Comparison of I-125 sources used for permanent interstitial implants

Bret H. Heintz[a)]
Department of Radiology, Radiological Science Division, University of Texas Health Science Center at San Antonio, 7703 Floyd Curl Drive, San Antonio, Texas 78229 and Cancer Therapy and Research Center, 7979 Wurzbach Road, San Antonio, Texas 78229

Robert E. Wallace
Department of Radiation Oncology, University of California, Los Angeles, Los Angeles, California 90095-6951

James M. Hevezi
Department of Radiology, Radiological Science Division, University of Texas Health Science Center at San Antonio, 7703 Floyd Curl Drive, San Antonio, Texas 78229 and Cancer Therapy and Research Center, 7979 Wurzbach Road, San Antonio, Texas 78229

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The increase in the number of manufacturers of ^{125}I sources used in prostate brachytherapy has generated many questions in the radiation oncology community. In this investigation, the physical and dosimetric characteristics were evaluated for the following sources listed by marketing company and source model: Nycomed-Amersham 6711 (OncoSeed), Nycomed-Amersham 6702, Mentor IoGold, UroMed Symmetra, Imagyn IsoSTAR, UroCor, (PSA, Mallincrkrodt) ProstaSeed, Syncor PharmaSeed, SourceTech Medical, (BARD) ^{125}Implant (BrachySource), Med-Tec I-Plant, Best Medical Model 2301, DraxImage BrachySeed, and International Brachytherapy, Inc. (IBT) InterSource^{125}. The investigation examined the differences in design, construction, and the dosimetric characteristics created from each source. The dosimetric characteristics of the new sources were compared to that of the Amersham 6711 source. Parameter studies have led to the development of a simple equation that can be used to clinically convert the standard 6711 source strength to an equivalent strength of a new source. [DOI: 10.1118/1.1359246]

Key words: brachytherapy, source, I-125, ^{125}I, dosimetry

I. INTRODUCTION

This article investigates the physical and dosimetric properties of eleven commercially available ^{125}I sources intended for use in prostate brachytherapy. With the increasing number of manufacturers and sources clinically available, many questions have surfaced. The most commonly asked questions are:

(1) What source do I use or would want to use?
(2) What are the physical and dosimetric characteristics of a particular source?
(3) Are the sources different? If so, how do they differ?
(4) Do the physical characteristics affect the source strength?
(5) How do I compare existing source dosimetric data with new source dosimetric data?
(6) What activity (source strength) do I use when planning with a particular source?
(7) How do I evaluate the new sources being introduced?

These are important questions. Some of the questions will not be addressed in this article. It is the intention of the authors that the data presented here will help in the evaluation of the referenced sources and present an approach that the reader can use to evaluate new sources when they are introduced in the future. The study was not designed to determine which source is the best, but rather to inform the radiation oncology and urology communities of the physical and dosimetric characteristics for the many sources available.

II. BACKGROUND

The external designs of the ^{125}I sources appear to be similar. However, in investigating the characteristics of the source differences become quite apparent.

A. Dosimetric characteristics

The AAPM Radiation Therapy committee recommends that each new brachytherapy source have a thorough and redundant dosimetric characterization before it is clinically used. The committee recommends that each manufacturer have at least one (preferably two) independent series of dosimetric measurements and one Monte Carlo dosimetric study performed to confirm the dosimetric characteristics.[1] All of the sources' dosimetric characteristics are reported according to the Task Group-43 (TG-43) recommendations.[2] Yet there is no protocol or standard on how to make measurements that characterizes a source. Even with the TG-43 report, there are no universal standards specifying the distances or angles where measurements should be taken. This makes source data comparison difficult as different researchers have used different methods.

The data presented in this article will be the dose rate constant, Λ, anisotropy factor, ϕ_{an}, anisotropy function, $F(r,\theta)$, radial dose function, $g(r)$, and the fifth-order polynomial for $g(r)$.

The PharmaSeed, ^{125}Implant, and InterSource^{125} source data presented in this investigation are Monte Carlo simulation results. The IoGold, ProstaSeed, Model 2301, and I-Plant source data are measured (TLD and ion chamber) data. The 6711, 6702, IsoSTAR, Symmetra, and BrachySeed source data are a combination of measured and Monte Carlo data.

New source data published by the manufacturers often reference and compare their sources to the Nycomed-Amersham 6711 and 6702 sources that have the longest history of clinical use and therefore are considered the benchmarks for the industry. Since the 6711 and 6702 sources have very different internal physical characteristics, manufacturers of new sources are able to select which source design best resembles their source for comparison.

Manufacturers often reference their source being dosimetrically similar to that of the Nycomed-Amersham 6702 source, yet the minimum available source strength is 5 mCi and is not used with the current permanent transperineal technique. The source will be used in the article as a reference for physical and dosimetric characteristics.

B. Physical characteristics

The physical characteristics of the sources can be divided into (a) the actual physical construction of the source; (b) the source imaging visualization properties; and (c) the distribution of the radioactivity within the internal core of the source. Figure 1 illustrates the cross sectional view of each source. Tables I and II describe the elements in each design.

There are two distinctly different source design types. Regarding the physical design of the internal core of the source, two types of designs have been used: (a) Rod/Wire/Cylinder and (b) Sphere. The internal physical design characteristics are used to aid in the visualization of the sources on a fluoroscopic, radiographic or CT image.

Four different types of materials have been used for the construction of the internal core of the sources: (a) Resin, (b) Ceramic, (c) Glass, (d) High-Z materials. The distribution of the I-125 within the internal core of the source is either: (a) Ab̲sorbed throughout the internal core (i.e., volume distributed), (b) Ad̲sorbed across the surface of the internal core of the source (i.e., surface distributed).

III. COMPARISONS

Dosimetric characteristics of each source type were estimated through measurements and calculations. Measurements were made using TLDs, film, ion chambers, and diodes. Calculations were performed with various Monte Carlo software programs and using various and differing photon interaction coefficient data. Monte Carlo results are intended to provide the manufacturer with a set of reference dosimetry parameters for which the experimental measurements can be confirmed.[3]

The values of the measured data for the 6711, 6702, and Symmetra sources are systematically higher than the Monte Carlo calculations. The percent differences ranged from 1.2% to 2.9% for the dose rate constant. The Symmetra source data showed that the Monte Carlo calculations underestimate the dose rate constant by 2.9% and under estimates the anisotropy and radial dose function as well.

The Monte Carlo calculations for the IsoSTAR and PharmaSeed sources were higher than the measured data. The percent differences ranged from 3.2% to 4.3% for the dose rate constant.[4,5] When measurements were performed in a phantom, a correction factor was applied to correct for differences between the phantom and liquid water. These correction factors were consistent with those published by Luxton[6] and Williamson[7] using Monte Carlo calculations to predict corrections between Solid Water™ and liquid water.

Tables III and IV show the dosimetric characteristics for each of the sources and the method in which the values were determined. The table includes the updated dose rate constants for the sources that have been updated.

A. Radial dose function, $g(r)$

The radial dose functions, $g(r)$ were evaluated for radii ranging from 0.1 to 14.0 cm. Typically, the measured data was taken at 0.5 cm intervals beyond 1 cm, whereas the calculated data was computed at 0.1 cm intervals to 1 cm and at 0.5 cm intervals from 1 cm out to 14 cm.[2–5,8–17]

The Symmetra, I-Plant, ^{125}Implant, and BrachySeed sources have radial dose functions that average 1.5% higher at 1.5 cm and 22% higher at 6 cm than the 6711 source. The commonality between these sources is the ceramic material used for the construction of the internal core of the source. Sources of this construction demonstrate a photon spectrum essentially that of the I-125 decay scheme. The contribution of characteristic x rays from internal components is minimal. The characteristic x rays generated from the gold visualization marker inside the Symmetra source are $L_{Iab}=14.35\,\mathrm{keV}$, $L_{IIab}=13.73\,\mathrm{keV}$, $L_{IIIab}=11.9\ \mathrm{keV}$, $L_{\gamma1}=13.3\,\mathrm{keV}$, $L_{\beta2}=11.58\,\mathrm{keV}$.[12,13,18] The characteristic x rays generated from the silver visualization marker of the I-Plant and the silver doped inside the glass of the BrachySeed are $K_{ab}=25.517\,\mathrm{keV}$, $K_{\beta2}=25.45\,\mathrm{keV}$, $K_{\beta1}=24.942\,\mathrm{keV}$, $K_{\alpha1}=22.16\,\mathrm{keV}$, $K_{\alpha2}=21.98\,\mathrm{keV}$.[18] With the silver inside the source and the I-125 absorbed throughout the ceramic substrate of the source the attenuation from the silver on the photon spectrum is minimal and the characteristic x ray contribution is minimal. With the exception of the ^{125}Implant having the I-125 adsorbed onto the copper skin covering the ceramic internal core, the I-125 is absorbed throughout the internal core of the sources.[14]

The 6702 and IoGold sources also have radial dose functions that average 1.2% higher at 1.5 cm and 10% higher at 4 cm than the 6711 source. The sources with a resin substrate have a photon spectrum from the I-125 decay scheme. The IoGold source has 2 Gold–Copper markers in the center of the sources for visualization.[7,10,18] The characteristics x rays generated from the gold (80%)/copper (20%) markers inside the IoGold source are $L_{Iab}=14.35\,\mathrm{keV}$, $L_{IIab}=13.73\,\mathrm{keV}$,

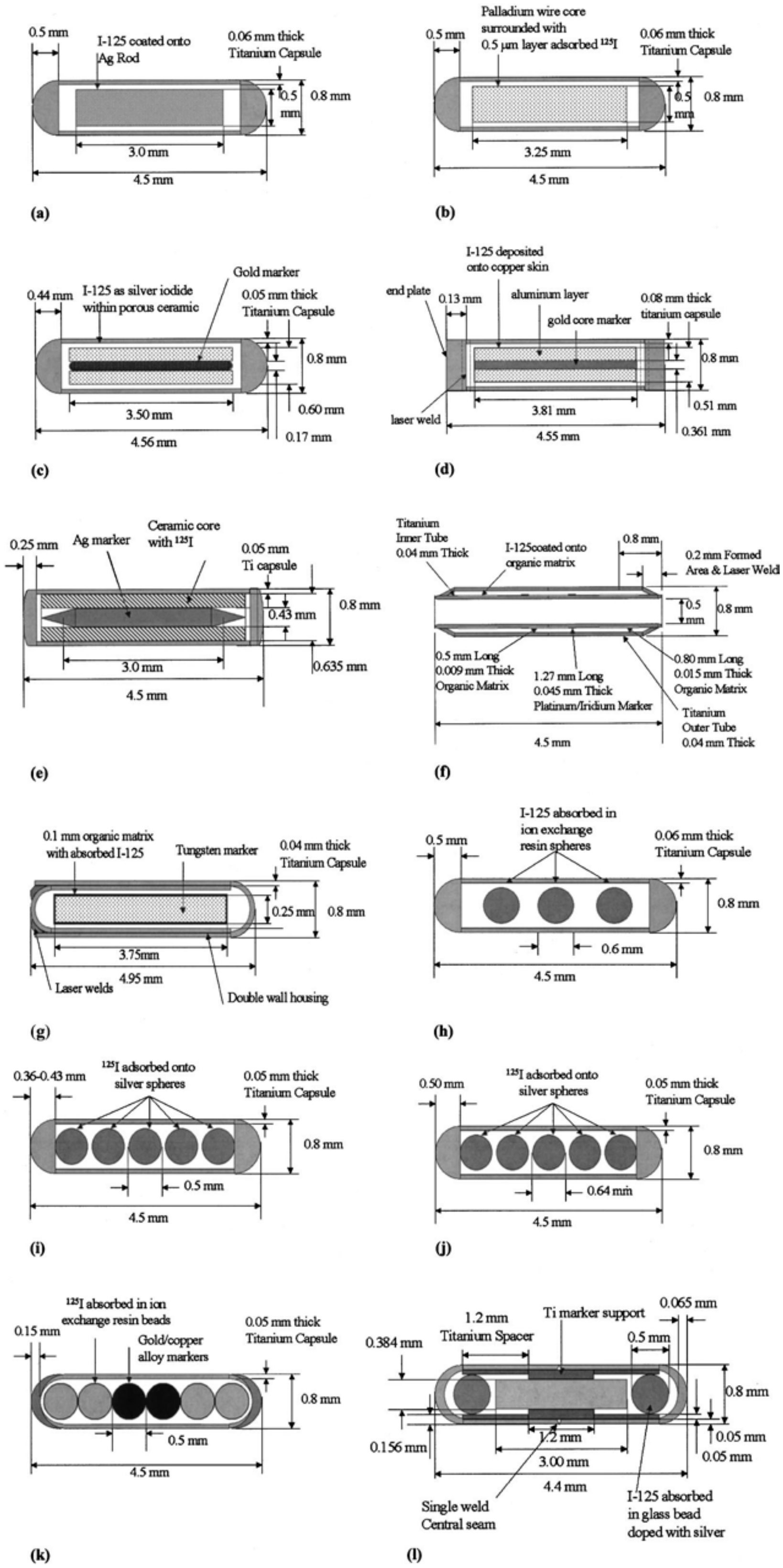

FIG. 1. Cross-Sectional drawings of sources with a Rod, Wire, or Cylinder internal core design; (a) Amersham 6711 OncoSeed, (b) Syncor PharmaSeed, (c) UroMed Symmetra, (d) SourceTech Medical ^{125}Implant, (e) Med-Tec I-Plant, (f) International Brachytherapy, Inc. InterSource^{125}, (g) Best Medical Model 2301 (h) Amersham 6702, (i) UroCor ProstaSeed, (j) Imagyn IsoSTAR, (k) Mentor's IoGold, (l) DraxImage BrachySeed.

$L_{IIIab}=11.9$ keV, $L_{\gamma 1}=13.3$ keV, and $L_{\beta 2}=11.58$ keV from the gold and $K_{ab}=8.98$ keV, $K_{\beta 2}=8.97$ keV, $K_{\beta 1}=8.90$ keV, $K_{\alpha 1}=8.047$ keV, and $K_{\alpha 2}=8.047$ keV from the copper. Detectable characteristic x rays generated due to the gold and copper have energies generally less than 12 keV. In phantom, these spectral components have no clinical significance and in air kerma determinations may be removed by judicious filtration.[19] The Monte Carlo programs used for

TABLE I. Physical characteristics of sources with an internal design of a rod, wire, or cylinder.

Source Marketing Company	Nycomed–Amersham	Syncor	UroMed	Source Tech Medical BARD	Med-Tec	International Brachytherapy, Inc	Best Medical International
Source Manufacturing Company	Nycomed–Amersham	Syncor	Bebig GmbH	Source Tech Medical	Implant Sciences	International Brachytherapy, Inc	Best Medical International
Source Trade Name	OncoSeed (6711)	PharmaSeed	Symmetra	^{125}Implant BrachySource	I-Plant	Intersource^{125}	Model 2301
Source Model Name	6711	BT-125-I	I25.S06	STM1251	Model 3500	1251L	Model 2301
Manufacturing Location	United States	China	Germany	United States	United States	Belgium	United States
External Length	4.5 mm	4.5 mm	4.5 mm	4.55 mm	4.5 mm	4.5 mm	4.95 mm
External Diameter	0.8 mm	0.8 mm	0.8 mm	0.81 mm	0.8 mm	0.8 mm	0.8 mm
Wall Thickness	0.05 mm	0.06 mm	0.05 mm	0.08 mm	0.05 mm	0.04 mm	0.04 mm single wall tubing
End Design	Laser Welded (Semi-circle)	Laser Welded (Semi-circle)	Laser Welded (Semi-circle)	Laser Welded (End Plates)	Laser Welded (End cap press fit into tube)	Formed Area and Laser Weld	Laser Welded around end of tube
End Thickness	0.5 mm	0.5 mm	0.44–0.48 mm	0.13 mm	0.25 mm	0.5 mm	0.14 mm
Internal Design Type	Rod	Wire	Cylinder/Rod	Rod/Cylinder	Cylinder/Rod	Cylinder/Rod	Rod (Marker)
Rod/wire/cylinder length	3.0 mm	3.25 mm	3.5 mm	3.8 mm	3.0 minus tips	2.3 mm (actual) 3.7 mm (physical)	3.75 mm
Rod/Wire/Cylinder	Silver Wire	Palladium Wire	Ceramic Cylinder	Aluminum Cylinder	Ceramic Cylinder	3-Organic Matrix Rings	Tungsten Marker
Outer Diameter	0.5 mm	0.5 mm	0.6 mm	0.51 mm	0.7 mm		0.25 mm
Inner Diameter			0.22 mm	0.36 mm	0.4 mm	0.55 mm	
Marker Type	Silver Wire	Palladium Wire	Gold Marker	Gold Core	Silver Marker	Platinum/Iridium	Tungsten Marker
Marker Diameter	0.5 mm	0.5 mm	0.17 mm	0.36 mm	0.4 mm	Width 1.27 mm Thickness 0.045 mm	0.25 mm
Internal Design Construction	^{125}I adsorbed onto Silver-halide rod	^{125}I adsorbed onto Palladium wire	^{125}I Radioactive ceramic cylindrical shell. Gold marker (rod) inside ceramic cylinder	^{125}I Deposited on top of a thin copper coating. Aluminum wire with gold core and a micro thin nickel layer for the adhesion of the copper	^{125}I ion implanted into ceramic cylindrical shell through dry process. Silver marker inside ceramic cylinder	^{125}I adsorbed onto 0.009 mm thick organic matrix ring in center of source and 0.015 mm thick organic matrix ring at both ends of source	^{125}I adsorbed onto 0.1 mm thick organic matrix coating tungsten marker
Radiographic Marker	Silver Wire	Palladium Wire	Gold Rod	Gold core/Aluminum Wire	Silver Marker	Platinum/Iridium Marker	Tungsten Marker
Minimum source strength	0.1 mCi	0.28 mCi	0.203 mCi	0.18 mCi	0.2 mCi	0.2 mCi	0.2 mCi
Maximum source strength	1.0 mCi	0.634 mCi	0.634 mCi	0.995 mCi	0.6 mCi	1.0 mCi	1.0 mCi
Figure	1a	1b	1c	1d	1e	1f	1g

TABLE II. Physical characteristics of sources with an internal design of spheres.

Source Marketing Company	Nycomed–Amersham	UroCor Mallinckrodt PSA (Prostate Services of America)	Imagyn Medical Technologies Incorporated	Mentor Corporation	DraxImage Inc.
Source Manufacturing Company	Nycomed–Amersham	Mills Biopharmaceuticals (A UroCor Company)	International Isotope Inc.	North American Scientific Inc.	DraxImage Inc. Cytogen (USA)
Source Trade Name	6702	ProstaSeed	IsoSTAR	IoGold	BrachySeed
Source Model Name	6702	I125-SL	12501	MED3631-A/M	LS-1
Manufacturing Location	United States	Unites States	United States	United States	Canada
External Length (mm)	4.5 mm	4.5 mm	4.5 mm	4.5 mm	4.4 mm
External Diameter (mm)	0.8 mm	0.8 mm	0.8 mm	0.8 mm	0.8 mm
Wall Thickness (mm)	0.06 mm	0.05 mm	0.05 mm	0.05 mm	0.05 mm
End Design	Laser Welded End Cap (Semi-circle)	Laser Welded End Cap (Semi-circle)	Laser Welded End Cap (Semi-circle)	Laser Crimp Weld End Cap (Semi-circle)	Hemisphere
End Thickness (mm)	average 0.5 mm	0.36–0.43 mm	average 0.5 mm	average 0.15 mm	0.065 mm
Internal Design Type	Spheres	Spheres	Spheres	Spheres	Spheres
Spheres Diameter	0.6 mm	0.5 mm	0.64 mm	0.5 mm	0.5 mm
Internal Design Construction	^{125}I absorbed by ion exchange into 3–5 resin spheres	^{125}I absorbed by ion exchange onto 5 silver microspheres	^{125}I is absorbed onto 5 silver microspheres with a silver iodide diffusion barrier.	^{125}I absorbed into 4 resin spheres. Two gold-copper spheres are in the middle of resin spheres.	^{125}I absorbed into 2 glass spears doped with silver
Radiographic Marker	none	5 silver microspheres	5 silver microspheres	2 gold-copper spheres	Pt/10% Ir Marker
Minimum source strength	5.0 mCi	0.28 mCi	0.1 mCi	0.213 mCi	0.08 mCi
Maximum source strength	40 mCi	0.97 mCi	1.0 mCi	0.483 mCi	40 mCi
Figure	1h	1i	1j	1k	1l

calculations ignore less than about 10 keV photons.[20] The 6702 source has no high Z material in the source to attenuate the photon fluence or significantly alter the photon spectrum.

InterSource[125] source has a radial dose function that is 2.9% higher at 1.5 cm and 37% higher at 6 cm than the 6711 source. The source is hollow in the middle making the organic matrix which the I-125 is coated onto wrap around the inside tube of the hollow source at each end of the source and around a Platinum–Iridium marker located in the middle of the source. The source has a photon spectrum from the I-125 decay scheme. The inside tube, I-125 bands, and Platinum–Iridium marker is encapsulated by an outside tube welded at each end. The Platinum–Iridium marker is used for source visualization.[17] The characteristic x rays generated from the Platinum–Iridium marker inside the source are $L_{Iab}=13.87$ keV, $L_{IIab}=13.27$ keV, $L_{IIIab}=11.56$ keV, $L_{\gamma 1}=112.94$ keV, and $L_{\beta 2}=11.58$ keV from the Platinum and $L_{Iab}=13.41$ keV, $L_{IIab}=12.82$ keV, $L_{IIIab}=11.21$ keV, $L_{\gamma 1}=12.51$ keV, and $L_{\beta 2}=10.92$ keV from the Iridium. Detectable characteristic x rays generated due to the platinum and iridium have energies generally less than 12 keV. In phantom, these spectral components have no clinical significance and in air kerma determinations may be removed by judicious filtration.[19] The Monte Carlo program used for the calculations of the InterSource125 source ignored energies less than about 4.5 keV photons.[17]

IsoSTAR, Model 2301, PharmaSeed, have radial dose functions that substantially match the 6711 source. Radial dose functions of these sources average 2.5% lower at 1.5 cm and 2.5% lower at 5 cm. The ProstaSeed source is 5.7% lower at 1.5 cm and 10% lower at 5 cm. The commonality between these sources is the material used for the construction of the internal core of the source is of a high atomic number and that all of the I-125 is adsorbed onto the surface of the core. The 6711, IsoSTAR, ProstaSeed have a silver internal core, PharmaSeed has a palladium internal core and Model 2301 has a tungsten internal core.[2,4,5,8,9] The characteristic x rays generated from the silver of the 6711, IsoSTAR, and the ProstaSeed sources is $K_{ab}=25.517$ keV, $K_{\beta 2}=25.45$ keV, $K_{\beta 1}=24.942$ keV, $K_{\alpha 1}=22.16$ keV, $K_{\alpha 2}=21.98$ keV. The characteristic x rays generated from the palladium of the PharmaSeed source is $K_{ab}=24.35$ keV, $K_{\beta 2}=24.3$ keV, $K_{\beta 1}=23.82$ keV, $K_{\alpha 1}=21.17$ keV, $K_{\alpha 2}=21.02$ keV. The characteristic x-ray spectral components can be considered identical among sources having silver (6711, IsoSTAR, ProstaSeed) or palladium (PharmaSeed) cores. For these sources, the net spectrum contains the characteristic x rays and those of the I-125 decay scheme. The Model 2301 has a tungsten characteristic x-ray spectrum of $L_{Iab}=12.09$ keV, $L_{IIab}=11.53$ keV, $L_{IIIab}=10.19$ keV, $L_{\gamma 1}=11.28$ keV, and $L_{\beta 2}=9.59$ keV. The Model 2301 characteristic x rays have no significant effect on the photon spectrum and the source emits an essentially pure I-125 decay scheme spectrum. Thus, in sources having high-Z internal components, the photon spectrum may be significantly softened thereby reducing both the photon fluence and the penetration. For a unit contained activity, this affects the values of the air kerma strength (and therefore) the dose-rate constant, and radial dose function.

In accord with the practice in the TG-43 report, the radial dose functions for each source design have been fit to a fifth order polynomial either by the manufacturer or one of sev-

TABLE III. Rod, wire, or cylinder source design dosimetric characteristics.

Marketing Company	Nycomed–Amersham	UroMed	Syncor	Source Tech BARD	Med-Tech	International Brachytherapy	Best Medical
Source Name	6711	I25.S06	BT-125-I	STM1250	Model 3500	1251L	Model 2301
Model Name	OncoSeed	Symmetra	PharmaSeed	^{125}Implant	I-Plant	Intersource^{125}	Model 2301
1999 Dose Rate Constant Λ_{1999} (cGy/hr/U)	0.98 (MC)[a]	1.04 (TLD)[b]	0.95 (MC)	0.980 (MC)	1.01 (TLD)		1.01 (TLD)
2000 Dose Rate Constant Λ_{2000} (cGy/hr/U)						1.02 (MC)	1.05 (TLD)
Anisotropy $\phi_{an}(r)$	0.93 (TLD)	0.939 (MC)	0.975 (MC)	0.942 (MC)	0.95 (TLD)	0.95 (MC)	0.982 (TLD)
Conversion U/mCi	1.27	1.27	1.27	1.27	1.27	1.27	1.27
Distance (cm)	Radial Dose Function $g(r)$ (TLD)	Radial Dose Function $g(r)$ (MC)	Radial Dose Function $g(r)$ (MC)	Radial Dose Function $g(r)$ (MC)	Radial Dose Function $g(r)$ (TLD)	Radial Dose Function $g(r)$ (MC)	Radial Dose Function $g(r)$ (TLD)
0.1		1.001	1.061				
0.2		1.0194	1.08	1.003			
0.3		1.0263	1.095	1.024		0.938	
0.4			1.084			0.980	
0.5	1.040	1.0289	1.073	1.033	1.029	1.000	1.048
0.6			1.058				
0.7			1.055				
0.75		1.0203		1.022			
0.8			1.035				
0.9			1.018				
1.0	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.5	0.926	0.9397	0.921	0.937	0.936	0.953	0.899
2.0	0.832	0.8593	0.814	0.856	0.856	0.891	0.824
2.5	0.731	0.7796		0.772	0.771	0.813	
3.0	0.632	0.6988	0.639	0.691	0.687	0.738	0.683
3.5	0.541	0.6218		0.612	0.608	0.662	
4.0	0.463	0.5481	0.483	0.54	0.535	0.591	0.522
4.5	0.397	0.4819		0.475		0.525	
5.0	0.344	0.4203	0.374	0.415	0.410	0.469	0.358
5.5	0.300					0.415	
6.0	0.264	0.3228	0.285	0.314	0.312	0.362	0.287
6.5	0.233					0.315	
7.0	0.204	0.2394	0.207	0.236	0.236	0.273	0.208
8.0		0.1816	0.152	0.176			0.159
9.0		0.1330	0.115	0.131			0.115
10.0		0.0995	0.09	0.097			0.083
11.0		0.0723		0.07			
12.0				0.051			
13.0				0.038			
14.0				0.026			
Fifth Order Polynomial							
A_0	1.0137	1.0152	1.0876	0.98279	1.00869	0.87843	1.1037
A_1	0.12274	0.076721	0.0026197	0.11792	0.109038	0.331992	−0.090085
A_2	−0.17302	−0.11646	−0.11222	−0.20996	−0.15269	−0.271909	−0.03332
A_3	0.040237	0.023837	0.027744	0.05749	0.037667	0.069762	0.0057713
A_4	−0.0038522	−0.00201	−0.0027189	−0.00713	−0.00413	−0.00825	−0.00025599
A_5	0.00013428	0.0000621	0.0000965	0.000338	0.000175	0.000373	
Range (cm)	7	11	10	7	7	7	10

[a]MC=Monte Carlo Simulations.
[b]TLD=Thermo Luminescent Dosimetry.

eral treatment planning system vendors. Tables III and IV show the radial dose function values and the fifth order polynomial for each source design. Figures 2 and 3 show a graphical comparison of the radial dose functions.

B. Anisotropy function, $(F(r,\theta))$

The anisotropy function, $F(r,\theta)$, for each source was calculated according to the recommendations of the TG-43 report. Each manufacturer reported their two-dimensional anisotropy functions, $F(r,\theta)$, at various radial distances ranging from 0.25 to 7 cm.

The Symmetra, ^{125}Implant, I-Plant, and BrachySeed have anisotropy values within ±10% of the 6711 source between 30 and 90 of the transverse axis.[12–16] The range of anisotropy values is between 0.414 and 0.734 at the longitudinal end of the source for the sources with a ceramic internal core. The

TABLE IV. Sphere source design dosimetric characteristics.

Marketing Company	Nycomed–Amersham	Mentor	Imagyn Medical Technologies	UroCor Mallinckrodt PSA	Draxis (canada) Cytogen (USA)
Source Name	6702	MED3631-A/M	12501	I125-SL	LS-1
Source Model	6702	IoGold	IsoSTAR	ProstaSeed	BrachySeed
1999 Dose Rate Constant Λ_{1999} (cGy/hr/U)	1.04 (MC)[a]	1.06 (TLD)[b]	0.94 (TLD/MC)	0.95 (TLD)	
2000 Dose Rate Constant Λ_{2000} (cGy/hr/U)					1.01 (MC)
Anisotropy $\phi_{an}(r)$	0.95 (TLD)	0.95 (TLD)	0.889 (MC)	0.94 (TLD)	0.975 (Film/MC)
Conversion U/mCi	1.27	1.27	1.27	1.27	1.27
Distance (cm)	Radial Dose Function $g(r)$ (TLD)	Radial Dose Function $g(r)$ (TLD)	Radial Dose Function $g(r)$ (MC)	Radial Dose Function $g(r)$ (TLD)	Radial Dose Function $g(r)$ (Film/MC)
0.1			1.022		
0.15			1.058		
0.2			1.084		
0.25			1.093		
0.3			1.093	1.180	
0.4			1.088		
0.5	1.04	1.069	1.08	1.129	0.990
0.75		1.037		1.065	
0.8			1.04		
1.0	1.000	1.000	1.000	1.000	1.000
1.5	0.934	0.915	0.907	0.873	0.935
2.0	0.851	0.825	0.808	0.754	0.867
2.5	0.76	0.735	0.715	0.647	0.782
3.0	0.67	0.651	0.618	0.552	0.700
3.5	0.587	0.575	0.533	0.471	0.623
4.0	0.511	0.509	0.463	0.405	0.553
4.5	0.445	0.453	0.404	0.351	0.490
5.0	0.389	0.406	0.348	0.308	0.432
5.5	0.431		0.296	0.274	0.379
6.0	0.301	0.331	0.253	0.247	0.330
6.5	0.266		0.226	0.225	0.286
7.0	0.235	0.265	0.193	0.205	0.247
7.5			0.172	0.186	0.214
8.0			0.149	0.168	0.185
8.5			0.122	0.150	0.161
9.0			0.099	0.133	0.139
9.5			0.088		0.119
10.0			0.0746		0.095
			Fifth Order Polynomial		
A_0	1.0231	1.1096	1.0672	1.2537	0.9698912
A_1	0.086375	−0.043833	0.0600571	−0.23884	0.117581
A_2	−0.13715	−0.086391	−0.15308	−0.02701	−0.1281618
A_3	0.0307795	0.022749	0.037692	0.013639	0.0260055
A_4	−0.0028694	−0.0022649	−0.003725	−0.001531	−0.0022491
A_5	0.000098755	0.000079185	0.0001328	0.0000562	0.0000726
Range (cm)	7	7	7	9	7

[a]MC=Monte Carlo Simulations.
[b]TLD=Thermo Luminescent Dosimetry.

BrachySeed has the most isotropic of the ceramic internal core sources.[16] The source's only weld is in the middle of the source eliminating the photon fluence attenuation problem inherent in end weld sources. The ^{125}Implant source has the most pronounced anisotropy characteristics of all the I-125 sources.[14] The anisotropy value at the longitudinal axis is 0.414, increases to 0.64 at 2 degrees then decreases to 0.551 at 7 degrees and then increases uniformly to 90 degrees. The source is within ±10% of the 6711 source between 10 and 90 degrees.

The 6702, IoGold, and InterSource^{125} sources have an anisotropy value within ±10% of the 6711 source from 30 to 90 degrees.[2,10,17] The significant variation between the two resin sources occurs at the longitudinal end of the source. The 6702 source has an anisotropy value of 0.528 where the IoGold source has a value of 0.722. The InterSource125

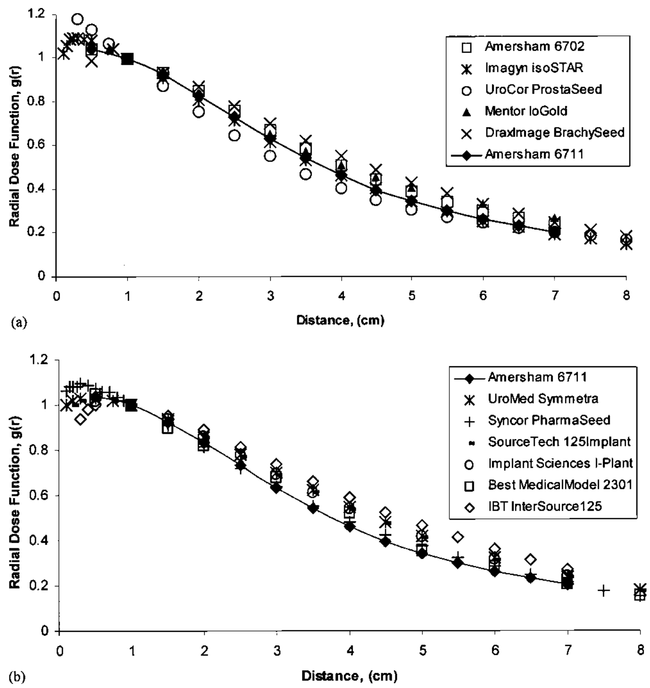

FIG. 2. Radial Dose Function $g(r)$; (a) Radial Dose Functions for the sources with an internal core of spheres, (b) Radial Dose Functions for the sources with an internal core of Rods, Wires and Cylinders.

source has an anisotropy value between that of the IoGold and 6702 source with a value of 0.656. This is a result of the InterSource125 source having a hollow core thus reducing the end thickness difference resulting in attenuation of the photon fluence through the end cap out to about 30 degrees.

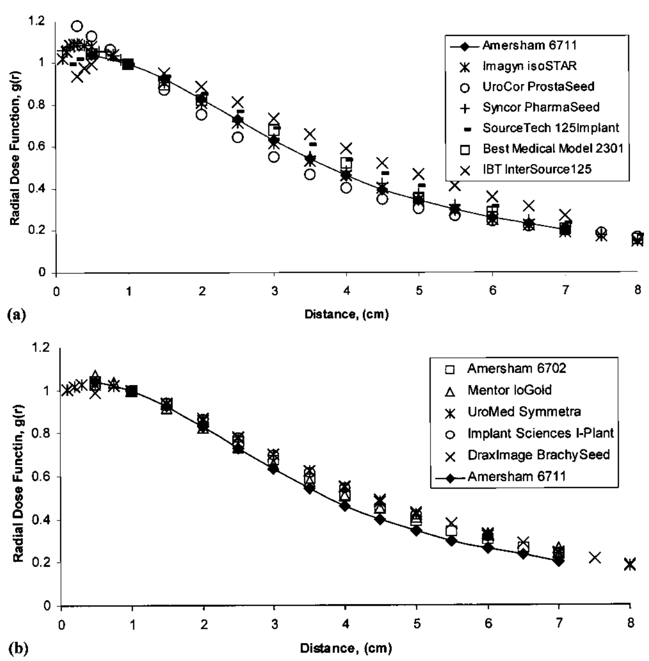

FIG. 3. Radial Dose Function $g(r)$; (a) Radial Dose Functions for the sources with the radioactivity adsorbed onto the internal core of the source, (b) Radial Dose Functions for the sources with the radioactivity absorbed onto the internal core of the source.

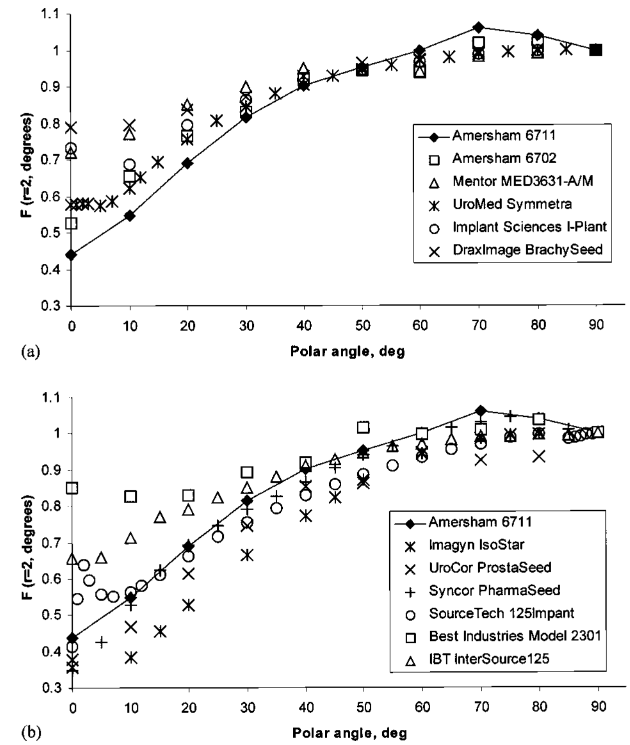

FIG. 4. Anisotropy Function $F(r,\theta)$; (a) Anisotropy Functions for the sources with the radioactivity absorbed onto the internal core of the source for a radius of 2 cm, (b) Anisotropy Functions for the sources with the radioactivity adsorbed onto the internal core of the source for a radius of 2 cm.

The 6702 source has an end thickness of 0.5 mm and the IoGold source has an end thickness of 0.15 mm. There exists a similarity between the IoGold and the 6702 sources anisotropy values at 50 and 60 degrees, where for both sources, the values of $F(r,\theta)$. Both values decrease and then increase.

The PharmaSeed source mimics the 6711 source from 10 to 90 degrees.[4] The ProstaSeed source parallels the 6711 source within $\pm 15\%$ from the longitudinal axis to 90 degrees.[8] With an end thickness of 0.5 mm and silver sphere diameters of 0.64 mm the IsoSTAR is the most anisotropic source.[5] This is a result of oblique filtration from the large surface area of the spheres and through the end welds. Model 2301 is the most isotropic of all the I-125 sources currently available.[9] The source is a double encapsulated source with a total wall thickness of 0.14 mm. The anisotropy is assumed to be symmetrical about both ends of the source even with two different end designs. It has an anisotropy value of 0.85 along the longitudinal axis and increases to 1 at 90 degrees.

The significant differences found in the anisotropy functions among the sources may be the result of the differences in the internal core substrate material, end cap thickness', source geometry, and the internal distribution of the activity. Figure 4 shows the anisotropy functions plotted for a radius of 2 cm.

C. Average anisotropy factor, $(\phi_{an}(r))$ and anisotropy constant (ϕ_{an})

For each source design, the average anisotropy factor, $\phi_{an}(r)$ has been calculated from the anisotropy functions,

TABLE V. Rod–wire source design dose rate values for an $S_k = 1.0$ U.

Source Name	6711	Symmetra	PharmaSeed	[125]Implant	I-Plant	InterSource[125]	Model 2301
Distance (cm)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)
0.5	0.948	1.005	0.994	0.951	0.980	0.969	1.081
1	0.911	0.977	0.926	0.923	0.960	0.969	1.031
1.5	0.844	0.918	0.843	0.865	0.902	0.923	0.927
2	0.758	0.839	0.754	0.790	0.828	0.863	0.850
2.5	0.666	0.761	0.668	0.713	0.747	0.788	
3	0.576	0.682	0.592	0.638	0.667	0.715	0.704
3.5	0.493	0.607	0.513	0.565	0.591	0.641	
4	0.422	0.535	0.447	0.499	0.520	0.573	0.538
4.5	0.362	0.471	0.394	0.439		0.509	
5	0.314	0.410	0.346	0.383	0.400	0.459	0.369
5.5	0.273		0.299			0.402	
6	0.241	0.315	0.264	0.290	0.304	0.351	0.296
6.5	0.212		0.231			0.305	
7	0.186	0.234	0.192	0.218	0.231	0.265	0.214

$F(r,\theta)$. The values recommended by the manufacturers for the anisotropy constant was determined from TLD measurements, GAFchromic™ film measurements and Monte Carlo calculations. Anisotropy values ranged from 0.889 to 0.982. Tables III and IV summarize the anisotropy factors for each source.[2–5,8–17]

D. Dose rate constant, Λ

The dose rate constant, Λ, was measured in solid phantoms with factors to convert the data to liquid water and or was calculated in liquid water using Monte Carlo simulation methods. The dose rate constants presented here are in terms of the 1999 and 2000 NIST calibration standards.[21,22]

The reported values for the dose rate constants ranged from 0.94 to 1.06 cGy/hr/U. Tables III and IV show the dose rate constants for each source design and as provided by each manufacturer.

E. Dose rate comparison

To illustrate the difference in the sources, a point dose calculation was been performed with source strength of 1 U along the transverse axis of the source to determine the appropriate source strength for each source. At 1 cm the sources dose rates ranged from 0.836 to 1.031 cGy/hr/U (8.31% lower than the 6711 source and 13.1% higher than the 6711 source).

The Symmetra, [125]Implant, and BrachySeed sources have dose rates that are between 5%–8% higher than the 6711 source at 1 cm and 27%–36% higher at 5 cm. The I-Plant sources which has the same internal core substrate as the Symmetra, [125]Implant, and BrachySeed has a dose rate 1.3% higher at 1 cm, 22% at 5 cm and 17% at 7 cm.

IoGold and 6702 have dose rates that are within 2% of each other between 1 and 4 cm while being about 9% higher than the 6711 source at 1 cm. The IoGold increases 20% over the 6702 and 40% over the 6711 source at 7 cm.

The InterSource[125] source has a dose rate that is 6.3% higher than the 6711 source at 1 cm. The InterSource[125] increases to 15% over the IoGold source and both sources increase to 40% over the 6711 source at 7 cm.

IsoSTAR, PharmaSeed, and Model 2301 sources have dose rates that parallel the 6711 source. The IsoSTAR source has an average dose rate of 9.5% lower, Model 2301 source 17.21% higher, and PharmaSeed source 4.23% higher than the 6711 source. The ProstaSeed source has a dose rate that decreases more quickly than the 6711 out to 4 cm and then equals the 6711 source at 7 cm. Tables V and VI show dose rate values between 0.5 and 7 cm. Figure 5 shows the graphical representation of the dose rate along the transverse axis.

F. Adsorbed vs absorbed radioactivity distribution within source

The manner in which the radioactivity is distributed inside the internal core of the source has a significant effect on the

TABLE VI. Sphere source design dose rate values for an $S_k = 1.0$ U.

Source Name	IoGold	IsoSTAR	ProstaSeed	BrachySeed
Distance (cm)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)	Dose Rate (cGy/hr)
0.5	1.076	0.903	1.008	0.975
1	1.007	0.836	0.893	0.985
1.5	0.921	0.758	0.780	0.921
2	0.831	0.675	0.674	0.854
2.5	0.740	0.597	0.577	0.770
3	0.656	0.516	0.493	0.689
3.5	0.579	0.445	0.421	0.613
4	0.513	0.387	0.361	0.545
4.5	0.456	0.338	0.313	0.483
5	0.409	0.291	0.275	0.425
5.5		0.247	0.245	0.373
6	0.333	0.211	0.221	0.325
6.5		0.189	0.201	0.282
7	0.267	0.161	0.183	0.243

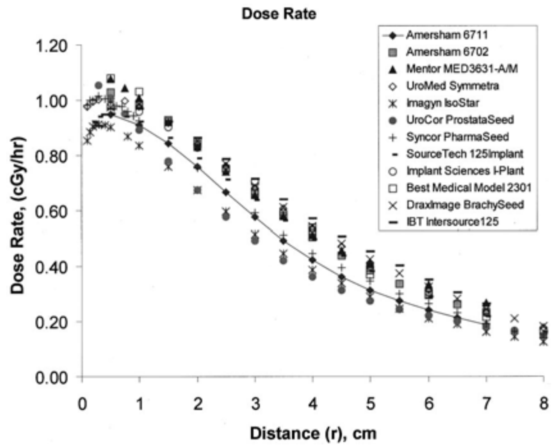

FIG. 5. Dose Rate Values for source strength of 1 *U*.

dose distribution around the source as well as the maximum source strength achievable by a source design. The 6711, PharmaSeed, ProstaSeed, IsoSTAR, ^{125}Implant, Model 2301, and InterSource^{125} sources each are designed with the radioactivity adsorbed onto the surface of an internal element or elements of the source.[2,4,5,8,9,14,15] The 6702, Symmetra, IoGold, I-Plant, and BrachySeed sources each are designed with the radioactivity absorbed throughout the internal element or elements of the source.[2,3,10–13,15,16]

There are significant spectral differences between the two types of radioactivity distributions. The energies of primary photons from ^{125}I sources are 27.4, 31.0 and 35.5 keV.[2,7,19,23] With the radioactivity adsorbed onto the internal core of the source, the average energy of the energy of the x-ray spectrum is decreased as a result of characteristic x rays generated from interactions as well as the attenuation of the photon fluence from and through the internal core of the source. The 6711, ProstaSeed, and IsoSTAR sources, each having silver in the internal core of the source, have fluorescent x rays resulting from the interaction of ^{125}I x rays with the silver that reduce the average energy of the unit source from 28.4 to 27.4 keV.[24] With the characteristics of palladium being very similar to silver, the average energy of the PharmaSeed source is also reduced from 28.4 to 27.4 keV. The Model 2301 source is different than the other adsorbed sources in that there are no characteristic x-rays produced in the I-125 range that significantly contribute to the energy spectrum. The characteristic x rays that are generated are in the L-series and are absorbed by the titanium capsule making the average energy of the source 28.4 keV and dosimetrically more like source designs having I-125 absorbed in low *Z* and low-density internal elements.

The 6702, and IoGold, Symmetra, I-Plant, and BrachySeed sources have the radioactivity absorbed throughout a low-density and low *Z* composite material (resin, ceramic, glass). The resulting energy spectrum is essentially due to the I-125 decay scheme, with an average energy of 28.4 keV. These sources are thus more penetrating than the adsorbed types above. The I-Plant radioactivity arises from neutron activation of xenon implanted into the glass surface using a dry process. The remaining sources are manufactured using radioactive materials directly, in a ''wet'' chemical process involving solutions of 125-I. The sources with low density, low *Z* materials emit photons with an average energy of about 28.4 keV, making them more penetrating than sources of the adsorbed type designs.

The significance in the differences between the adsorbed and absorbed sources is apparent on inspection of the dose rate constants and the anisotropy values. The average dose rate for the adsorbed source designs is 0.927 cGy/hr at 1 cm, about 6% lower than the value, 0.983 cGy/hr, for the absorbed source designs. The differences in dose and in the anisotropy values at the end of the source may be a result of the radioactivity distribution within the source, end thickness', as well as the internal design source material. These same factors affect the geometry function specific to each source design.[25]

G. How to determine the appropriate source strength for a source

The source strength required to deliver a prescribed dose to a point or volume is dependent on the physical and dosimetric characteristics of the source. Numerous authors have described how to use the dose from a single source and from multiple sources have been used to compare implants.[26,27] The difference in the doses for the single and multiple source calculations was used to determine the source strengths needed to deliver the prescribed dose. The distance from the source(s) is a very important factor when comparing sources with different radial dose functions as shown in Fig. 5.

In this investigation the one-dimensional TG-43 equation [Eq. (1)] was used to compare the dose rates for each source. Tables V and VI show the results of the dose rate for each source, using the 6711 model as the reference source. In evaluating the means to determine an appropriate source strength for a given source design, the dose rate was calculated for several radial distances ranging from 0.3 and 1.5 cm.

It was found that calculating the dose rate at 1 cm provided the best approximation to determine the source strength for each source design. Equation (2) was derived from Equation (1) with the respect to the dose rate at 1 cm of the Nycomed-Amersham 6711 source.

To verify the hypothesis, retrospective patients with ^{125}I CT post implant films were used to investigate the calculated source strengths and the differences with respect to the Nycomed-Amersham 6711 source. The prostate volumes, source locations, and calculation matrices were not modified between plans. Implant descriptors identified by the ABS (American Brachytherapy Society) were used to compare the plans.[28] The following quantifiers recommended by the ABS were used to compare the CT post-plans for each source: (1) D_{100}, D_{90}, D_{80}; the dose that covers 100%, 90%, and 80% of the prostate respectively, (2) V_{200}, V_{150}, V_{100}, V_{90}, V_{80}; the fractional volume of the prostate that receives 200%, 150%, 100%, 90%, and 80% of the prescribed dose, respectively. These Dosimetric and Volumetric quantifiers were determined from the calculated cumulative dose volume histo-

TABLE VII. Recommended source strengths normalized to the Nycomed–Amersham 6711 source. Note: Data referenced to 0.32 mCi for Amersham 6711 source.

	Calculated Source Strength (U)	Calculated Activity (mCi)
Rod–Wire Source Design		
6711 (OncoSeed)	0.406	0.320
Symmetra	0.377	0.297
PharmaSeed	0.400	0.315
^{125}Implant	0.401	0.316
I-Plant	0.385	0.303
InterSource^{125}	0.382	0.301
Model 2301	0.358	0.282
Sphere Source Design		
IoGold	0.363	0.286
ProstaSeed	0.415	0.327
IsoSTAR	0.443	0.349
BrachySeed	0.375	0.296

Note: Data referenced to 0.32 mCi for Amersham 6711 source.

gram generated for each plan for each source.

The post implant films showed that the calculated source strengths from Equation (2) generated a maximum standard deviation of 2.872 cc for the V_{150} and a minimum standard deviation of 0.822 cc for the V_{150} volumetric quantifiers. A maximum standard deviation of 519.33 cGy for the D_{90} and a minimum standard deviation of 272.6 cGy for the D_{90} dosimetric quantifier were calculated. The V_{150} and D_{90} quantifiers were mentioned because they are ones that authors have recognized to relate to patient outcome. Table VII shows the appropriate source strength for each source.

IV. CONCLUSION

This report investigates the physical and dosimetric characteristics of several of the ^{125}I sources available for use in interstitial brachytherapy implants. The investigation showed that there are physical design and dosimetric differences among the sources.

The internal core of the sources is based on the physical design, the internal composition, and the distribution of the radioactivity with in the internal core of the source. The two physical design types are of (a) rod–cylinder–wire design, and (b) sphere design. Depending upon the source model, the composition of the internal core may consist of (a) Resin, (b) Ceramic, or High *Z* materials. The radioactivity is distributed throughout the internal core of the source by way of being either adsorbed or absorbed.

The dosimetric properties are quite different for the different sources. Dose rates ranged from −8.3% to +13.1% between sources with reference to the 6711 source at 1 cm. The differences in the dosimetric characteristics between the sources also a result of the method by which the source characteristics are measured. The Monte Carlo simulation programs provides more measurement points allowing for a more detailed representation of the anisotropy factors and radial dose functions. The accuracy of such results depends largely on the sophistication of the model used to represent the source under simulation. Direct measurement, using film, TLD, or ionization chambers, is often limited in spatial resolution and by dosimetric correction factors specific to each type of physical dosimeter. This is one reason that the AAPM specifies multiple evaluations of new sources' dosimetry in phantom, including Monte Carlo simulation.[1]

The results of this report indicate that clinically significant differences can be reduced to the dose rate at a single point (1 cm from the source). Hence, the effective source strength of the new sources can be calculated using Eq. (2). The one-dimensional dose calculation formalism of TG-43 underlies our results, although we may expect the results to remain unchanged when employing the TG-43 two-dimensional calculation model.

Finally and not investigated in this report but of clinical utility are source visibility and signature in radiographs. The imaging properties of each source should be investigated by the medical physicist and physician under fluoroscopy, on planar radiographs, and on CT studies. In this way, local variations in imaging technique are assessed with respect to brachytherapy source visibility in radiographic images. The medical physicist should discuss the differences in the source characteristics (physical, dosimetric, and radiographic) with the physician before using the source clinically.

V. DISCLAIMER

At the time of publication some of the sources have not been clinically tested, and thus the data presented in this investigative article might change. It is the responsibility of the medical physicist to contact the source manufacturer for complete specifications and dosimetric characteristics before clinically implementing source data into a treatment planning system.

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Syncor Corporation—www.syncor.com
SourceTech Medical Corporation—www.stmseed.com
BARD—www.BARD.com
UroMed Corporation—www.uromed.com
UroCor Corporation—www.urocor.com
Prostate Services of America (PSA)—www.prostateservices.com
Imagyn Medical Technologies Inc.—www.imagyn.com
Implant Sciences—www.implantsciences.com
Med-Tec Corporation—www.brachyseeds.com
Best Medical International—www.best—medical.com
Draxis (DraxImage)—www.draxis.com
Cytogen—www.cytogen.com
International Brachytherapy, Inc. (IBT)—www.ibt4seeds.com

APPENDIX

Equation (1): One-dimensional TG-43 Point Dose Calculation Formalism.

$$\dot{D}(r)=S_k\times\Lambda\left(\frac{1}{r^2}\right)\times g(r)\times\overline{\phi}_{\mathrm{an}},$$

$$S_k=\text{Source Strength (U)}$$

$$\Lambda=\text{dose rate Constant(cGy/hr}\times\text{U)},$$

$$\left(\frac{1}{r^2}\right)=\text{Inverse Square Law},$$

$$g(r)=\text{Radial Dose Function},$$

$$\overline{\phi}_{\mathrm{an}}=\text{Anisotropy Factor}$$

Equation (2): Source Strength calculation equation.

$$(S_k)_{\mathrm{unknown}}=\left[\frac{\Lambda_{6711}\times(\overline{\phi}_{\mathrm{an}})_{6711}}{\Lambda_{\mathrm{unknown}}\times(\overline{\phi}_{\mathrm{an}})_{\mathrm{unknown}}}\right]\times(S_k)_{6711}.$$

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