Key Clinical Applications Needing Advanced Dose Calculation in Brachytherapy

Regina K Fulkerson, PhD

Potential Conflict of Interest

Regina Fulkerson is a consultant with Standard Imaging, Inc.

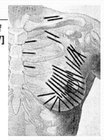
References

- Rivard MJ, Venselaar JLM, Beaulieu L. **The evolution of brachytherapy treatment planning**. Med Phys 2009;36:2136–53.
- Papagiannis P, Pantelis E, Karaiskos P. **Current state of the art brachytherapy treatment planning dosimetry algorithms**. Br J Radiol 2014;87(1041):20140163.
- Beaulieu L, Carlsson Tedgren A, Carrier J-F, Davis SD, Mourtada F, Rivard MJ, et al. **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**. Med Phys 2012;39(10):6208–36.
- **Comprehensive Brachytherapy: physical and clinical aspect**. JLM Venselaar, D Baltas, AS Meigooni and P.J. Hoskin. CRC Press, Taylor & Francis, 2013.

Brachytherapy

- Foundation of all radiotherapy
  - 1898: Discovery of Radium
- Classical treatment planning methods based on tabulated activity data
  - Corrections for radionuclide and source encapsulation

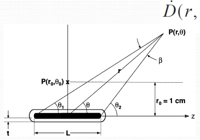
Radionuclide	$T_{1/2}$	Maximum energy of emitted particle [keV]
^{177}Lu	6.7 d	497
^{67}Cu	61.9 h	575
^{131}I	8 d	606
^{153}Sm	48.28 h	810
^{186}Re	3.8 d	1077
^{165}Dy	2.3 h	1285
^{89}Sr	50.5 d	1491
^{166}Ho	26.8 h	1854
^{188}Re	17.0 h	2120
^{90}Y	64.1 h	2284



Brachytherapy

- "Modern" treatment planning
  - TG-43 formalism
  - Parameters account for source attenuation and geometry
  - Assumption of an infinite water environment

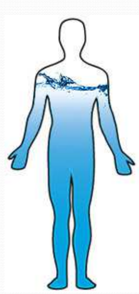
$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot F(r,\theta)$$

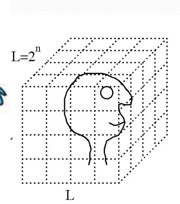


Rivard et al, *Med Phys* 31, 633-674 (2004)

Humans are not water

- Mostly water
- What do we do?
- Analytical solutions
  - Discretize parameters
    - Energy
    - Angle
    - Composition





Images Courtesy of: www.physiologyforwards.wordpress.com and www.graphics.stanford.edu accessed of 25 May 15

Physics of heterogeneity corrections

- The Linear Boltzmann Equation or LTBE

$$\hat{\Omega}\cdot\nabla\Phi_{\Omega,E}\left(\boldsymbol{r},E,\hat{\Omega}\right)=Q_{sc}\left(\boldsymbol{r},E,\hat{\Omega}\right)+\frac{Q_{prim}\left(E,\hat{\Omega}\right)}{4\pi}\delta\left(\boldsymbol{r}-\boldsymbol{r}_p\right)-\sigma_t(\boldsymbol{r},E)\Phi_{\Omega,E}\left(\boldsymbol{r},E,\hat{\Omega}\right) \quad (3)$$

$$\Phi_{\Omega,E}=\Phi^{prim}_{\Omega,E}+\Phi^{sc}_{\Omega,E}$$

$$\hat{\Omega}\cdot\nabla\Phi^{prim}_{\Omega,E}=\frac{Q_{prim}\left(E,\hat{\Omega}\right)}{4\pi}\delta\left(\boldsymbol{r}-\boldsymbol{r}_p\right)-\sigma_t(\boldsymbol{r},E)\,\Phi^{prim}_{\Omega,E} \quad (5)$$

✔ Trivial!

$$\hat{\Omega}\cdot\nabla\Phi^{sc}_{\Omega,E}=Q_{sc}-\sigma_t(\boldsymbol{r},E)\,\Phi^{sc}_{\Omega,E} \quad (6)$$

✖ No analytical solution

Papagiannis , Pantelis, Karaiskos, Br J Radiol, 87, 20141063 (2014)

Treatment planning - today

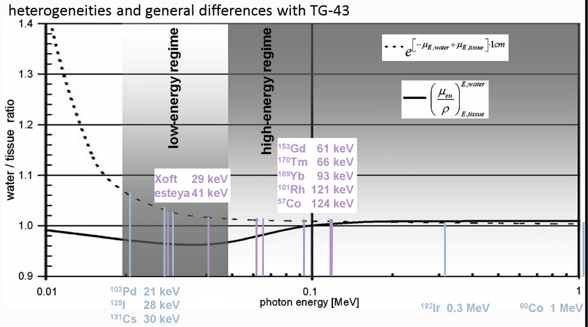
- Commercially available approaches
  - CPE assumed (Dose = Kerma): Primary dose = analytical using ray-tracing with scaling; 1st scatter dose, estimated from Scerma.
  - Scatter dose:
    - Grid-Based Boltzmann Solves (GBBS): iteratively solve the LTBE by space (finite elements), angles (discrete ordinate) and energy (energy groups) discretization.
      - Acuros – BrachyVision (Varian Medical Systems)
  - Collapsed Cone Superposition: Scatter dose is separated into 1st and multiple scatter contributions. MC-derived point kernels and angular discretization ensure that every voxel in the geometry is intercepted at least once.
      - Advanced Collapsed-cone Engine - ACE, Elekta

Does it matter?

- Clinical results show we are doing something right
  - But do we really know what we are delivering? (TG-43)
  - Novel sources on the market
    - Electronic brachytherapy (eBT)
      - Xoft® - 29 keV
      - Esteya® - 41 keV
    - Radionuclides
      - ^{57}Co – 124 keV
      - ^{153}Gd – 61 keV
      - ^{169}Yb – 93 keV

Does it matter? - YES

Sensitivity of dosimetry for novel radionuclides and eBT sources to material heterogeneities and general differences with TG-43



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

Vision 20/20 paper

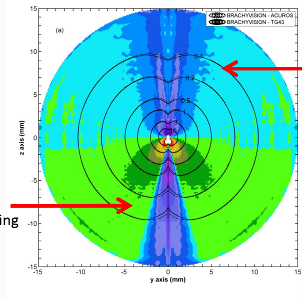
anatomic site	photon energy	absorbed dose	attenuation	shielding	scattering	beta/kerma dose
prostate	high					
	low	XXX	XXX	XXX		
breast	high				XXX	
	low	XXX	XXX	XXX		
GYN	high			XXX		
	low	XXX	XXX			
skin	high			XXX	XXX	
	low	XXX		XXX	XXX	
lung	high				XXX	XXX
	low	XXX	XXX		XXX	
penis	high				XXX	
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

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

Current state of affairs

- Commercially available algorithms – ^{192}Ir only
- Monte Carlo methods – random sampling of probability distribution functions of physics processes
  - EGSnrc/BrachyDose, Geant4, MCNP
- TG-186 – Model-based dose calculation methods
  - Level 1 – Reproducing TG-43 parameters
  - Level 2 – Testing capabilities of MBCDAs

Acuros vs TG43: TG-43 conditions

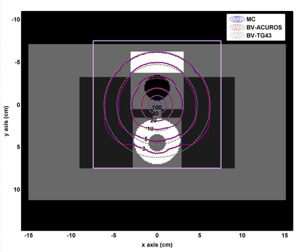


TG43 anisotropy function

Difference in source modeling

Papagiannis, Pantelis, Karaiskos, Br J Radiol, 87, 20141063 (2014)

Single catheter esophagus in phantom



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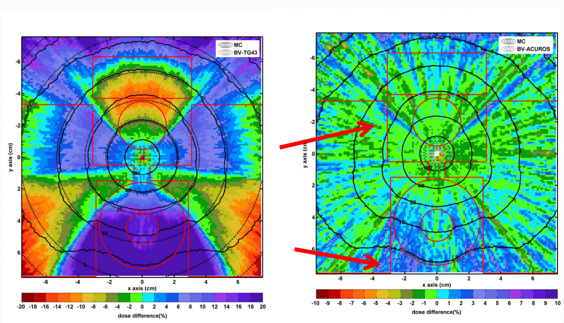
Heterogeneous geometry



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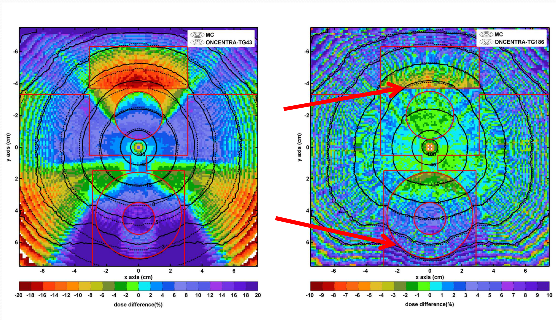
Heterogeneous geometry



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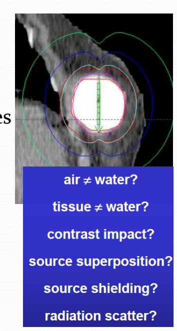
Clinical example: APBI

Images Courtesy of: Dr. Firas Mourtada

Clinical example: APBI

- Dose perturbations due to <u>contrast medium</u> and air
- The effect of patient inhomogeneities
- <u>Air bubbles</u>
- Dose to skin
- Chest wall/rib dose
- Patient specific planning vs. class solutions to estimate the effect



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

Contrast

TABLE II. Percentage reduction (Δ%) in dose rate at 1 cm from the balloon due to contrast, relative to water, for the various balloon diameters.

Balloon diameter (cm)	Δ% 5% contrast	10% contrast	15% contrast	20% contrast	25% contrast
4	−0.8%	−1.6%	−2.4%	−3.2%	−4.0%
5	−1.0%	−1.6%	−2.7%	−3.8%	−4.9%
6	−1.4%	−2.9%	−4.3%	−5.4%	−5.7%

Contrast effects on dosimetry of a partial breast irradiation system

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(Received 24 February 2004; revised 6 April 2004; accepted for publication 22 April 2004; published 17 June 2004)

Papagiannis , Pantelis, Karaiskos, Br J Radiol, 87, 20141063 (2014)

→ Contrast recommendations were made!

Kassas, Mourtada, Horton, Lane, Med. Phys 31(7),1976-1979 (2004).

Air

Dosimetric effects of an air cavity for the SAVI™ partial breast irradiation applicator

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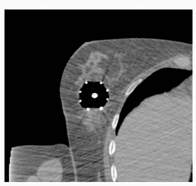
(Received 8 July 2009; revised 3 June 2010; accepted for publication 5 June 2010; published 12 July 2010)

Purpose: To investigate the dosimetric effect of the air inside the SAVI™ partial breast irradiation device.
Methods: The authors have investigated how the air inside the SAVI™ partial breast irradiation device changes the delivered dose from the homogeneously calculated dose. Measurements were made with the device filled with air and water to allow comparison to a homogenous dose calculation done by the treatment planning system. Measurements were made with an ion chamber, TLDs, and film. Monte Carlo (MC) simulations of the experiment were done using the EGSnrc suite. The MC model was validated by comparing the water-filled calculations to those from a commercial treatment planning system.
Results: The magnitude of the dosimetric effect depends on the size of the cavity, the arrangement of sources, and the relative dwell times. For a simple case using only the central catheter of the largest device, MC results indicate that the dose at the prescription point 1 cm away from the air-water boundary is about 9% higher than the homogeneous calculation. Independent measurements in a water phantom with a similar air cavity gave comparable results. MC simulation of a realistic multidwell position plan showed discrepancies of about 5% on average at the prescription point for the largest device.
Conclusions: The dosimetric effect of the air cavity is in the range of 3%–9%. Unless a heterogeneous dose calculation algorithm is used, users should be aware of the possibility of small treatment planning dose errors for this device and make modifications to the treatment delivery, if necessary. © *2010 American Association of Physicists in Medicine.* [DOI: 10.1118/1.3457328]



Richardson, Ramino, Med Phys, 37(8), 3919-3926 (2010)

TABLE II. Comparison between MC doses calculated at selected distances from the edge of the device using different sized devices for single and multidwell position plans with and without air cavity present. The treatment planning benchmark is shown for comparison to the MC in water. The percent difference represents the absolute difference between the MC in water and MC in air calculation.

Distance (cm)	Single-dwell positions: TPS dose	MC water	MC air	Absolute % difference	Multiple dwell positions: TPS dose	MC water	MC air	Absolute % difference
Six-strut device								
1.0	340.2	340.2	352.4	3.6	360.8	369.4	381.2	3.2
1.5	232.6	232.9	241.9	2.7	243.6	245.0	252.6	2.1
2.0	168.8	169.2	177.2	2.3	177.2	178.0	183.9	1.6
3.0	100.0	102.0	106.4	1.3	106.1	106.0	110.7	1.3
4.0	65.6	67.2	70.1	0.9	70.2	71.8	76.5	1.3
5.0	46.0	47.4	49.5	0.6	49.4	51.4	58.2	1.9
10.0	12.3	14.6	15.3	0.2	13.4	14.3	15.5	0.3
Eight-strut device								
1.0	340.2	348.8	369.7	6.0	334.1	346.1	362.1	4.6
1.5	249.6	254.8	272.0	4.9	239.6	245.9	259.8	4.0
2.0	190.9	196.8	210.7	4.0	180.2	183.8	194.4	3.1
3.0	121.3	125.7	134.8	2.6	112.6	117.5	118.6	0.3
4.0	83.2	86.6	92.6	1.7	76.6	80.8	83.9	0.9
5.0	60.1	62.8	67.2	1.3	55.1	57.6	60.1	0.7
10.0	17.1	20.2	21.6	0.4	15.6	16.4	21.5	1.5
Ten-strut device								
1.0	340.3	345.4	373.9	8.3	371.5	370.8	402.7	8.6
1.5	258.2	263.3	285.7	6.5	265.2	263.2	275.9	3.4
2.0	202.2	208.1	226.6	5.3	201.2	199.2	202.9	1.0
3.0	132.9	137.0	149.5	3.6	128.5	129.8	112.6	4.6
4.0	93.2	96.7	105.8	2.6	89.0	91.6	81.6	2.7
5.0	68.3	71.1	78.0	2.0	64.8	66.1	60.3	1.6
10.0	20.0	23.1	25.2	0.6	18.7	19.8	21.3	0.4

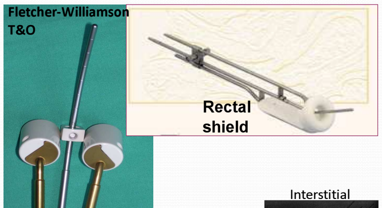
0-4%

0-6%

0-9%

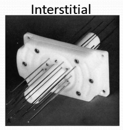
Clinical example: GYN

- Shielding
- Scatter
- Packing
- Attenuation



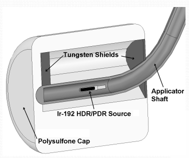
Standard Cylinder
Regular or
shielded

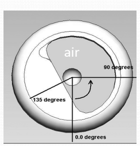
Interstitial



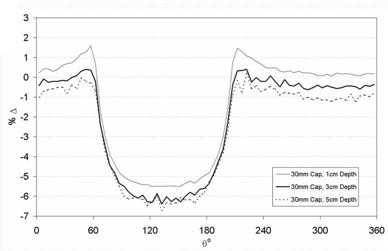
Images Courtesy of: Dr. Luc Beaulieu

Shielded applicators with cap





MCNPX 2.5 simulations compared with
TG-43 predicted doses (Plato TPS)



Price, Horton, Eifel, Mourtada, ABS annual meeting, 2007

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

Ye, Brezovich, Shen, Duan, Popple, Pareek, Med Phys, 31 (7), 2097-2106 (2004)

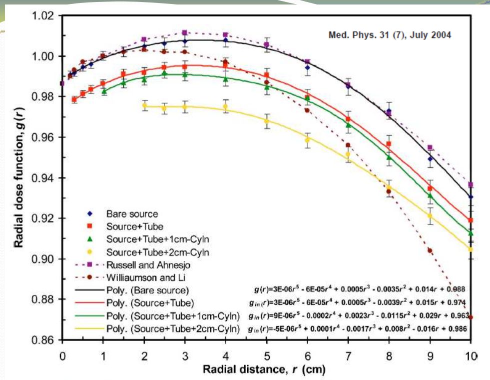
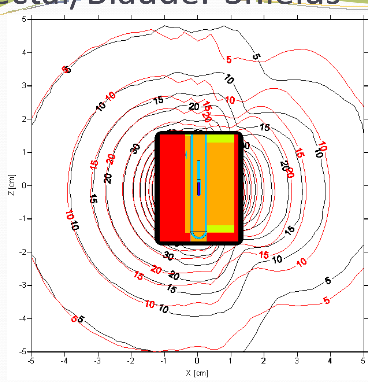


FIG. 5. Radial dose functions calculated for a bare source and a source embedded in various cylindrical applicators and their comparisons to published data. Fifth-order polynomial fittings to our calculated radial dose functions are also presented.

Rectal/Bladder Shields



cGy/hr Comparison

- PDR (red)
- LDR (black)
- XZ-plane
- 20mg equivalent

Mourtada, Horton, 2004

Clinical example: Skin

- Shielding
- Collimation
- Electron contamination
- Positioning

Clinical needs

- LDR prostate implants (^{125}I, ^{103}Pd)
  - Seed geometry
  - Inter-seed effects
  - Cross-section (Energy)
- Low-energy x-ray sources (Xoft, Intrabeam)
  - Source geometry and composition
  - Cross-section (Energy)

Summary

- Dosimetry and planning methods have made huge strides since the inception of brachytherapy
- ^{192}Ir is the only radionuclide available for use in commercialized treatment planning systems to date
- A large cohort of TG-43 data exists for the creation of retrospective studies (data is needed: H&N, skin)
- Stay tuned for specific clinical results…