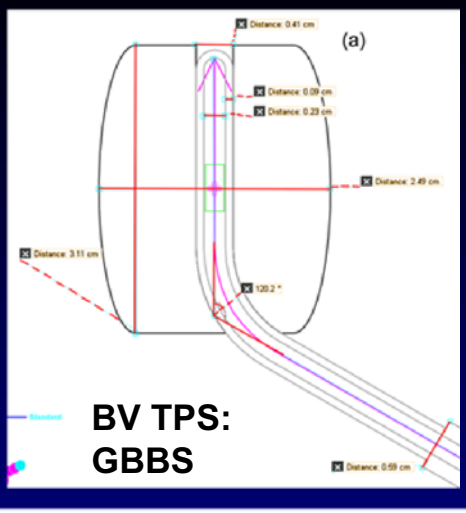
% D diffs BV-TG43 relative to MC

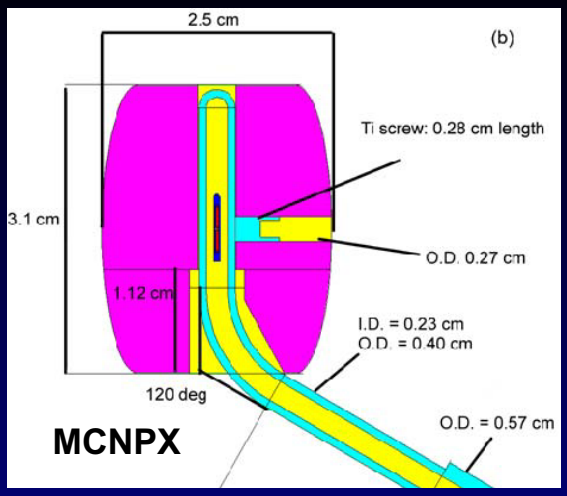


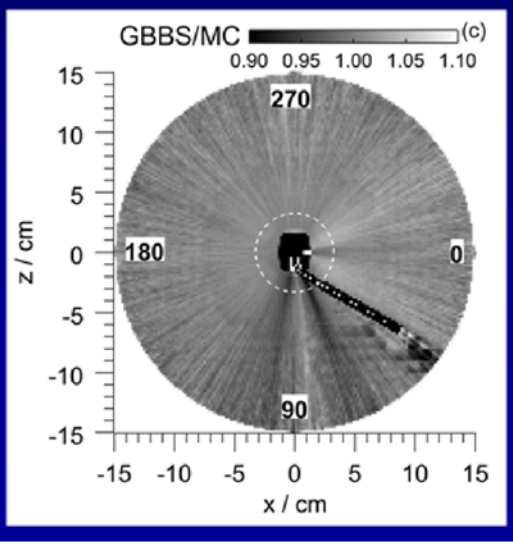
% D. diffs BV-Acuros relative to MC

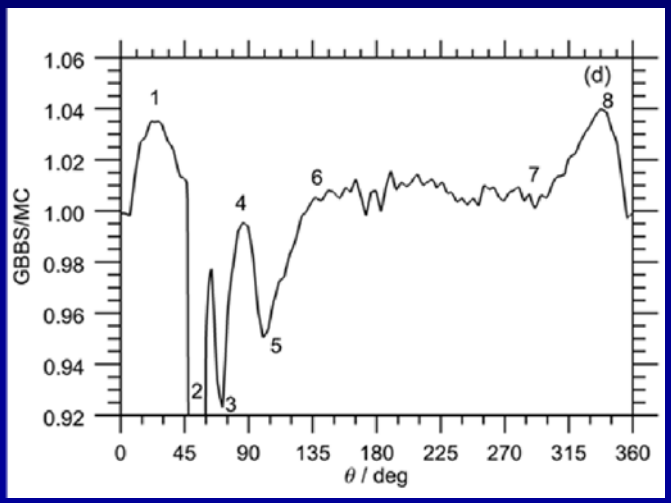


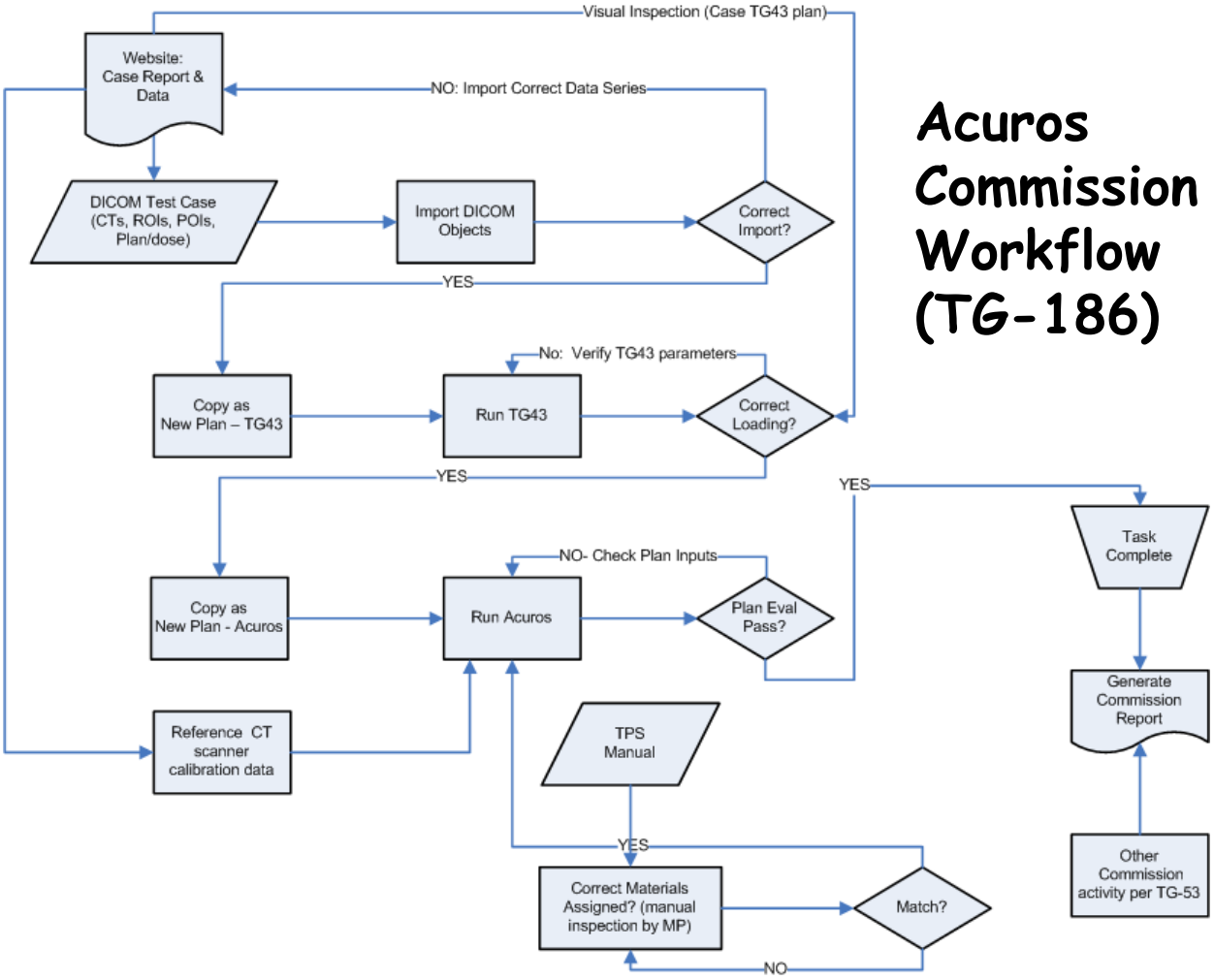
Medical Physics, Vol. 37, No. 2, pp. 649–661, February 2010





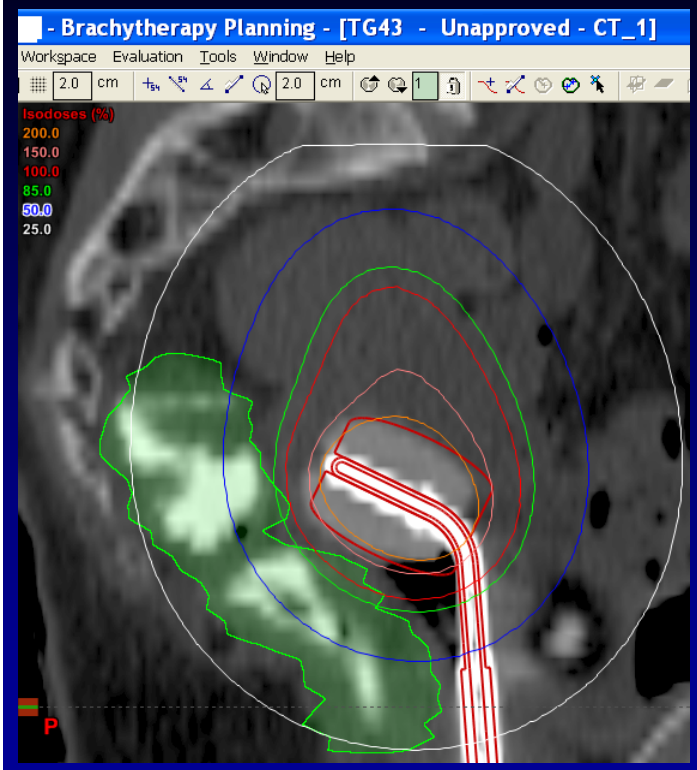




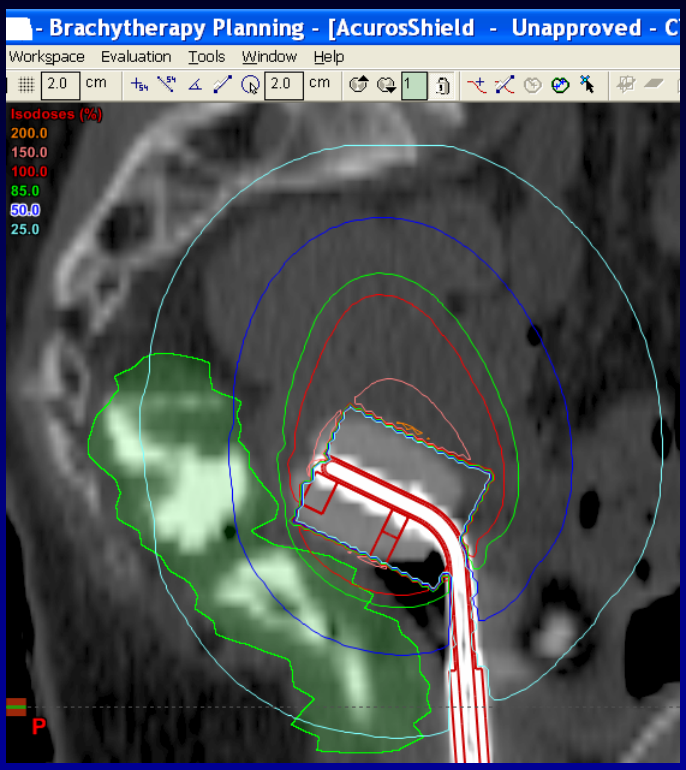


Clinical Implications

BrachyVision-TG43 vs. BrachyVision-Acuros (Shielded Ovoids)

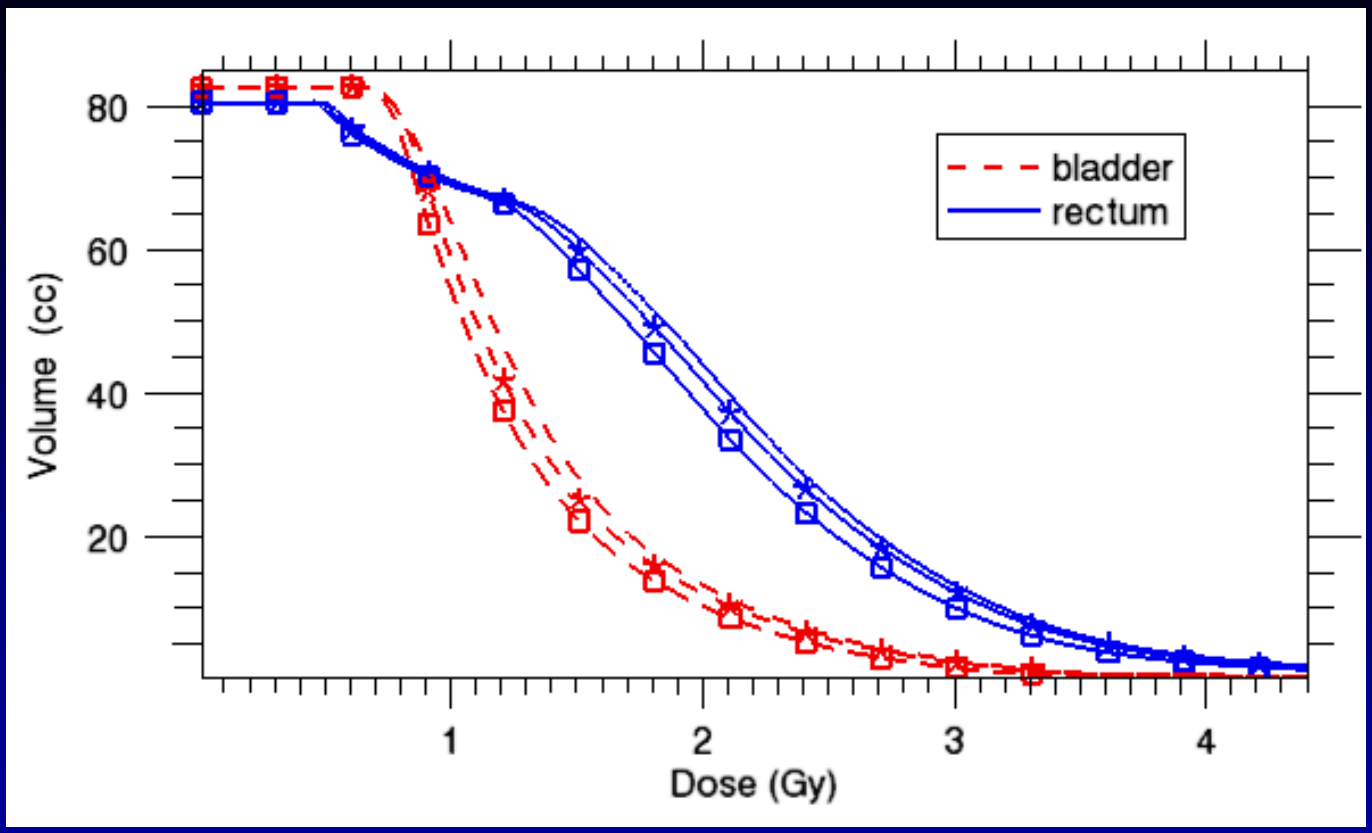


BV-TG43 (water)



Acuros

F. Mourtada- RadOnc 2010



Rectum (solid) and Bladder (dashed) for the 3 cases described above: 1) TG43 [none], 2) Acuros(CT/MR) [star], 3) Acuros/shielded [square]

Acuros vs. TG43 Clinical Results

	TG43 (Gy)	CT/MR (Gy)	CT/MR (%TG43)	Shield (Gy)	Shield (%TG43)
Bladder	3.14	3.10	-1.3	2.92	-7.0
Rectum	4.35	4.28	-1.6	4.11	-5.5

MDACC analyzing 26 patients doses based – work in progress!

Conclusions

- Brachytherapy TPS advances recently reached market
  - Heterogeneous –based brachy dose is now available
  - Expect clinical implementation paradigm shift
  - Remember the 1990s,
    - external beam heterogeneous dose calculations
  - Clinical brachy transition period is required

Texas long horn