Recent Advances in Brachytherapy Dose Calculation Methods –

The Need for Standardization is Now More than Ever!

CIRMS Conference April 29, 2015

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THE UNIVERSITY OF TEXAS
MD Anderson ~~Cancer~~ Center

Jefferson™
Kimmel Cancer Center
NCI-designated

Disclosure

- Member of AAPM TG-186
- Member of AAPM Working Group - WGMBDCA

Learning Objectives

- Review of brachytherapy approaches.
- Describe the dosimetric uncertainty in modern brachytherapy.
- Review the AAPM TG-186 and WGMBDCA guidelines to commission modern dose calculation engines.
- Identify factors requiring standarization to achieve dosimetric consistency among clinics.

Acknowledgements

TG-186

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Rowan Thomson, Carleton University
Frank Verhaegen, Maastro Clinic

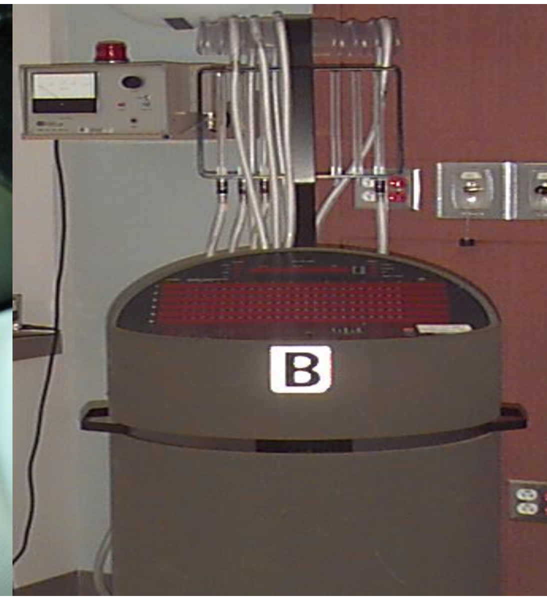
Common Past/Present Radionuclides in Brachytherapy (LDR/HDR)

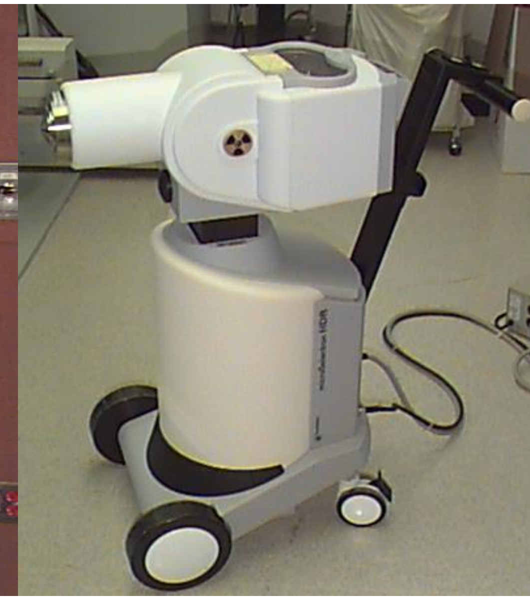
Radionuclides	$T_{1/2}$	E_{avg}(KeV)
^{226}Ra	1,622 y	830
^{60}Co	5.26 y	1,250
^{137}Cs	30 y	662
^{192}Ir	74.1 d	380
^{198}Au	2.7 d	410
^{131}Cs	~10 d	29
^{125}I	~60 d	28
^{103}Pd	~17 d	22

Low E (<50 keV)

+eBT

From Multiple Sources/Manual Loading to a Single Source/Afterloading

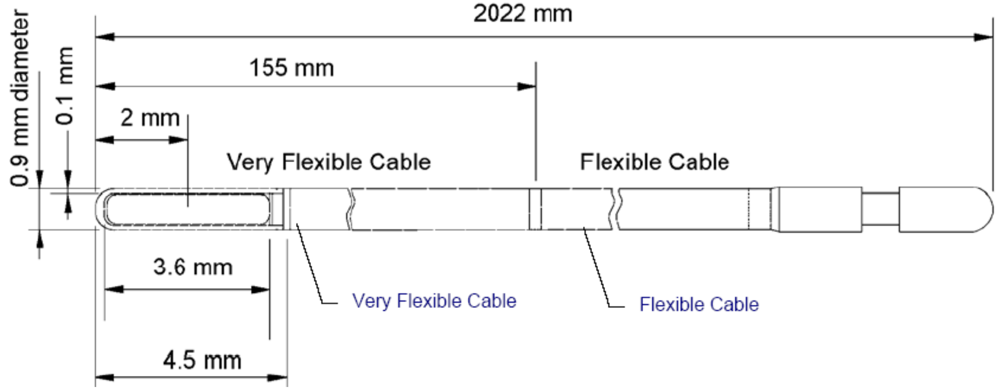


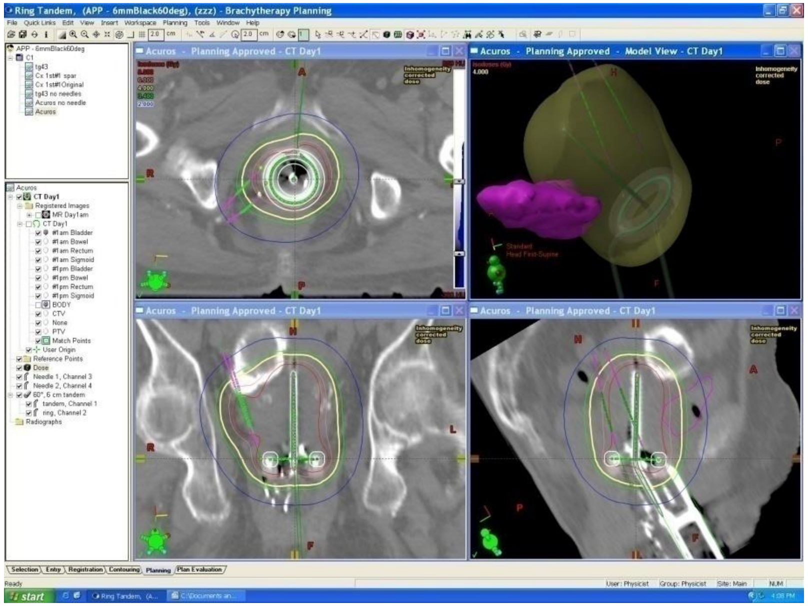


Ra-226 Tubes (manual) →Cs-137 Tubes (manual) →Cs-137 Pellet LDR (afterloading) → Ir-192 PDR/HDR (afterloading)

HDR/PDR Remote Afterloader

HDR: 10 Ci
PDR: 1-2 Ci

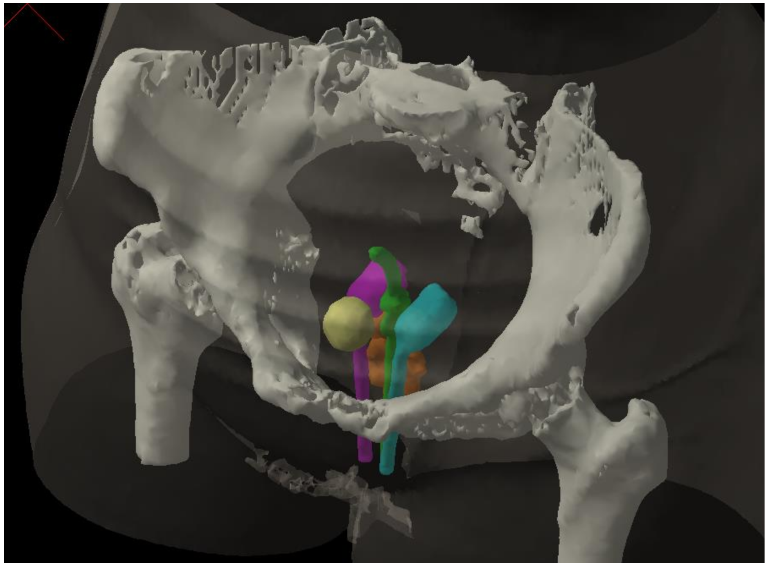


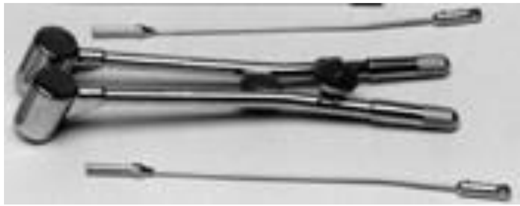


F. Mourtada, Ph.D.

ICBT- Gynecology

- Intracavitary: Places radioactive sources within a body cavity (cervical cancer)
- LDR (temporary, 48hrs) or HDR (temporary, minutes)



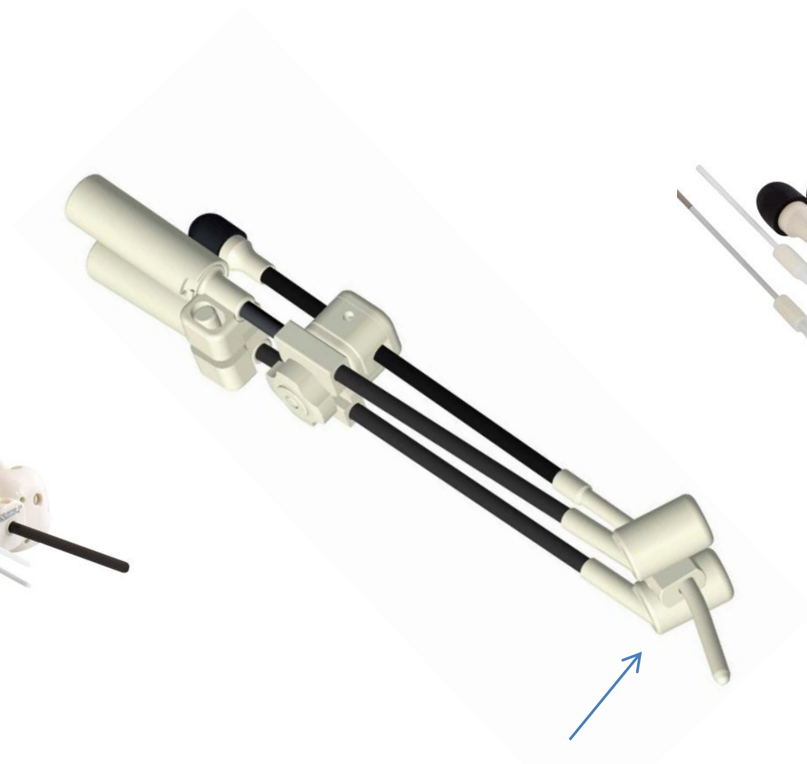


Fletcher Cs-137 Manual Loading

Recently Introduced Applicators CT/MR (HDR/PDR Afterloader)

Utrecht Interstitial Fletcher

Fletcher Shielded



Shielded ovoids

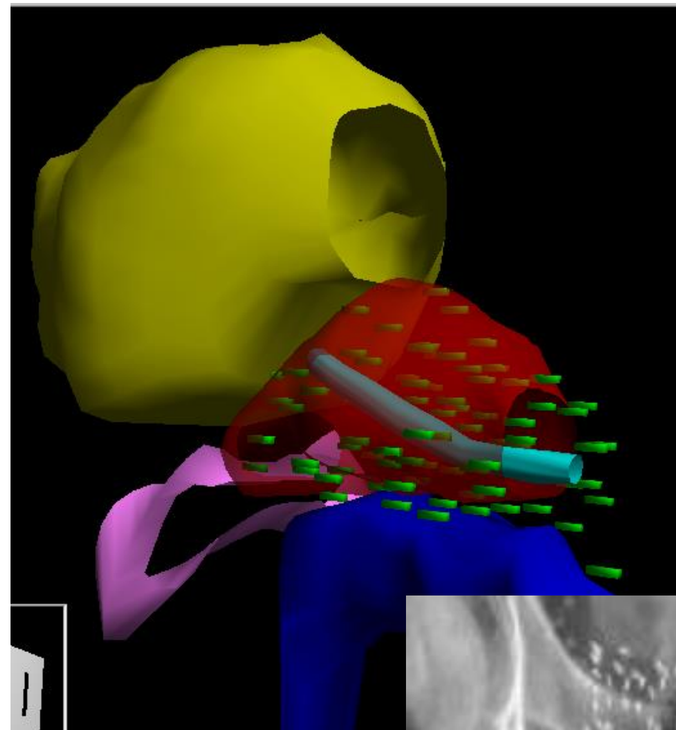
Interstitial Ring

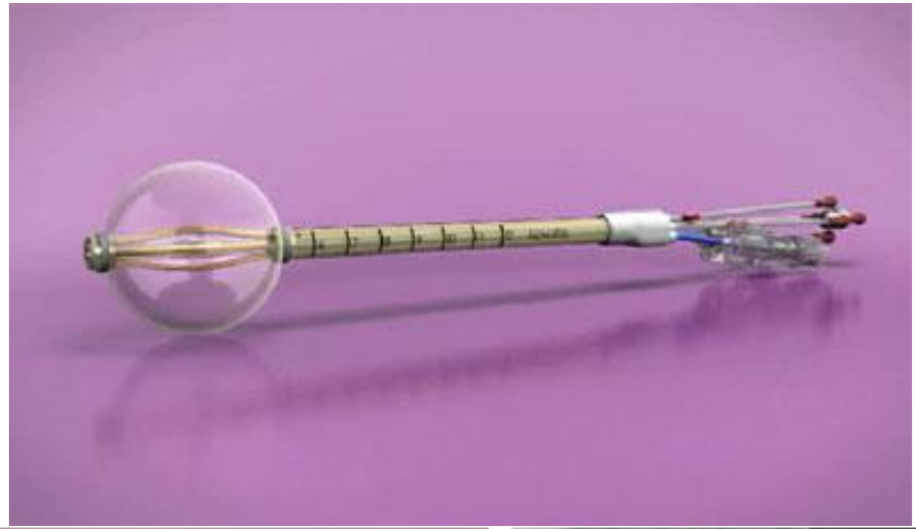
Interstitial Examples

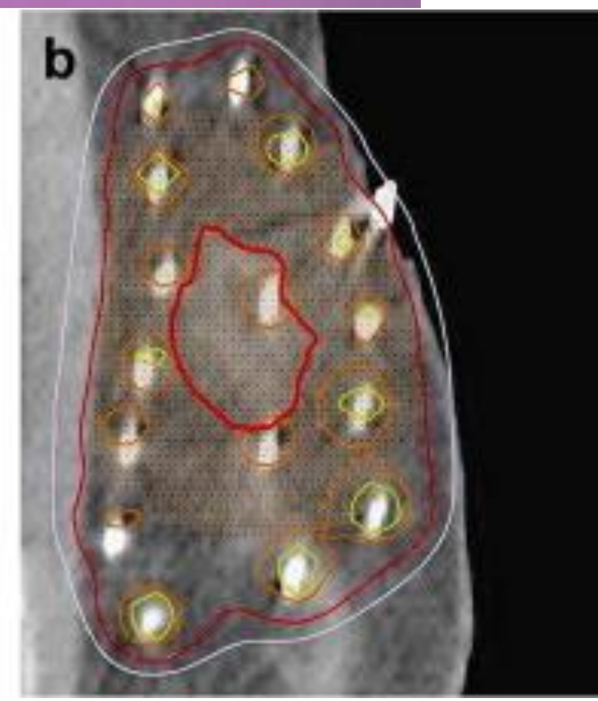
- Interstitial
  - Permanent
    - GU - prostate

(I-125, Pd-103, Cs-131)

- GYN - pelvic side wall (Au-198)
- GI - rectum (Au-198)





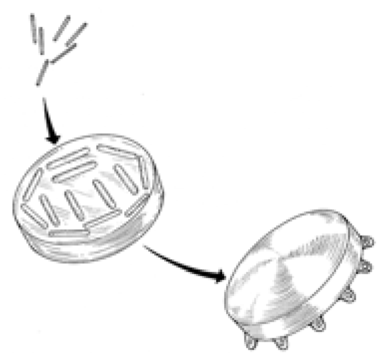


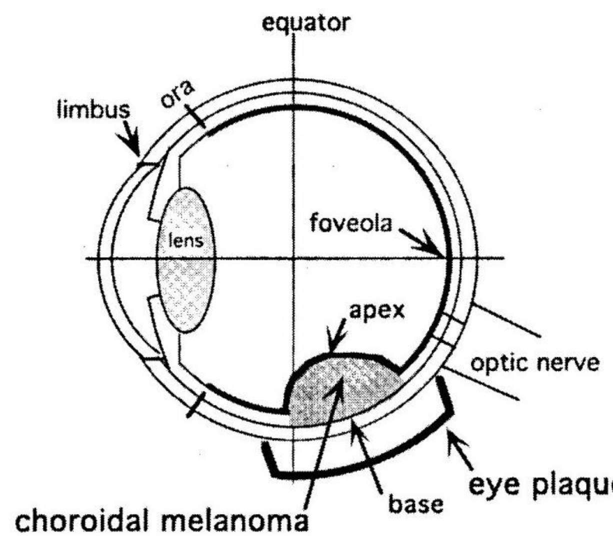
CLINICAL APPLICATION
TO APBI (ACCELERATED PARTIAL BREAST IRRADIATION)

Surface (Topical)

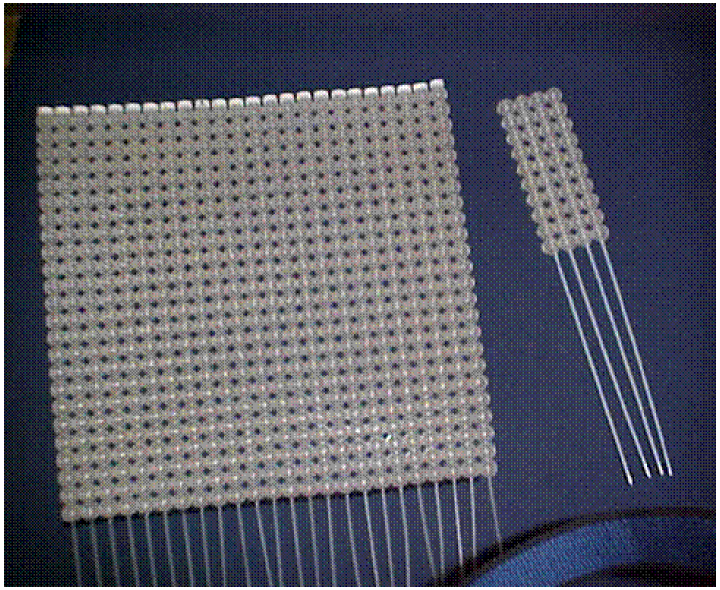
- Places the radioactive sources on top of the area to be treated (choroidal melanoma)
- Temporary: ~72hrs (LDR)

A custom-made radiation plaque. On the left is the inside of a plaque with the radiation seeds. On the right is the gold coating on the outside of the plaque.





Skin Surface Applicators
Ir-192 HDR

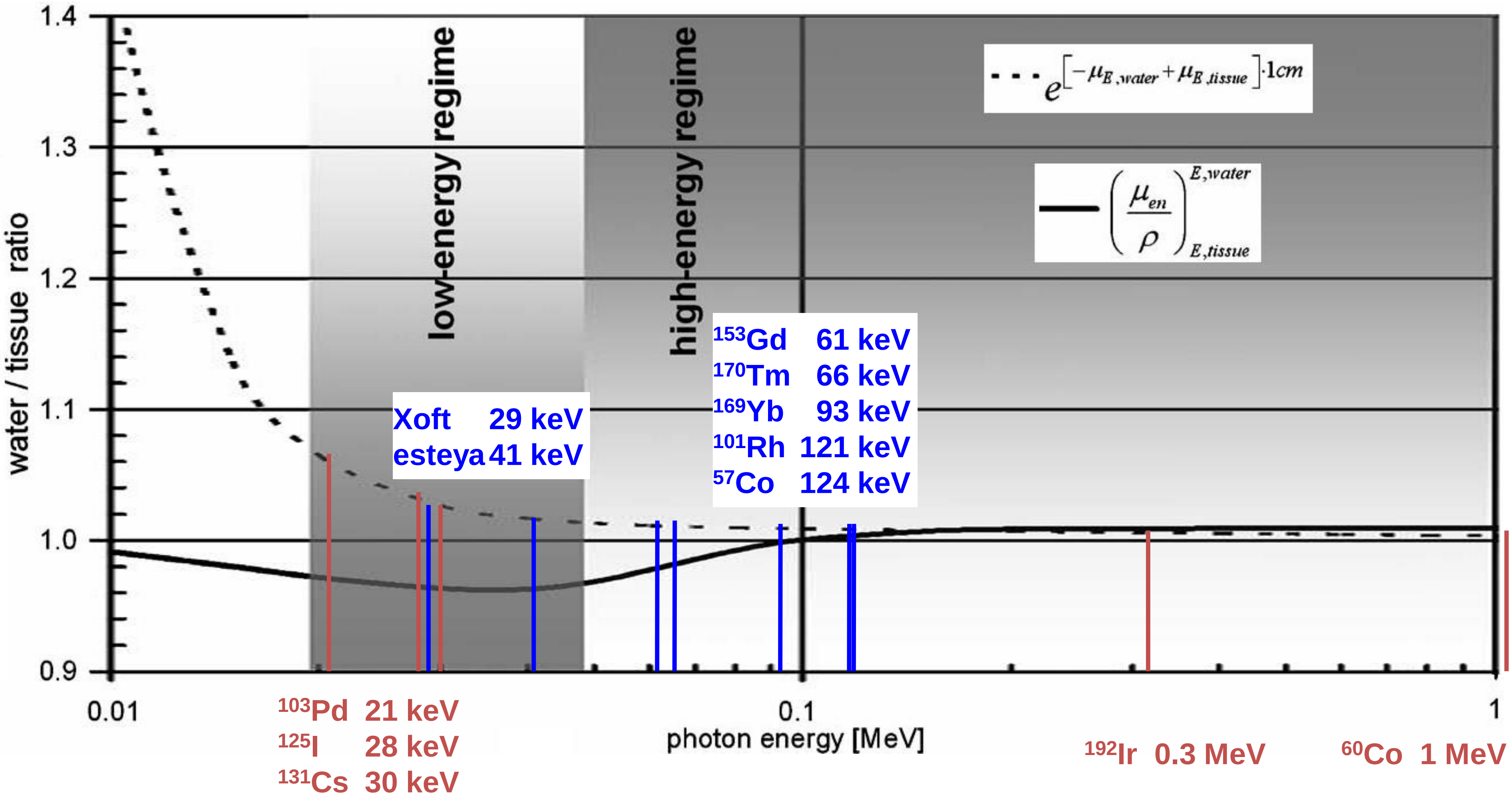


Freiburg Flap

Leipbzig (shielded)

New BT Sources

- How sensitive is dosimetry for novel radionuclides and eBT to material heterogeneities (and general differences with TG-43)?



Slide from Rivard

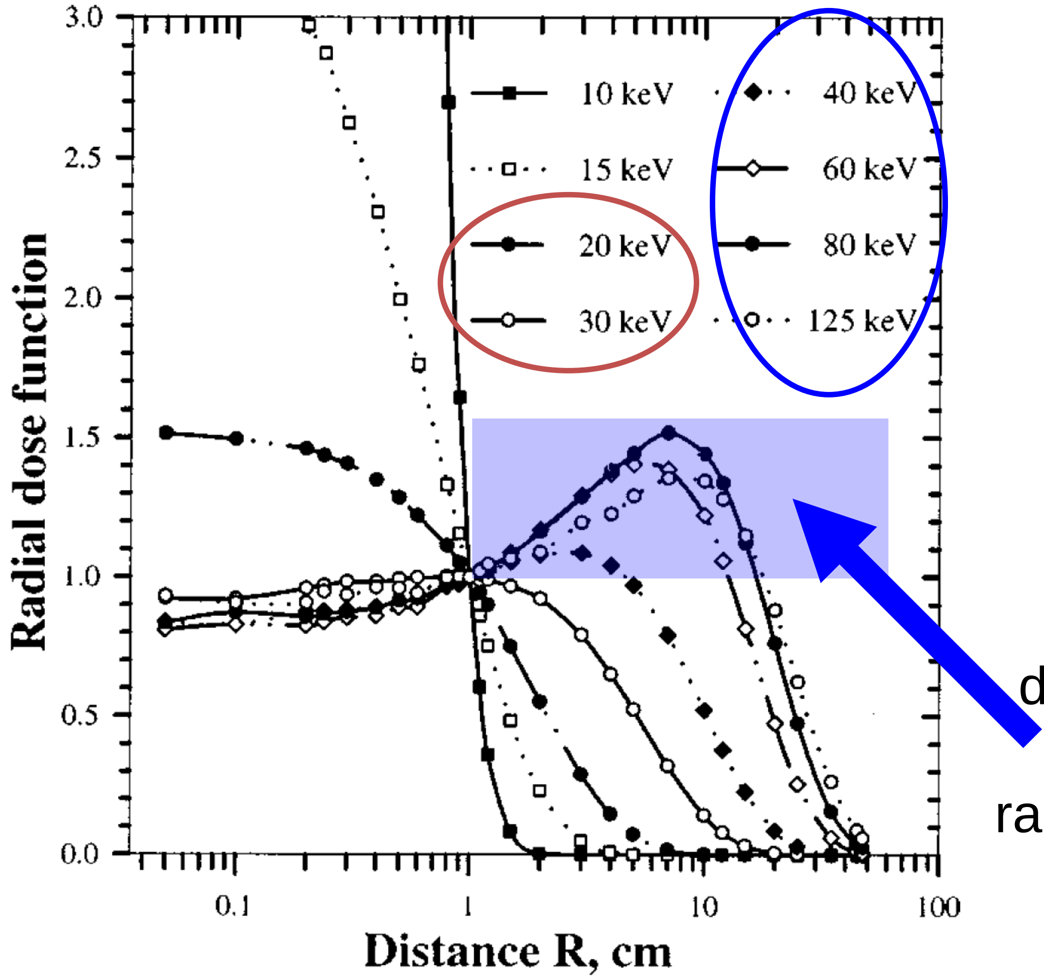
Rivard, Venselaar, Beaulieu, *Med Phys* 36, 2136-2153 (2009)

New BT Sources

"Dose-rate falloff differences" as a FN of E

established sources

^{103}Pd 21 keV
^{125}I 28 keV
^{131}Cs 30 keV



novel sources

Xoft 29 keV
esteya 41 keV

^{153}Gd 61 keV
^{170}Tm 66 keV
^{169}Yb 93 keV
^{101}Rh 121 keV
^{57}Co 124 keV

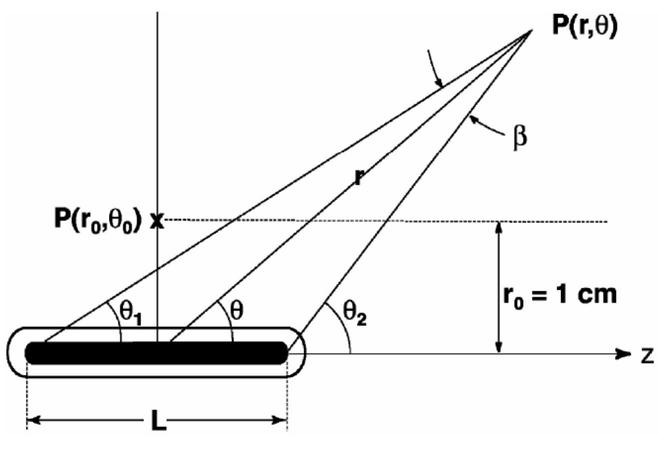
dose increase due to radiation scatter

Slide from Rivard

Luxton and Jozsef, *Med Phys* 26, 2531-2538 (1999)

Brachytherapy Dose Calculation (i.e. since 1995)

- TG43 formalism is the standard methodology for dose calculation.
- TG43 was created primarily for interstitial low energy brachytherapy purposes.
- Dose calculation is done assuming material is uniform water phantom.



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

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

$\dot{D}(r,\theta)$	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

History

- 1995 – TG43 (I-125, Pd-103)
  - Provided recommendations for dose calculation for low energy source dosimetry (E<50keV).
- 2004 – TG43U1
  - Clarifications, 1D vs 2D formalism, etc.
- 2007 – TG43U1S1
  - Increased number sources, etc.
- 2010 “Erratum” of TG43U1S1

Prior to TG-43:
Sievert Integral Source Geometry

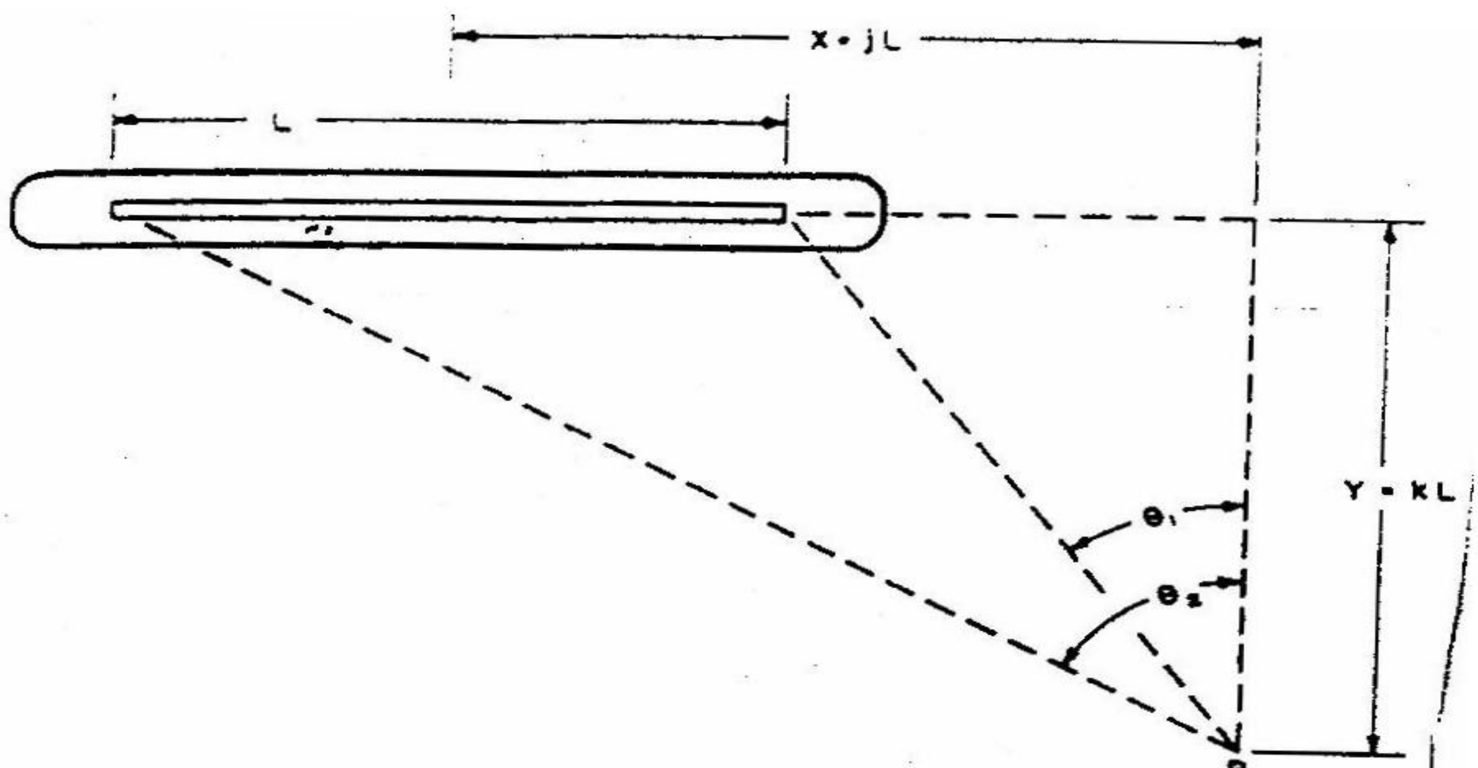


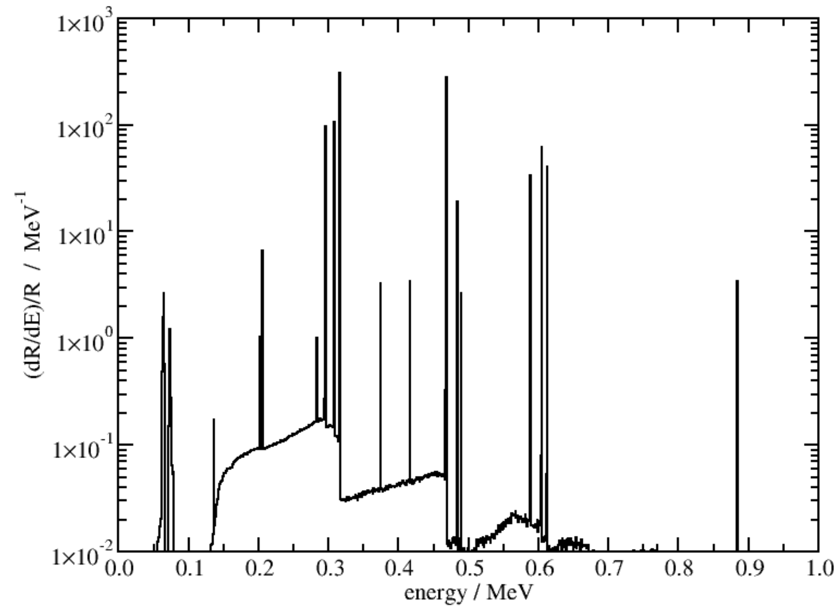
FIG. 1.
Geometry of dose calculation for linear radium sources.

Consensus Data Sets

- Report gives recommendations on how to experimentally and theoretically obtain dosimetric parameters for sources.
  - Experimentally: detector type, volume averaging effects, phantom materials, energy response characterization, etc.
  - Theroetically (MC): Cut off thresholds, good practice guidelines (e.g. # of histories)
- Uncertainty analysis

Clinical Source Registry Available

- 3 current source registries available
  - IROC- Houston (RPC)
  - Carlton University (CAN)
  - ESTRO



High-Energy Brachytherapy Sources-examples

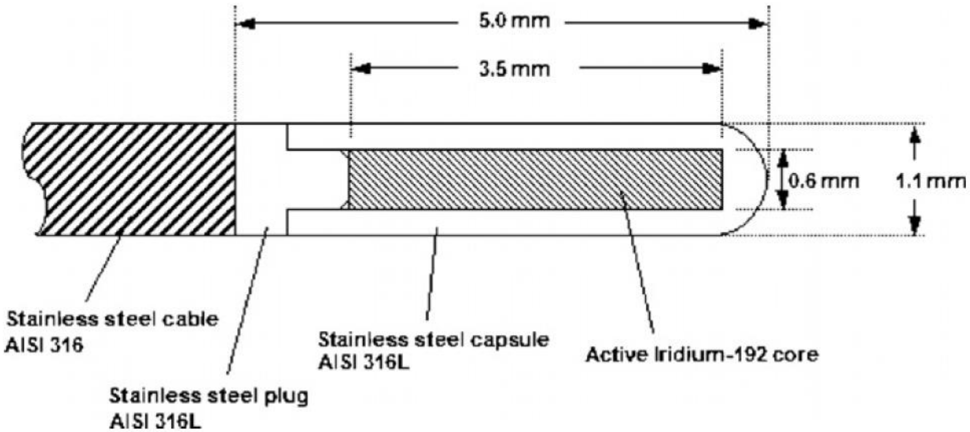
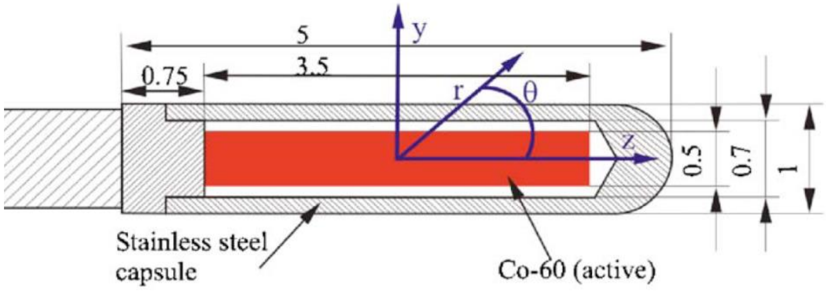


Figure 1. Schematic drawing of the Nucletron 'Classic' ^{192}Ir HDR brachytherapy source.



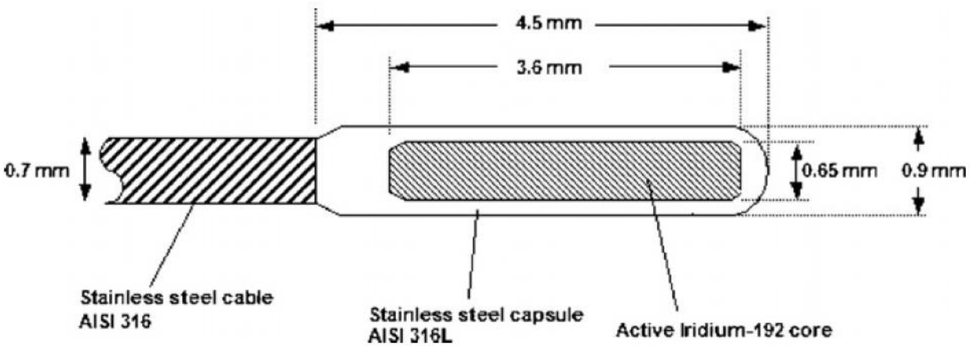
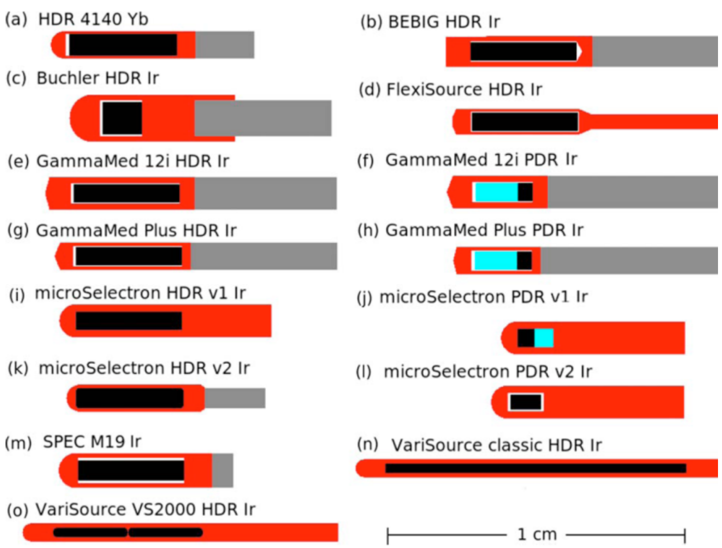
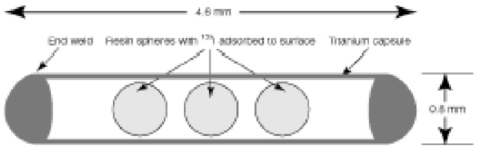


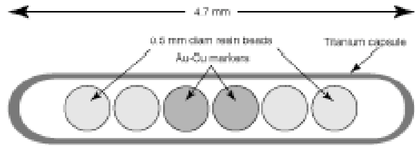
Figure 2. Schematic drawing of the Nucletron 'V2' ^{192}Ir HDR brachytherapy source.



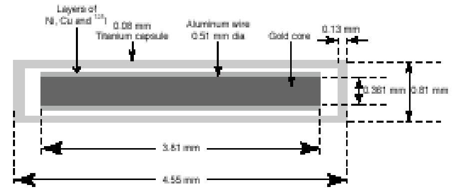
Low-Energy Brachytherapy Sources- examples



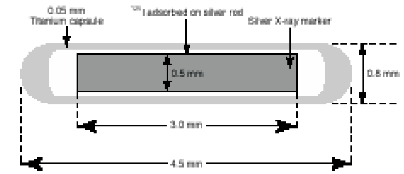
Amersham Health model 6702 source



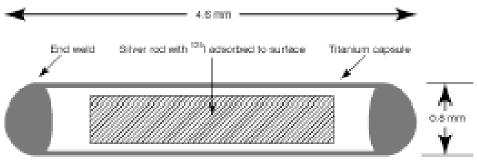
NASI model MED3631-A/M or MED3633 source



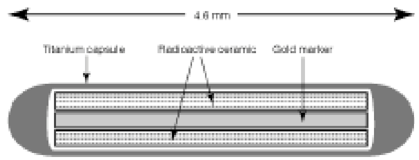
Source Tech Medical
STM1251 seed



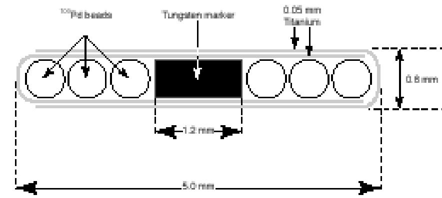
IsoAid Advantage



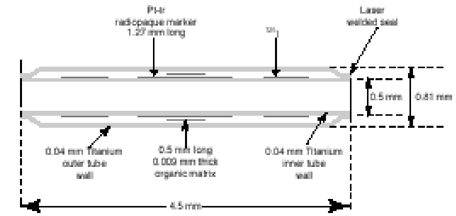
Amersham-Health model 6711 source



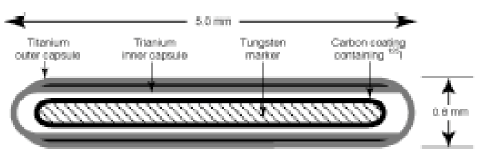
Bebig model I25.S06 source



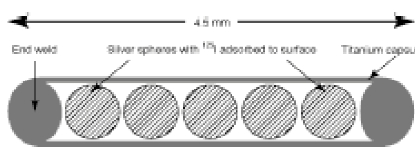
Best Pd



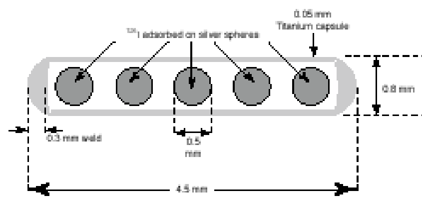
International Brachytherapy
InterSource



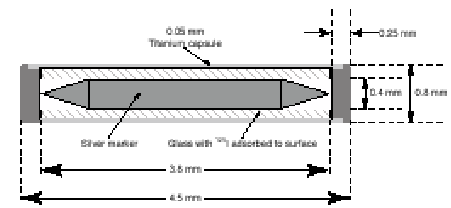
Best model 2301 source



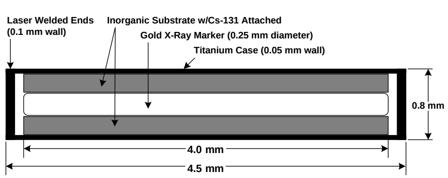
Imagyn model IS-I2501 source



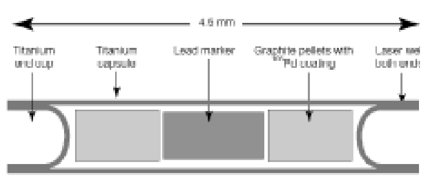
Mentor Prostaseed



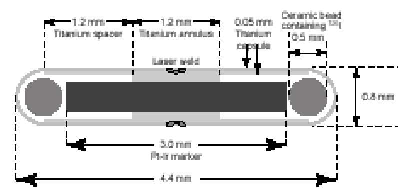
Implant Sciences 3500



IsoRay model CS-1 Rev2



Theragenics model 200 source



DraxImage LS-1

Axxent electronic BT source: 27 keV

TG-43 Protocol Phantom Size Requirement

- TG43 has recommendations for “along and away” dose rate tables to distances far away from the source (e.g. 5cm for I-125)

- Requires phantom sizes in MC calculations to be large enough to give full scatter at large distances (10+ cm for HEB)
  - Radius of 40 cm recommended.

Advantages of TG43

- An analytic, uniform approach standardizes dose calculation worldwide.

- Simple to implement into the TPS and 2nd calculation spreadsheet for a clinical phyisicist

Limitations of TG43

- Assumes a water medium with superpositions of single source positions.
  - No inter-source attenuation effects
  - Full scatter conditions
    - Most low energy applications have full scatter e.g. prostate implants
  - No variable tissue composition
    - More of an issue for low energy sources than for high energy sources

Limitations of TG43, cont

- High energy brachytherapy sources suffer more from effects of the scatter conditions than low energy brachytherapy sources.
  - Applications can range from deep (gyn) to shallow (skin).
- Neglects applicator shielding effects for treatments such as shielded ovoids or cylinders.
  - Incorrect correlation of doses reported with toxicities

TG43 has served us well!

- Is still!
- Worldwide uniformity
- Well-define process for source parameters
- Source specific
- Fast
- Dose optimization (IP)

Report #229

Dose Calculation for Photon-Emitting Brachytherapy Sources with Average Energy Higher than 50 keV: Full Report of the AAPM and ESTRO

Report of the

High Energy Brachytherapy Source Dosimetry (HEBD) Working Group

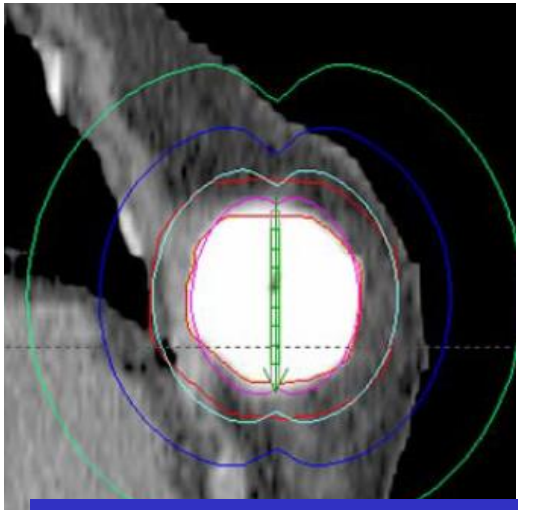
August 2012

TG-229 Report Contains

1. Review the construction and available published dosimetry data for high-energy ^{192}Ir, ^{137}Cs, and ^{60}Co sources.
2. Perform a critical review of the existing TG-43U1 formalism applied to HEB.
3. Develop a complete consensus dataset to support clinical planning for each source model.
4. Develop guidelines on the use of computational and experimental dosimetry of high-energy brachytherapy sources.

TG43-based TPS can fail to accurately calculate dose

- Dose perturbations due to contrast medium and air pockets
- Effect of patient tissue inhomogeneities
- What is the impact on
  - PTV
  - Skin
  - Chest wall/ribs



air ≠ water?

tissue ≠ water?

contrast impact?

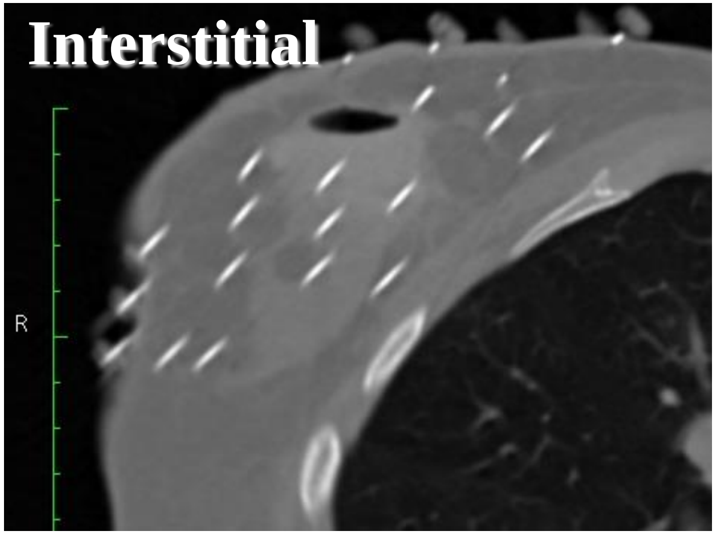
source superposition?

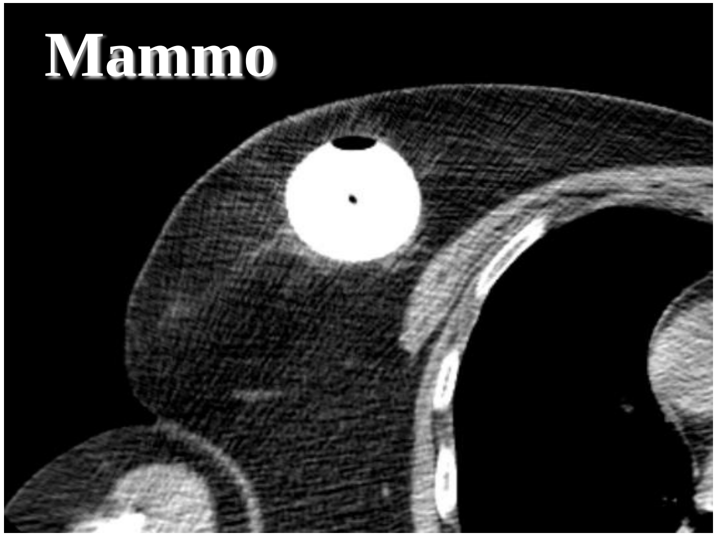
source shielding?

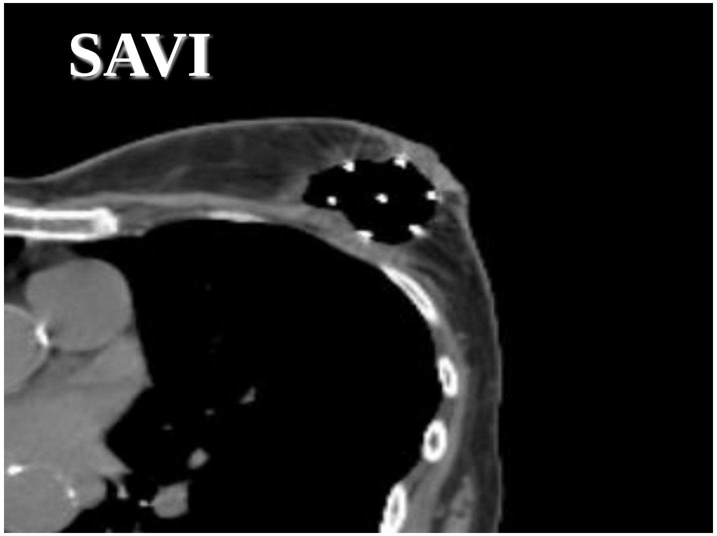
radiation scatter?

Rivard, "Brachytherapy Dose Calculation Formalism Dataset Evaluation, and treatment planning system Implementation (AAPMSS 2009)

One size does not fit all!







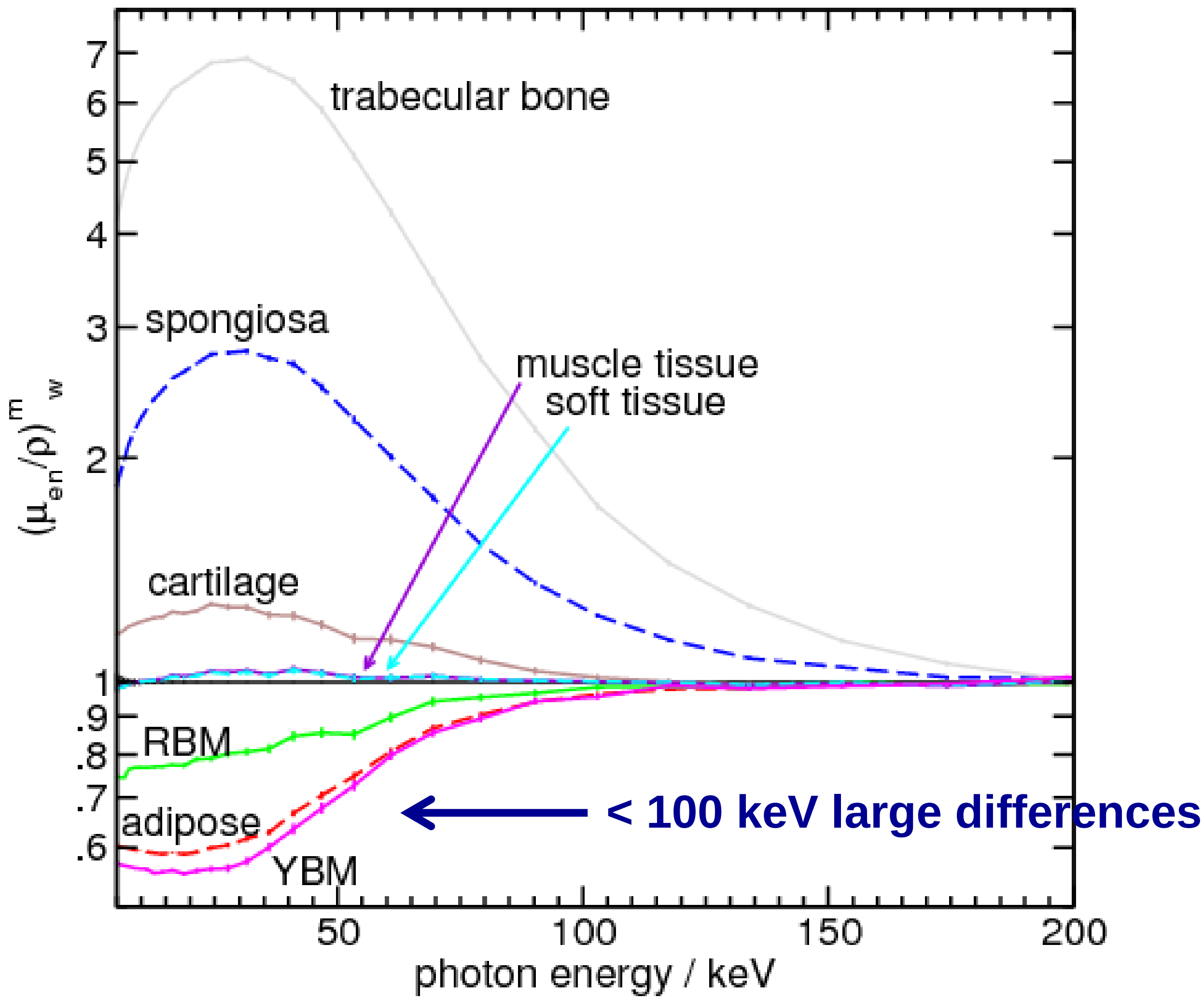
Sensitivity of Anatomic Sites to Dosimetric Limitations of Current Planning Systems

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)

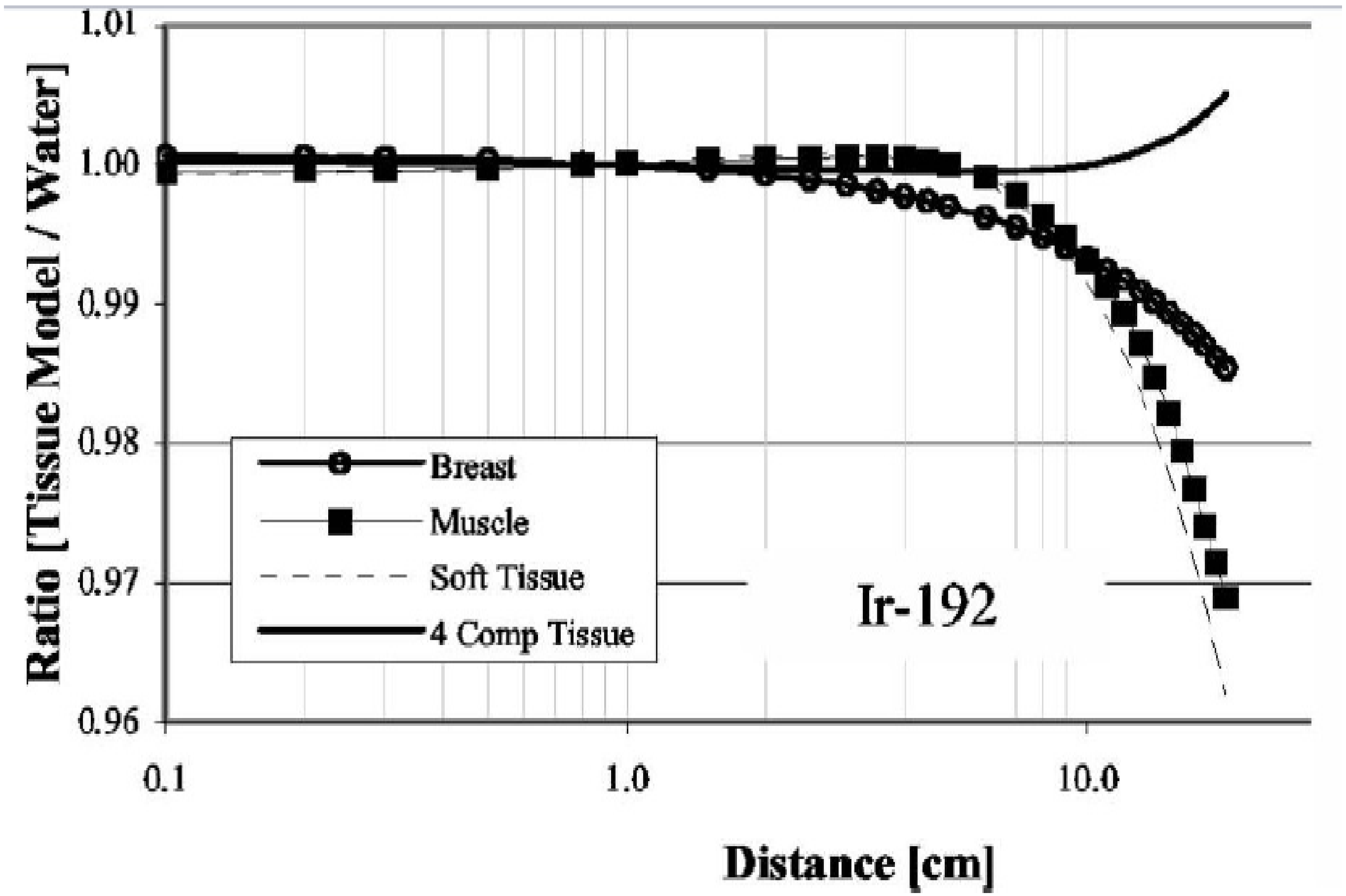
Importance of the Physics: Water vs Tissues

Mass Energy-Absorption Coefficients Relative to Water as a function of Energy



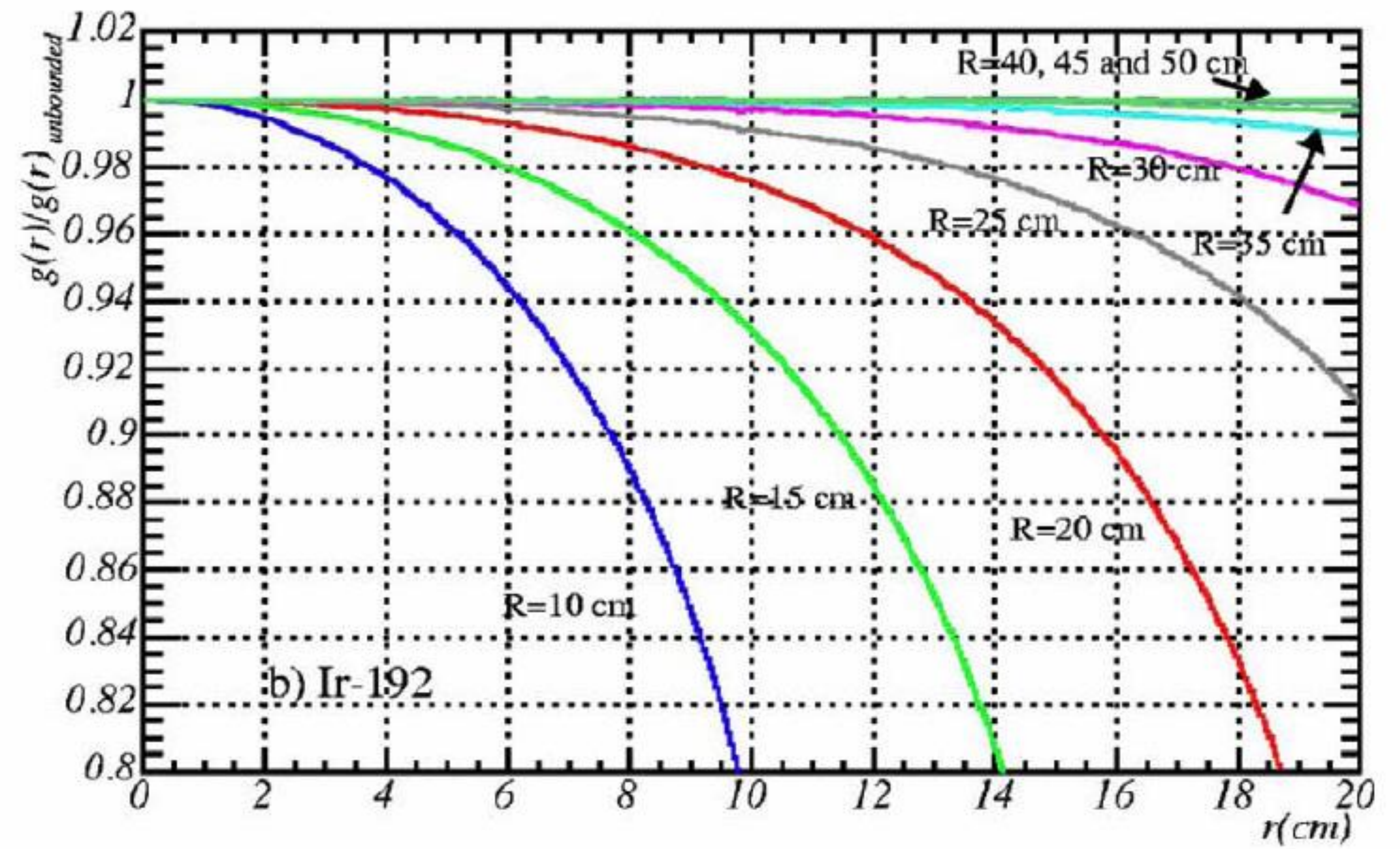
TG-186

Tissue composition impact is minimal (Ir-192)



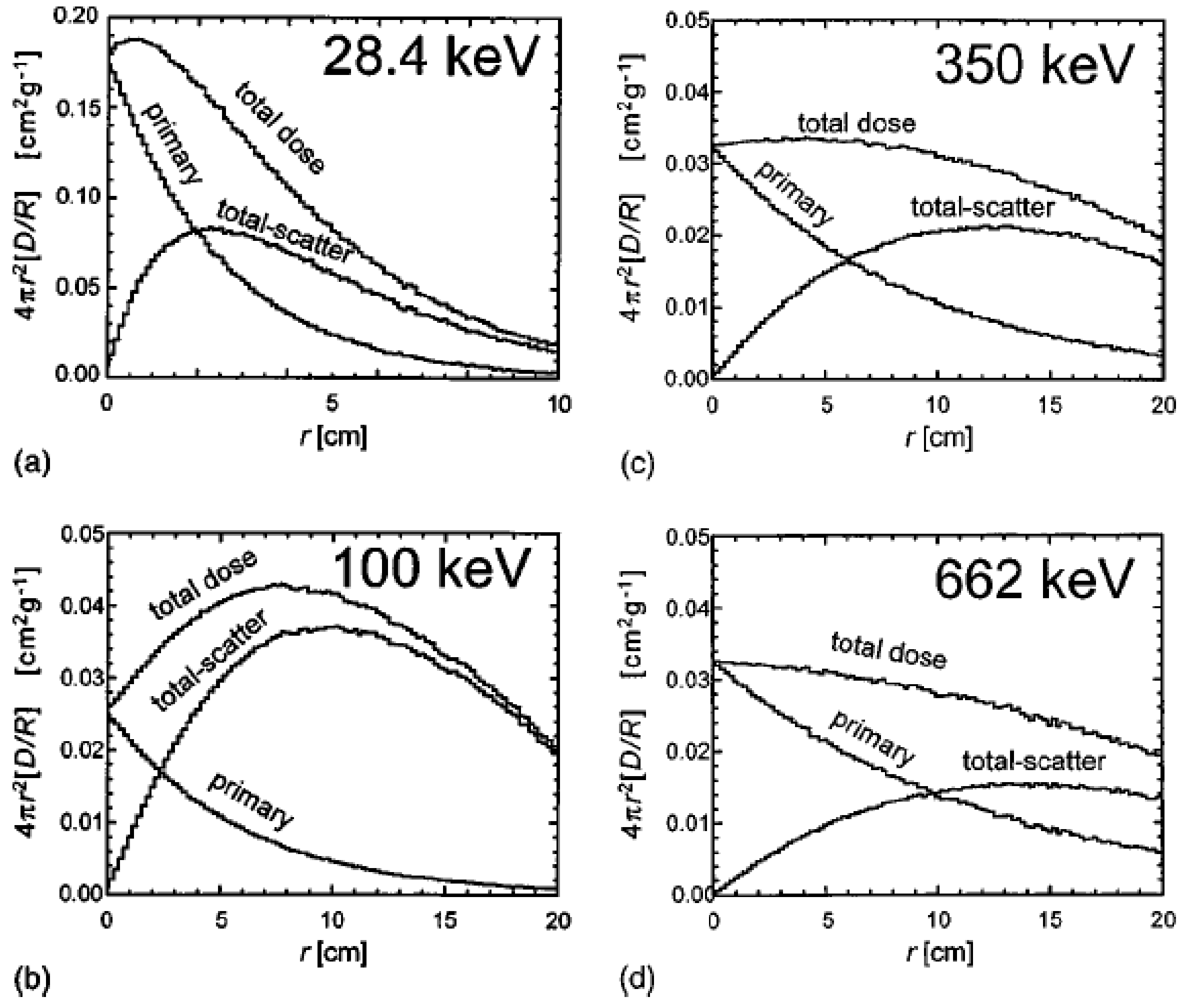
Melhus C S, Rivard M J, « Approaches to calculating AAPM TG-43 brachytherapy dosimetry parameters for Cs-137, Ir-192, Pd-103, and Yb-169 sources », Med. Phys., 33(6), 2006

But- Effect of Phantom Size



Perez-Calatayud, Granero, Ballester MedPhys (2004)

Scattered Photon Contribution in Brachy



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

Physics « Rule of Thumb »

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

Alternatives to TG43

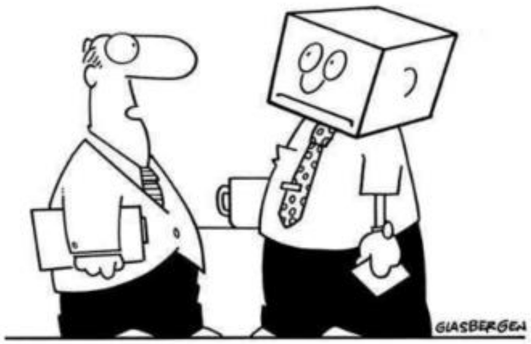
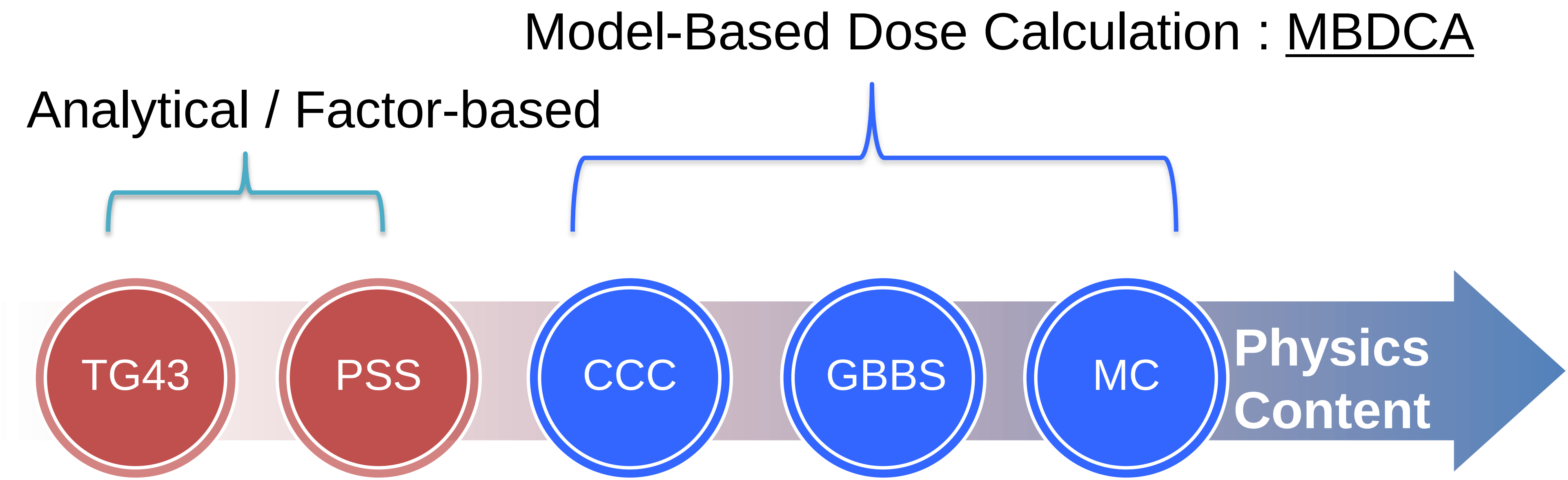


TABLE I. Status of MBDCAs that can account for radiation scatter conditions and/or material heterogeneities and were useable in brachytherapy treatment planning systems as of 12 May 2010.

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



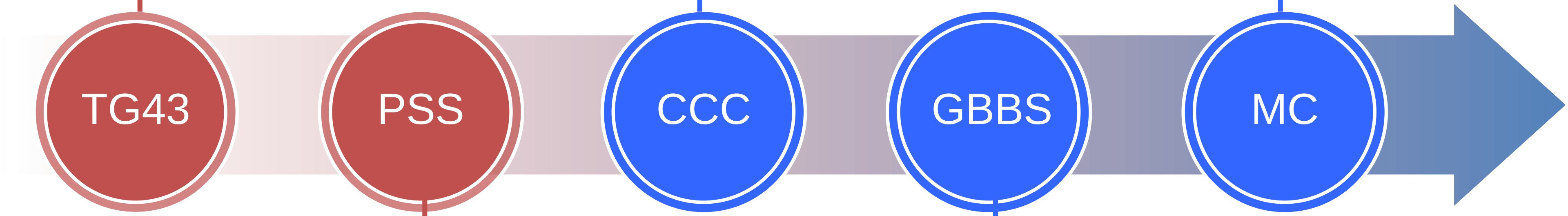
Rivard, Beaulieu and Mourtada, Vision 20/20, Med Phys 2010

BT Dose Calc.

Current STD: Full scatter water medium

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

Gold STD for source characterization and other applications



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

Solves numerically transport equtations. Full heteregoneities.

Grid-Based Boltzmann Solver (GBBS)

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

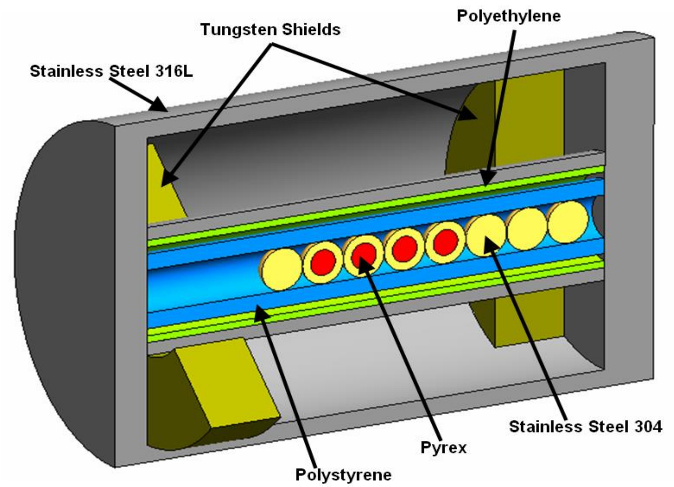
– Position: $\vec{r} = (x, y, z)$	mesh position discretization (finite elements)
– Energy: *E*	*Energy bins (cross section)*
– Direction: $\hat{\Omega} = (\theta, \phi)$	Angular discretization

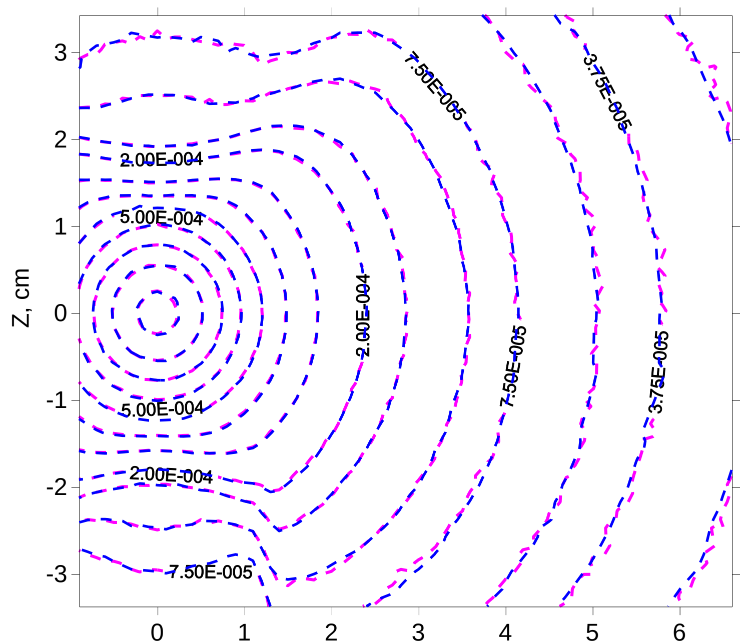
« multi-group discrete ordinates grid-based …»

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

GBBS Benchmarks for ^{137}Cs Pellets

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)

AAPM Annual Meeting Pittsburg, PA, 2004

ACUROS benchmark

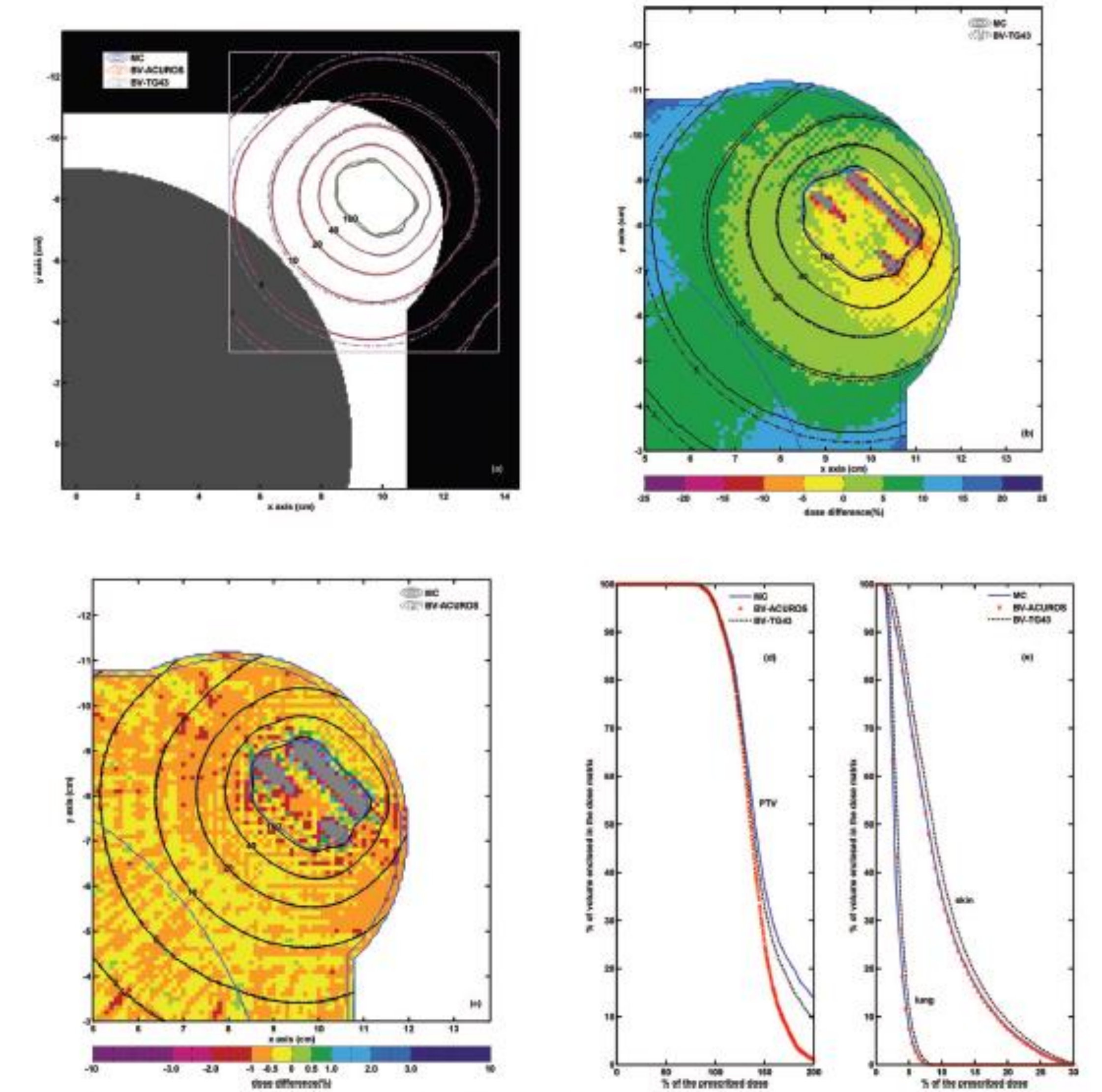


FIG. 2. (a) The central image of the voxelized mathematical breast model with BV-TG43, BV-ACUROS, and MC dose calculation results for the same breast brachytherapy plan presented in the form of percentage isodose lines within the extent of the dose calculation grid. (b) A colormap representation of the spatial distribution of percentage differences between BV-TG43 and MC results ($\frac{D_{BV-TG43}}{D_{MC}} - 1$) on the plane presented in (a). (c) A colormap representation of the spatial distribution of percentage differences between BV-Acuros and MC results ($\frac{D_{BV-ACUROS}}{D_{MC}} - 1$) on the plane presented in (a). (d) Cumulative DVH results for the PTV derived from the 3D dose distributions calculated using BV-TG43, BV-ACUROS and MC. (e) Same as (d) for the skin and lung OARs.

Dosimetric accuracy of a deterministic radiation transport based ^{192}Ir brachytherapy treatment planning system. Part III. Comparison to Monte Carlo simulation in voxelized anatomical computational models

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(Received 26 July 2012; revised 15 November 2012; accepted for publication 16 November 2012; published 18 December 2012)

MBDCA Calculation Speed…

- Can be relatively fast
  - Can be done within a few minutes
  - < 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
  - See D'Amours et al IJROBP 2011; Hossoiny et al, Med Phys 2012

CURRENT ISSUES/RESEARCH AREA

Factor-based vs Model-based

TG43

INPUT	CALCULATION	OUTPUT
Source characterization →	Superposition of data from source characterization →	$D_{\text{w-TG43}}$

MBDC

INPUT	CALCULATION	OUTPUT
Source characterization →	**Model-Based Dose Calculation Algorithms** →	$D_{m,m}$
Tissue/applicator information →		$D_{w,m}$

From Åsa Carlsson-Tedgren

TG-186 Report

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

1. Recommendations to MBDCA early-adopters to evaluate:
    - phantom size effect
    - inter-seed attenuation
    - material heterogeneities within the body
    - interface and shielded applicators
2. Commissioning process to maintain inter-institutional consistency
3. Patient-related input data
4. Research is needed on:
    - tissue composition standards
    - segmentation methods
    - CT artifact removal

<u>Approved by</u>

ESTRO (EIR, ACROP)
AAPM (BTSC, TPC)
ABS (Phys Cmte, BoD)
ABG (Australia)

Beaulieu et al, *Med Phys* 39, 6209-6236 (2012)

Three main areas identified as critical

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

Dose reporting possibilities

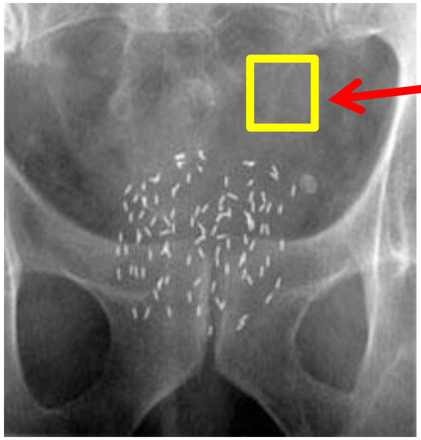
$$D_{x,y}$$

x: dose specification medium

y: radiation transport medium

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

$$D_{m,m}$$



Voxel for dose scoring

Dose reporting possibilities

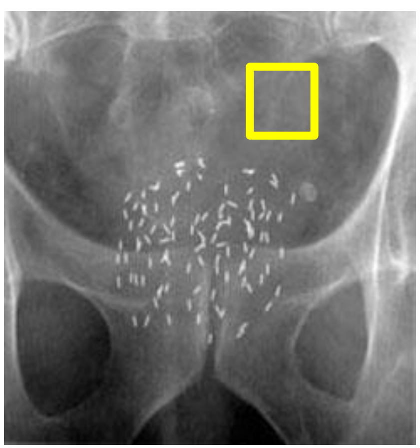
$D_{x,y}$

x: dose specification medium

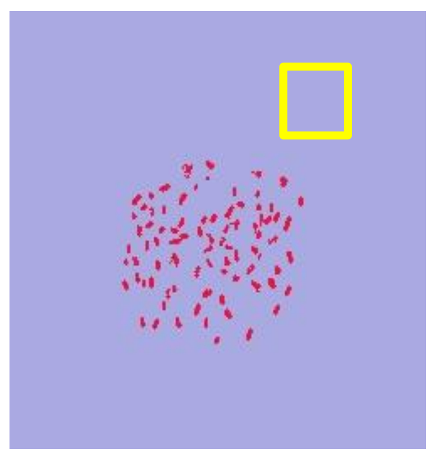
y: radiation transport medium

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

$D_{m,m}$



$D_{w,w}$



Dose reporting possibilities

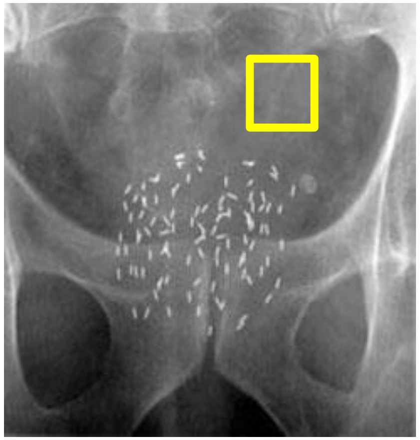
$D_{x,y}$

x: dose specification medium

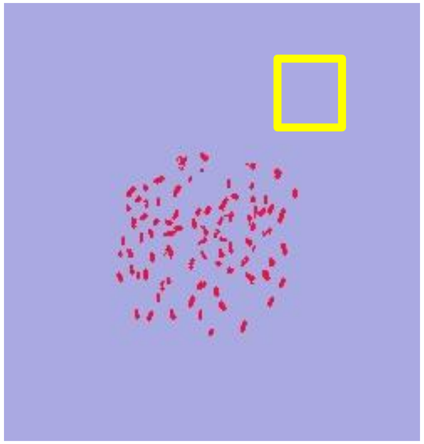
y: radiation transport medium

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

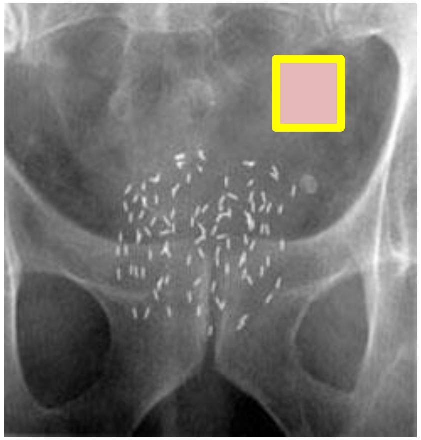
$D_{m,m}$



$D_{w,w}$



$D_{w,m}$



Heterogeneity effects: low energies

Ignored in TG-43 $D_{w,w}$ formalism	Approx. magnitude of effect ($D_{m,m}$) for prostate ^{125}I or ^{103}Pd treatments
Tissues	~10%+
Non-water 'objects'	Calcifications ~ 8% Applicator shielding ~ 50%
Photon attenuation by seeds	~15% local 2-4% global

Thomadsen *et al*, Med Phys **35** (2008).

Heterogeneity effects: higher energies (^{192}Ir)

- Differences between $D_{w,w}$ and $D_{m,m}$ for soft tissues generally < 2%
- Esophageal ^{192}Ir HDR[1]:
  - $D_{w,w}$ 13-15% lower than $D_{m,m}$ for spinal chord, sternum bone
- Breast ^{192}Ir HDR[2]:
  - $D_{w,w}$ is 5% higher than $D_{m,m}$ for skin; 10% higher for lung

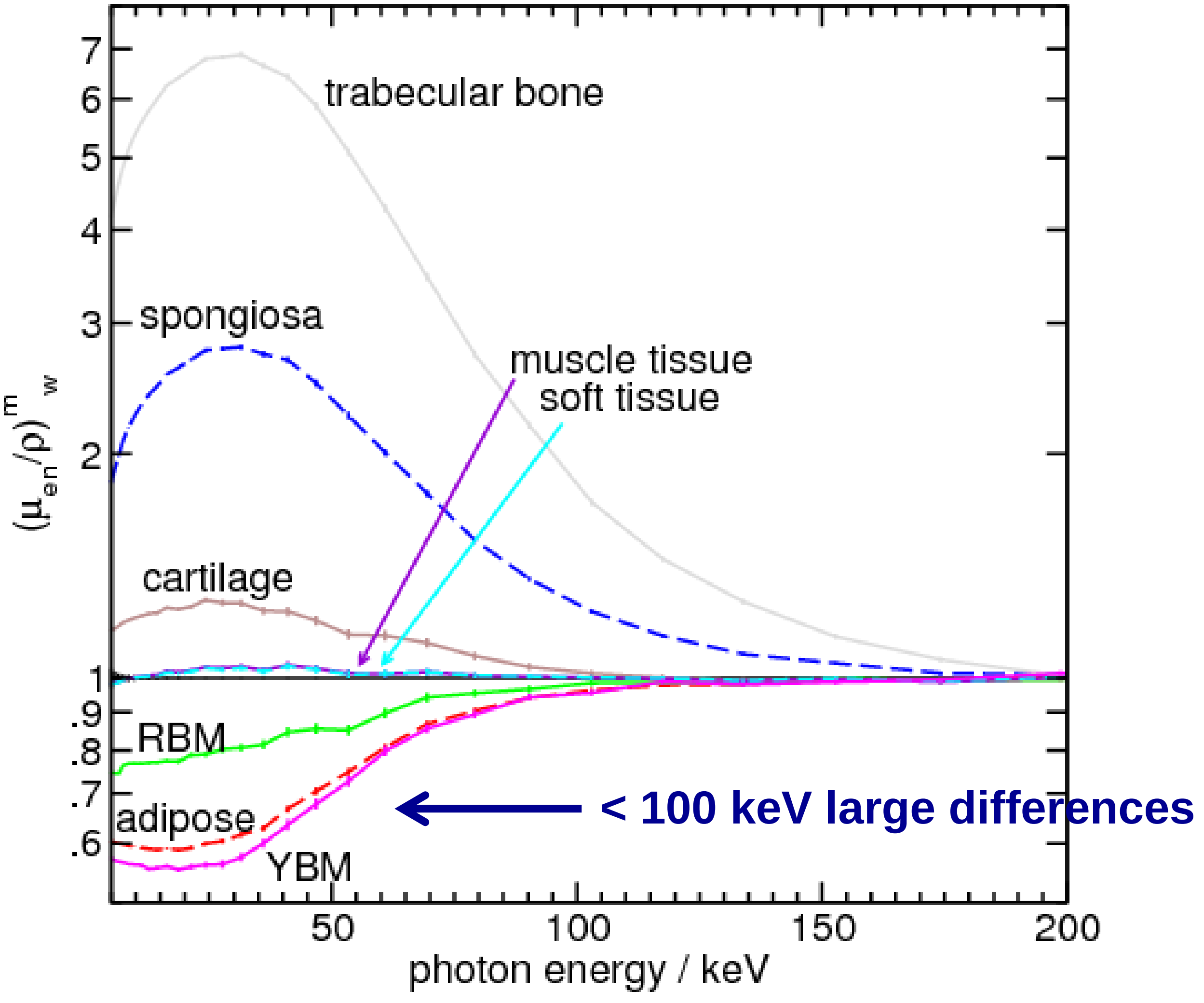
[1]Lymperpolou et al, Med Phys **33** (2006).
[2]Poon & Verhaegen *et al*, Med Phys **36** (2009).

$D_{m,m}$ versus $D_{w,m}$ brachytherapy comparison

- MBDCA compute $D_{m,m}$
- Large cavity theory: $D_{w,m} = (\mu_{en}/\rho)^{w}{}_{m}\ D_{m,m}$
- Differences between $D_{w,m}$ and $D_{m,m}$ given by $(\mu_{en}/\rho)^{w}{}_{m}$ values

- Differences between $D_{w,m}$ and $D_{m,m}$ are most significant below 50 keV: as high as 70-80% for soft tissues and factor of 7 for bone!

Importance of the Physics: Water vs Tissues



TG-186

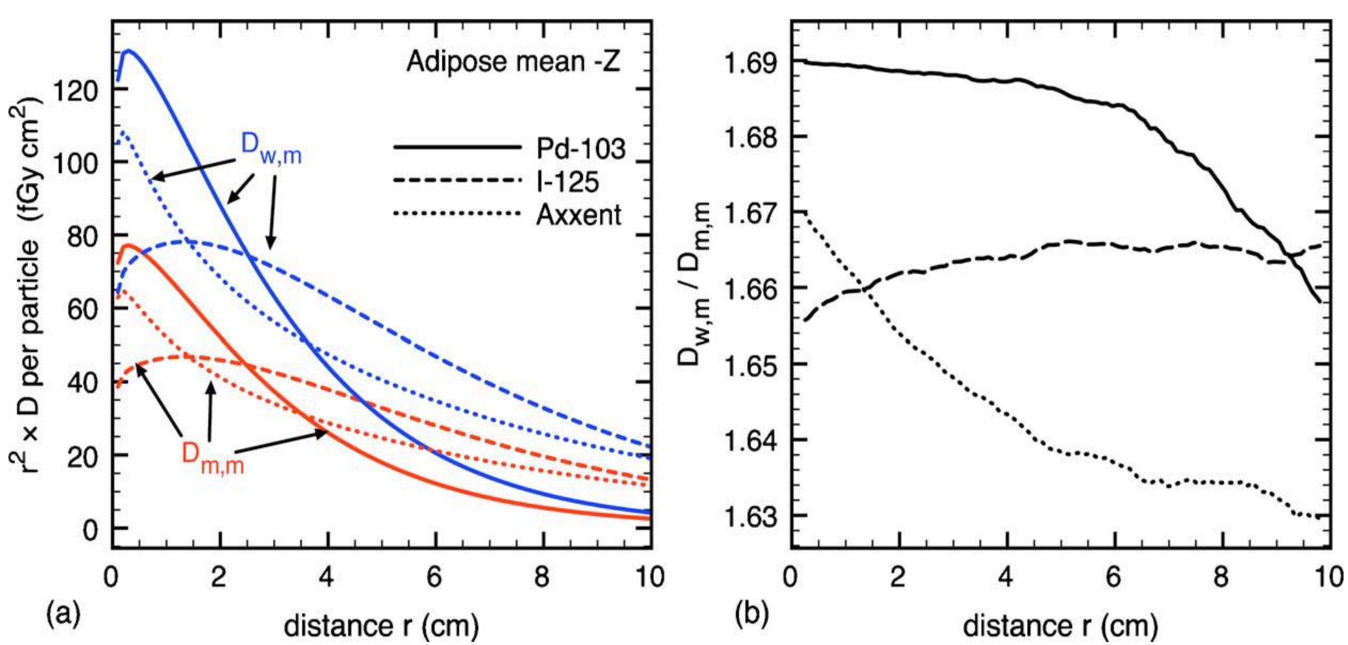
Difference in reporting dose to water or medium

Left: Radial $D_{w,m}$ *and* $D_{m,m}$ *in adipose mean-Z*

Three different brachytherapy photon sources: ^{103}Pd, ^{125}I, Axxent

Right: Ratio $D_{w,m}/D_{m,m}$

differences up to 70%, highly dependent on source



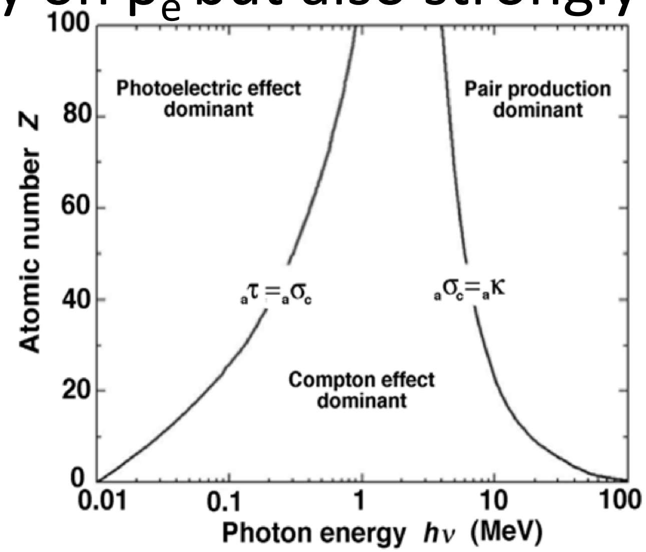
Summary & Recommendations

- $D_{m,m}$, $D_{w,m}$ and $D_{w,w}$(TG43) differ considerably, particularly for low energy brachytherapy:
  - Adoption of MBDCA: potential for significant impact on dose metrics
  - Cannot generally motivate reporting $D_{w,m}$ to connect with previous clinical experience

<u>TG186 recommendation is to report $D_{m,m}$ along with current TG43 $D_{w,w}$</u>

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

Better ways to distinguish tissues: dual-energy CT?

- Use dual energy CT to extract ρ_e and Z directly from CT images

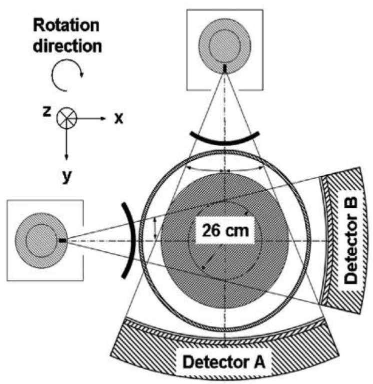
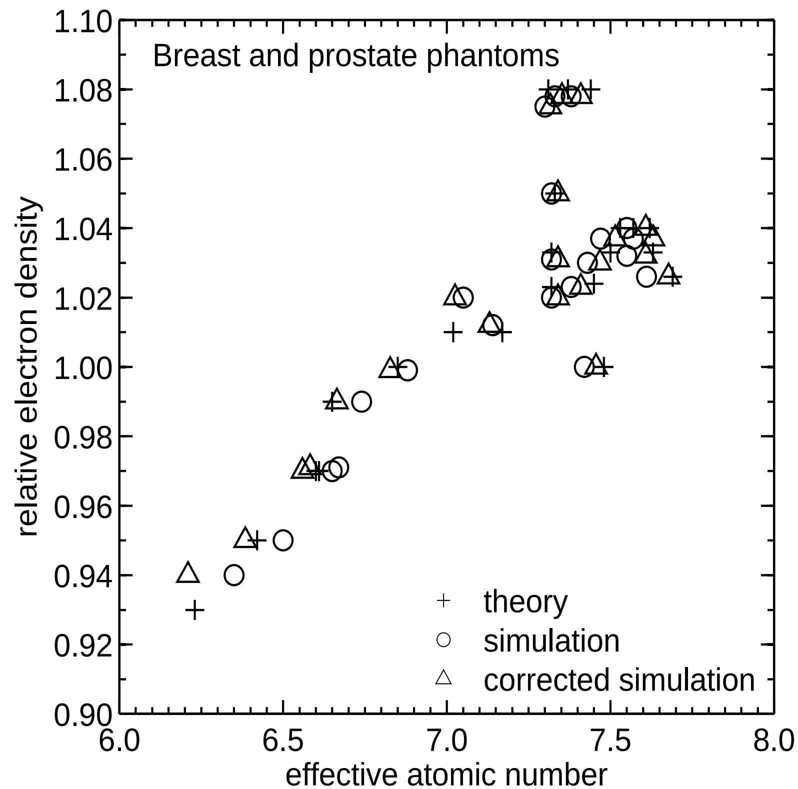


FIG. 1. Technical realization of a DSCT system (SOMATOM Definition, Siemens Healthcare, Forchheim, Germany). One detector (A) covers the entire scan field of view with a diameter of 50 cm, while the other detector (B) is restricted to a smaller, central field of view.



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

Summary & Recommendations

- Low energy brachytherapy dose calcs very sensitive to tissue composition
  - Recommendations on tissue composition/assignment
  - Recommendations on tissue segmentation
- $D_{m,m}$ and $D_{w,m}$ are very different
  - Recommendations on dose perscription
- Recommendations on further research on tissue typing, imaging modalities (DECT), …

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

    - <u>This is not sustainable for the clinical physicists</u>

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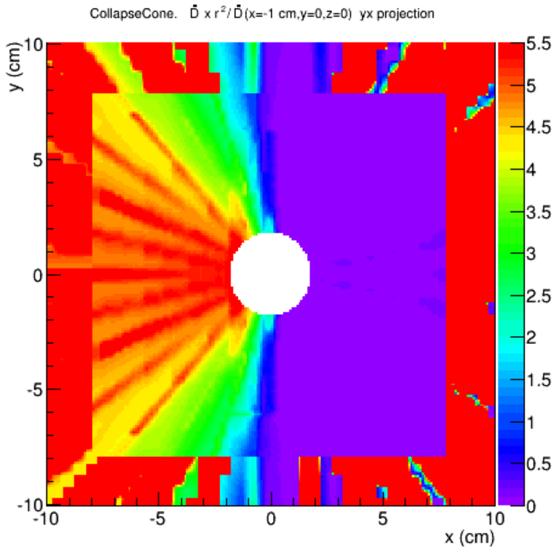
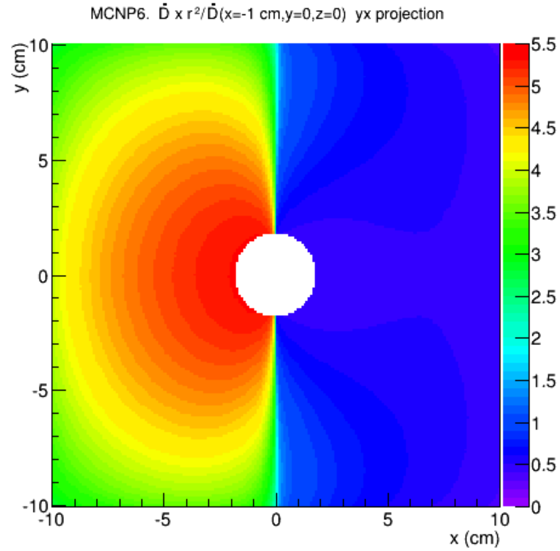
MBDCA-WG Commission for Shielded Applicators

Preliminary Results



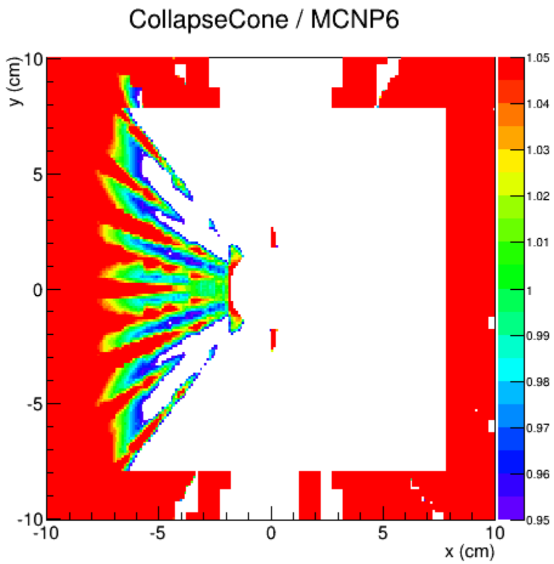


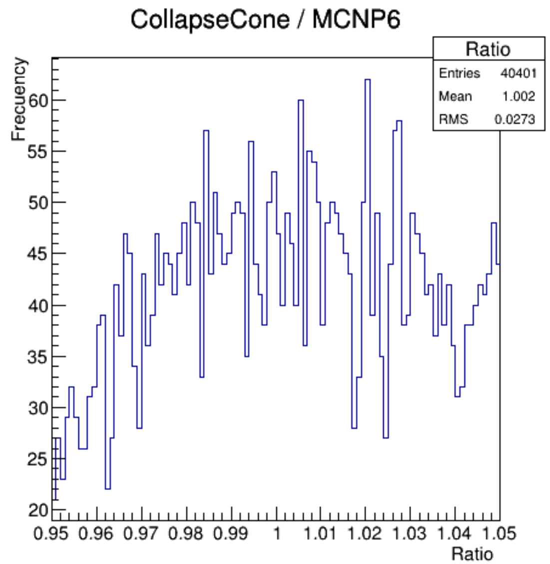
Case III

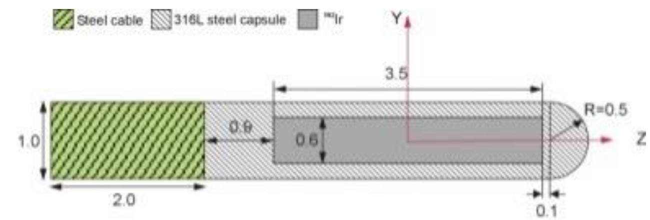
Applicator and source centered at DICOM in air

CollapseCone Vs. MCNP6

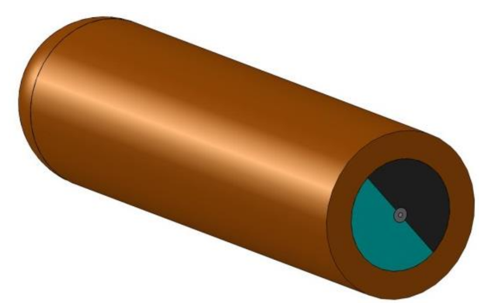
Plane z = 0.0 cm







HDR ^{192}Ir model MBDCA-WG source



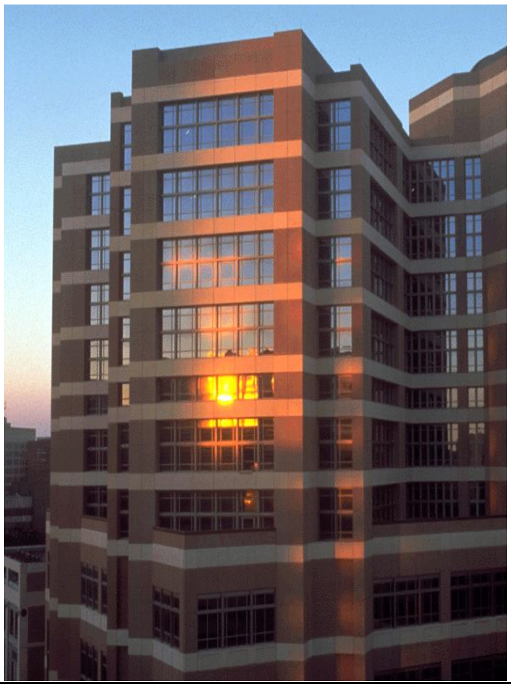
Conclusions

- With the recent introduction of heterogeneity correction algorithms for brachytherapy, the Medical Physics community is <u>still unclear</u> on how to commission and implement these into clinical practice.
- Recently-published AAPM TG-186 report discusses important issues for clinical implementation of these algorithms.

Conclusions

- AAPM-ESTRO-ABG Working Group on MBDCA in Brachytherapy (WGMBDCA) is
  - Creating a set of well-defined test case plans, available as references in the software commissioning process to be performed by clinical end-users.
- Need for *standardization* of such tasks is now needed for brachytherapy treatment planning transition from TG43 formalism to MBDCA.

Thank You



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