

# Recommendations of the American Association of Physicists in Medicine on $^{103}\text{Pd}$ interstitial source calibration and dosimetry: Implications for dose specification and prescription

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The National Institute of Standards and Technology (NIST) introduced a national standard for air kerma strength of the TheraSeed<sup>®</sup> Model 200  $^{103}\text{Pd}$  source (the only  $^{103}\text{Pd}$  seed available until 1999) in early 1999. Correct implementation of the NIST-99 standard requires the use of dose rate constants normalized to this same standard. Prior to the availability of this standard, the vendor's calibration procedure consisted of intercomparing Model 200 seeds with a  $^{109}\text{Cd}$  source with a NIST-traceable activity calibration. The AAPM undertook a comprehensive review of  $^{103}\text{Pd}$  source dosimetry including (i) comparison of the vendor and NIST-99 calibration standards; (ii) comparison of original Task Group 43 dosimetry parameters with more recent studies; (iii) evaluation of the vendor's calibration history; and (iv) evaluation of administered-to-prescribed dose ratios from the introduction of  $^{103}\text{Pd}$  sources in 1987 to the present. This review indicates that for a prescribed dose of 115 Gy, the administered doses were (a) 124 Gy for the period 1988–1997 and (b) 135 Gy for the period 1997–1999. The AAPM recommends that the following three steps should be undertaken concurrently to implement correctly the 1999 dosimetry data and NIST-99 standard for  $^{103}\text{Pd}$  source: (1) the vendor should provide calibrations in terms of air kerma strength traceable to NIST-99 standard, (2) the medical physicist should update the treatment planning system with properly normalized (to NIST-99) dosimetry parameters for the selected  $^{103}\text{Pd}$  source model, and (3) the radiation oncologist in collaboration with the medical physicist should decide which clinical experience they wish to duplicate; the one prior to 1997 or the one from 1997 to 1999. If the intent is to duplicate the experience prior to 1997, which is backed by the long-term follow-up and published outcome studies, then the prior prescriptions of 115 Gy should be replaced by 124 Gy to duplicate that experience. © 2000 American Association of Physicists in Medicine.

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## I. INTRODUCTION

Brachytherapy sources containing  $^{103}\text{Pd}$  are widely used for permanent implants of the prostate and other anatomic sites. Due to evolution of new source strength standards and improvements in dosimetry of low-energy brachytherapy sources, current dose estimates around  $^{103}\text{Pd}$  brachytherapy sources may differ by as much as 17% from doses as evaluated by standard dosimetry protocols. This has resulted in time-dependent discrepancies between prescribed and ad-

ministered doses conceptually similar to  $^{125}\text{I}$  brachytherapy.<sup>1</sup> The purpose of this communication is to review these  $^{103}\text{Pd}$  source dosimetry developments and to present correction factors defining the relationship between prescribed and administered dose and dose as a function of time period within the history of  $^{103}\text{Pd}$  brachytherapy. The term “administered dose” is understood to denote the dose calculated using 1999-era dosimetry parameters and source-strength standards. The goal is to assist radiation oncologists in selecting

the prescribed dose that best realizes their clinical intent. This document represents the guidance of the American Association of Physicists in Medicine (AAPM) on this issue and was prepared by AAPM's Low Energy Interstitial Brachytherapy Dosimetry Subcommittee (Chair, J. Williamson) and approved by its Radiation Therapy Committee and Science Council.

The first  $^{103}\text{Pd}$  interstitial brachytherapy source was the Model 200 (TheraSeed®) source, introduced by Theragenics Corporation in 1987, which remained the sole  $^{103}\text{Pd}$  source on the market until 1999. Since no primary standard for air-kerma strength ( $S_K$ ) was available until 1999, apparent activity ( $A_{\text{app}}$ ), as measured by an in-house assay method developed and maintained by the vendor, was used to specify Model 200 source strength. Using a NaI (Tl) photon spectrometer,  $A_{\text{app}}$  was measured by intercomparing the transverse-axis photon fluence rate of Model 200 seeds with that of a  $^{109}\text{Cd}$  source standard bearing an activity calibration traceable to the National Institute of Standards and Technology (NIST) primary activity standard. Given this operational definition, no *a priori* relationship between  $A_{\text{app}}$  and more fundamental quantities such as activity, air kerma, or air-kerma strength ( $S_K$ ) can be assumed. Only recently was  $S_K$  per unit  $A_{\text{app}}$  rigorously measured.

Most clinics have used the dose distribution recommended by Task Group 43 (TG 43)<sup>2</sup> for dosimetric treatment planning and evaluation of Model 200  $^{103}\text{Pd}$  seed implants. The TG-43 dose-rate constants, radial dose functions, anisotropy functions, and anisotropy factors were derived from the TLD dose-rate measurements about the Model 200 source reported by Meigooni<sup>3</sup> and Chiu-Tsao.<sup>4</sup> To estimate the dose-rate constant, dose-rate measurements at 1 cm were normalized to nominal  $S_K$  inferred from the  $A_{\text{app}}$  value provided by the vendor at that time (1988 and 1989). Although this approach does not utilize a well-defined physical quantity for source strength specification, it is a consistent system. As long as Theragenics'  $A_{\text{app}}$  calibration assays are reproducible from batch-to-batch and remain constant over time, the accuracy of computed  $^{103}\text{Pd}$  dose distributions is limited only by the accuracy of the dose-rate measurements underlying the TG-43 recommendations.

Several developments have raised questions regarding the accuracy and constancy of the current  $^{103}\text{Pd}$  dose-calculation system described above. These include the following

- (1) The development of an air-kerma strength primary standard at NIST applicable to Model 200 seeds as well as other low-energy photon-emitting interstitial brachytherapy sources. This standard is based upon the wide angle free-air chamber (WAFAC) developed by Loevinger.<sup>5-7</sup> The nominal  $S_K$  derived from the vendor's  $A_{\text{app}}$  calibration differs from WAFAC measurements by  $-24\%$ .<sup>8</sup>
- (2) Reports from several Model 200 users that the activity values,  $A_{\text{app}}$ , supplied by Theragenics abruptly shifted by approximately  $-10\%$  in the fall of 1997. At this time, Theragenics informed their users that indeed such a change had occurred and attributed it to adopting a new

$^{109}\text{Cd}$  calibration standard.<sup>9</sup> After further evaluation of their calibration constancy data, Theragenics stated that, relative to the 1988–1990 standard,  $A_{\text{app}}$  values were essentially constant until 21 September 1997, at which time the reported source strengths were reduced by  $8\%$ .<sup>10</sup>

- (3) The availability of several new  $^{103}\text{Pd}$  interstitial products with calibrations traceable to the NIST WAFAC standard along with dosimetry parameters<sup>11,12</sup> normalized to this standard. The availability of different  $^{103}\text{Pd}$  products based upon different and potentially incompatible dosimetry systems has created a situation where it is unclear which prescribed dose should be selected in order to reproduce previous clinical experience.
- (4) Recent experimental<sup>13</sup> and Monte Carlo<sup>14</sup> estimates of the Model 200 dose-rate constant are  $18\%$  smaller than the TG-43 value obtained by renormalization to the new NIST standard.

These developments indicate that there is a systematic discrepancy between prescribed dose and dose actually administered to  $^{103}\text{Pd}$  brachytherapy patients similar to that in  $^{125}\text{I}$  brachytherapy.<sup>1</sup> However, unlike the  $^{125}\text{I}$  case, this discrepancy is time dependent due to the 1997 shift in Theragenics' calibration standard. For the purpose of this report, "administered dose," denoted by  $D_{99D,N99S}^{\text{Rx}}$ , means calculated dose based upon Model 200 dose measurements and Monte Carlo simulations performed in 1999 ( $=99D$ ), and normalized to air-kerma strength calibrations,  $S_{K,N99}$ , which are traceable to NIST's 1999 standard ( $=N99S$ ).

The problem of relating prescribed to administered dose is common to all types of  $^{103}\text{Pd}$  interstitial sources regardless of manufacturer. Because the entire evaluated and published clinical experience of  $^{103}\text{Pd}$  brachytherapy is based upon patients treated with the Model 200 source, a detailed analysis of the Model 200 source dosimetry parameters and Theragenics' calibration practice is necessary to determine the relationship between prescribed and administered dose as a function of time. Only by reference to the clinical experience and prescribed-to-administered dose ratios associated with this product can radiation oncologists rationally select a prescribed dose for implants using  $^{103}\text{Pd}$  seeds manufactured by others.

## II. METHOD AND MATERIALS

### A. Manufacturer calibration techniques for the Model 200 source

Prior to the implementation of NIST's WAFAC standard in 1999, a primary  $S_K$  standard was not available for  $^{103}\text{Pd}$  or any other low-energy interstitial seed with the exceptions of the 3M (now Nycomed Amersham)  $^{125}\text{I}$  seeds, models 6701, 6702, and 6711.<sup>15</sup> Consequently, in the 1980s, Theragenics developed a method of measuring apparent activity using a NaI (Tl) scintillation detector. A  $^{103}\text{Pd}$  seed is calibrated through intercomparison to a source with a similar photon spectrum, which has a NIST-traceable contained activity calibration.  $^{103}\text{Pd}$  emits photons with energies of 20.1 keV

TABLE I. Relationship between Theragenics source strength assay, NIST traceable air-kerma strength, prescribed dose and delivered dose as a function <sup>109</sup>Cd calibration standard used, and time period for the Model 200 source. All numbers have three significant figures (generally, one more than is justified) to avoid round-off error in the final administered doses.

(1) Row No.	(2) Source strength standard	(3) Time period <i>nn</i>	(4) $S_K$ designator <i>nn</i>	(5) $\frac{S_{K,Tnn_{i-1}}}{S_{K,Tnn_i}}$	(6) $\frac{S_{K,Tnn}}{S_{K,N99}}$	(7) $\frac{D_{99D,N99S}^{Rx}}{D_{95D,TnnS}^{Px}}$
1	<sup>109</sup> Cd Standard no. 1	5/88–3/90	$S_{K,T88}$	N/A	0.833	1.079
2	<sup>109</sup> Cd Standard no. 2	4/90–11/93	$S_{K,T90}$	0.986	0.845	1.064
3	<sup>109</sup> Cd Standard no. 3	12/93–6/94	$S_{K,T93}$	1.033	0.818	1.099
4	<sup>109</sup> Cd Standard no. 4	7/94–9/15/97	$S_{K,T94}$	0.963	0.849	1.059
5	<sup>109</sup> Cd Standard no. 5 <sup>d</sup>	9/22/97–2000 (?)	$S_{K,T97}$	1.107	0.767	1.172
6	<sup>109</sup> Cd <sup>d</sup> Standard no. 6 or greater <sup>d</sup>	<sup>a</sup> 1st quarter 2000 (?)–20??	$S_{K,T97}$	1.107 ± 2%	0.767 ± 2%	1.172 ± 2%
	Standard	Time period	$S_K$ designator	$\left(\frac{S_{K,T97}}{S_{K,N99}}\right)$	...	$\frac{D_{99D,N99S}^{Rx}}{D_{95D,N99S}^{Px}}$
7	NIST WAFAC	<sup>b</sup> 1 Jan 1999– <sup>a</sup> 1st quarter 2000–	$S_{K,N99}$	0.767	...	0.899

<sup>a</sup>Proposed Theragenics implementation.

<sup>b</sup>NIST/AAPM ADCL implementation.

<sup>c</sup> $D_{Px}$  assumes  $A_{95D,T88S}$  used with  $S_{K,N99}$  calibration.

<sup>d</sup>Beginning Dec 1999, Theragenics will maintain  $A_{app}$  at fall 1997 levels independently of <sup>109</sup>Cd source standards used.

(64.7%) and 23.0 keV (12.3%) with a half-life of 16.99 days.<sup>16</sup> A suitable calibration standard is <sup>109</sup>Cd, which has photon energies of 22 keV (85.2%), 25 keV (16.81%), and 88 keV (3.61%), and a half-life 462.6 days.<sup>16</sup> The <sup>109</sup>Cd calibration standards are purchased with NIST-traceable activity calibrations with an assigned uncertainty of ±5%. These sources are calibrated in terms of activity by intercomparing their 88 keV photon emission rates with NIST's emission-rate standard. Theragenics uses <sup>109</sup>Cd low-to-high energy branching ratios to calibrate their spectrometer with respect to the low-energy photon emission rate. The spectrometer is then used to measure the 20–23 keV photon emission rate from Model 200 seeds representing each batch, which are in turn converted to apparent activity using tabulated photon yields per disintegration. The symbol " $A_{app,Tnn}$ " is used to denote the quantity measured by Theragenics' assay, where the " $T$ " of the subscript " $Tnn$ " denotes Theragenics and " $nn$ " denotes the year, e.g., 19 $nn$ , that the <sup>109</sup>Cd standard, to which the measurement is traceable, was implemented. As defined by Theragenics,  $A_{app,Tnn}$  is the activity of an unencapsulated point source that has the same photon emission rate as the given seed on its transverse axis. For each batch, the apparent activity calibration is transferred to a dose calibrator for assaying the remaining seeds in the batch. Note that  $A_{app,Tnn}$  is fundamentally different from apparent activity as defined by the AAPM,<sup>17</sup>  $A_{app,N99}$ , which is a quantity derived from NIST's 1999 standard,  $S_{K,N99}$ .

Theragenics replaces their <sup>109</sup>Cd sources approximately every three years (see Table I, column 3) in order to maintain

an appropriate strength standard for weekly verification of NaI (Tl) spectrometer sensitivity. Recently, Theragenics analyzed some of its weekly efficiency check data going back to 1988. For each calibration source, the last 6 NaI (Tl) efficiency measurements (count rate/<sup>109</sup>Cd activity) performed were compared to the first six efficiency measurements performed with its replacement.<sup>10</sup> By comparing the average efficiency measured before ( $nn_{i-1}$ ) and after ( $nn_i$ ) replacement of the <sup>109</sup>Cd source implemented in year ( $nn_{i-1}$ ), the fractional change in apparent activity values,  $A_{app,Tnn_{i-1}}/A_{app,Tnn_i}$ , due to calibration source replacement, can be estimated. The corresponding nominal air-kerma strength,  $S_{K,Tnn}$  is given by<sup>2,17</sup>

$$\begin{aligned}
 S_{K,Tnn} &= A_{app,Tnn} \cdot (\Gamma_\delta)_x \cdot \left(\frac{W}{e}\right) \\
 &= A_{app,Tnn} \cdot 1.476 \frac{\text{R} \cdot \text{cm}^2}{\text{mCi} \cdot \text{h}} \cdot 0.876 \text{ cGy/R} \\
 &= A_{app,Tnn} \cdot 1.293 \text{ U/mCi}.
 \end{aligned} \tag{1}$$

The unit of  $S_K$ , denoted by  $U$ , is defined as  $1U = 1 \mu\text{Gy} \cdot \text{m}^2 \cdot \text{h}^{-1} = 1 \text{cGy} \cdot \text{cm}^2 \cdot \text{h}^{-1}$ . Thus, the apparent activity ratio is identical to  $S_{K,Tnn_{i-1}}/S_{K,Tnn_i}$  (see column 5 of Table I). The first calibration source, implemented in year  $nn = 1988$ , covers the 1988–1990 time period during which the Meigooni<sup>3</sup> and Chiu-Tsao<sup>4</sup> dose-rate measurements were performed. These data indicate that Theragenics' assay was essentially constant until fall 1997, when the air-kerma

strength ratio,  $S_{K,T94}/S_{K,T97}$ , increased by 10.7% (column 5, row 5 of Table I) corresponding to the decrease in  $A_{\text{app}}$  initially observed by several physicists in 1997. Beginning with replacement of  $^{109}\text{Cd}$  source no. 5 (anticipated first quarter of 2000), Theragenics will maintain their  $A_{\text{app}}$  calibration within  $\pm 2\%$  of its post-1997 level regardless of the  $^{109}\text{Cd}$  source standard used.

The above analysis depends on the assumptions that (a) calibration shifts have been caused only by variations in the low-energy photon emission rate per unit stated strength of the  $^{109}\text{Cd}$  standards, and (b)  $S_K$ , when independently measured by an appropriate instrument such as the WAFAC, is proportional to NaI (TI) count rate. This view is supported by the fact that  $A_{\text{app},T97}$ -to- $S_{K,N99}$  ratios (where  $S_{K,N99}$  represents air-kerma strength as measured by NIST's WAFAC) are nearly constant over the range of internal source geometries characteristic of the Model 200 manufacturing history.<sup>8</sup> The uncertainty of the  $^{109}\text{Cd}$  low-energy photon emission rate could be larger than the  $\pm 5\%$  uncertainty specified by its vendor because the 20–25 keV photon emission rate per unit activity may vary from source-to-source, relative to the 88 keV emission rate upon which traceability of its activity calibration is based, due to small variations in source geometry. Theragenics' calibration protocol requires  $^{103}\text{Pd}$  seed calibration to be based on the most recently implemented  $^{109}\text{Cd}$  standard without correcting for shifts in spectrometer efficiency relative to either the immediately preceding standard or the one used in 1988. In practice, Theragenics has attributed these observed shifts to actual changes in the NaI (TI) spectrometer efficiency, not to differences in the low-energy photon emission rate per unit activity between different calibration sources. Hence the corresponding readjustments in  $A_{\text{app},Tnn}$  per unit spectrometer reading were viewed as corrections needed to maintain accuracy of the calibration procedure.

## B. NIST calibration techniques for the Model 200 source

The WAFAC is a cylindrically symmetric free-air chamber with circular electrodes on its proximal and distal faces consisting of very thin aluminized Mylar<sup>5–7</sup> with a collection volume large enough that individual  $^{103}\text{Pd}$  and  $^{125}\text{I}$  seeds can be calibrated. Since 1 January 1999, the WAFAC has been the basis of the U.S. national standard for air-kerma strength. Over the period December 1998 to July 1999, NIST calibrated 12 Model 200 seeds in terms of  $S_{K,N99}$  in preparation for standardizing the Model 200 source in terms of air-kerma strength.<sup>8</sup> The NIST measurements deviated significantly from the vendor's  $S_{K,T97}$ :

$$\frac{S_{K,\text{vendor}}}{S_{K,\text{NIST}}} = \frac{S_{K,T97}}{S_{K,N99}} = \frac{[A_{\text{app}} \cdot (\Gamma_{\delta})_x \cdot (W/e)]_{T97}}{S_{K,N99}} = 0.767 \pm 0.8\%. \quad (2)$$

Differences of this magnitude are not unexpected, given the influence of the Model 200 source geometry on the  $^{103}\text{Pd}$

spectrum, the poor energy resolution of NaI (TI) scintillators, and uncertainty of the low-energy photon emission rate derived from the  $^{109}\text{Cd}$  sources. This discrepancy will not cause patient dose delivery errors, if  $\Lambda$  is accurately measured and  $A_{\text{app}}$  has a constant relation to true  $S_K$ . By combining Eq. (2) and column (5) of Table I, the ratio  $S_{K,Tnn}/S_{K,N99}$  can be derived. Between 1988 and fall 1997, this ratio has remained constant within  $\pm 2\%$  of its average value:  $S_{K,T<97}/S_{K,N99} = 0.836$ . As noted above, Theragenics has declared its intention to maintain their  $A_{\text{app}}$  assay at post-1997 levels regardless of which  $^{109}\text{Cd}$  calibration source is used. Thus the ratio  $S_{K,T97}/S_{K,N99} = 0.767$  will be valid for the foreseeable future. To minimize round-off errors, all intermediate quantities, including the above ratios, carry an additional digit beyond the number justified.

## C. Recent dose-rate constant measurements and calculations

The dose-rate constant recommended by TG 43 for the Model 200 source is based upon TLD dose-rate measurements reported by Meigooni<sup>3</sup> and Chiu-Tsao.<sup>4</sup> To estimate the dose-rate constant,  $\Lambda_{95D,T88S}$ , TG 43 took the average of these two reported measurements and applied a multiplicative correction (1.048) to convert from solid water measurement medium to a liquid water reference phantom:

$$\Lambda_{95D,T88S} = \frac{\dot{D}_{95D}(\theta = \pi/2, r = 1 \text{ cm})}{S_{K,T88}} = 0.74 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}. \quad (3)$$

The first subscript, 95D, refers to source of measured dose rate at 1 cm,  $\dot{D}_{95D}(\theta = \pi/2, r = 1 \text{ cm})$ , which in this case is the TG-43 report published in 1995 (The ‘‘D’’ stands for ‘‘dosimetry.’’) The second subscript, terminating in an ‘‘S’’ for ‘‘strength,’’ refers to the source calibration standard, which in this case is Theragenics'  $A_{\text{app}}$  assay from the period 1988–1990 (T88). In preparation for implementing the  $S_{K,N99}$  standard, Theragenics has commissioned two dose-rate constant determinations. Using TLD dosimeters in a solid water phantom, Nath<sup>13</sup> reported a dose-rate constant,  $\Lambda_{99D,N99S}$ , value of  $0.65 \pm 0.05 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}$ . Using Monte Carlo simulation techniques, Williamson<sup>14</sup> reported a value of  $0.68 \pm 0.02 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}$ . Averaging these two estimates, we obtain  $\Lambda_{99D,N99S} = 0.665 \pm 0.03 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}$ .

## D. Constancy of TG-43 dosimetric parameters over Model 200 life span

The Model 200 source has undergone small changes in its internal geometry (mostly changes in thickness of the Pd metal coating the graphite pellets) resulting from the vendor's transition from lower specific activity reactor-produced  $^{103}\text{Pd}$  (hereafter denoted as ‘‘heavy seeds’’), to higher specific activity accelerator-produced radioactive material (‘‘light seeds’’). To evaluate prescribed-to-administered dose ratios over the Model 200 lifespan, the validity of the ‘‘99D’’ dosimetry parameters must be independent of these

geometry changes. In addition, any significant differences between the “99D” relative dosimetric ratios and the corresponding TG-43 data must be accounted for.

As of this writing, all published descriptions of Model 200 source dose measurements, with the exception of Nath<sup>13</sup> (which is limited to the dose-rate constant), are based upon the heavy seed design. Recently, Williamson<sup>14</sup> used Monte Carlo simulations to evaluate the sensitivity of the Model 200 parameters to specific activity. His study shows that  $\Lambda_{99D,N99S}$  is nearly independent of the internal geometry variations associated with the transition from heavy to light seeds. In addition, calculated radial dose functions,  $g(r)$ , for simulated heavy and light seeds are nearly identical, and are in good agreement with the TG-43 data and other “heavy seed” measurements.<sup>3,4,18</sup> The calculated anisotropy functions for heavy and light seeds are also similar, with light seeds exhibiting somewhat smaller (2%) anisotropy constants,  $\bar{\phi}_{\text{an}}(r)$ . The calculated heavy-seed  $F(r, \theta)$  data are in reasonable agreement with measured data. However, there are no directly measured  $F(r, \theta)$  data in the literature for currently produced light seeds. Weaver<sup>19</sup> has used Monte Carlo simulation techniques to infer  $F(r, \theta)$  from photon fluence anisotropy profiles measured in air at 1 m from “light” seeds. The resultant value of  $\bar{\phi}_{\text{an}} = 0.87$  is consistent with Williamson’s calculations but about 3% smaller than the 0.90 value recommended by TG 43. However, in the absence of empirically validated Monte Carlo anisotropy calculations, the AAPM does not believe there is sufficient evidence to warrant revision of the TG-43 anisotropy constant at this time. To summarize, for the purposes of reconstructing  $^{103}\text{Pd}$  dose administration history, the AAPM recommends the following approximations:

$$\begin{aligned} \Lambda_{99D,N99S} &= 0.665 \text{ cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}, & g_{99D}(r) &\approx g_{95D}(r), \\ F_{99D}(r, \theta) &\approx F_{95D}(r, \theta), & \bar{\phi}_{\text{an},99D} &\approx \bar{\phi}_{\text{an},95D}. \end{aligned} \quad (4)$$

### E. Dose calculation formalisms: Prescribed versus administered dose

The discussion above suggests that the dose received by a patient implanted with Model 200 sources depends both on the source of dosimetry data and the year the sources were calibrated by Theragenics. In this section, an expression is derived that relates dose prescribed based on a given dosimetry dataset and source strength standard to administered dose (dose calculated using 99D dosimetry data and calibrations traceable to  $S_{K,N99}$ ). For an arbitrary dosimetry data set,  $kk$ , and Theragenics calibration standard,  $Tnn$ , the dose-rate from a single seed using the isotropic point-source formalism<sup>2</sup> is given by

$$\dot{D}_{kkD,TnnS}(r) = S_{K,Tnn} \cdot \Lambda_{kkD,TppS} \left[ \left( \frac{r_0}{r} \right)^2 \cdot g(r) \cdot \bar{\phi}_{\text{an}} \right]_{kkD}, \quad (5)$$

where  $r_0 = 1 \text{ cm}$  is the reference distance. The subscript “ $Tpp$ ” denotes the Theragenics calibration standard to which the dose-rate constant is normalized while “ $Tnn$ ” denotes the standard to which the strength of the implanted

seeds is traceable. In general  $Tpp \neq Tnn$ . Then, the total dose at a point  $\vec{r}$ ,  $D(\vec{r})_{kkD,TnnS}$ , near an implant consisting of  $M$  seeds is

$$D(\vec{r})_{kkD,TnnS} = 1.443 \cdot T_{1/2} \sum_{i=1}^M \dot{D}_{kkD,TnnS}(|\vec{r} - \vec{r}_i|), \quad (6)$$

where  $\vec{r}_i$  is the position of the  $i$ th seed and  $T_{1/2}$  is half-life of  $^{103}\text{Pd}$ . As discussed by Bice,<sup>20</sup> the relationship between prescribed dose,  $D_{95D,TnnS}^{Px}$  (based on the  $kk = 95$  relative dosimetry parameters,  $\Lambda_{95D,T88S}$ , year  $nm$  Theragenics calibration,  $A_{\text{app},Tnn}$ ), and the administered dose,  $D_{99D,N99S}^{Rx}$  (derived from 1999 dosimetry normalized to the 1999 NIST standard), is given by averaging the ratio of the doses calculated in the two systems with respect to position  $\vec{r}$  in a typical implant. This yields

$$\frac{D_{99D,N99S}^{Rx}}{D_{95D,TnnS}^{Px}} = \left\langle \frac{D(\vec{r})_{99D,N99S}}{D(\vec{r})_{95D,TnnS}} \right\rangle, \quad (7)$$

where the brackets denote averaging over position. In the general case, the radial dose functions used by the prescription and administration dosimetry systems could differ significantly, requiring numerical evaluation of (7). However, in our case, combining Eqs. (5)–(7) with Eq. (4) yields the following simplified expression:

$$\frac{D_{99D,N99S}^{Rx}}{D_{95D,TnnS}^{Px}} = \left[ \frac{\Lambda_{99D,N99S}}{\Lambda_{95D,T88S}} \right] \cdot \left[ \frac{S_{K,N99}}{S_{K,Tnn}} \right]. \quad (8)$$

This gives the dose administered to dose prescribed ratio for patients who were treated according to TG-43 dose calculations using seeds with vendor-supplied year  $nm$  calibrations, relative to 1999 dosimetry calculations based upon the NIST WAFAC standard. The ratio  $S_{K,N99}/S_{K,Tnn}$  is the ratio of source strengths as measured relative to the indicated standards for same physical seed at the same time.

### III. RESULTS AND DISCUSSION

The main results of this communication, the  $D_{99D,N99S}^{Rx}/D_{95D,TnnS}^{Px}$  ratios as a function of year of treatment, are given in Tables I and II. Column 7 of Table I gives the ratio of administered dose to prescribed dose for the time period covered by each  $^{109}\text{Cd}$  calibration source used by Theragenics. During the period 1988 to September 1997, this ratio ranged from 1.059 to 1.099, averaging 1.075. Columns 6–8 of Table II recapitulate the same data, except that the dose ratio for the 1988–1997 period is replaced by a single average. Columns 7 and 8 of Table II give the administered doses for an assumed prescribed dose of 115 Gy. The AAPM recognizes that although 115 Gy is a widely used dose prescription, other values have been used. To obtain the administered dose corresponding to a different prescribed dose value, the latter should be multiplied by the appropriate ratio in column 7 of Table I or column 6 of Table II.

These results show the following:

- (a) For implants performed during the period 1988–1997, the administered doses are estimated to be approximately 8% higher than prescribed doses. Thus a typical

TABLE II. Simplified version of Table I obtained by averaging results for time periods 5/88 to 9/97. The dose prescription of 115 Gy is used for illustrative purpose only and does not imply AAPM endorsement of this policy.

(1) Row no.	(2) Year NN	(3) $S_K$ Standard <i>nn</i>	(4) $S_{K,Tnn}/S_{K,N99}$	(5) Dose-rate constant <i>kk</i>	(6) $\frac{D_{99D,N99S}^{Rx}}{D_{kkD,nnS}^{Px}}$	(7) Prescribed dose $D_{kkD,nnS}^{Px}$ (Gy)	(8) Administered dose $D_{99D,N99S}^{Rx}$ (Gy)
1	1988–1997	$S_{K,T<97}$ = average of $S_{K,T88}$ to $S_{K,T94}$	0.836	$\Lambda_{95D,T88S}$	1.075	115	124
2	1997–20??	$^{109}\text{Cd}$ No 5 or greater: $S_{K,T97}$	0.767	$\Lambda_{95D,T88S}$	1.172	115	135
3	>1999	$S_{K,N99}$	1.00	$\Lambda_{95D,T88S}$	0.899	115	103
4	>1999	$S_{K,N99}$	1.00	$\Lambda_{99D,N99S}$	1.000	115	115

<sup>a</sup> $D_{Px}$  assumes  $\Lambda$  value in column (5) used with  $S_K$  standard in column (4).

prescribed dose of 115 Gy, planned on the basis of TG-43 dosimetry parameters ( $\Lambda_{95D,T88S}$ ) and the vendor's  $S_{K,T<97}$  assay, resulted in an administered dose of 124 Gy based upon 1999 dosimetry ( $\Lambda_{99D,N99S}$  and  $S_{K,N99}$ ) estimates.

- (b) For implants performed during the period 1997–1999, the administered doses are estimated to be approximately 17% higher than prescribed doses. Thus a typical prescribed dose of 115 Gy, planned on the basis of TG-43 dosimetry parameters ( $\Lambda_{95D,T88S}$ ) and the vendor's  $S_{K,T97}$  assay, resulted in an administered dose of 135 Gy based upon 1999 dosimetry. Beginning with implementation of the sixth  $^{109}\text{Cd}$  standard, Theragenics will maintain their calibration assay at post-1997 levels. Thus the administered-to-prescribed dose ratio will remain at 1.17 for the foreseeable future.
- (c) For all types of  $^{103}\text{Pd}$  interstitial sources, including the Model 200 seed, treatment plans based on the NIST 1999 standard ( $S_{K,N99}$ ) and appropriately measured or calculated 1999 dosimetry data ( $\Lambda_{99D,N99S}$ ) will result in equality of prescribed and administered dose. Hence a prescribed dose of 115 Gy will result in an administered dose of 115 Gy. As of this writing, such data<sup>11–14</sup> is available for the Mentor PdGold seed.
- (d) Finally, if a clinician were to continue using unmodified TG-43 dosimetry parameters ( $\Lambda_{95D,T88S}$ ) in conjunction with the 1999 NIST standard, the administered dose would be approximately 10% lower than the prescribed dose, i.e., 115 Gy prescribed would result in an administered dose of 103 Gy.

The data presented here indicate that most of the patients treated with a prescribed dose of 115 Gy received, on average, 124 Gy prior to 1997. This cohort of patients includes all of those followed for more than 5 years and is our best estimate of the monotherapy prostate implant doses actually administered to the patients included in published retrospective reviews assessing clinical outcomes.<sup>21,22</sup> Therefore, a prescribed dose of 124 Gy best reproduces the evaluated clinical experience based solely on the limited physical issues addressed by this report. However, a large cohort of patients treated between 1997 and the present time have received a larger average dose 135 Gy for the same prescribed

dose of 115 Gy. To date, no publications are available to quantify the effects on tumor control and complications, if any, resulting from this larger administered dose. The goal of the AAPM is to provide radiation oncologists and clinical physicists with conversion factors relating prescribed and administered doses for different dosimetry data and calibration standards that will aid in selecting the prescribed dose that best serves their clinical intention.

The dose administered/dose prescribed ratios presented here describe only the systematic effects of modified dosimetry data and source-strength standards. Many other effects, such as dose heterogeneity within individual implants, uncertainties in individual seed calibrations, and patient-to-patient variations in prostate coverage achieved, may affect the relationship between prescribed and administered dose for individual patients. These factors, which vary significantly between patients and brachytherapists, are not considered here. Indeed, one possible clinical interpretation is that the 10%–20% systematic changes in administered dose considered by this report are unimportant in view of the large, apparently random patient-to-patient fluctuations in the administered-to-prescribed dose ratio. However, the AAPM emphasizes that the issues addressed by this report are systematic changes that influence all patient treatments in addition to the normal “random” uncertainties in treatment delivery.

No rigorous evaluation of the uncertainty in the administered-to-prescribed dose ratios of Tables I and II has been performed. The  $S_{K,T97}/S_{K,N99}$  ratio was measured by NIST and has an uncertainty of about 1%, while the  $\bar{\phi}_{an}$  and  $\Lambda_{99D,N99S}$  estimates have uncertainties of about 3% and 5%, respectively. The  $S_{K,Tnn_{i-1}}/S_{K,Tnn_i}$  ratios were based upon a retrospective review of proprietary data by Theragenics personnel and were provided to the Subcommittee without uncertainty estimates. Assuming that the  $S_{K,Tnn_{i-1}}/S_{K,Tnn_i}$  ratios have uncertainties of about 3%, the administered dose values of Tables I and II have uncertainties on the order of 6%.

#### IV. CONCLUSIONS AND RECOMMENDATIONS

To implement the recommendations of this report, the following three steps need to be implemented concurrently.

- (1) The AAPM recommends that vendor calibrations of  $^{103}\text{Pd}$  interstitial brachytherapy sources be indirectly traceable to NIST's WAFAC-based air-kerma strength standard. Vendor calibration certificates should specify calibrations in terms of air-kerma strength,  $S_{K,N99}$ , directly.
- (2) The AAPM recommends that medical physicists should utilize dose-rate constants ( $\Lambda_{99D,N99S}$ ) that are normalized to the  $S_{K,N99}$  calibrations, described above, in all treatment planning and evaluation dose calculations.
- (3) The AAPM recommends that radiation oncologists (with the assistance of medical physicists) convert dose specifications and prescriptions based upon older dosimetry systems into the current recommended dosimetry system (using  $\Lambda_{99D,N99S}$ ) using the conversion factors given in Tables I and II of this report. This effort requires the radiation oncologist to identify the clinical experience to be duplicated or improved upon.

The system for specifying absorbed dose described by recommendations (1)–(3) should be used for prescribing treatments, documenting treatments in the medical record, and communicating treatment results and protocols to others. Dose prescriptions based upon older dosimetry data and obsolete source-strength standards not meeting these criteria should be translated into these terms using Tables I and II.

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## APPENDIX: EXAMPLES AND FREQUENTLY ASKED QUESTIONS

(1) *My practice is based upon using Model 200 seeds along with TG-43 dosimetry data and Theragenics' 1997 source-strength assay. Being very conservative, I decline to implement Recommendations (1) and (2) and will continue to use Theragenics'  $A_{\text{app}}$  assay values with the original TG-43 dosimetry parameters. Which prescribed dose should I use to ensure that my patients receive administered doses characteristic of the 1988–1997 era?*

**Answer:** Row 1 of Table II shows that the pre-1997 patients received administered doses of 124 Gy. Beginning in fall 1997 and through the remaining life of the Theragenics  $A_{\text{app}}$  assay, the administered-to-prescribed dose ratio of 1.172 (Table II, row 2) will be applicable. To administer 124 Gy, 106 Gy ( $= 124 \text{ Gy} \div 1.172$ ) should be prescribed. Care should be taken to distinguish between  $A_{\text{app},T97}$  (the Theragenics apparent activity) and  $A_{\text{app},N99}$  (the value derived from the NIST 1999 standard as recommended by AAPM<sup>17</sup> as  $A_{\text{app},N99}$  is 30% larger than  $A_{\text{app},T97}$ ).

(2) *What prescribed dose should I use in conjunction with Mentor PdGold Seeds or other vendor supplying seeds with 1999 dosimetry data and NIST 1999 calibrations, if I want to*

*duplicate TheraSeed® treatments given in the 1997–1999 period based on a stated prescribed dose of 115 Gy?*

**Answer:** It is expected that Mentor and other  $^{103}\text{Pd}$  source vendors will give calibrations traceable to the 1999 NIST standard ( $S_{K,N99}$ ) and use dosimetry data (99D) properly normalized to this quantity. Thus administered and prescribed dose will be equal. If you want to duplicate the pre-1997 experience, you should prescribe 124 Gy. Alternatively, if you want to duplicate the 1997–2000 experience, you should prescribe 135 Gy for an administered dose of 135 Gy.

(3) *I am using Model 200 seeds with calibrations traceable to the NIST 1999 standard and 1999 dosimetry data normalized to this standard. Which prescribed dose should I use?*

**Answer:** See the reply to question (2) above. Once all vendors have implemented the 1999 NIST standard and compatible dosimetry is available for all source models, dose prescription issues will be identical for all source models.

(4) *Which seed type (Model 200 TheraSeed®, Mentor PdGold, or other source types which are entering the market) guarantees the most accurate, clinically appropriate or conceptually straightforward method for selecting the prescribed dose for my patients?*

**Answer:** With regard to the issues addressed by this report, all seed types are equal. Radiation oncologists using TheraSeed® must recognize that administered doses and prescribed doses have never been equal and that this relationship changed in 1997. They must decide whether to continue using the larger post-1997 administered dose of 135 Gy, reduce the dose to pre-1997 levels, or select an intermediate dose. With other source types, radiation oncologists should review the history of TheraSeed® treatments as given in Table II and make the same decision. Using Table II, any “old dosimetry” TheraSeed® treatment can be translated into 1999 dose-specification language. After Theragenics adopts the NIST  $S_K$  standard early in 2000, dose specification issues will be identical for all seed types.

(5) *I have been using the Memorial Hospital nomograph<sup>23</sup> for determining what source strength to order for Model 200 implants. Can I use this tool for other  $^{103}\text{Pd}$  source models using 1999 dosimetry and  $S_{K,N99}$ ?*

**Answer:** Not without significant modifications. For a given seed spacing and target volume, the Anderson nomograph gives the source strength in mCi needed to deliver a prescribed dose of 115 Gy assuming Model 200 seeds, the  $A_{\text{app},T88}$  calibration and the dosimetry parameters published by Chiu-Tsao which differ slightly from the TG-43 parameters. The nomograph results must be corrected for the choice of prescribed dose relative to 115 Gy and any difference between the 1999 dosimetry parameters appropriate for the seed type you have selected and the  $S_{K,N99}$  standard to which its calibrations are traceable and those of Chiu-Tsao which are based on the Model 200 source and Theragenics'  $A_{\text{app},T88}$  assay method.

## 1. Whom to contact for further assistance

If you have questions regarding the recommendations of this report or implementing them in your clinic, please contact the Radiological Physics Center (RPC) at MD Anderson Cancer Center, Houston, TX at (713) 792-3226.

## SYMBOL GLOSSARY

NIST	National Institute of Standards and Technology
Model 200 (TheraSeed®) source:	Theragenics Corporation $^{103}\text{Pd}$ interstitial brachytherapy source
$S_K$	air-kerma strength in units of U where $1 \text{ U} = 1 \mu\text{Gy} \cdot \text{m}^2 \cdot \text{h}^{-1} = 1 \text{ cGy} \cdot \text{cm}^2 \cdot \text{h}^{-1}$
WAFAC	wide angle free air chamber: NIST's experimental realization of the primary $S_K$ standard for low-energy (<50 keV) photon-emitting brachytherapy sources
$S_{K,N99}$	$^{103}\text{Pd}$ source air-kerma strength traceable to NIST's (N) WAFAC-based primary standard implemented in 1999.
$A_{\text{app}}$	apparent activity in traditional units of mCi
$A_{\text{app},N99}$	apparent activity derived from $S_{K,N99}$ as defined by the AAPM: <sup>17</sup>
	$A_{\text{app},N99} = \frac{S_{K,N99}}{(\Gamma_\delta)_x \cdot (W/e)} = \frac{S_{K,N99}}{1.293 \text{ U/mCi}}$
$A_{\text{app},Tnn}$	Apparent activity value measured by Theragenics ( $T$ ) relative to the $^{109}\text{Cd}$ calibration source implemented in year $nn$ .
$nn_i, nn_{i-1}$	$nn_i$ is the year that the $i$ th calibration source was implemented by Theragenics. The source strength standard under discussion is denoted by the subscript ( $i$ ) and the previously used source, implemented in year $nn_{i-1}$ , is denoted by the subscript ( $i-1$ ).
$S_{K,Tnn}$	nominal air-kerma strength derived from $A_{\text{app},Tnn}$ using AAPM's recommended conversion factor 1.293 U/mCi.
$D_{kkD,XnnS}$	total calculated dose based upon dosimetry (denoted by "D") parameters published or measured in year $kk$ and source strength assays traceable to the standard (denoted by "S") maintained by $X$ ( $X=T$ for Theragenics or $X=N$ for NIST) as implemented in year $nn$ .
$\Lambda_{kkD,XppS}$	the dose-rate constant in units of $\text{cGy} \cdot \text{h}^{-1} \cdot \text{U}^{-1}$ as derived from dose measurements performed/published in year $kk$ normalized to the source strength standard $X$ as implemented in year $pp$ .
$\Lambda_{95D,T88S}$	the TG-43 dose-rate constant for the Model 200 source published in 1995 ("95D") and based upon TLD measurements performed in 1989 and normalized to Ther-

agenics' assay based upon the  $^{109}\text{Cd}$  standard No. 1 implemented in 1988 ( $Xpp = T88$ )

$\Lambda_{99D,N99S}$

the dose-rate constant for the Model 200 based upon recent TLD measurements or Monte Carlo calculations ("99D") and normalized to the NIST 1999 standard,  $S_{K,N99}$ .

$D_{99D,N99S}^{\text{Rx}}$

dose administered to a patient based on dose calculations assuming (i) seed calibrations traceable to the  $S_{K,N99}$  and (ii) dosimetry parameters, including  $\Lambda_{99D,N99S}$ , based upon recent dose measurements/Monte Carlo simulations normalized to  $S_{K,N99}$ .

$D_{95D,TnnS}^{\text{Px}}$

dose prescribed to a patient based upon dose calculations assuming (i) seed calibrations traceable to the Theragenics assay  $A_{\text{app},Tnn}$  and (ii) the TG-43 dosimetry parameters, including  $\Lambda_{95D,T88S}$ . Note that  $nn$  need not denote 1988.

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<sup>1</sup>F. Williamson, B. M. Coursey, L. A. DeWerd, W. F. Hanson, R. Nath, and G. Ibbott, "Guidance to users of Nycomed Amersham and North American Scientific, Inc. I-125 Interstitial Sources: Dosimetry and calibration changes: Recommendation of the American Association of Physicists in Medicine Radiation Therapy Committee Ad Hoc Subcommittee on Low-Energy Seed Dosimetry," *Med. Phys.* **26**, 570–573 (1999).

<sup>2</sup>R. Nath, L. L. Anderson, G. Luxton, K. A. Weaver, J. F. Williamson, and A. S. Meigooni, "Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43," *Med. Phys.* **22**, 209–234 (1995).

<sup>3</sup>A. S. Meigooni, S. Sabnis, and R. Nath, "Dosimetry of palladium-103 brachytherapy sources for permanent implants," *Endocurietherapy/Hyperthermia Oncology* **6**, 107–117 (1990).

<sup>4</sup>S.-T. Chiu-Tsao and L. L. Anderson, "Thermoluminescent dosimetry for  $^{103}\text{Pd}$  seeds (model 200) in solid water phantom," *Med. Phys.* **18**, 449–452 (1991).

<sup>5</sup>R. Loevinger, "Wide-angle free-air chamber for calibration of low-energy brachytherapy sources," *Med. Phys.* **20**, 907 (abstract) (1993)

<sup>6</sup>S. M. Seltzer, P. J. Lamperti, R. Loevinger, C. G. Soares, and J. T. Weaver, "New NIST air-kerma strength standards for I-125 and Pd-103 brachytherapy seeds (abstract)," *Med. Phys.* **25**, 170 (1998).

<sup>7</sup>S. M. Seltzer and P. J. Lamperti, *Status of NIST Primary Standards for  $^{125}\text{I}$  and  $^{103}\text{Pd}$  Therapy Seeds Based on the Wide-Angle Free-Air Chamber (WAFAC): Proceedings of a CIRMS Workshop*, National Institute of Standards and Technology, 1999.

<sup>8</sup>B. M. Coursey, Model 200 Air-Kerma Calibration, personal communication, November 1999, National Institutes of Standards and Technology, Ionizing Radiation Division, Gaithersburg, MD.

<sup>9</sup>M. C. Jacobs, letter to its customers, Personal Communication, 15 October 1997, Theragenics Corporation.

<sup>10</sup>T. Robin and J. Rodgers, Theragenics Cd-109 Source Change History—TheraSeed® Model 200, personal communication, 30 August 1999, Theragenics Corporation, Buford, GA.

<sup>11</sup>Z. Li, "Monte Carlo calculations and experimental measurements of dosimetry parameters of a new Pd-103 source," Report to North American Scientific, Inc., Radiation Oncology, University of Florida, 1999.

<sup>12</sup>R. E. Wallace and J. J. Fan, "Dosimetric characterization of a new design  $^{103}\text{Pd}$  palladium brachytherapy source," *Med. Phys.* **26**, 2465–2470 (1999).

<sup>13</sup>R. Nath, N. Yue, K. Shahnazi, and P. J. Bongiorni, "Measurement of dose-rate constant for  $^{103}\text{Pd}$  seeds with air-kerma strength calibration

- based upon a primary national standard," *Med. Phys.* **27**, 655–658 (2000).
- <sup>14</sup>J. F. Williamson, "Monte Carlo modeling of the transverse-axis dose distribution of the Model 200  $^{103}\text{Pd}$  interstitial brachytherapy source," *Med. Phys.* **27**, 643–654 (2000).
- <sup>15</sup>T. P. Loftus, "Exposure Standardization of Iodine-125 Seeds Used for Brachytherapy," *J. Res. Natl. Bur. Stand.* **89**, 295–303 (1984).
- <sup>16</sup>S. Y. F. Chu, L. P. Ekström, and R. B. Firestone, "WWW Table of Radioactive Isotopes, database version 2/28/99 from URL <http://nucleardata.nuclear.lu.se/nucleardata/toi/>"
- <sup>17</sup>J. F. Williamson, B. M. Coursey, L. A. DeWerd, W. F. Hanson, R. Nath, M. J. Rivard, and G. Ibbott, "On the use of apparent activity ( $A_{\text{app}}$ ) for treatment planning of  $^{125}\text{I}$  and  $^{103}\text{Pd}$  interstitial brachytherapy sources: Recommendations of the American Association of Physicists in Medicine Radiation Therapy Committee Subcommittee on Low-Energy Brachytherapy Source Dosimetry," *Med. Phys.* **26**, 2529–2530 (1999).
- <sup>18</sup>E. E. Furhang and L. L. Anderson, "Functional fitting of interstitial brachytherapy dosimetry data recommended by AAPM Radiation Therapy Committee Task Group 43," *Med. Phys.* **26**, 153–160 (1999).
- <sup>19</sup>K. Weaver, "Anisotropy functions for  $^{125}\text{I}$  and  $^{103}\text{Pd}$  sources," *Med. Phys.* **25**, 2271–2278 (1998).
- <sup>20</sup>W. S. Bice, B. R. Prestidge, J. J. Prete, and D. F. Dubois, "Clinical impact of implementing AAPM Task Group 43 on permanent prostate brachytherapy using I-125," *Int. J. Radiat. Oncol., Biol., Phys.* **40**, 1237–1241 (1998).
- <sup>21</sup>M. Dattoli, K. Wallner, R. Sorace, J. Koval, J. Cash, R. Acosta, C. Brown, J. Etheridge, M. Binder, R. Brunelle, N. Kirwan, S. Sanchez, D. Stein, and S. Wasserman, " $^{103}\text{Pd}$  brachytherapy and external beam irradiation for clinically-localized, high-risk prostatic carcinoma," *Int. J. Radiat. Oncol., Biol., Phys.* **35**, 875–879 (1996).
- <sup>22</sup>R. G. Stock, N. N. Stone, J. K. DeWyngaert, P. Lavagnini, and P. D. Unger, "Prostate specific antigen findings and biopsy results following interactive ultrasound-guided transperineal brachytherapy for early stage prostate carcinoma," *Cancer* **77**, 2386–2392 (1996).
- <sup>23</sup>L. L. Anderson, J. V. Moni, and L. B. Harrison, "A nomograph for permanent implants of palladium-103 seeds," *Int. J. Radiat. Oncol., Biol., Phys.* **27**, 129–135 (1993).