Specification of source strength and its use in the treatment planning system

Yakov Pipman D. Sc.

TG43U1

Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations

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Current recommendations

- Specify the sources in units of reference air kerma rate, traceable to ADCL
- Documentation (standard sources and calibration factors of measuring systems),
- Manufacturer certificates
- Treatment planning system
- Prescription and reporting
(ICRU 1985, AAPM 1987, ICRU 1997).

Specify the sources in units of reference air kerma rate, traceable to ADCL

- **The reference air kerma rate is obtained at the reference distance of 1 meter**
- **units are μGy.h^{-1},**
- **A μGy.h^{-1} is numerically equivalent to a cGy.h^{-1} at 1 cm.**
- **AAPM recommends that sources be specified in terms of air kerma strength - S_k**

S_k = the product of the air kerma rate and the square of the calibration distance.

$$S_k\ (\mu G \bullet h^{-1} \bullet m^2) = K\ (\mu G \bullet h^{-1}) \bullet r^2\ (m)$$

S_k is numerically equal to R with the same units and conditions, i.e. corrected for air attenuation and scatter.

- To simplify equations, a new unit has been defined and is now widely accepted

$$1\ U = 1\ \mu Gy.h^{-1}.m^2$$

Source Certificates

- Before accepting a source, the user must study carefully the certificate(s) and specifications that accompany the sources
- This should be independent of the necessary dosimetric verification or calibration by the user.
- Caution! Manufacturers are still using one or more of the old units in their documentation
- Specifications may include
  - Nominal exposure rate,
  - Activity
  - Apparent activity (which include an estimate of the source capsule absorption effects).

When the classical specifications are maintained, there is a high probability of errors in clinical dosimetry, where conversion factors from/to “activity” or “apparent activity” are used for different isotopes and across systems

Exposure rate constant values reported for different source models:

- **0.3 to 0.331 mR.h^{-1}.m^{2} for 137-Cs (10% variation)**
- **0.4 to 0.5 mR.h^{-1}.m^{2} for 192-Ir. (20% variation !!)**
- Jayaraman et al (1983)

- **Variations for lower energy isotopes are more sensitive to source design and will be larger.**

In the physicist does not obtain an independent measurement, and instead uses the manufacturer’s value, specified in terms of source activity, significant errors can be made due to the different values of exposure rate constant (or kerma) available from literature.

Letter to the Editor

Third party brachytherapy seed calibrations and physicist responsibilities

(Received 3 October 2005; revised 11 November 2005; accepted for publication 12 November 2005; published 28 December 2005)

- **AAPM TG-56 (1997): "Every institution practicing brachytherapy shall have a system for measuring source strength with secondary traceability for all source types used in its practice."**
- **"The institution should compare the manufacturer's stated value with the institution's standard."**
- **AAPM TG-64 (1999): "In whatever form the seeds are procured, the manufacturer's assay *must* be independently confirmed."**
- **For those using a third party calibration service, a prudent approach would be to develop and implement an in-house system for checking the validity of third party calibrations on a routine basis.**

The constant used for the TPS calculations may be different from that used by the manufacturer to obtain activity

The input of source strength into the treatment planning system

- Should be exclusively in terms of reference air kerma rate. AAPM (1987)
- This is *not* the current status of all TPS's.
- If the required input is activity, it is important to know whether this is apparent, equivalent or contained activity (i.e., without correction for self absorption and filtration).
- The user should also be aware as to how the source certificate is specified and how the TPS handles the input reference air kerma rate, source activity, etc.
- The points above should all be considered:
  - Prior to acceptance and commissioning of the treatment planning system.
  - Any time that a new model source is introduced.

Table 1. Physical Characteristics of Various Radionuclides Used for Brachytherapy

Radionuclide	Half-life	Principal or mean energies from encapsulated sources, MeV*		
		Photon	Beta	Neutron
Radium-226	1622 y	0.830		
Cesium-137	30 y	0.662		
Iridium-192	74 d	0.380		
Gold-190	2.7 d	0.412		
Iodine-125	60 d	0.028		
Palladium-103	17 d	0.021		
Strontium-90	29 y		0.50	
Ytterbium-90	64 h		2.27	
Phosphorus-32	14 d		1.71	
Californium-252	2.65 y			2.15

*These are nominal values assuming typical encapsulation for sources.

Joint AAPM/RPC Registry of Brachytherapy Sources Meeting the AAPM Dosimetric Prerequisites

Seeds registered with the RPC as of November 2007

^{125}I Sources			^{103}Pd Sources		
Manufacturer	**Sources**	**Model**	**Manufacturer**	**Sources**	**Model**
Amersham	OncoSeed	6711	Best Medical International Inc	Best Palladium - 103	2335
	EchoSeed	6733	IsoAid, LLC	Advantage Pd-103	IAPd-103A
BEBIG GmbH	IsoSeed®I-125	I25.S06	North American Scientific	Prospera Pd -103	Med 3633
Best Industries	Best® I-125 Source	2301	Theragenics Corporation ®	TheraSeed®	200
IBt	Intersource125	1251L			
IsoAid, LLC	Advantage I-125	IAI-125A			
Mills Biopharmaceuticals, LLC	ProstaSeed ®	125SL 125SH			
North American Scientific	Prospera I-125	Med 3631-A/M			
Nucletron	SelectSeed I-125	130.002			
Bard Urological Division	125 Implant Seeds	STM1251			
Theragenics Corporation®	I-Seed I-125	I25.S06			

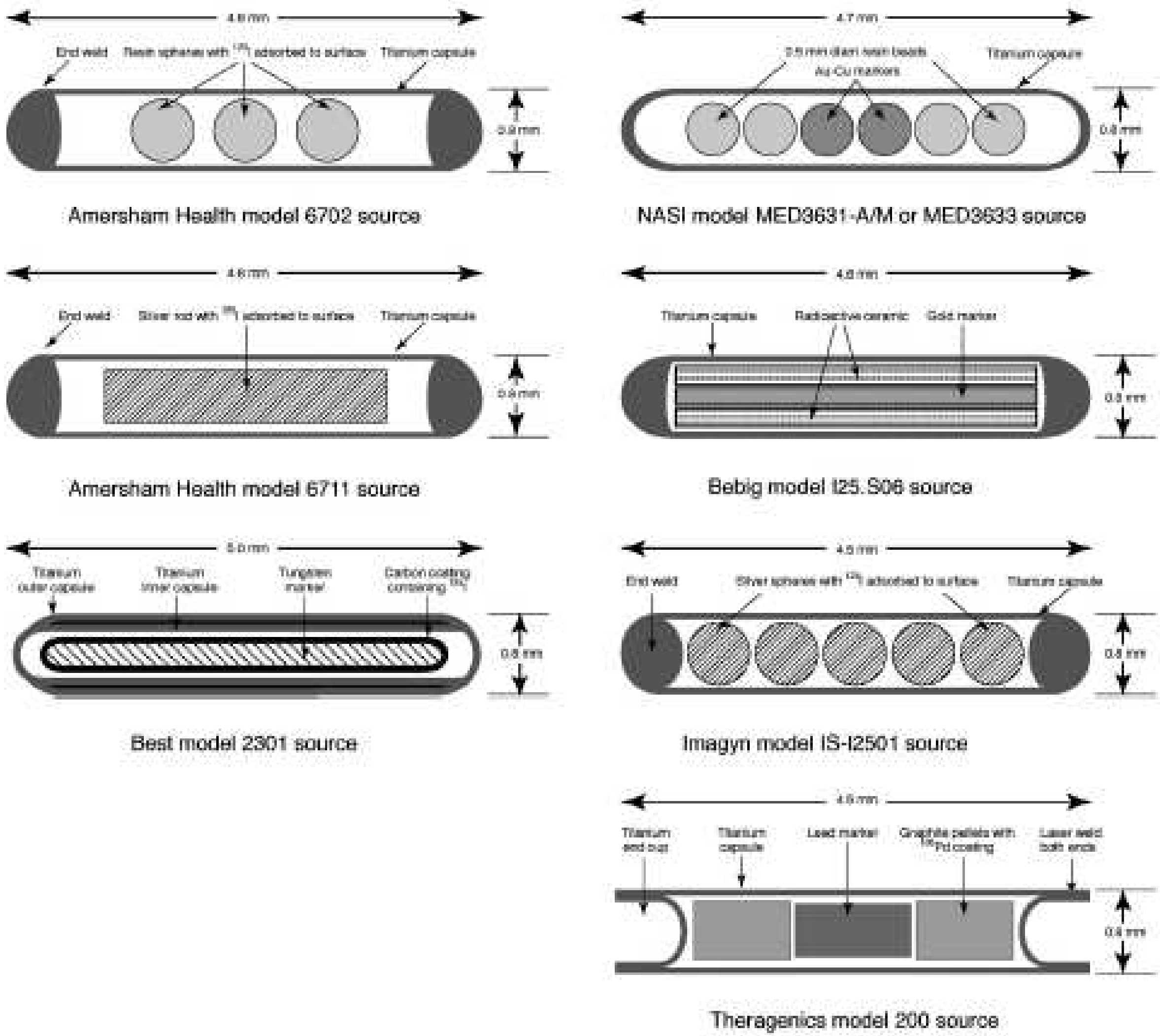
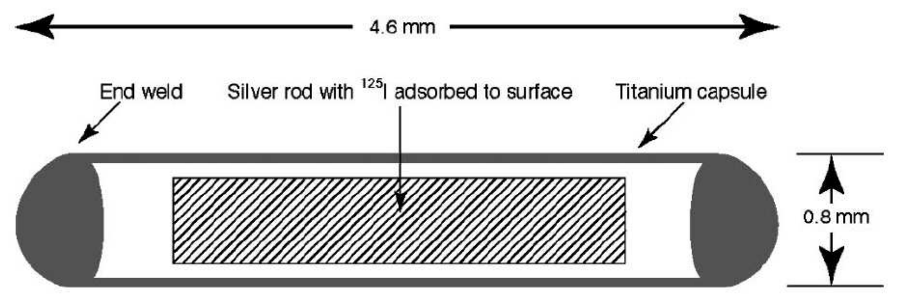
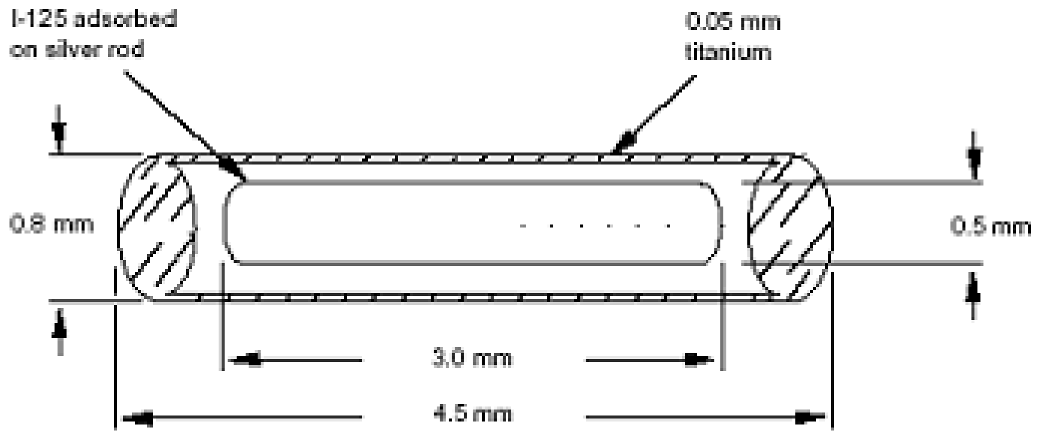
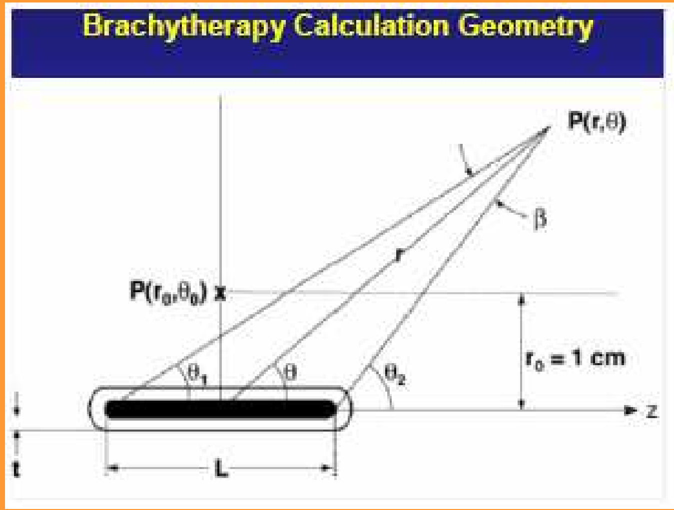


FIG. 2. Brachytherapy seeds examined in this report: (a) Amersham model 6702 source, (b) Amersham model 6711 source, (c) Best model 2301 source, (d) NASI model MED3631-A/M or MED3633 source, (e) Bebig/Theragenics Corp. model I25.S06 source, (f) Imagyn model IS-12501 source, and (g) Theragenics Corp. model 200 source. The titanium capsule is 0.06 mm thick for the Amersham and Theragenics seeds, while each capsule of the Best seed is 0.04 mm thick. The capsule thickness of the remaining seeds is 0.05 mm.



Amersham Health model 6711 source





637 Rivard *et al.*: AAPM TG-43 update

A. General 2D formalism

The general, two-dimensional (2D) dose-rate equation from the 1995 TG-43 protocol is retained,

$$\dot{D}(r,\theta)=S_K\cdot\Lambda\cdot\frac{G_L(r,\theta)}{G_L(r_0,\theta_0)}\cdot g_L(r)\cdot F(r,\theta), \qquad (1)$$

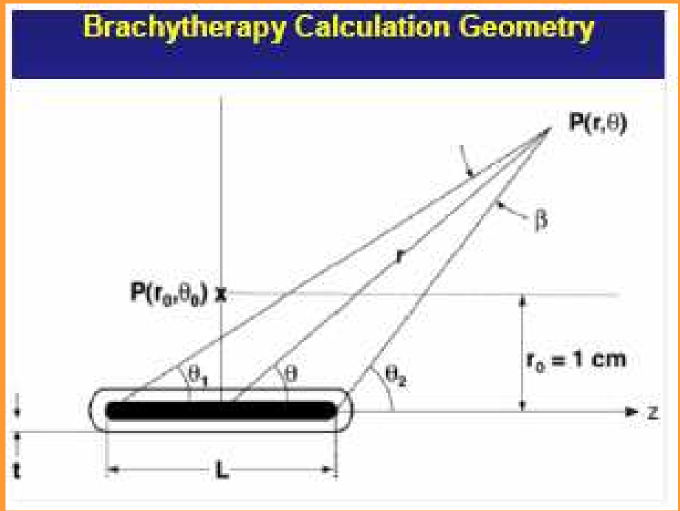
$\dot{D}(r,\theta)$	dose rate to water at point P(r,θ)
S_K	air kerma strength
Λ	dose rate constant
$g_L(r)$	radial dose function
$G_L(r,\theta)$	geometry function (line source approximation)
$F(r,\theta)$	2-D anisotropy function

2. Dose-rate constant

The definition of the dose-rate constant in water, Λ, is unchanged from the original TG-43 protocol: it is the ratio of dose rate at the reference position, $\dot{D}(r_0,\theta_0)$, and S_K. Λ has units of $\mathrm{cGy\,h^{-1}\,U^{-1}}$ which reduces to $\mathrm{cm^{-2}}$,

$$\Lambda = \frac{\dot{D}(r_0,\theta_0)}{S_K}. \tag{3}$$

The dose-rate constant depends on both the radionuclide and source model, and is influenced by both the source internal design and the experimental methodology used by the primary standard to realize S_K.



Geometry function

$$G_P(r,\theta) = r^{-2} \quad \text{point-source approximation,}$$

$$G_L(r,\theta) = \begin{cases} \dfrac{\beta}{Lr\sin\theta} & \text{if} \quad \theta \neq 0^\circ \\ (r^2 - L^2/4)^{-1} & \text{if} \quad \theta = 0^\circ \end{cases} \quad \text{line-source approximation,}$$

4. Radial dose function

The radial dose function, $g_X(r)$, accounts for dose fall-off on the transverse-plane due to photon scattering and attenuation, i.e., excluding fall-off included by the geometry function. $g_X(r)$ is defined by Eq. (6), and is equal to unity at $r_0 = 1$ cm.

$$g_X(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} \frac{G_X(r_0\theta_0)}{G_X(r,\theta_0)}. \qquad (6)$$

Parameter fit to g(r) is often used in TP systems

$$g_X(r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5. \qquad (7)$$

Parameters a_0 through a_5 should be determined so that they fit the data within $\pm 2\%$. Also, the radial range over which the fit meets this specification should be clearly specified.

5. 2D anisotropy function

The 2D anisotropy function, $F(r,\theta)$, is defined as

$$F(r,\theta)=\frac{\dot{D}(r,\theta)}{\dot{D}(r,\theta_0)}\frac{G_L(r,\theta_0)}{G_L(r,\theta)}. \qquad (8)$$

F(r,θ):

- **Is 1 in the transverse plane**
- **Decreases**
  - **As "r" decreases**
  - ***As θ goes to 0 or 180***
  - ***As the encapsulation thickness increases***
  - ***As the energy decreases***

Comparison of 1-D Formalisms

BAD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_P(r) \cdot \phi_{an}(r)$$

BAD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{r_0}{r}\right)^2 \cdot g_L(r) \cdot \phi_{an}(r)$$

GOOD $$\dot{D}(r) = S_K \cdot \Lambda \cdot \left(\frac{r_0}{r}\right)^2 \cdot g_P(r) \cdot \phi_{an}(r)$$

BEST $$\dot{D}(r) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta_0)}{G_L(r_0,\theta_0)} \cdot g_L(r) \cdot \phi_{an}(r)$$

Air-kerma strength, S_K, is the air-kerma rate, $\dot{K}_\delta(d)$, *in vacuo* and due to photons of energy greater than δ, at distance d, multiplied by the square of this distance, d^2,

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

TABLE II. Consensus $g(r)$ values for six ^{125}I sources. Interpolated data are boldface, and italicized data are nonconsensus data obtained from candidate datasets.

	Line source approximation						Point source approximation					
r [cm]	Amersham 6702 $L=3.0$ mm	Amersham 6711 $L=3.0$ mm	Best 2301 $L=4.0$ mm	NASI MED3631-A/M $L=4.2$ mm	Bebig I25.S06 $L=3.5$ mm	Imagyn IS12501 $L=3.4$ mm	Amersham 6702	Amersham 6711	Best 2301	NASI MED3631-A/M	Bebig I25.S06	Imagyn IS12501
0.10	1.020	1.055	1.033		*1.010*	*1.022*	0.673	0.696	0.579		*0.613*	*0.631*
0.15	**1.022**	1.078	1.029		**1.018**	*1.058*	**0.809**	0.853	0.725		**0.760**	*0.799*
0.25	**1.024**	1.082	1.027	*0.998*	*1.030*	*1.093*	**0.929**	0.982	0.878	*0.842*	*0.908*	*0.969*
0.50	1.030	**1.071**	1.028	*1.025*	*1.030*	1.080	1.008	1.048	0.991	*0.985*	*1.001*	1.051
0.75	1.020	**1.042**	1.030	*1.019*	**1.020**	**1.048**	1.014	**1.036**	1.020	*1.008*	**1.012**	**1.040**
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.50	0.935	0.908	0.938	0.954	0.937	0.907	0.939	0.912	0.945	0.962	0.942	0.912
2.00	0.861	0.814	0.866	0.836	0.857	0.808	0.866	0.819	0.875	0.845	0.863	0.814
3.00	0.697	0.632	0.707	0.676	0.689	0.618	0.702	0.636	0.715	0.685	0.695	0.623
4.00	0.553	0.496	0.555	0.523	0.538	0.463	0.557	0.499	0.562	0.530	0.543	0.467
5.00	0.425	0.364	0.427	0.395	0.409	0.348	0.428	0.367	0.432	0.401	0.413	0.351
6.00	0.322	0.270	0.320	0.293	0.313	0.253	0.324	0.272	0.324	0.297	0.316	0.255
7.00	0.241	0.199	0.248	0.211	0.232	0.193	0.243	0.200	0.251	0.214	0.234	0.195
8.00	0.179	0.148	0.187		0.176	0.149	0.180	0.149	0.189		0.178	0.150
9.00	0.134	0.109	0.142		0.134	0.100	0.135	0.110	0.144		0.135	0.101
10.00	0.0979	0.0803	0.103		0.0957	0.075	0.0986	0.0809	0.104		0.0967	0.076

TABLE V. $F(r,\theta)$ for Amersham model 6711.

Polar angle θ (degrees)	r [cm]					
	0.5	1	2	3	4	5
0	0.333	0.370	0.442	0.488	0.520	0.550
5	0.400	0.429	0.497	0.535	0.561	0.587
10	0.519	0.537	0.580	0.609	0.630	0.645
20	0.716	0.705	0.727	0.743	0.752	0.760
30	0.846	0.834	0.842	0.846	0.848	0.852
40	0.926	0.925	0.926	0.926	0.928	0.928
50	0.972	0.972	0.970	0.969	0.969	0.969
60	0.991	0.991	0.987	0.987	0.987	0.987
70	0.996	0.996	0.996	0.995	0.995	0.995
80	1.000	1.000	1.000	0.999	0.999	0.999
$\phi_{an}(r)$	0.973	0.944	0.941	0.942	0.943	0.944

TABLE X. $F(r,\theta)$ for Theragenics Corp. model 200. Italicized data are nonconsensus data obtained from candidate datasets.

Polar angle θ (degrees)	r (cm)								
	0.25	*0.5*	0.75	1	2	3	4	5	*7.5*
0	*0.619*	*0.694*	*0.601*	0.541	0.526	0.504	0.497	0.513	*0.547*
1	*0.617*	*0.689*	*0.597*	0.549	0.492	0.505	0.513	0.533	*0.580*
2	*0.618*	*0.674*	*0.574*	0.534	0.514	0.517	0.524	0.538	*0.568*
3	*0.620*	*0.642*	*0.577*	0.538	0.506	0.509	0.519	0.532	*0.570*
5	*0.617*	*0.600*	*0.540*	0.510	0.499	0.508	0.514	0.531	*0.571*
7	*0.579*	*0.553*	*0.519*	0.498	0.498	0.509	0.521	0.532	*0.568*
10	*0.284*	*0.496*	*0.495*	0.487	0.504	0.519	0.530	0.544	*0.590*
12	*0.191*	*0.466*	*0.486*	0.487	0.512	0.529	0.544	0.555	*0.614*
15	*0.289*	*0.446*	*0.482*	0.490	0.523	0.540	0.556	0.567	*0.614*
20	*0.496*	*0.442*	*0.486*	0.501	0.547	0.568	0.585	0.605	*0.642*
25	*0.655*	*0.497*	*0.524*	0.537	0.582	0.603	0.621	0.640	*0.684*
30	*0.775*	*0.586*	*0.585*	0.593	0.633	0.654	0.667	0.683	*0.719*
40	*0.917*	*0.734*	*0.726*	0.727	0.750	0.766	0.778	0.784	*0.820*
50	*0.945*	*0.837*	*0.831*	0.834	0.853	0.869	0.881	0.886	*0.912*
60	*0.976*	*0.906*	*0.907*	0.912	0.931	0.942	0.960	0.964	*0.974*
70	*0.981*	*0.929*	*0.954*	0.964	0.989	1.001	1.008	1.004	*1.011*
75	0.947	*0.938*	*0.961*	0.978	1.006	1.021	1.029	1.024	*1.033*
80	*0.992*	*0.955*	*0.959*	0.972	1.017	1.035	1.046	1.037	*1.043*
85	*1.007*	*0.973*	0.960	0.982	0.998	1.030	1.041	1.036	*1.043*
$\phi_{an}(r)$	*1.130*	*0.880*	*0.859*	0.855	0.870	0.884	0.895	0.897	*0.918*

TABLE XIII. Recommended nuclear data for ^{125}I and ^{103}Pd for brachytherapy dosimetry.

^{125}I (half-life = 59.40 ± 0.01 days)		^{103}Pd (half-life = 16.991 ± 0.019 days)	
Photon energy (keV)	Photons per disintegration	Photon energy (keV)	Photons per disintegration
27.202	0.406	20.074	0.224
27.472	0.757	20.216	0.423
30.98	0.202	22.72	0.104
31.71	0.0439	23.18	0.0194
35.492	0.0668	39.75	0.00068
		294.98	0.00003
		357.5	0.00022
		497.1	0.00004
Weighted mean energy = 28.37 keV	Total = 1.476	Weighted mean energy = 20.74 keV	Total = 0.7714
^{125}I $\Gamma_{5\,\mathrm{keV}} = 0.0355\ \mu\mathrm{Gy}\cdot\mathrm{m}^2\cdot\mathrm{h}^{-1}\cdot\mathrm{Bq}^{-1}$		^{103}Pd $\Gamma_{5\,\mathrm{keV}} = 0.0361\ \mu\mathrm{Gy}\cdot\mathrm{m}^2\cdot\mathrm{h}^{-1}\cdot\mathrm{Bq}^{-1}$	

TABLE XV. Dose rates ($cGy \cdot h^{-1} \cdot U^{-1}$) as a function of distance for 8 brachytherapy sources using the 1D dosimetry formalism of Eq. (11) with interpolation for $g_L(r)$ and $\phi_{an}(r)$.

r (cm)	Amersham model 6702	Amersham model 6711	Best model 2301	NASI model MED3631-A/M	Bebig model I25.S06	Imagyn model IS-12501	Theragenics model 200	NASI model MED3633
0.5	4.119	3.937	3.813	4.112	3.922	3.426	3.014	3.184
1.0	0.995	0.911	0.962	0.986	0.950	0.815	0.587	0.626
1.5	0.413	0.368	0.413	0.420	0.398	0.334	0.199	0.215
2.0	0.213	0.186	0.220	0.207	0.205	0.169	0.0837	0.0914
3.0	0.0768	0.0643	0.0783	0.0746	0.0733	0.0582	0.0206	0.0227
4.0	0.0344	0.0284	0.0347	0.0325	0.0323	0.0246	0.00634	0.00697
5.0	0.0169	0.0134	0.0171	0.0157	0.0157	0.0118	0.00221	0.00247
6.0	0.00890	0.00688	0.00908	0.00811	0.00840	0.00592	0.000846	0.000933
7.0	0.00490	0.00373	0.00506	0.00429	0.00459	0.00328	0.000342	0.000364

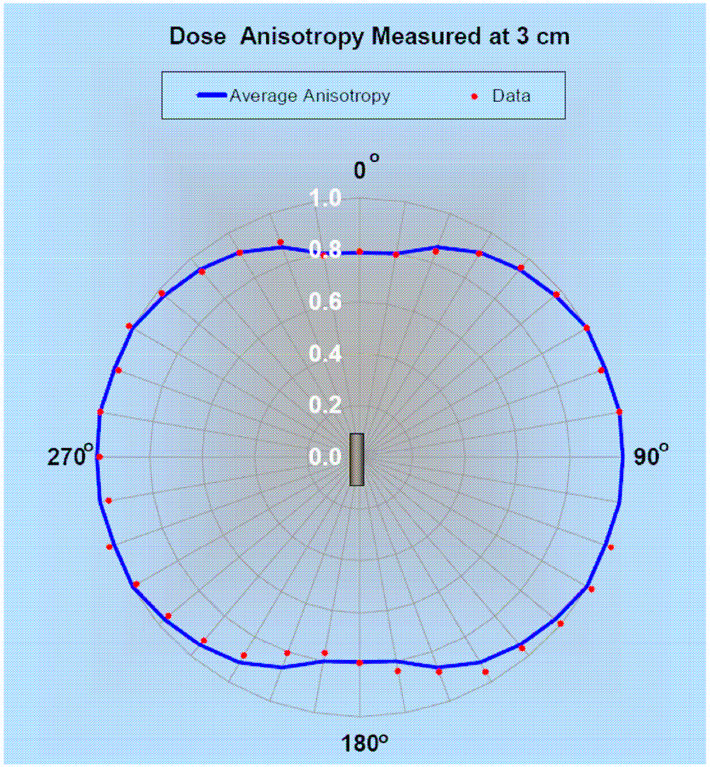
Use this data to test RTP calculations for a single source

Source calibration traceability

- ‘‘*Direct traceability* is established when either a source or a transfer instrument ~e.g., well chamber is calibrated against a national standard at an ADCL or at NIST itself.’’
- ‘‘*Secondary traceability* is established when the source is calibrated by comparison with the same radionuclide and design that has a directly traceable calibration or by a transfer instrument that bears a directly traceable calibration.’’
- ‘‘*Secondary traceability by statistical inference* is established when a source is one of a group of sources of which a suitable random sample has direct or secondary traceability.’’

New seeds

The IsoRay Medical, Inc. Cs-131 seed is designed to produce a nearly isotropic dose distribution. The radiation dose contour of the Cs-131 seed at a radius of 3 cm from the source, taken from actual measurements, appears in the figure below.

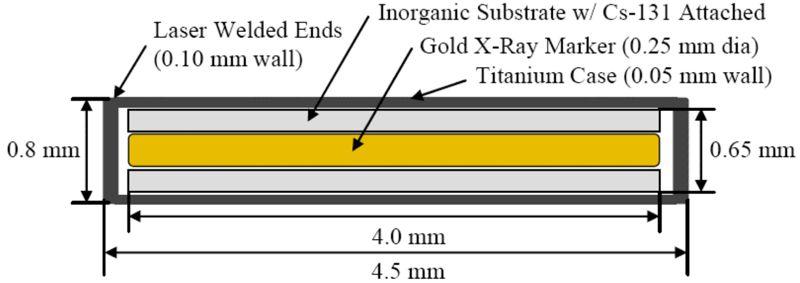


The dose characteristics of the Cs-131 seed have also been confirmed through extensive Monte Carlo evaluations in accordance with American Association of Physicists in Medicine (AAPM) Task Group 43 (TG-43) guidelines [5]. The Cs-131 seed has an anisotropy factor of 1.01 at 0.5 cm from the source and an average anisotropy factor of 0.97. [11]

IsoRay Medical, Inc. Cesium-131 Brachytherapy Seed

Model No. CS-1

The IsoRay Medical, Inc. Cs-131 brachytherapy seed consists of a welded titanium capsule containing the low energy gamma (X-ray) emitting isotope, Cesium-131, adsorbed onto an internal inorganic substrate. The seed configuration is designed to generate near isotropic emission of therapeutic radiation.



Physical Characteristics

Principle Radionuclide:	Cesium-131	(Cs-131)
Half-life of Cs-131	9.69 days	(232.6 hr)
Radiation Energy:	29.5, 29.8, 33.6 keV	
Half-Value Thickness:[1]	0.025 mm of Lead	

Decay Mode: Cs-131 decays by electron capture with the emission of characteristic low-energy X-ray photons and electrons. The electrons are absorbed by the titanium wall of the seed.

Radionuclide Purity:	> 99.85%	Cs-131
	< 0.10%	Cs-132
	< 0.05%	All other radioisotopes

IsoRay Medical, Inc. Cs-131 seeds are available with apparent activities from 0.20 to 50.0 mCi [Air-Kerma strength 0.13 to 33 microGray meter squared per hour ($\mu Gy\ m^2/h$)]. [12-14]. AAPM guidelines for brachytherapy should be followed for independent verification of source output.[5-7] A certificate of analysis is provided with each shipment that includes: customer order number, lot number, number of seeds, reference date, implant date, and average and total activities expressed as apparent activity (mCi) and Air Kerma strength ($\mu Gy\ m^2/h$) traceable to NIST (National Institute of Standards and Technology). Additional information, including patient and physician names, may be provided upon request.

REDUNDANT SYSTEM FOR SOURCE CHECKS

- Two component system
  - Calibrator and long half life standard source
  - Calibrator and manufacturer’s specification
- Three component system
  - Calibrator and two different standard sources
  - Two different calibrators and one standard source
  - calibrator, standard source and manufacturer’s specification

Calibration of an HDR source:

A TRUE *half* LIFE STORY

$$A(t) = A_r e^{-t/\tau}$$

or

$$A(t) = A_r (0.5)^{t/T}$$

or

$$A(t)=A_r e^{-t/(1.443xT)}$$

Elapsed Days t	Correct Decay Factor	"Not-So-Correct" Decay Factor	Difference
6	0.955	0.936	2.1%

[redacted]

Elapsed Days t	Correct Decay Factor	"Not-So-Correct" Decay Factor	Difference
6	0.955	0.936	2.1%
8	0.929	0.899	3.4%

[redacted]

Elapsed Days t	Correct Decay Factor	"Not-So-Correct" Decay Factor	Difference
6	0.955	0.936	2.1%
8	0.929	0.899	3.4%
10	0.912	0.875	4.2%

[redacted]

Elapsed Days t	Correct Decay Factor	"Not-So-Correct" Decay Factor	Difference
6	0.955	0.936	2.1%
8	0.929	0.899	3.4%
10	0.912	0.875	4.2%
30	0.758	0.670	13.1%

The Moral of the Story

Tolerances are important. Training and experience.

Two checks are better than one.

Investigate discrepancies until you can explain them away.