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: tubes placed in tubular organs such as bronchus or arteries

Categories: by Dose Rate

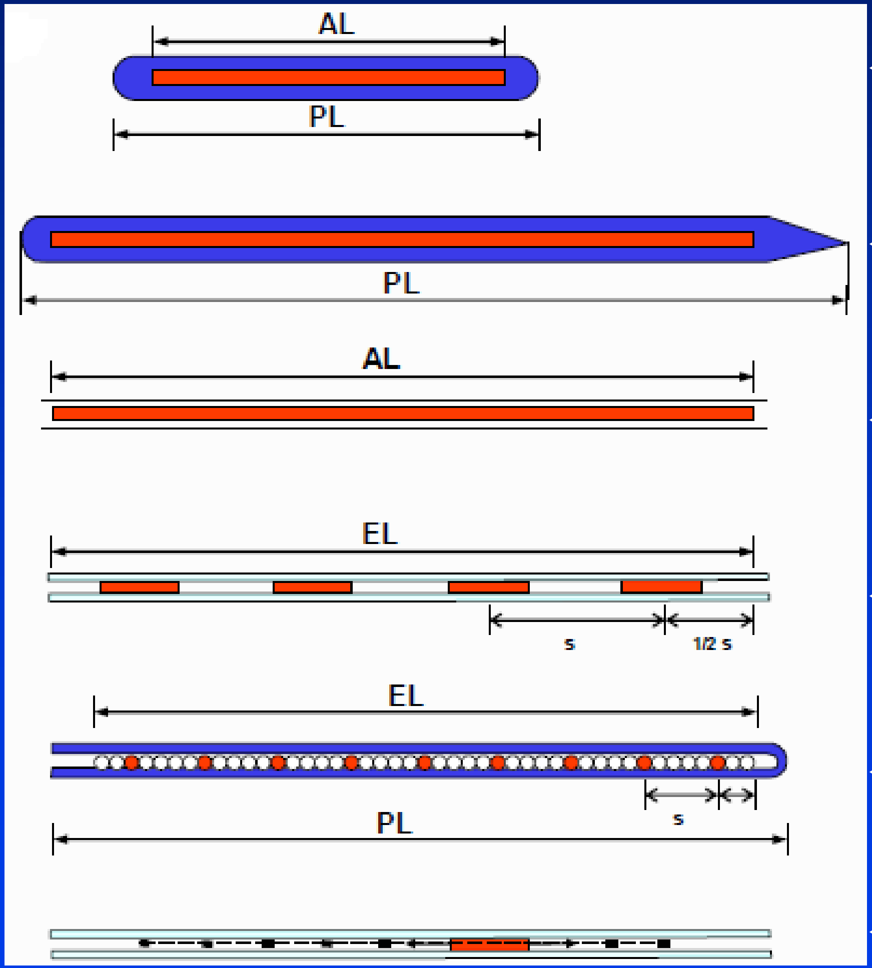
- Permanent: < 30 cGy/hr* (decaying)
- Low Dose Rate (LDR): 30 - 100 cGy/hr*
- Medium Dose Rate: 100 - 1200 cGy/hr* (has problem with radiobiology so little used)
- High Dose Rate (HDR): >1200 cGy/hr (fractionated)
- Pulsed: many small HDR fractions, simulating LDR

*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



← tube

← needle

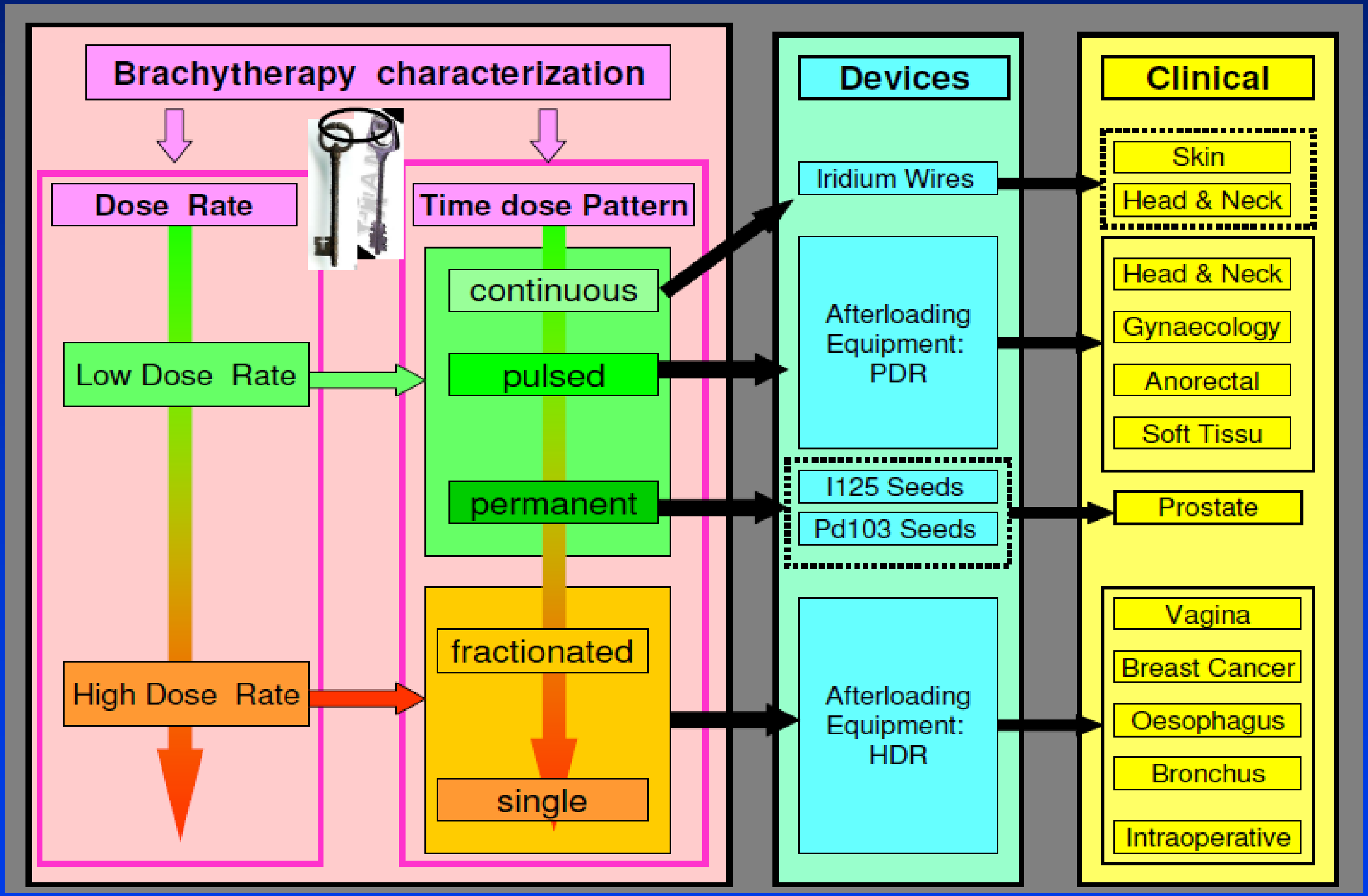
← wire

← seeds in a ribbon

← Co-60 spheres with spacers

← stepping source in catheter

Clinical applications of brachytherapy



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

- $t_{1/2}$ = 30 years
- Mean Energy = 660 keV
- HVL in Pb = 5.5 mm
- Γ = 2.37 R cm^2 mCi^{-1} hr^{-1}
- Specific activity = 86 Ci g^{-1}
- Principle use: 1st replacement for radium (for LDR)

Specific gamma ray constant, Γ

- Relates contained activity to output
- Source of error in traditional systems since relies on accurate knowledge of the activity and effect of encapsulation
- Not used in present-day brachytherapy source specification
  - *replaced by the dose rate constant* Λ

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*
- Used as replacement for Cs-137 for seed implants and as an HDR stepping source

Important high-energy isotopes: Co-60

- $t_{1/2}$ = 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: 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*

Properties 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

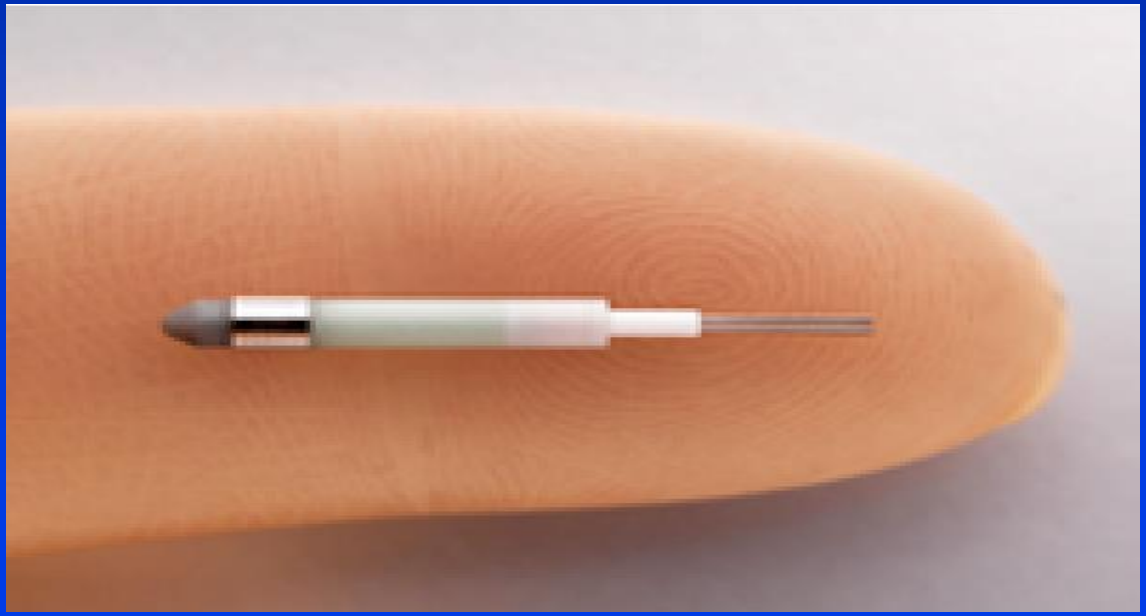
- $t_{1/2}$ = 17 days
- Mean Energy = 22 keV
- HVL in Pb = 0.008 mm
- Principle use: permanent implants of prostate and some other sites

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 higher specific activity (smaller sources)*
- 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

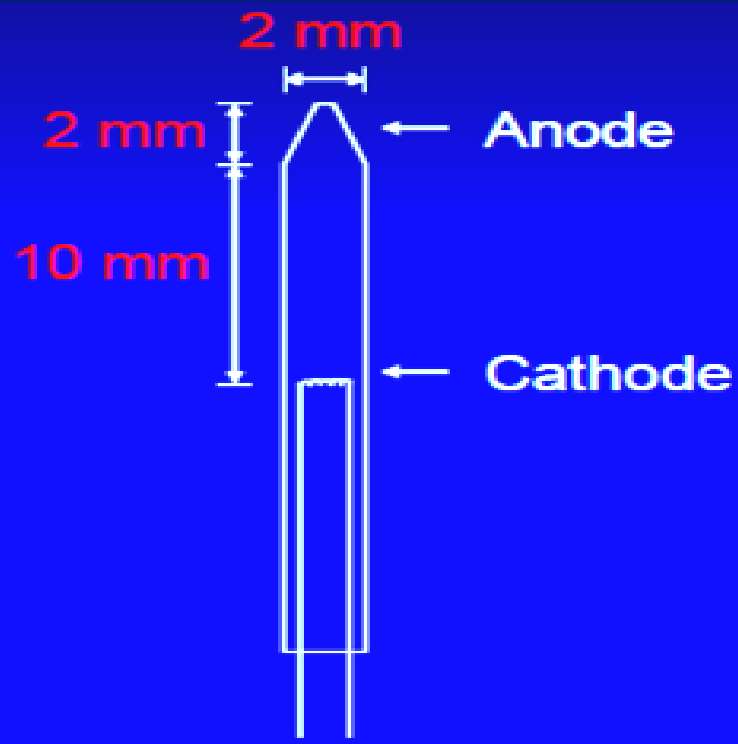


Electronic brachytherapy

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

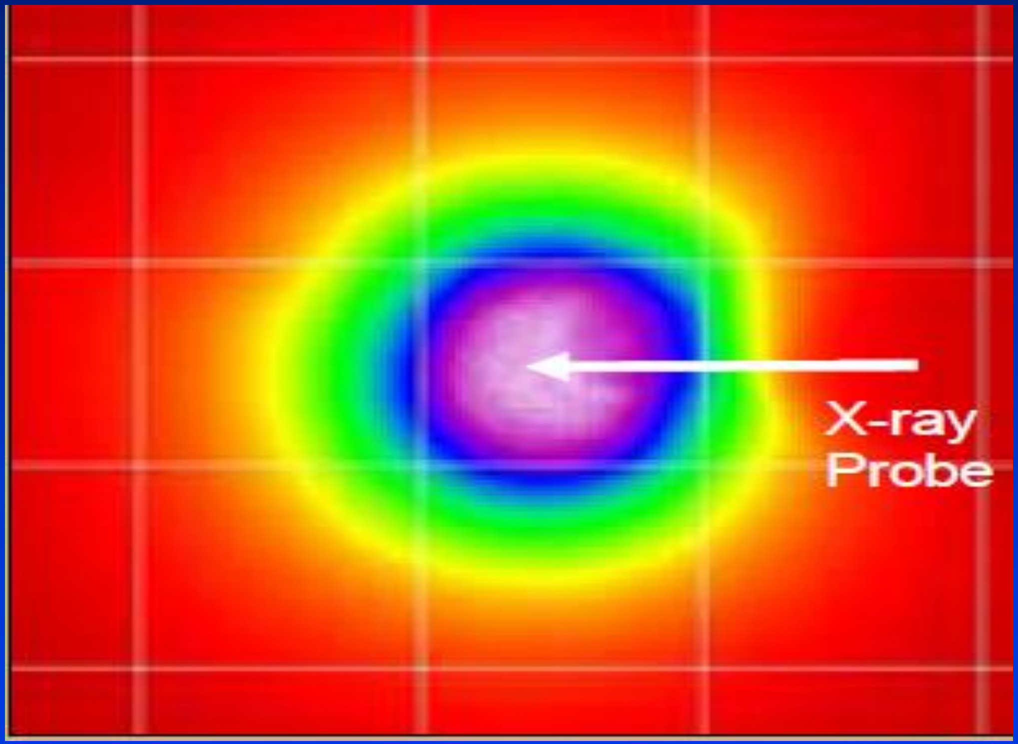
Axxent® Source

- 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, specific gamma ray constants published for Ir-192 ranged from 3.9 to 5.0 R cm^2 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 is the product of the air kerma rate $\dot{K}_{\delta}(d)$ due to photons of energy greater than δ for a small mass of air in vacuo at distance *d*, and the square of the distance

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

- This is a property that can be related to a measurement for each source
- The air kerma rate is usually inferred from transverse plane air-kerma rate measurements performed in a free-air geometry 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

Why *in vacuo*?

- The qualification "*in vacuo*" 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*

Why energy greater than δ?

- The energy cutoff, δ, is intended to exclude low-energy or contaminant photons that increase the air kerma strength without contributing significantly to dose at distances greater than 0.1 cm in tissue
- The value of δ is typically 5 keV

Units of air-kerma strength

$$S_K = \dot{K}_\delta(d)d^2$$

SI unit: $\mu Gy\ m^2\ h^{-1}$

Special unit: $1U = 1\ \mu Gy\ m^2\ h^{-1}$

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: μGy h^{-1} (assumed at 1 m)

Steps in calculation of dose around a source

1. Determine dose rate along the transverse axis *in vacuo* close to the source, e.g. at 1 cm

2. Account for effect of absorption and scattering in tissue on dose rate along the source axis

3. Calculate the dose rate off the transverse axis due to inverse square law effects only

4. Account for absorption and scattering on off-axis dose rates

1. Dose rate along the transverse axis at 1 cm

- We need a factor that will convert the source strength (typically defined at 1 m from the source) into the dose rate at a reference point close to the source
- For TG-43, this is a point at a distance r_0 = 1 cm along the transverse axis of the source
- This factor is the dose rate constant Λ

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

2. Account for absorption and scattering in tissue on dose rates along the transverse axis

- In TG-43 this is accomplished by 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, excluding fall-off included by the geometry function, and is equal to unity at r_0
- 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.

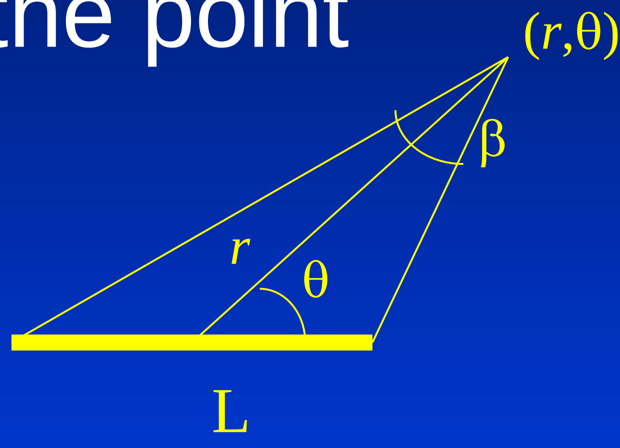
	$g_L(r)$									
	Nucletron mHDR-v1	Nucletron mHDR-v2	Varian VS2000	E&Z BEBIG Buchler	Varian GammaMed HDR 12i	Varian GammaMed HDR Plus	E&Z BEBIG GI192M11	E&Z BEBIG Ir2.A85-2	SPEC M-19	Isodore Control Flexisource
r [cm]	$L = 0.35$ cm	$L = 0.35$ cm	$L = 0.5$ cm	$L = 0.13$ cm	$L = 0.35$ cm	$L = 0.35$ cm	$L = 0.35$ 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

3. Effect of source geometry off the transverse axis?

- In TG-43 this is accomplished by the geometry function $G(r,\theta)$
  - *this is the ratio of dose rates in air at the point of interest at radial distance r to that at the reference point at r_0 ignoring photon absorption and scattering in the source structure*
- Determined by integrating over the volume of the source but, since this is used a ratio of $G(r,\theta)/G(r_0,\pi/2)$, , it is possible to use approximate solutions

Geometry Function G(r,θ)

- G(r,θ) takes the place of $1/r^2$ in the point source model
- Accounts for distribution of activity
- Simplified form of the integral
  - *For line sources given by: $G(r,\theta) = \beta/(Lr\sin\theta)$*
  - *For point source: reduces to $1/r^2$*



4. Absorption and scatter at off-axis points

- In TG-43 this is accomplished by the 2D anisotropy function $F(r,\theta)$
- The anisotropy function accounts for the anisotropy of dose distribution around the source, including the effects of absorption and scatter in the medium
- 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:

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

Dose rate at point (r,ϑ)

Air kerma strength

Dose-rate constant

Geometry factor ratio

Radial dose function

Anistrotropy function

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

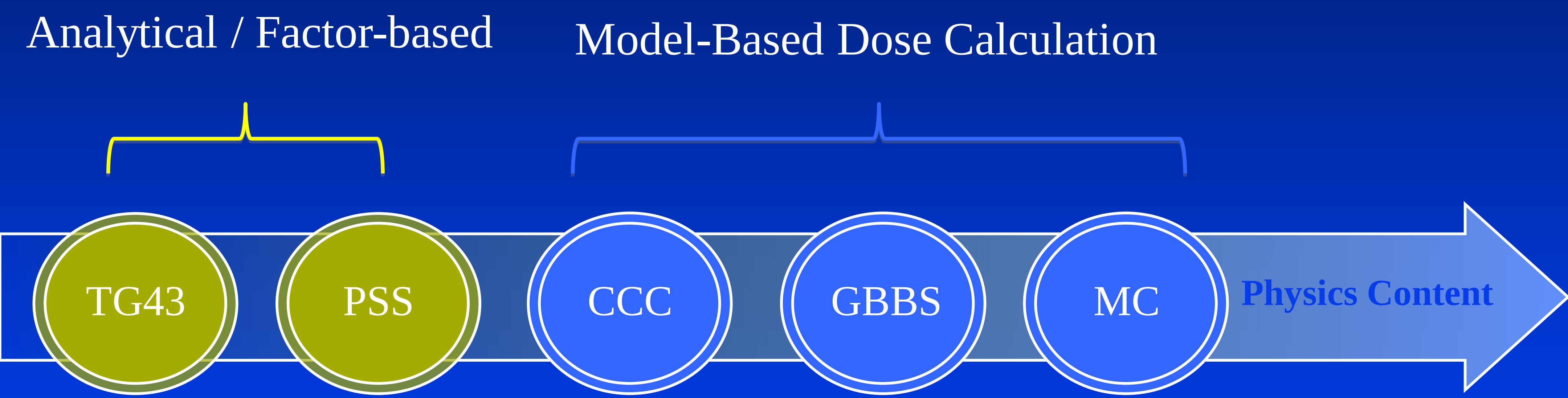
Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation

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 STD:
Full scatter
water medium

Elekta's Advanced Collapsed-cone Engine (ACE): Heterogeneities. Accurate to 1st scatter

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

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

Varian AcurosBV. Solves numerically transport equations. Full heterogeneities

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