Photon energy spectrum emitted by a novel polymer-encapsulated ^{103}Pd source and its effect on the dose rate constant

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(Received 17 August 2007; revised 21 January 2008; accepted for publication 22 January 2008; published 14 March 2008)

Two independent groups have published intrinsic dosimetry parameters for the recently introduced OptiSeed¹⁰³ interstitial brachytherapy source which contains ^{103}Pd encapsulated by a novel polymer shell. The dose rate constant (Λ) reported by the two groups, however, differed by more than 6% and there is currently no AAPM recommended consensus value for this source in clinical dosimetry. The aim of this work was to perform an independent determination of Λ for the OptiSeed¹⁰³ source using a recently developed photon spectrometry technique. Three OptiSeed¹⁰³ sources (model 1032P) with known air-kerma strength were used in this study. The photon energy spectrum emitted along the radial direction on the source's bisector was measured in air using a high-resolution intrinsic germanium spectrometer designed and established for low-energy brachytherapy source spectrometry. The dose rate constant of each source was determined from its emitted energy spectrum and the spatial distribution of radioactivity in the source. Unlike other sources made with traditional titanium encapsulation, the photons emitted by the OptiSeed¹⁰³ sources exhibited only slight spectral hardening, yielding a relative energy spectrum closer to that emitted by bare ^{103}Pd . The dose rate constant determined by the photon spectrometry technique for water was $0.664 \pm 0.025 \text{ cGy h}^{-1} \text{ U}^{-1}$. This value agreed, within experimental uncertainties, with the Monte Carlo-calculated value ($_{\text{MC}}\Lambda$) of $0.665 \pm 0.014 \text{ cGy h}^{-1} \text{ U}^{-1}$ and the TLD-measured value (with a Monte Carlo-calculated solid-phantom-to-water conversion factor) of $0.675 \pm 0.051 \text{ cGy h}^{-1} \text{ U}^{-1}$ reported by Wang and Hertel [Appl. Radiat. Isot. **63**, 311–321 (2005)]. However, it differed by -6.7% from the $_{\text{MC}}\Lambda$ of $0.712 \pm 0.043 \text{ cGy h}^{-1} \text{ U}^{-1}$ reported by Bernard and Vynckier [Phys. Med. Biol. **50**, 1493–1504 (2005)]. The results obtained in this work provide additional information needed for establishing a consensus value for the dose rate constant for the OptiSeed¹⁰³ source. It suggests that an eventual consensus value of Λ for the OptiSeed¹⁰³ source is likely to be closer to a value of $0.668 \text{ cGy h}^{-1} \text{ U}^{-1}$ rather than $0.693 \text{ cGy h}^{-1} \text{ U}^{-1}$ as initially recommended by the source manufacturer based on the two previously published results. © 2008 American Association of Physicists in Medicine. [DOI: [10.1118/1.2870231](https://doi.org/10.1118/1.2870231)]

Key words: dose rate constant, palladium-103, energy spectrum, polymer encapsulation

I. INTRODUCTION

In the summer of 2004, the U.S. Food and Drug Administration approved a new ^{103}Pd source (model 1032P) manufactured by International Brachytherapy (IBt) and distributed by International Brachytherapy, Inc. (Norcross, Georgia) under the trademark of OptiSeed¹⁰³ for interstitial brachytherapy.¹ Unlike the traditional titanium encapsulation used in all existing low-energy sources, the OptiSeed¹⁰³ source uses a novel biocompatible polymer shell for source encapsulation. The polymer encapsulation is expected to reduce encapsulation-induced spectral hardening of the photons emitted by ^{103}Pd and to improve the uniformity of dose distribution around the source. Although two independent research groups have reported dosimetry characterizations for the OptiSeed¹⁰³ source,^{2,3} there are currently no AAPM recommended consensus dosimetry values for use in clinical dosimetry. In particular, the dose rate constants reported by the two previous studies differed from each other by more than 6%. In the meantime, clinical applications of the OptiSeed¹⁰³ source have already begun in the United States

since July 2005.¹ There is an urgent need to develop an AAPM consensus value for the dose rate constant of the OptiSeed¹⁰³ source. The aim of this work was to investigate the effects of polymer encapsulation on the relative photon energy spectrum emitted by the OptiSeed¹⁰³ source and to perform an independent determination of its dose rate constant using a recently developed photon spectrometry technique.⁴

II. METHOD AND MATERIALS

Three OptiSeed¹⁰³ sources with known air-kerma strength were used in this study. Figure 1 depicts a picture of the sources and a schematic drawing of the nominal source geometry from a brochure of the manufacturer. The OptiSeed¹⁰³ sources are manufactured with the usual cylindrical shape (with a length of 5.0 mm and diameter of 0.8 mm) and are compatible with standard source implantation devices. Each source contains a 1.944 mm long radio-opaque gold marker flanked by two polymer-based activity carriers at the ends. The source is designed to have the radioactive

FIG. 1. Physical appearance (left panel) of the OptiSeed¹⁰³ sources and a schematic cut-away view of the internal geometry (right panel) of the source as depicted in a manufacturer's brochure.

¹⁰³Pd distributed uniformly in the carrier matrix. The two activity carriers also have a cylindrical shape with a 0.4-mm diameter and a 0.7-mm length. The nominal distance between the center of each activity carrier and the source's geometric center is 1.55 mm. These internal components are encapsulated in a biocompatible polymer shell instead of the titanium capsule used by existing source models.

The photon energy spectrum emitted along the radial direction on a source's bisector was measured in air using a high-resolution intrinsic germanium spectrometer previously established in our laboratory for photon-emitting low-energy brachytherapy sources.⁴ The air attenuation for photons of different energies was taken into account explicitly in the calibration of the detector's energy response. The calibration and validation of the spectrometry system and its use in the determination of dose rate constant for brachytherapy sources have been described in detail by Chen and Nath,⁴ which will not be reproduced here. The use of the photon spectrometry technique for dose rate constant determination is described briefly as follows. Once the relative energy spectrum emitted by a source was measured, the dose rate constant in water (defined as the ratio of dose rate produced by the source in water at the reference position, 1 cm from the center of the source on the source's bisector, and the source's air-kerma strength) for the source was calculated from the following equation,⁴

$$\Lambda = \frac{\sum_i n(E_i) E_i (\mu_{\text{en}}(E_i)/\rho)_{\text{air}} \Lambda(E_i)}{\sum_i n(E_i) E_i (\mu_{\text{en}}(E_i)/\rho)_{\text{air}}} \quad (1)$$

where $n(E)$ denotes the number of emitted photons with energy E , $[\mu_{\text{en}}(E)/\rho]_{\text{air}}$ is the mass energy absorption coefficient of air, and $\Lambda(E)$ is the dose rate constant of a monoenergetic photon source with energy E given by

$$\Lambda(E) = [\mu_{\text{en}}(E)/\rho]_a^w \frac{1}{A} \int_{-L/2}^{L/2} dx \rho(x) \times e^{-\mu(E)\sqrt{x^2+y^2}} (x^2+y^2)^{-1} B_{\text{en}}(\mu(E)\sqrt{x^2+y^2})|_{y=1 \text{ cm}}. \quad (2)$$

In Eq. (2), A is the apparent activity of the source, $[\mu_{\text{en}}(E)/\rho]_a^w$ is the ratio of mass energy absorption coefficients of water to air, $\mu(E)$ is the mass attenuation coefficient of water, and $B_{\text{en}}(\mu(E)r)$ is the energy buildup factor that accounts for the relative dose contribution from the scattered photons in water.⁵ In numerical calculations, the mass attenuation and mass energy absorption coefficients were taken

FIG. 2. Plot of the raw spectra (pulse-height distributions) measured for an OptiSeed¹⁰³ source (top panel) and a model 200 ¹⁰³Pd source (lower panel). Please consult text for the convention and origin of the labeled spectral peaks. X-ray escape peaks are labeled in black for the spectrum shown in the top panel only.

from the database maintained by NIST (Ref. 6) and the energy buildup factor was taken from the data published by Angelopoulos *et al.*,⁷ which included both Rayleigh scattering and Compton scattering with bound atomic electrons as well as the transport of secondary electrons. Since the nominal radioactivity in the OptiSeed¹⁰³ source is designed to distribute equally among the two activity carriers at 1.55 mm from the source center, $\sqrt{x^2+y^2}|_{y=1 \text{ cm}}$ in Eq. (2) equals to $\sqrt{(0.155 \text{ cm})^2 + (1 \text{ cm})^2} \approx 1.012 \text{ cm}$.

III. RESULTS AND DISCUSSION

Figure 2 plots the measured in-air “raw spectra” (pulse-height distribution) emitted by an OptiSeed¹⁰³ source (top panel) and a clinically well-established model 200 TheraSeed ¹⁰³Pd source (lower panel) along the radial direction on the source's bisector. The principal photon emissions from ¹⁰³Pd inclined K_α and K_β x-rays and one of the gamma rays. The other spectral peaks belong to one of the two categories: the x-ray escape peaks resulting from the Ge fluorescent x-rays escaping the detector (labeled using the naming convention of, for example, $K_\alpha(K_\beta)$ for the escape peak resulting from Ge- K_α characteristic x-rays, produced by the ¹⁰³Pd K_β photons leaving the detector) and fluorescent x-ray peaks produced either in the source's construction materials (Ti- K_α and K_β) or in the detector's construction materials (Fe- K_α and Cu- K_α and K_β). For clarity of presentation the x-ray escape peaks were labeled only in the plot for the OptiSeed¹⁰³ source. The fluorescent peaks at 6.4, 8.0, and 8.9 keV were found to originate from the steel protective end cap of the detector and traces of copper in the detector assembly.⁴ These fluorescent peaks were excluded in the determination

TABLE I. Measured relative photon energy spectra.

Radiation type	Level	Energy (keV)	Relative energy spectrum		
			Bare source ^a	OptiSeed (model 1032P)	TheraSeed (model 200)
X ray	K_{α}	20.1	1	1	1
X ray	K_{β}	22.9	0.185 ± 0.005	0.199 ± 0.007	0.228 ± 0.008
Gamma		39.7	0.001 ± 0.0	0.001 ± 0.0	0.002 ± 0.0
Gamma		>39.7	<0.001	<0.001	<0.001

^aNational Nuclear Data Center, information extracted from the NuDat database, see Ref. 2. The uncertainty for the relative spectrum was estimated from the uncertainties reported for individual photon emission modes following the standard error propagation rules as described in the text.

of the dose rate constant. The titanium fluorescent x rays at 4.5 keV originating from the titanium capsule were present only in the TheraSeed model 200 as expected. Because the fluorescent x-ray peaks originating from the titanium capsule are eliminated in the current NIST air-kerma strength standard for the ¹⁰³Pd sources,⁸ they were also excluded in the calculation of the dose rate constant. To obtain an accurate relative spectrum emitted by a brachytherapy source, the raw spectrum was first corrected with the spectrometer's energy and efficiency calibration curves followed by quantitative measurement of the spectral intensities using the spectrum analysis tools supplied with the spectrometry system.⁴

Table I lists the relative energy spectra measured for the two source models and the theoretical spectrum of bare ¹⁰³Pd (derived from the NuDat database maintained by Brookhaven National Laboratory).⁹ The relative spectrum was obtained by normalizing a measured or a theoretical spectrum to their respective K_{α} spectral intensity. For the bare ¹⁰³Pd source, the overall uncertainty of the calculated relative K_{β} and γ intensities was estimated as follows. First, the uncertainty for the total intensity of K_{α} (and K_{β}) emission was estimated from the uncertainties of the individual $K_{\alpha 1}$ and $K_{\alpha 2}$ (and $K_{\beta 1}$, $K_{\beta 2}$, and $K_{\beta 3}$) emissions provided by the NuDat database using the standard error propagation rule of $\sigma_z = \sqrt{\sigma_x^2 + \sigma_y^2}$ for $z = x + y$. Second, the error propagation rule of $\sigma_z = \bar{z} \sqrt{(\sigma_x/\bar{x})^2 + (\sigma_y/\bar{y})^2}$ for $z = x/y$ was used to estimate the uncertainty of the relative K_{β} and γ intensities (normalized by the K_{α} intensity). The uncertainties for the measured relative spectra were estimated according to the method described in detail in Ref. 4 which includes the uncertainties of the spectrometry system and the standard deviation among the three OptiSeed¹⁰³ sources included in this study. It is clear from Table I that the use of source encapsulation increased the relative K_{β} intensity by about 7.5% and 23%, respectively, for the OptiSeed¹⁰³ and the TheraSeed model 200 sources when compared to that emitted by the bare source. However, the use of polymer encapsulation for the OptiSeed¹⁰³ source has significantly reduced the encapsulation-induced spectral hardening, yielding a relative energy spectrum closer to that emitted by bare ¹⁰³Pd.

Table II compares the dose rate constant in water¹⁴ determined by the photon spectrometry technique with those reported previously for the OptiSeed¹⁰³ source. The dose rate constant determined by the photon spectrometry technique

was within -0.2% of the Monte Carlo-calculated value and -1.6% of the TLD-measured value (after applying a Monte Carlo-calculated solid-phantom-to-water conversion factor) reported by Wang and Hertel.² However, it differed by -6.7% from another Monte Carlo-calculated value reported by Bernard and Vynckier.³ It is worth noting that the two Monte Carlo-calculated dose rate constants were both based on the MCNP Monte Carlo code system except that one used the MCNP4C version (Bernard and Vynckier³) while the other used a later version of MCNP5 (Wang and Hertel²). The MCNP5 code also used a new photoatomic data library MCPLIB04 which provided significant improvement over the previously released MCNP4C DLC-200 library for low-energy photon dosimetry.^{10,11} The difference between the two Monte Carlo-calculated dose rate constants highlights the need for careful benchmarking of Monte Carlo calculations using different code systems and/or photoatomic data libraries.¹²

As shown in our previous publications,^{4,13} the dose rate constants determined by the photon spectrometry technique had excellent agreement ($< \pm 2\%$) with AAPM recommended consensus values¹⁴ for the models 6702, 6711, 12501, and I25.S06 ¹²⁵I sources as well as for the model 200 ¹⁰³Pd source. As described in detail in Ref. 4, the overall 1σ uncertainty for the dose rate constant determined by the photon spectrometry technique was estimated to be 3.8%.⁴ Since the measured relative spectra for the three OptiSeed¹⁰³ sources used in this study were nearly identical and the MCNP4C code with the earlier version of photoatomic data library is known to be inaccurate for low energy photons, our results suggest that the eventual consensus value for the dose

TABLE II. Comparison of dose rate constants in water (Ref. 14).

Reference	Technique	Λ (cGy h ⁻¹ U ⁻¹)	Relative difference of our work compared to other published results (%)
This work	Photon spectrometry	0.664 ± 0.025	-
2	MCNP5	0.665 ± 0.014	-0.2
	TLD	0.675 ± 0.051	-1.6
3	MCNP4C	0.712 ± 0.043	-6.7
1	Recommendation	0.693	-4.2

rate constant of the OptiSeed¹⁰³ source is likely to be closer to a value of $0.668 \text{ cGy h}^{-1} \text{ U}^{-1}$ rather than $0.693 \text{ cGy h}^{-1} \text{ U}^{-1}$ as initially recommended by the source manufacturer¹⁵ based on the two previously reported values.

Although no explicit derivation was given, the value $0.693 \text{ cGy h}^{-1} \text{ U}^{-1}$ recommended initially by the manufacturer is numerically equal to the arithmetic mean of the TLD-determined dose rate constant from Ref. 2 ($0.675 \text{ cGy h}^{-1} \text{ U}^{-1}$) and the Monte Carlo-calculated value from Ref. 3 ($0.712 \text{ cGy h}^{-1} \text{ U}^{-1}$). Since the Monte Carlo value of Ref. 3 is now known to be inaccurate because of its use of an older version of photoatomic data library, we have excluded it in the estimation of a likely “consensus” value. In addition, because the photon spectrometry technique for dose rate constant determination is a hybridized technique which utilizes both an experimentally measured energy spectrum and the Monte Carlo-calculated dose rate constant for monoenergetic photons in water, it cannot be classified simply as either a pure experimental technique or a pure theoretical technique. We have treated it as an independent technique in the derivation of a likely consensus value for dose rate constant. Specifically, the value $0.668 \text{ cGy h}^{-1} \text{ U}^{-1}$ was obtained as an arithmetic mean of the photon spectrometry result of this work and the TLD and Monte Carlo results of Ref. 2, i.e., $[(\Lambda_{\text{TLD}} + \Lambda_{\text{PST}} + \Lambda_{\text{MC}})/3]$. This value is very close to the values derived from other two possible combinations, $[(\Lambda_{\text{TLD}} + \Lambda_{\text{PST}})/2 + \Lambda_{\text{MC}}]/2$ and $[\Lambda_{\text{TLD}} + (\Lambda_{\text{PST}} + \Lambda_{\text{MC}})/2]/2$, with a relative difference of less than 0.5%. The AAPM low-energy brachytherapy source subcommittee will ultimately determine the appropriate derivation for an AAPM consensus value.

IV. CONCLUSIONS

An independent determination of the dose rate constant for the OptiSeed¹⁰³ source has been carried out. The results obtained in this work provide additional information needed for establishing an AAPM consensus value for the dose rate constant of the OptiSeed¹⁰³ source. It suggests that an eventual AAPM consensus value for the dose rate constant of the OptiSeed¹⁰³ source is likely to be closer to a value of $0.668 \text{ cGy h}^{-1} \text{ U}^{-1}$ rather than $0.693 \text{ cGy h}^{-1} \text{ U}^{-1}$ as initially recommended by the source manufacturer based on the two previously published reports.

ACKNOWLEDGMENTS

The authors would like to thank Mark J. Rivard, Ph.D. for reviewing the initial version of the manuscript and for his valuable comments. Supported in part by NIH Grant No. R01CA100863.

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¹IBt, http://www.ibt4seeds.com/corporate_highlights.asp, 2007.

²Z. Wang and N. E. Hertel, “Determination of dosimetric characteristics of OptiSeedTM a plastic brachytherapy (103)Pd source,” *Appl. Radiat. Isot.* **63**, 311–321 (2005).

³S. Bernard and S. Vynckier, “Dosimetric study of a new polymer encapsulated palladium-103 seed,” *Phys. Med. Biol.* **50**, 1493–1504 (2005).

⁴Z. J. Chen and R. Nath, “Photon spectrometry for the determination of the dose-rate constant of low-energy photon-emitting brachytherapy sources,” *Med. Phys.* **34**, 1412–1430 (2007).

⁵M. J. Berger, “Energy deposition in water by photons from point isotropic sources,” *J. Nucl. Med., Suppl.* **1**, 17–25 (1968).

⁶J. H. Hubbell and S. M. Seltzer, *Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients (version 1.4)* (National Institute of Standards and Technology, Gaithersburg, MD, 2004).

⁷A. Angelopoulos *et al.*, “Accurate Monte Carlo calculations of the combined attenuation and build-up factors, for energies (20–1500 keV) and distances (0–10 cm) relevant in brachytherapy,” *Phys. Med. Biol.* **36**, 763–778 (1991).

⁸S. M. Seltzer *et al.*, “New National air-kerma-strength standards for ¹²⁵I and ¹⁰³Pd brachytherapy seeds,” *J. Res. Natl. Inst. Stand. Technol.* **108**, 337–358 (2003).

⁹National Nuclear Data Center, information extracted from the NuDat 2 database, <http://www.nndc.bnl.gov/nudat2/> (last accessed March 6, 2007).

¹⁰M. C. White, “Photoatomic data library MCPLIB04: A new photoatomic library based on data from ENDF/B-VI release 9,” Los Alamos National Laboratory Internal Memorandum X-5:MCW-02-111, available <http://www-xdiv.lanl.gov/PROJECTS/DATA/nuclear/pdf/mcw-02-111.pdf>, 2002.

¹¹J. J. Demarco, R. E. Wallace, and K. Boedeker, “An analysis of MCNP cross-sections and tally methods for low-energy photon emitters,” *Phys. Med. Biol.* **47**, 1321–1332 (2002).

¹²M. J. Rivard, “Brachytherapy dosimetry parameters calculated for a ¹³¹Cs source,” *Med. Phys.* **34**, 754–762 (2007).

¹³R. Nath and Z. Chen, “Silver fluorescent x-ray yield and its influence on the dose rate constant for nine low-energy brachytherapy source models,” *Med. Phys.* **34**, 3785–3793 (2007).

¹⁴M. J. Rivard *et al.*, “Update of AAPM Task Group No. 43 Report: A revised AAPM protocol for brachytherapy dose calculations,” *Med. Phys.* **31**, 633–674 (2004).

¹⁵The manufacturer recommended value was given on <http://www.ibt4seeds.com> under headings of “Optiseed” and “TG43 parameters.” The company has recently updated their website to a new URL and this information is no longer provided.