Brachytherapy Technology and Dosimetry: Categories by Route

- Intracavitary: applicator in natural cavity
- Interstitial: needles, catheters or seeds placed directly into tissue
- Surface: applicator applied externally
- Intraluminal: sources placed in tubular organs such as bronchus or arteries

Categories: by Dose Rate

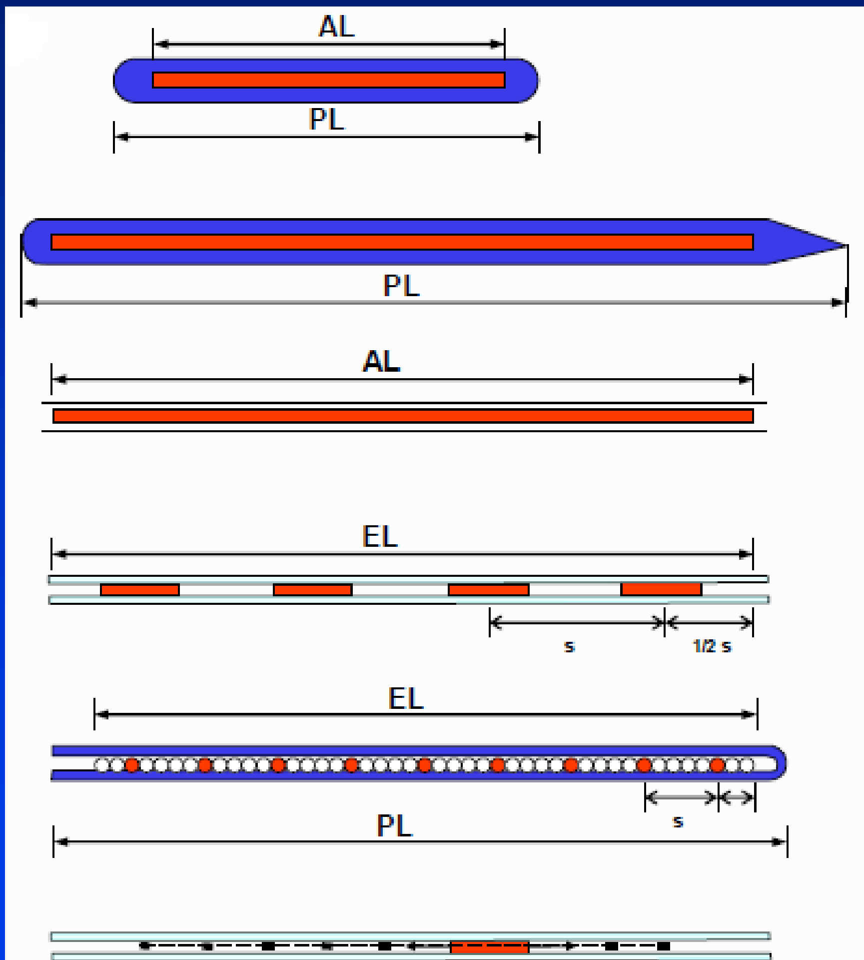
- Permanent: < 30 cGy/hr* (decaying)
- Low Dose Rate (LDR): 30 - 100 cGy/hr*
- Medium Dose Rate: 100 - 1200 cGy/hr* (has problem with radiobiology so little used)
- High Dose Rate (HDR): >1200 cGy/hr (fractionated)
- Pulsed: many small HDR fractions, simulating LDR

*These are my definitions of dose-rate ranges

Categories by Loading

- Manual: “hot” loading in Operating Room
- Manual Afterloading: unloaded applicator at surgery, sources placed later for continuous treatment
- Remote Afterloading: source managed by machine, usually fractionated or pulsed

Brachytherapy source types



← tubes

← needles

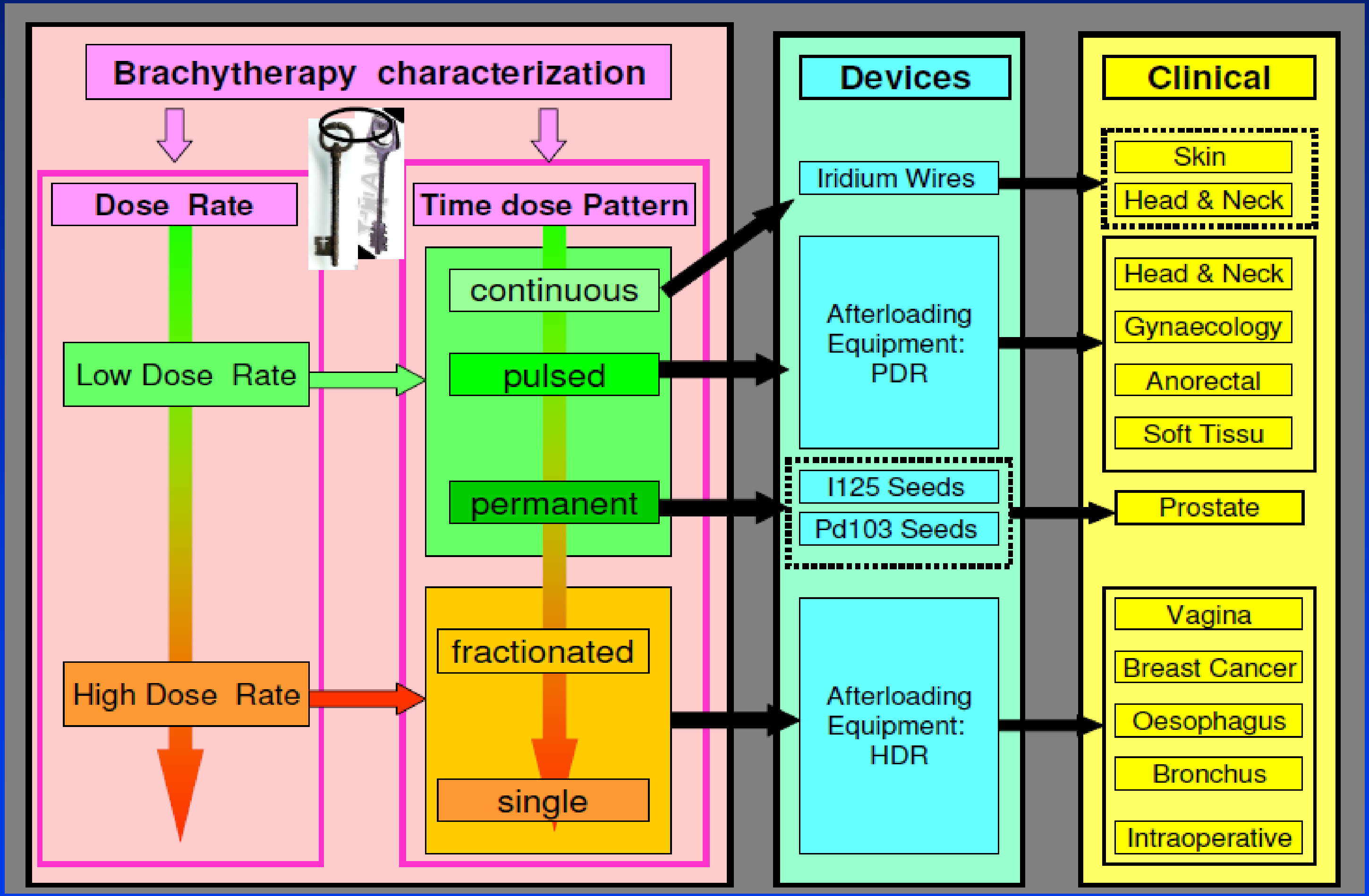
← wires

← seeds in a ribbon

← Co-60 spheres with spacers

← stepping source in catheter

Clinical applications of brachytherapy



+gynaecology

Courtesy of Alex Rijnders

Source energy

- All photon-emitting isotopes may be grouped into two categories
- High-energy (> 50 keV)
  - *these have similar attenuation characteristics in tissue, vary principally in shielding characteristics*
- Low-energy (<50 keV)
  - *isotopes such as I-125 and Pd-103, which have different attenuation and shielding characteristics*

Important high-energy isotopes: Cs-137

- $t_{½}$ = 30 years
- Mean Energy = 660 keV
- HVL in Pb = 5.5 mm
- Specific activity = 86 Ci g^{-1}
- Principle use: 1st replacement for radium (for LDR)

Important high-energy isotopes: Ir-192

- $t_{½}$ = 74 days
- Mean Energy = 330 keV
- HVL in Pb = 2.5 mm
- Specific activity = 9300 Ci g^{-1}
  - *about two orders of magnitude higher than Cs-137*
  - *means that the sources can be much smaller*
- Used as replacement for Cs-137 for implants and as a stepping source for remote afterloading

Important high-energy isotopes: Co-60

- $t_{½}$ = 5.26 years
- Mean Energy = 1.2 MeV
- HVL in Pb = 11 mm
- Specific activity = 1140 Ci g^{-1}
  - *about an order of magnitude lower than Ir-192*
- Principle use in brachytherapy: HDR intracavitary
  - *advantage over Ir-192 because of long half life but disadvantage due to large source size and high energy requiring lots of shielding*

High-energy sources compared

Property	Cs-137	Ir-192	Co-60
HVL mm Pb	5.5	2.5	11
Specific activity Ci g^{-1}	87	9300	1140
Half life years	30	0.20	5.3

Ir-192 is easiest to shield (lowest HVL) and has the highest specific activity (smallest sources), which is why it is the preferred source for HDR units although, if source replacement is a problem, the longer half life Co-60 is sometimes used

Important low-energy isotopes: I-125

- $t_{1/2}$ = 60 days
- Mean Energy = 28 keV
- HVL in Pb = 0.025 mm
- Permanent implants of prostate and some other sites (at low activity)
- Temporary implants for brain and eye plaques (at high activity)

Important low-energy isotopes: Pd-103

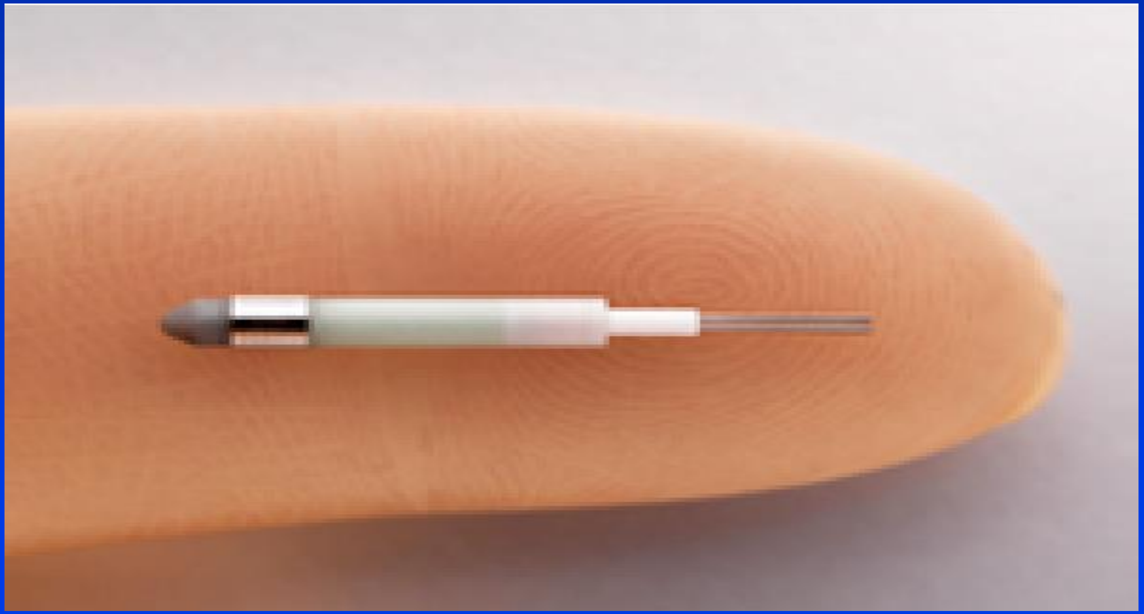
- $t_{½}$ = 17 days
- Mean Energy = 22 keV
- HVL in Pb = 0.008 mm
- Principle use: permanent implants of prostate and some other sites

New brachytherapy sources

- Yb-169: mean energy 93 keV, $t_{1/2}$ = 32 d
  - *Potential replacement for Ir-192 due to lower energy (less shielding) and comparable specific activity*
- Cs-131: $t_{1/2}$ = 9.65 d, mean energy 29 keV
  - *Because of it's short $t_{1/2}$ and low energy is a candidate for permanent implants for rapidly growing cancers*
- Electronic brachytherapy

What is Electronic Brachytherapy?

Electronic brachytherapy is brachytherapy using a miniature x-ray tube instead of a radioactive source

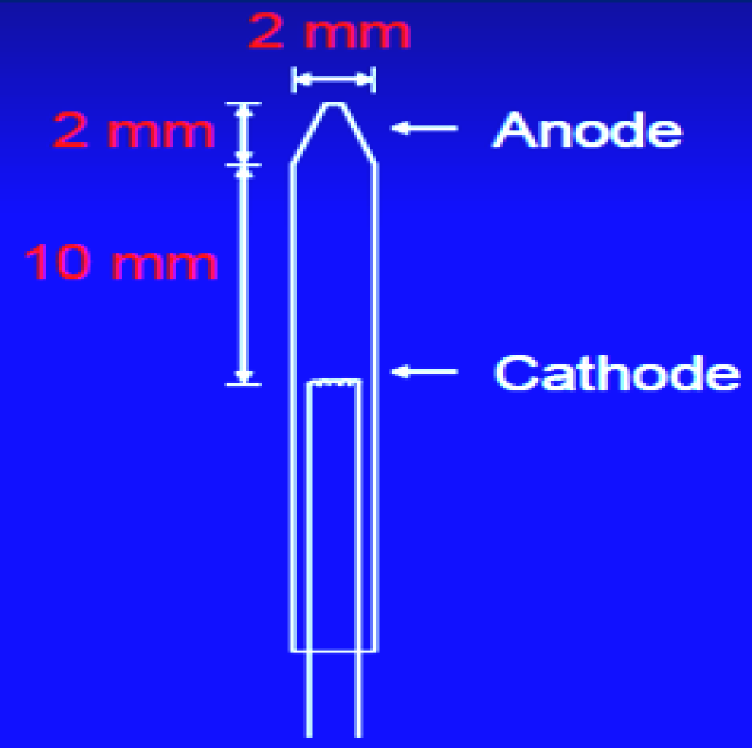


Electronic brachytherapy

- The X-ray tube is inserted into catheters implanted in the tumor much like how HDR is administered
- Replaces Ir-192 HDR brachytherapy
- Obvious shielding, storage, and handling advantages

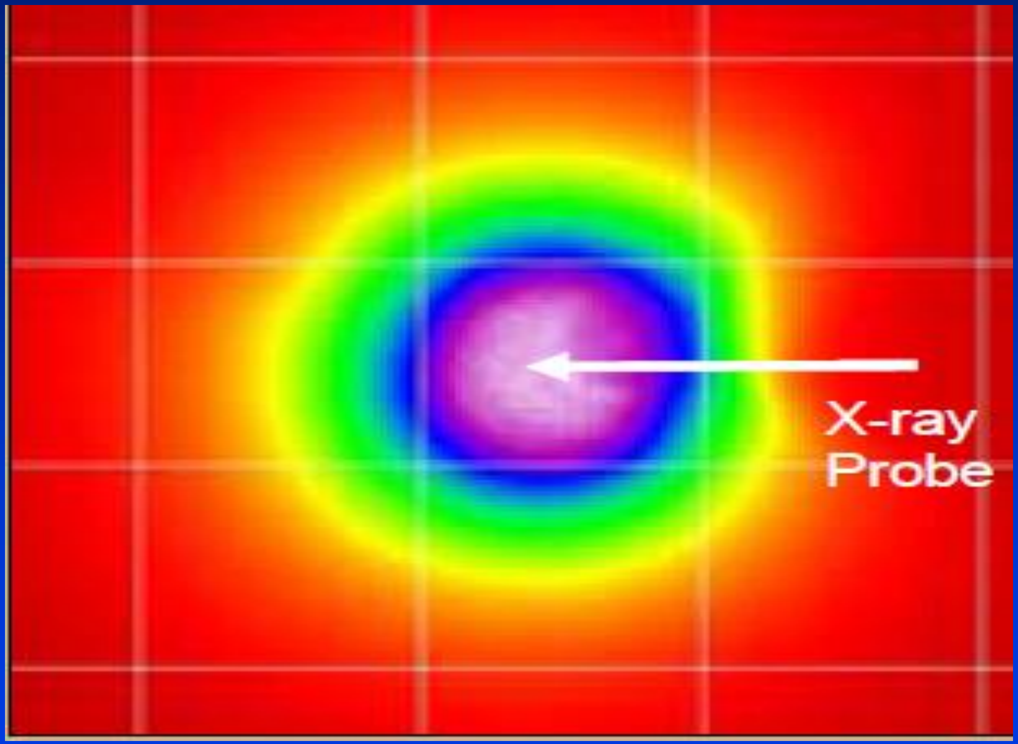
Axxent® Source

- X-ray source is ~ 2 mm diameter
- Placed in flexible cooling sheath
- Tube voltages from 30 kV to 50 kV
- Air kerma rates comparable to 10 Ci HDR ^{192}Ir



S. Davis, "Characterization of a Miniature X-ray Source for Brachytherapy." Oral presentation at North Central Chapter of the AAPM meeting, 2004.

Dose distribution



S. Chiu-Tsao, et al, "Radiochromic Film Dosimetry for a new Electronic Brachytherapy Source." Presented at the AAPM meeting, 2004.

Modern brachytherapy dosimetry

The current method used in treatment planning computers is based on AAPM Task Group Report No. 43, 1st published in 1995 (TG-43) and updated in 2004 (TG-43U1)

What was wrong with the "old" dosimetry?

- Specification of source strength as "activity"
  - *Difficult to measure accurately and reproducibly both by the vendor and the user*
  - *Variability in the factor to convert activity to dose in the patient e.g. prior to 1978, published exposure rates at 1 cm for Ir-192 sources ranged from 3.9 to 5.0 R mCi^{-1} hr^{-1}!!!*
- Preferable to use only quantities directly derived from dose rates in a water medium near the actual source

Source strength specification

- Old units
  - *mg (for Ra-226 only)*
  - *mgRaEq (equivalent mass of radium)*
  - *activity (or apparent activity)*
- For TG-43 needed a new unit that could be directly related to an in-house verification of the strength of each source

New unit: Air-kerma strength

Air kerma strength $\dot{K}(d)d^2$ is the product of the square of the distance and the air kerma rate due to photons for a small mass of air in free space at distance *d*

What exactly is the air-kerma rate $\dot{K}(d)$

- The air kerma rate is usually inferred from transverse plane air-kerma rate measurements performed in free space at distances large in relation to the maximum linear dimensions of the detector and source, typically of the order of 1 meter
- Because of the large distance, the effect of source size and shape is negligible
- This is a property that can be related to a measurement for each source

Why *in free space*?

- The qualification "*in free space*" means that the measurements should be corrected for:
  - *photon attenuation and scattering in air and any other medium interposed between the source and detector*
  - *photon scattering from any nearby objects including walls, floors, and ceilings*

Units of air-kerma strength $\dot{K}(d)d^2$

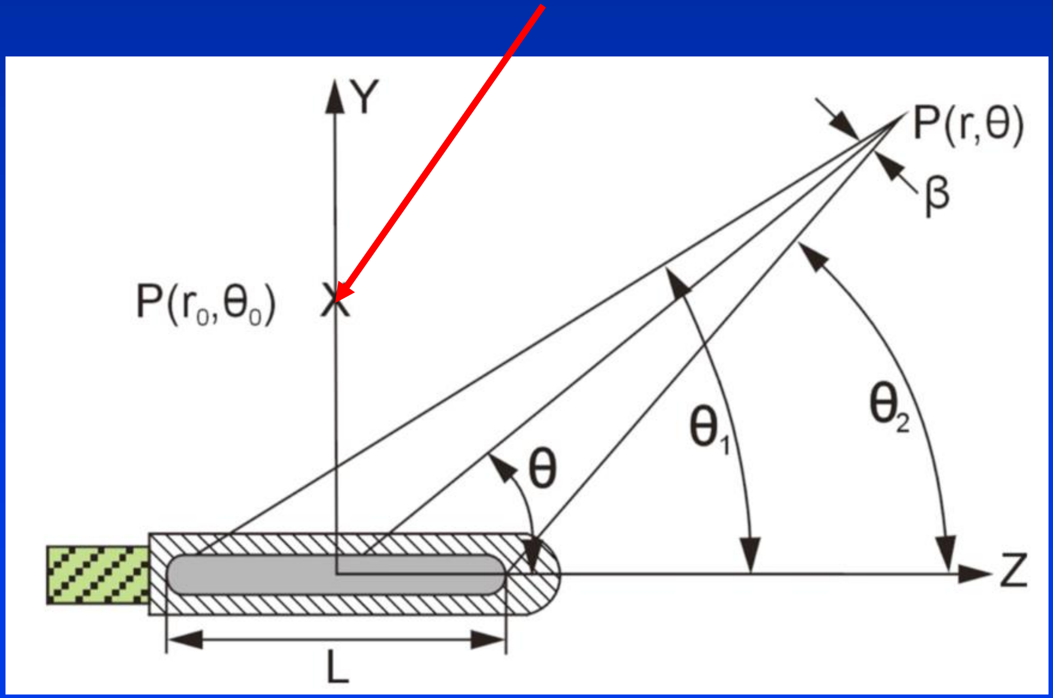
- SI unit: μGy m^2 h^{-1}
- Special unit: 1U = 1 μGy m^2 h^{-1}
- Note that this is the same as 1 cGy cm^2 h^{-1}

Alternative unit: Reference air-kerma rate

- European equivalent of air-kerma strength
- Numerically equal to air-kerma strength
- Reference distance is explicitly 1 m
- Units: $\mu Gy\ h^{-1}$ (assumed at 1 m)

Four steps needed to accurately calculate the dose rate at point P

1. Determine the dose rate at a normalization point $P(r_0,\theta_0)$ which is at 1 cm distance along the transverse axis of the source using the dose-rate constant Λ



What is the dose rate constant Λ?

- This is the dose rate per unit air-kerma strength at 1 cm along the transverse axis (r_0 = 1 cm, $\theta = \pi/2$ radians) of the source
  - *includes the effects of source geometry, the spatial distribution of radioactivity within the source, encapsulation, self-filtration within the source, and scattering in water surrounding the source*
- Λ depends on source structure and values have been published for various sources and incorporated into treatment planning systems

Published data: AAPM TG 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

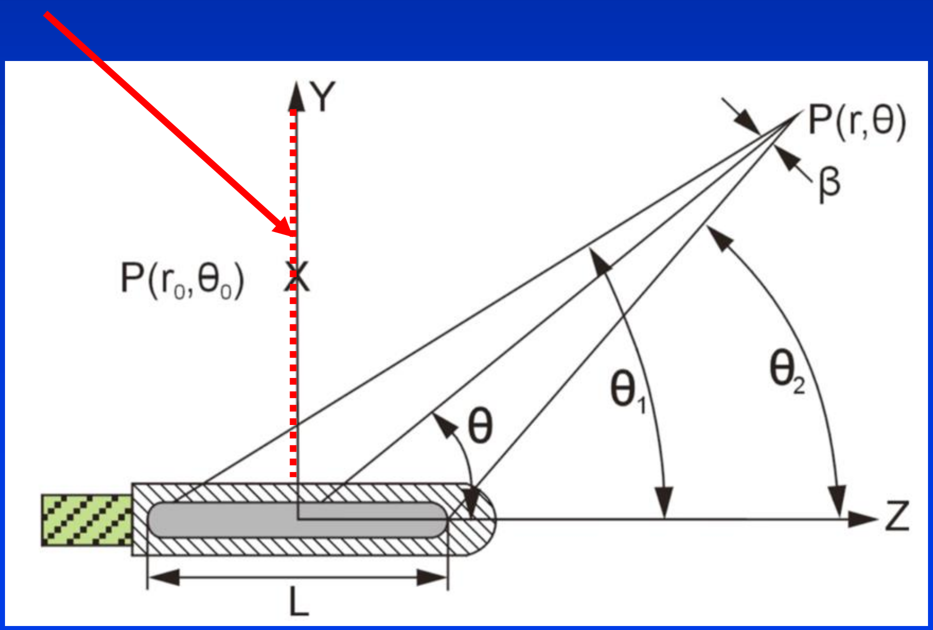
Consensus data published in this report based mainly on Monte Carlo calculations

TG Report 229 consensus dose rate constants for HDR ^{192}Ir sources

Source Name (Manufacturer)	$_{CON}\Lambda$ [$cGy \cdot h^{-1} \cdot U^{-1}$]
mHDR-v1 (Nucletron)	1.116
mHDR-v2 (Nucletron)	1.109
VS2000 (Varian)	1.100
Buchler (E&Z BEBIG)	1.117
GammaMed HDR 12i (Varian)	1.118
GammaMed HDR Plus (Varian)	1.117
GI192M11 (E&Z BEBIG)	1.110
Ir2.A85-2 (E&Z BEBIG)	1.109
M-19 (SPEC)	1.114
Flexisource (Isodose Control)	1.113

Step 2 in calculation of the dose rate at point P

Determine the effect of scattering and absorption in the medium and the source and its encapsulation on dose rates at distances r along the transverse axis (Y) relative to that r_0, with inverse square law fall of ignored using the radial dose function g(r)



What is the radial dose function?

- The radial dose function, $g(r)$, accounts for dose fall-off on the transverse axis of the source due to photon scattering and attenuation in the medium, the source and its encapsulation, with inverse square law fall off removed
- Consensus values of $g(r)$ are published for all source types in, for example, AAPM Report No. 229

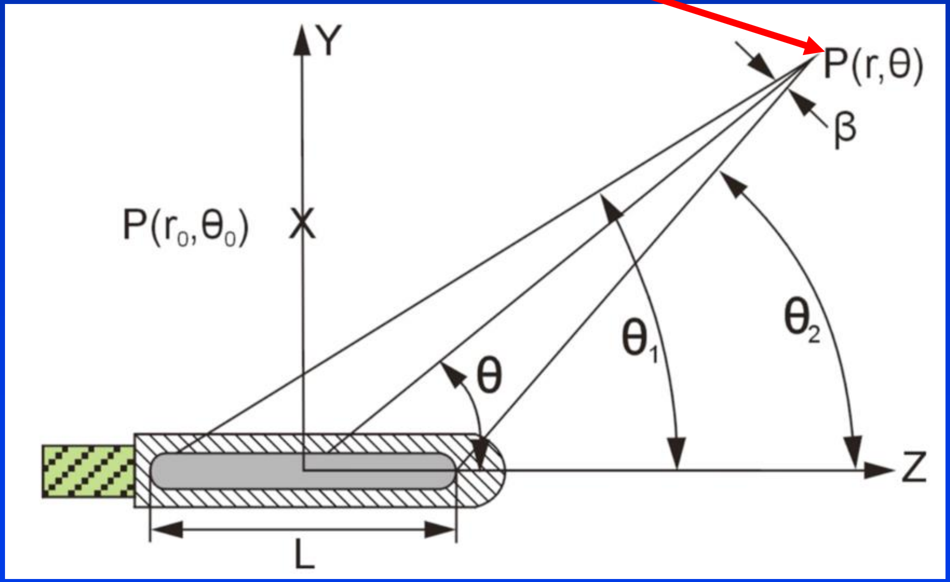
Sample $g(r)$ values from AAPM Report No. 229

Table V. Radial dose function values for HDR sources. Interpolated/extrapolated data are **boldface**/underlined. Values inside the source are in *italics*. In [brackets] are the corrected values from bounded to unbounded geometry.

	$g_L(r)$									
	Nucletron mHDR-v1	Nucletron mHDR-v2	Varian VS2000	E&Z BEBIG Buchler	Varian GammaMed HDR 12i	Varian GammaMed HDR Plus	E&Z BEBIG GI192M11	E&Z BEBIG Ir2.A85-2	SPEC M-19	Isodore Control Flexisource
r [cm]	L = 0.35 cm	L = 0.35 cm	L = 0.5 cm	L = 0.13 cm	L = 0.35 cm	L = 0.35 cm	L = 0.35 cm	L = 0.35 cm	L = 0.35 cm	L = 0.35 cm
0.00	*[0.991]*	*1.276*	*0.986*	*1.023*	*0.992*	*0.998*	*0.990*	*0.990*	*0.993*	*0.991*
0.06		1,276								
0.08		1,199								
0.10		1,110								
0.15		1,018								
0.20	[0.991]	1,001	0.986	1.023	0.992	0.998				
0.25	**[0.992]**	0.995	0.991	**1.018**	**0.992**	**0.997**	0.990	0.990	0.993	0.991
0.50	[0.997]	**0.997**	0.997	**1.002**	**0.994**	**0.996**	0.996	0.996	0.995	0.997
0.75	**[0.999]**	0.998	0.999	**0.999**	**0.997**	**0.998**	0.998	0.998	0.998	0.998
1	1	1	1	1	1	1	1	1	1	1
1.5	[1.002]	1,003	1.005	1.003	1.004	1.003	1.003	1.002	1.001	1.002
2	[1.004]	1,005	1.010	1.004	1.006	1.006	1.004	1.004	1.005	1.004
3	[1.006]	1,008	1.012	1.008	1.008	1.006	1.005	1.005	1.008	1.005
4	[1.006]	1,007	1.013	1.007	1.005	1.004	1.004	1.003	1.003	1.003
5	[1.001]	1,003	1.011	1.002	0.999	0.999	0.999	0.999	0.999	0.999
6	[0.993]	0.996	1.003	0.995	0.991	0.993	0.992	0.991	0.994	0.991
8	[0.970]	0.972	0.982	0.971	0.968	0.968	0.968	0.968	0.969	0.968
10	[0.934]	0.939	0.949	0.941	0.936	0.935	0.935	0.935	0.939	0.935

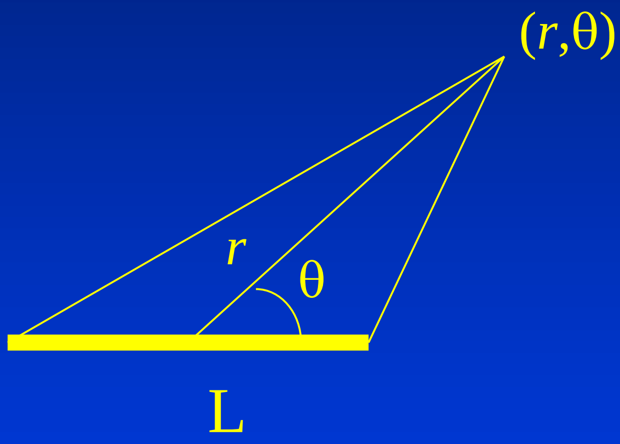
Step 3 in calculation of the dose rate at point P

Determine the effect of inverse square law fall off of dose rate at all points P(r, θ), distance r from the center of the source due to the linear nature of the source (i.e. not a point) using the geometry factor G(r, θ)



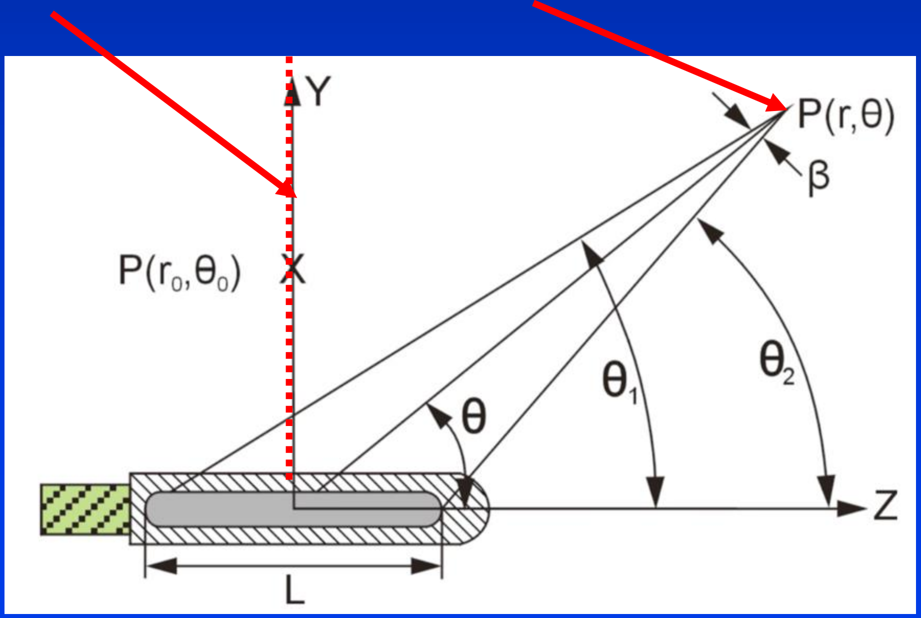
What is the geometry factor $G(r,\theta)$?

- This accounts for the fact that the source is linear and not a point source and is purely an inverse square law function
- Determined by integrating over the volume of the source
- Ignores scattering and absorption in the medium, the source and its encapsulation
- For point sources: reduces to $1/r^2$



Step 4 in calculation of the dose rate at point P

Determine the effect of absorption and scatter in the medium and the source and encapsulation on dose rate at all points P(r, θ) relative to the dose rates at the same radial distance r along the transverse axis of the source (Y) using the anisotropy function F(r, θ)



What is the anisotropy function $F(r,\theta)$?

- The anisotropy function accounts for the anisotropy of dose distribution around the source due to the effects of absorption and scatter in the medium, the source and its encapsulation
- It is the ratio of anisotropy effects at points at distance r along a line at angle θ, to anisotropy effects at distance r along the transverse axis of the source
- Consensus values of $F(r,\theta)$ are published for all source types in, for example, AAPM Report No. 229

Sample $F(r,\theta)$ values from AAPM Report No. 229

Table VI. $F(r,\theta)$ for the Nucletron mHDR-v1 source. Extrapolated data are underlined. Values inside the source are in *italics*.

θ(deg)	r (cm) 0	0.25	0.5	1	2	3	4	5	7.5	10
0	*0.683*	*0.683*	0.664	0.626	0.634	0.655	0.677	0.697	0.743	0.776
1	*0.683*	*0.683*	0.664	0.624	0.638	0.661	0.683	0.704	0.746	0.779
2	*0.682*	*0.682*	0.663	0.625	0.646	0.669	0.691	0.713	0.754	0.784
3	*0.677*	*0.677*	0.664	0.637	0.656	0.681	0.701	0.722	0.762	0.791
5	*0.683*	*0.683*	0.675	0.658	0.679	0.701	0.719	0.738	0.775	0.799
7	*0.704*	*0.704*	0.697	0.684	0.702	0.724	0.740	0.760	0.790	0.814
10	*0.738*	*0.738*	0.733	0.722	0.739	0.759	0.773	0.789	0.816	0.835
12	*0.762*	*0.762*	0.758	0.748	0.764	0.780	0.792	0.807	0.830	0.849
15	*0.798*	*0.798*	0.793	0.783	0.796	0.811	0.821	0.833	0.851	0.865
20	*0.845*	*0.845*	0.842	0.836	0.844	0.855	0.862	0.871	0.884	0.894
25	*0.885*	*0.885*	0.880	0.871	0.880	0.888	0.891	0.897	0.908	0.915
30	*0.910*	*0.910*	0.906	0.898	0.906	0.912	0.915	0.918	0.928	0.930
35	*0.931*	*0.931*	0.928	0.921	0.927	0.932	0.936	0.941	0.945	0.948
40	*0.952*	*0.952*	0.947	0.936	0.943	0.948	0.948	0.953	0.955	0.956
45	*0.962*	*0.962*	0.959	0.953	0.958	0.962	0.962	0.966	0.968	0.968
50	*0.971*	*0.971*	0.969	0.965	0.968	0.971	0.972	0.975	0.977	0.975
55	*0.984*	0.984	0.976	0.971	0.977	0.980	0.979	0.980	0.982	0.983
60	*0.989*	0.989	0.983	0.978	0.984	0.988	0.988	0.989	0.989	0.990
65	*0.992*	0.992	0.988	0.986	0.989	0.991	0.989	0.993	0.996	0.993
70	*0.995*	0.995	0.994	0.991	0.993	0.996	0.994	0.995	0.997	0.995
75	*0.997*	0.997	0.995	0.993	0.996	0.997	0.996	0.997	0.999	0.996
80	*0.998*	0.998	1.000	0.995	0.999	1.000	0.999	1.003	1.000	0.999
85	*0.999*	0.999	1.000	0.995	0.998	0.999	1.001	1.003	1.002	1.000
90	*1*	1	1	1	1	1	1	1	1	1

Dose rate at a point

The full TG-43 equation is:

Dose-rate constant

Radial dose function

$$\dot{D}(r,\theta) = S_k \cdot \Lambda \cdot \frac{G(r,\theta)}{G(r_0,\pi/2)} \cdot g(r) \cdot F(r,\theta)$$

Air kerma strength

Dose rate at point (r,ϑ)

Anistrotropy function

Geometry factor ratio

What if the orientation of the source is unknown?

- With typical seed implants not in catheters, the orientation is unknown so a 1D version of $F(r,\theta)$ is used
- $F(r,\theta)$ is replaced by the 1-D anisotropy function $\phi_{an}(r)$ (originally called the anisotropy factor in TG-43) which is the ratio of the dose rate averaged over the entire 4π space, to the dose rate at the same distance r on the transverse plane

1D dose rate equation

$$\dot{D}(r) = \frac{S_k \Lambda}{r^2} g_p(r) \phi_{an}(r)$$

Where the geometry factor ratio is simply $1/r^2$ and $\phi_{an}(r)$ and $g_p(r)$ [the point source version of $g(r)$] values for seeds are published in AAPM Report No. 84

Recent improvements: Model-based dose calculations

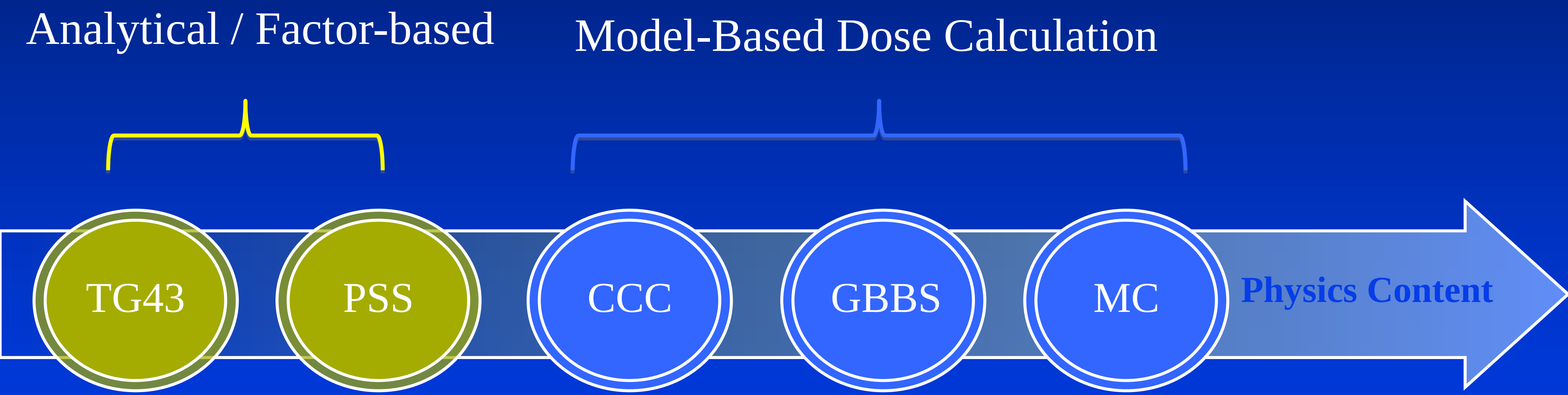
Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

Luc Beaulieu, Åsa Carlsson Tedgren, Jean-François Carrier, Stephen D. Davis, Firas Mourtada, Mark J. Rivard, Rowan M. Thomson, Frank Verhaegen, Todd A. Wareing and Jeffrey F. Williamson

Methods compared in TG-186

- TG-43
- PSS: primary and scatter separated method
- CCC: collapsed-cone superposition/convolution
- GBBS: grid-based Boltzmann equation solvers
- MC: Monte Carlo

Advanced Dose Calculation Methods



Courtesy of Luc Beaulieu

Calculation methods compared

Current standard:
Full scatter water medium

<u>Elekta's Advanced Collapsed-cone Engine (ACE)</u>:
Heterogeneity corrections.
Accurate to 1st scatter

Explicit particle transport simulation. Gold standard for source characterization and other applications

No particle transport.
No heterogeneity corrections

<u>Varian Acuros:</u>
Solves transport equations.
Heterogeneity corrections

Courtesy of Luc Beaulieu

Summary

- Brachytherapy can be administered by various routes, dose-rates, loading methods, source types and energies
- TG-43 significantly improved brachytherapy dosimetry
- Model-based dose calculations are beginning to be incorporated into commercial treatment planning systems