# On determining dose rate constants spectroscopically

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**Purpose:** To investigate several aspects of the Chen and Nath spectroscopic method of determining the dose rate constants of $^{125}$I and $^{103}$Pd seeds [Z. Chen and R. Nath, Phys. Med. Biol. **55**, 6089–6104 (2010)] including the accuracy of using a line or dual-point source approximation as done in their method, and the accuracy of ignoring the effects of the scattered photons in the spectra. Additionally, the authors investigate the accuracy of the literature's many different spectra for bare, i.e., unencapsulated $^{125}$I and $^{103}$Pd sources.

**Methods:** Spectra generated by 14 $^{125}$I and 6 $^{103}$Pd seeds were calculated *in vacuo* at 10 cm from the source in a 2.7 × 2.7 × 0.05 cm$^3$ voxel using the EGSnrc BrachyDose Monte Carlo code. Calculated spectra used the initial photon spectra recommended by AAPM's TG-43U1 and NCRP (National Council of Radiation Protection and Measurements) Report 58 for the $^{125}$I seeds, or TG-43U1 and NNDC(2000) (National Nuclear Data Center, 2000) for $^{103}$Pd seeds. The emitted spectra were treated as coming from a line or dual-point source in a Monte Carlo simulation to calculate the dose rate constant. The TG-43U1 definition of the dose rate constant was used. These calculations were performed using the full spectrum including scattered photons or using only the main peaks in the spectrum as done experimentally. Statistical uncertainties on the air kerma/history and the dose rate/history were $\leq$0.2%. The dose rate constants were also calculated using Monte Carlo simulations of the full seed model.

**Results:** The ratio of the intensity of the 31 keV line relative to that of the main peak in $^{125}$I spectra is, on average, 6.8% higher when calculated with the NCRP Report 58 initial spectrum vs that calculated with TG-43U1 initial spectrum. The $^{103}$Pd spectra exhibit an average 6.2% decrease in the 22.9 keV line relative to the main peak when calculated with the TG-43U1 rather than the NNDC(2000) initial spectrum. The measured values from three different investigations are in much better agreement with the calculations using the NCRP Report 58 and NNDC(2000) initial spectra with average discrepancies of 0.9% and 1.7% for the $^{125}$I and $^{103}$Pd seeds, respectively. However, there are no differences in the calculated TG-43U1 brachytherapy parameters using either initial spectrum in both cases. Similarly, there were no differences outside the statistical uncertainties of 0.1% or 0.2%, in the average energy, air kerma/history, dose rate/history, and dose rate constant when calculated using either the full photon spectrum or the main-peaks-only spectrum.

**Conclusions:** Our calculated dose rate constants based on using the calculated on-axis spectrum and a line or dual-point source model are in excellent agreement (0.5% on average) with the values of Chen and Nath, verifying the accuracy of their more approximate method of going from the spectrum to the dose rate constant. However, the dose rate constants based on full seed models differ by between +4.6% and −1.5% from those based on the line or dual-point source approximations. These results suggest that the main value of spectroscopic measurements is to verify full Monte Carlo models of the seeds by comparison to the calculated spectra.  [http://dx.doi.org/10.1118/1.4770284]

Key words: brachytherapy, dose rate constant, initial decay spectrum, Monte Carlo, EGSnrc

## I. INTRODUCTION

Permanent implantation of low-energy photon-emitting radionuclides is frequently used in prostate brachytherapy treatment. Iodine-125 ($^{125}$I) and palladium-103 ($^{103}$Pd) are commonly used in such implants and manufacturers are regularly introducing new models that may potentially have dosimetric behavior differing from their previous model of the same or similar seeds. The AAPM's Task Group 43 (Refs. 1 and 2) proposed a protocol for brachytherapy dose calculation which is based on the dose rate constant, air kerma strength, radial dose function, and anisotropy function. It provides consensus datasets of the required parameters for different seed models for clinical implementation. At present, many brachytherapy treatment planning systems have adopted this protocol to calculate delivered dose distributions in both the target volume and neighboring tissue. The dose rate constant is the cornerstone of the dose calculation because it is the only parameter of the TG-43U1 dosimetry protocol that requires an absolute dose when it is determined. Clinical medical physicists use the dose rate constant to transform the other relative dose functions presented in TG-43U1 into the absolute three-dimensional dose distribution for treatment plan designs. The dose rate constant is defined by TG-43U1 as the ratio of the absolute dose rate delivered by the source at 1 cm in water on the transverse source axis, $D_w(1\text{ cm}, \frac{\pi}{2})$, and the source's air kerma strength, $S_K$. This parameter depends on the radionuclide, the materials, and the internal design of the seed model.

Chen and Nath[3–5] have proposed a methodology for the determination of the dose rate constant of low-energy photon-emitting brachytherapy sources by using spectroscopic techniques. This hybrid method incorporates experimental measurements and theoretical calculations while avoiding the difficulties faced in dosimetry measurements with TLDs in low-energy photon fields[6,7] or possibly inaccurate seed models used in Monte Carlo calculations. The method employs a low-energy germanium (LEGe) detector to measure the spectrum of the source and then uses the main peaks in the spectrum to calculate the dose rate constant. The method uses a line or dual-point source model of the seed and then averages the dose rate constants of monoenergetic photon sources for each peak weighted by the proportion of each peak in the measured spectrum.[3,5]

Interest in measuring and calculating the spectrum of each particular brachytherapy seed model has also increased recently. Usher-Moga *et al.*[8] measured the spectra of 15 brachytherapy seed models using a LEGe detector and Seltzer *et al.*[9] at the National Institute of Standards and Technology (NIST) made similar measurements for most of the seed models then in the market. Rivard *et al.*[10] investigated the influence of nuclear data as initial photon spectra from brachytherapy sources on Monte Carlo simulations of air kerma strength and dose rate constant. Rather than using the recommended initial photon spectra from TG-43U1,[2] they recommended using the $^{125}$I and $^{103}$Pd initial photon spectra from the National Nuclear Data Center (NNDC), Brookhaven National Laboratory[11] because it is a national lab dedicated to evaluating these data. However, as seen in Tables I and II, this poses some problems since the NNDC data keep changing slightly. In particular, the NNDC values in 2000 for $^{125}$I, as reported by Chen and Nath in 2007 (Ref. 4) and 2010,[5] are virtually identical to those in Report 58 of the National Council of Radiation Protection and Measurements (NCRP) but differ from the NNDC spectra on-line in 2010 as reported by Rivard *et al.*[10] which differ from those on-line in 2012.[11] Rivard *et al.*[10] noted that the differences in the spectra recommended by NNDC(2010) and by TG-43U1 had little impact on relative quantities such as the dose rate constant but did produce a difference in the calculated air kerma per disintegration or the dose per disintegration due to the different overall intensities.

As Table I shows, the initial photon spectrum of $^{125}$I recommended in NCRP Report 58 (Ref. 12) actually differs more than the initial photon spectra from the other information sources, especially regarding the intensity of the 31.0 keV line(s) relative to the major line at 27.3 keV. Similarly, for the $^{103}$Pd initial photon spectrum presented in NNDC(2000) the 22.7 keV peak's relative intensity is quite different from that recommended by TG-43U1 (see Table II). More importantly, as we will show below, the initial photon spectra from NCRP Report 58 for $^{125}$I and NNDC(2000) for $^{103}$Pd lead to better fits with the measured $^{125}$I and $^{103}$Pd spectra of Chen and Nath,[5] Seltzer *et al.*,[9] and Usher-Moga *et al.*[8]

The novel method to determine the dose rate constant presented by Chen and Nath[3–5] uses a line or dual-point source approximation in its calculations and does not account for the scatter generated in the components of the seed. This scatter is clearly detectable in LEGe measurements and Monte Carlo calculations. Does the scatter produced by the different components in the seed, such as encapsulation, markers, and the source itself, affect the dose rate constant determination based on the peaks alone? Does using a line or dual-point source approximation with isotropic radiation rather than a full model of the seed and its anisotropies affect the calculation of the dose rate constant? The aim of this work is to answer these two questions.

As a verification of the accuracy of our Monte Carlo models of the brachytherapy seeds, this work also compares measured photon spectra with Monte Carlo values calculated using the initial photon spectra of $^{125}$I and $^{103}$Pd as recommended by TG-43U1 (Ref. 2) vs those calculated using the initial photon spectra presented in NCRP Report 58 (Ref. 12) and NNDC(2000), respectively. The goal is to see if the measured data indicate which initial photon spectrum is more correct. This work also investigates if differences in the initial photon spectra play an important role in the air kerma strength, dose rate, and dose rate constant calculations in Monte Carlo simulations.

## II. METHODS

The EGSnrc user code BrachyDose is used to calculate the photon spectrum, air kerma at 10 cm distance per initial history, dose at the reference point per initial history, and the dose rate constant of several brachytherapy seed models. BrachyDose is a fast EGSnrc-based[13,14] Monte Carlo code developed by Yegin and co-workers[15–17] to perform brachytherapy dose calculations. BrachyDose uses a tracklength estimator to calculate collision kerma (equivalent to absorbed dose at these energies) per history in voxels. The voxel-based BrachyDose Monte Carlo calculations of TG-43U1 dosimetry parameters have been benchmarked by Taylor *et al.*[16] Calculations of TG-43U1 dosimetry parameters in this study are based on the procedure established by Taylor *et al.*[16]

Four different brachytherapy seed models, two $^{125}$I (GE HealthCare/Oncura 6711 as described by Williamson[18] and Dolan *et al.*[19] and Imagyn IsoSTAR model 12501 as described by Gearheart *et al.*[20] and Nath and Yue[21]) and two $^{103}$Pd seeds (Theragenics 200 as described by Monroe and Williamson[22] and Best Industries 2335 as described by Meigooni *et al.*[23]) are used in detailed investigations of the effect of scatter on the dose rate constant determination using spectroscopic techniques. Simulations to determine the air kerma per history for these four seed models were performed using the Wide Angle Free Air Chamber (WAFAC) and point detector geometry. Sixteen additional seed models were also simulated using only the WAFAC geometry. Geometry description and calculation methodology are similar to those used by Taylor and Rogers[16,24] (see also Sec. II.B). All phantom calculations in this study are for water phantoms with photon cutoff energies set to 1 keV although use of 5 keV made no difference to these calculations. Rayleigh scatter, bound Compton scatter, photoelectric absorption, and flu-

TABLE I. Initial photon spectra for $^{125}$I from the AAPM TG-43U1 (Ref. 2) report, NCRP Report No. 58 (Ref. 12), and those provided by the National Nuclear Data Center (NNDC) as accessed in January, 2010, as reported in Ref. 10, and as accessed in November 2012 (Ref. 11). The values in italics are 2 or 3 lines summed for comparison to the older data which reported only one line at 31 keV. The intensity is presented as the absolute number of photons per disintegration (/dis) or normalized to the lines at 27.02 keV and 27.47 keV(norm).

| AAPM TG-43U1 Report | | | NCRP Report No. 58[a] | | | NNDC 2010 | | | NNDC 2012 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Energy (keV) | Intensity /dis | Intensity norm | Energy (keV) | Intensity /dis | Intensity norm | Energy (keV) | Intensity /dis | Intensity norm | Intensity /dis | Intensity norm |
| – | – | – | 3.77 | 0.15 | 0.132 | 3.77 | 0.149 | 0.131 | 0.148 | 0.131 |
| 27.202 | 0.406 | | 27.2017 | 0.397 | | 27.202 | 0.401 | | 0.396 | |
| | | 1.000 | | | 1.000 | | | 1.000 | | 1.000 |
| 27.472 | 0.757 | | 27.4723 | 0.741 | | 27.472 | 0.740 | | 0.731 | |
| 30.98 | 0.202 | | | | | 30.98[b] | 0.200 | | 0.197 | |
| (*31* | *0.246* | *0.212*) | 31 | 0.257 | 0.226 | (*31* | *0.238* | *0.209* | *0.235* | *0.209*) |
| 31.71 | 0.0439 | | | | | 31.71 | 0.038 | | 0.038 | |
| 35.492 | 0.067 | 0.058 | 35.4919 | 0.067 | 0.059 | 35.492 | 0.067 | 0.059 | 0.067 | 0.059 |
| Total | 1.476 | – | Total[c] | 1.462 | | Total[c] | 1.446 | | Total[c] | 1.429 |
| | | – | Total | 1.612 | | Total | 1.595 | | Total | 1.577 |

[a]NNDC values from 2000 as reported in Refs. 4 and 5 are within 0.001 of the normalized values from NCRP Report 58 (except for the 3.77 keV line).
[b]The 30.98 keV line is actually two at 30.944 keV and 30.995 keV.
[c]Total without the 3.77 keV line for comparison to the TG-43U1 value.

orescent emission of characteristic x rays were included in the simulations. Photon cross sections from the XCOM (Ref. 25) database were used in all calculations. Electrons were not transported. One standard deviation statistical uncertainties on the dose rate constant for the full seed model calculations and for the simplified line source models were kept less than 0.3% and 0.2%, respectively.

### II.A. $^{125}$I and $^{103}$Pd photon spectra

As mentioned above, the initial spectra recommended by TG-43U1 are significantly different from other recommended values (see Tables I and II). To study any variability in the calculation of TG-43U1 dosimetric parameters due to the $^{125}$I and $^{103}$Pd initial photon spectral differences, various initial spectra for each radionuclide were used in our Monte Carlo simulations. The spectra generated by the $^{125}$I and $^{103}$Pd brachytherapy seed models were calculated in a 2.7 × 2.7 × 0.05 cm$^3$ voxel with the front face of the voxel at 10 cm from the source. The spectra averaged over this volume were shown to be the same as those in a 0.1 × 0.1 × 0.1 cm$^3$ small voxel on-axis at the same distance. Calculations were done in vacuum as per the definition of air kerma strength. The widths of the energy bins were set at 0.2 keV and values were assigned to the center of the bin (0.1 keV, 0.3 keV, 0.5 keV, etc). Calculations have a statistical uncertainty <0.1% (one standard deviation) on the bins representing the main peaks of the spectrum.

TABLE II. Initial photon spectra for $^{103}$Pd from the AAPM TG-43U1 (Ref. 2) report and those provided by NNDC as accessed in June 2008 (as reported by Ref. 8) and as accessed in August 2000 as reported in Ref. 4. The intensity is presented as the absolute number of photons per disintegration (/dis) or normalized to the lines at 20.1 keV(norm). Some higher energy lines which contribute well less than 0.1% to the air kerma are not listed.

| AAPM TG-43U1 Report[a] | | | NNDC 2000[b,c] | | NNDC 2008[b,d] | |
|---|---|---|---|---|---|---|
| Energy (keV) | Intensity /dis | Intensity norm | Intensity /dis | Intensity norm | Intensity /dis | Intensity norm |
| 20.07 | 0.2240 | | 0.2206 | | 0.2240 | |
| | | 1.000 | | 1.000 | | 1.000 |
| 20.2 | 0.4230 | | 0.4193 | | 0.4250 | |
| 22.7 | 0.1040 | | | | 0.1040 | |
| | | 0.191 | 0.1305 | 0.204 | | 0.1855 |
| 23.18 | 0.0194 | | – | – | 0.0164 | |
| 39.75 | $6.8 \times 10^{-4}$ | 0.002 | $6.8 \times 10^{-4}$ | 0.002 | $6.8 \times 10^{-4}$ | 0.002 |
| Total | 0.772 | – | Total | 0.771 | Total | 0.770 |

[a]Same data as reported by NIST as from NNDC accessed in February 2001 (Ref. 9).
[b]NNDC also provides data for a 2.7 keV peak. However, TG-43U1 did not include this peak in its recommended $^{103}$Pd initial spectrum presumably due to its irrelevance in the TG-43U1 brachytherapy parameters calculation.
[c]NNDC values from 2000 as reported in Ref. 4.
[d]NNDC values from 2008 as reported in Ref. 8. Data still posted on the NNDC website December 7, 2012.

### II.B. Calculating the dose rate constant with and without scatter

As proposed by Chen and Nath,[4] the dose rate constant for brachytherapy seeds can be determined by measuring the spectrum generated by the seed (20 cm, 10 cm, or 5 cm from the source) and using only the main peaks for a theoretical calculation of the dose rate constant. These calculations were based on isotropic emission from a line source geometry(using the standard TG-43U1 effective source length) or a dual-point source model for seeds containing micro-spheres on either side of a central marker. Pre-computed Monte Carlo values of air kerma in vacuum and dose at 1 cm in a phantom for monoenergetic photons are then used to evaluate the dose rate constant. To test the effect of suppressing the scatter in determining the dose rate constant, in most cases it was calculated for a line source (with the standard TG-43U1 effective source length[16]) using both the full photon spectrum calculated for each brachytherapy seed model and the main peaks only for each spectrum. However, for seed models having a central marker, a point source was modeled at each side of the center at a distance equal to the distance to the center of the activity distribution as done by Chen and Nath[5] [specific distances supplied by Chen (private communication, June 2012): see values in Table VI below]. This was done for all of the $^{103}$Pd seed models and two of the $^{125}$I seed models (NASI MED3631 and Draximage LS-1).

As done by Taylor *et al.*,[16] the air kerma per history was scored in either a 0.1 × 0.1× 0.05 cm$^3$ or 2.7 × 2.7 × 0.05 cm$^3$ voxel with the voxel's face at 10 cm distance from the center of the source. The small voxel corresponds to a point measurement and the larger to a measurement using the NIST WAFAC geometry which has a primary collimator of 8 cm diameter located 30 cm from the source. This primary collimator projects a circle of approximately 2.7 cm in diameter at 10 cm from the source. The normalized air kerma, ($k_{air}$), is

$$k_{air} = k_\delta(d) \times d^2 \times k_{r^2}, \tag{1}$$

with

$$k_{r^2} = \frac{1}{d^2 \times w^2 \times t \times L} \int_{-L/2}^{L/2} \int_{d}^{d+t} \int_{-w/2}^{w/2} \int_{-w/2}^{w/2} [(x-c)^2 + y^2 + z^2]\, dx\, dy\, dz\, dc \tag{2}$$

$$= \frac{1}{d^2} \left[ \frac{L^2}{12} + \frac{2w^2}{12} + d^2 + dt + \frac{t^2}{3} \right], \tag{3}$$

where $k_{r^2}$ represents the ratio to $d^2$ of the average distance $r^2$ between a vertical line source of length L centered on the origin and the scoring volume with its front face at a distance $d$ from the origin, $w$ and $t$ are the width and thickness of the voxel, respectively, $k_\delta(d)$ represents the average air kerma per initial history due to photons of energy greater than $\delta$ in the voxel at distance $d$. The factor $k_{r^2}$ is roughly a 2% correction in the WAFAC geometry used, but inclusion of the effect for a line source of length 5 mm causes only an additional 0.02% effect and hence the distinction between line and dual-point source models is ignored for this factor. Air kerma calculations were performed *in vacuo* and the photon energy cutoff was set to 5 keV to eliminate the low-energy characteristic x rays generated in the titanium encapsulation since they are also eliminated in the NIST air-kerma determination.[9] Dose per history calculations were performed with the seed centered in a 30 × 30 × 30 cm$^3$ water phantom (mass density of 0.998 g/cm$^3$) which provides satisfactory full scatter conditions for TG-43U1 dosimetric parameter calculations.[26] Dose per history was scored in a 0.01 × 0.01 × 0.01 cm$^3$ voxel centered at 1 cm from the source axis on the transverse axis, i.e., (1 cm, $\frac{\pi}{2}$).

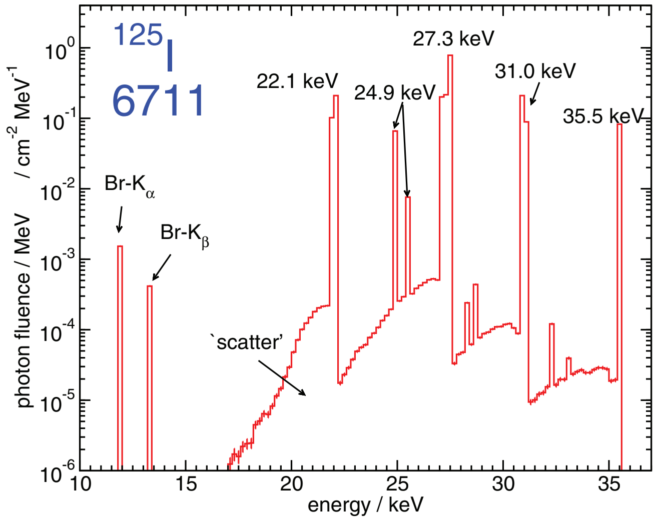


FIG. 1. Spectrum in vacuum on the transverse axis at 10 cm from the seed's mid-point for the $^{125}$I 6711 seed. It shows the main peaks, scatter and the characteristic x rays generated by photoelectric interactions with bromine. The initial photon spectrum is from NCRP Report 58 (Ref. 12).

## III. RESULTS AND DISCUSSION

### III.A. $^{125}$I and $^{103}$Pd photon spectra

Figures 1 and 2 show the Monte Carlo calculated on-axis photon spectra generated by the $^{125}$I GE HealthCare/Oncura

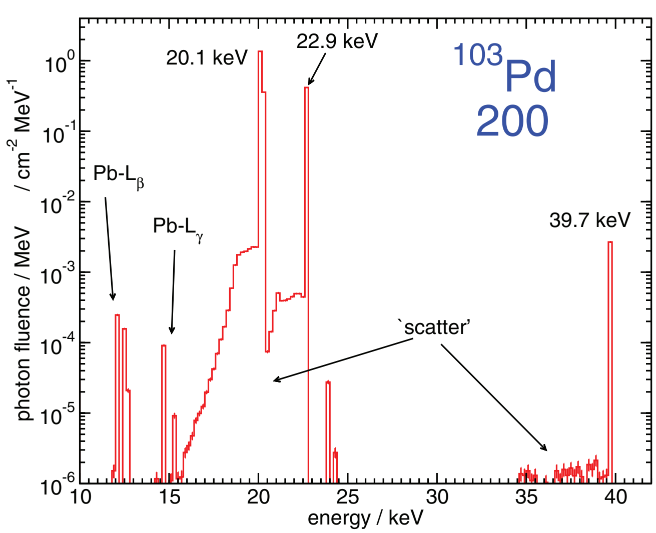


FIG. 2. As in Fig. 1 but for the $^{103}$Pd Theragenics 200 seed. The initial photon spectrum is from NNDC 2000 (Ref. 4).

TABLE III. Monte Carlo calculated (MC) vs measured (denoted by *) intensity ratios of three $^{125}$I seed models. Aside from the absence of lines from silver fluorescent x rays from seed models without any silver content, the main difference is in the 31 keV photon peak. Statistical uncertainties on the calculations are typically 0.1%.

| peak energy/keV | 22.1[a] | 24.9[a] | 27.3 | 31.0 | 35.5 | Avg. E (keV) |
|---|---|---|---|---|---|---|
| **GE HealthCare/Oncura model 6711** | | | | | | |
| MC (TG-43U1) | 0.257 | 0.061 | 1.000 | 0.233 | 0.068 | 27.26 |
| MC (NCRP58) | 0.260 | 0.062 | 1.000 | 0.249 | 0.068 | 27.29 |
| *Chen (Ref. 5) | 0.268 | 0.067 | 1.000 | 0.249 | 0.067 | 27.25 |
| *Usher-Moga (Ref. 8) | 0.274 | 0.076 | 1.000 | 0.250 | 0.068 | 27.23 |
| *Seltzer (Ref. 9) | 0.249 | 0.071 | 1.000 | 0.251 | 0.069 | 27.32 |
| **Imagyn IS-12051** | | | | | | |
| MC (TG-43U1) | 0.249 | 0.057 | 1.000 | 0.225 | 0.064 | 27.25 |
| MC (NCRP58) | 0.252 | 0.058 | 1.000 | 0.241 | 0.065 | 27.28 |
| *Chen (Ref. 5) | 0.272 | 0.067 | 1.000 | 0.247 | 0.067 | 27.23 |
| *Seltzer (Ref. 9) | 0.248 | 0.071 | 1.000 | 0.251 | 0.068 | 28.32 |
| **Best International 2301** | | | | | | |
| MC (TG-43U1) | 0.000 | 0.001 | 1.000 | 0.229 | 0.066 | 28.37 |
| MC (NCRP58) | 0.000 | 0.001 | 1.000 | 0.245 | 0.067 | 28.41 |
| *Chen (Ref. 5) | 0.000 | 0.000 | 1.000 | 0.250 | 0.068 | 28.42 |
| *Usher-Moga (Ref. 8) | 0.000 | 0.000 | 1.000 | 0.248 | 0.067 | 28.42 |
| *Seltzer (Ref. 9) | 0.000 | 0.000 | 1.000 | 0.251 | 0.068 | 28.43 |

[a]Silver fluorescent x ray components.

model 6711 and $^{103}$Pd Theragenics 200 seed models, respectively. The spectra are scored on the transverse axis at 10 cm distance. The main peaks used by Chen and Nath[4,5] are labeled as well as the scattered photons which are ignored in their technique. In the present work, the term "scatter" means every photon with an energy that is not included in the main peaks used by Chen and Nath in their spectroscopic technique, independent of its origin. However, distinctive labels are also included for the $K_\alpha$ and $K_\beta$ characteristic x rays generated by photoelectric interactions in bromine (Z = 35) from the BrI in the $^{125}$I GE HealthCare/Oncura model 6711 and the $L_\beta$ and $L_\gamma$ characteristic x rays from the lead markers (Z = 82) in the $^{103}$Pd Theragenics model 200. The characteristic x rays generated in the titanium encapsulation (typically less than 5 keV) are not included in the energy spectra shown in Figs. 1 and 2. They are filtered out in the NIST protocol for calibrating brachytherapy seeds. They were also eliminated in our air-kerma calculation by setting the fluorescent x-ray energy cut-off at 5 keV. Overall, the scatter represents up to 1.8% of the total photon fluence (depending on the seed model). Similar spectral shapes with differing relative intensities of the peaks were calculated for the other seed models used in this work.

Table III compares the Monte Carlo calculated photon spectra for three $^{125}$I seed models [GE HealthCare/Oncura 6711, Imagyn IsoSTAR IS-12051, and Best Industries 2301 (Ref. 27)] with the intensity ratios measured for each seed model by three groups using spectroscopy techniques. The main difference in these calculated spectra is in the 31 keV peak. On average, for these 3 seed models the 31 keV peaks calculated using the $^{125}$I initial photon spectrum recommended by TG-43U1 show 6.5% fewer photons relative to the main peak at 27.3 keV than the same ratio calculated with the $^{125}$I initial photon spectrum from NCRP Report 58. Moreover, the intensity ratios for the 31 keV line relative to the 27.3 keV line as calculated with the initial photon spectrum in NCRP Report 58 are in closer agreement (0.5%, 1.9%, 3.2% vs 7.3%, 9.2%, 10.7%) with the three sets of measured data which agree with each other within an average of 1.2%. The photon spectra were also calculated for 11 additional $^{125}$I seed models currently in the market and the measured intensity ratio for the 31 keV peak relative to the main peak was on average 6.8% greater than the intensity ratios calculated using the initial photon spectrum suggested by TG-43U1.[2] In general, measured data show an average spread between the three results of 1.8% for the 14 $^{125}$I seed models and the average difference between the measured intensity ratio and the ratio calculated using the NCRP Report 58 initial spectrum is 0.9%.

In contrast, no detectable difference is found in the average energy, air kerma per history, dose per history, or dose rate constant calculations. In other words, when the calculation is performed with either initial photon spectrum, any difference is within the statistical uncertainty of 0.2%. Rivard *et al.*[10] used a spherical source approximation for the source geometry to investigate the same issue. Our results are consistent with their observations of no differences when comparing the results of dose rate constant calculations using the initial spectra recommended by the AAPM TG-43U1 (Ref. 2) or by the NNDC (January 2010 data). In the present case, the differences in the initial intensity ratios are considerably greater than in Rivard *et al.* but there are still no significant differences in these calculated quantities.

Rivard *et al.*[10] found a 2% difference in the air kerma per Bq and dose per Bq when calculated with the different spectra because the absolute number of photons per disintegration vary by that much (see Table I). In practice, this has no effect on brachytherapy dosimetry using the AAPM TG-43U1 dose

TABLE IV. Monte Carlo calculated (MC) vs measured (denoted by *) intensity ratios of six $^{103}$Pd seed models. Data have been normalized to the 20.1 keV peak which represents contributions of the 20.07 keV and 20.2 keV lines. The lines at 22.7 keV and 23.18 keV have also been joined and are represented by the peak at 22.9 keV [for comparison with Chen and Nath (Ref. 5 data)]. The main difference is in the 22.9 keV photon peak. Statistical uncertainties on calculated values is $\leq$0.1%.

| peak energy/keV | 20.1 | 22.9 | 39.7 | Avg. E (keV) |
|---|---|---|---|---|
| **Theragenics 200** | | | | |
| MC (TG-43U1) | 1.000 | 0.228 | 0.002 | 20.65 |
| MC (NNDC 2000) | 1.000 | 0.243 | 0.002 | 20.68 |
| *Chen (Ref. 5) | 1.000 | 0.228 | 0.002 | 20.65 |
| *Usher-Moga (Ref. 8) | 1.000 | 0.248 | 0.002 | 20.69 |
| *Seltzer (Ref. 9) | 1.000 | 0.258 | 0.002 | 20.70 |
| **NASI MED3633** | | | | |
| MC (TG-43U1) | 1.000 | 0.215 | 0.001 | 20.61 |
| MC (NNDC 2000) | 1.000 | 0.229 | 0.001 | 20.64 |
| *Chen (Ref. 5) | 1.000 | 0.252 | 0.002 | 20.69 |
| *Usher-Moga (Ref. 8) | 1.000 | 0.242 | 0.002 | 20.68 |
| *Seltzer (Ref. 9) | 1.000 | 0.258 | 0.002 | 20.70 |
| **Best 2335** | | | | |
| MC (TG-43U1) | 1.000 | 0.231 | 0.002 | 20.66 |
| MC (NNDC 2000) | 1.000 | 0.246 | 0.002 | 20.68 |
| *Chen (Ref. 5) | 1.000 | 0.241 | 0.002 | 20.67 |
| *Usher-Moga (Ref. 8) | 1.000 | 0.250 | 0.002 | 20.69 |
| *Seltzer (Ref. 9) | 1.000 | 0.258 | 0.002 | 20.70 |
| **Draximage Pd-1** | | | | |
| MC (TG-43U1) | 1.000 | 0.232 | 0.002 | 20.66 |
| MC (NNDC 2000) | 1.000 | 0.247 | 0.002 | 20.69 |
| *Chen (Ref. 5) | 1.000 | 0.249 | 0.002 | 20.69 |
| **IBt 1032P** | | | | |
| MC (TG-43U1) | 1.000 | 0.191 | 0.001 | 20.57 |
| MC (NNDC 2000) | 1.000 | 0.204 | 0.001 | 20.59 |
| *Chen (Ref. 5) | 1.000 | 0.199 | 0.001 | 20.58 |
| **IsoAid IAPD-103** | | | | |
| MC (TG-43U1) | 1.000 | 0.214 | 0.001 | 20.61 |
| MC (NNDC 2000) | 1.000 | 0.228 | 0.001 | 20.64 |
| *Chen (Ref. 5) | 1.000 | 0.229 | 0.002 | 20.65 |

calculation formalism since the dosimetry parameters are all ratios of quantities.

Table IV shows the measured and calculated intensity ratio for all six $^{103}$Pd seed models studied. Experimental data for $^{103}$Pd seeds are not as consistent as the measurements for $^{125}$I seeds. For instance, the measured intensity ratios of the 22.9 keV peak from the Theragenics 200 seed vary by 12% although other seed models have better agreement. Despite the variability in the measurements, one can still observe some trends when compared with calculated values. The main difference between the $^{103}$Pd peak intensity ratio calculated using the TG-43U1 initial spectrum and the one calculated using the NNDC(2000) initial spectrum is the proportion of the 22.9 keV peak relative to the 20.1 keV peak. This peak exhibits an average 6.2% lower intensity ratio compared to the 20.1 keV peak when calculated with the TG-43U1 initial spectrum vs the NNDC(2000) initial spectrum. On average, the difference in the 22.9 keV intensity ratio between the measurements and the calculations using the NNDC(2000) initial spectrum is only 1.7%, and most of this comes from the NASI model MED3633 seed which disagrees by 9.5% despite the experimental results agreeing within ±3.5% of their average value. Excluding the NASI MED3633, the average agreement between the calculations (NNDC 2000) and measurements is 0.16%. On the other hand, calculations using the TG-43U1 initial spectrum give an average discrepancy of 8.4% vs the measurements. However, there are no significant differences in the calculated TG-43U1 brachytherapy parameters when using either initial spectrum. Differences in the air kerma per history, dose per history and dose rate constant calculations fall in the statistical uncertainty range which is $\leq$0.2%.

### III.B. Dose rate constants

Table V shows the values of the normalized air kerma, dose/history, and dose rate constant for the seed and line or dual-point source models used in this work for four seed models. The entries for the line or dual-point sources (full) and (peaks) represent calculations using the full spectrum of the seed and peaks-only spectrum, respectively, applied to a line

TABLE V. Values for the normalized air kerma [($k_{air}$, Eq. (1)], dose/hist ($D_w$) and dose rate constant, ($\Lambda$), calculated using WAFAC and point geometry for the full seed model and the simplified line source model with spectrum. Values from Chen and Nath (Ref. 5) are shown in bold for comparison. Calculations are done with the initial spectrum from NCRP Report 58 (Ref. 12) for $^{125}$I and from TG-43U1 for $^{103}$Pd (values are within statistics if NNDC(2000) initial spectrum is used). The uncertainties on the Monte Carlo calculations represent the statistical component of uncertainty, calculated as one standard deviation.

| | $k_{air}$ ($10^{-14}$ Gy cm$^2$/hist) | $D_w$ ($10^{-14}$ Gy/hist) | $\Lambda$ [(cGy/h)/U] |
|---|---|---|---|
| **GE HealthCare/Oncura model 6711** | | | **0.960 ± 3.8%** (Ref. 5) |
| Seed WAFAC | 3.772 ± 0.1% | 3.499 ± 0.2% | 0.928 ± 0.2% |
| Seed point | 3.714 ± 0.2% | | 0.943 ± 0.3% |
| Line source WAFAC (full) | 7.490 ± 0.1% | 7.150 ± 0.2% | 0.955 ± 0.2% |
| Line source point (full) | 7.494 ± 0.2% | | 0.954 ± 0.3% |
| Line source WAFAC (peaks) | 7.456 ± 0.1% | 7.151 ± 0.2% | 0.959 ± 0.2% |
| Line source point (peaks) | 7.455 ± 0.2% | | 0.959 ± 0.3% |
| **Imagyn IS-12051** | | | **0.959 ± 3.7%** (Ref. 5) |
| Seed WAFAC | 4.363 ± 0.1% | 4.029 ± 0.2% | 0.924 ± 0.2% |
| Seed point | 4.354 ± 0.2% | | 0.925 ± 0.3% |
| Line source WAFAC (full) | 7.456 ± 0.1% | 7.123 ± 0.2% | 0.955 ± 0.2% |
| Line source point (full) | 7.458 ± 0.2% | | 0.955 ± 0.3% |
| Line source WAFAC (peaks) | 7.452 ± 0.1% | 7.124 ± 0.2% | 0.956 ± 0.2% |
| Line source point (peaks) | 7.442 ± 0.2% | | 0.957 ± 0.3% |
| **Theragenics 200 Pd-103** | | | **0.678 ± 3.8%** (Ref. 5) |
| Seed WAFAC | 7.145 ± 0.1% | 4.893 ± 0.2% | 0.685 ± 0.3% |
| Seed point | 6.433 ± 0.2% | | 0.761 ± 0.3% |
| Dual-point sources WAFAC (full) | 26.11 ± 0.1% | 17.62 ± 0.2% | 0.675 ± 0.2% |
| Dual-point sources point (full) | 26.14 ± 0.2% | | 0.674 ± 0.3% |
| Dual-point sources WAFAC (peaks) | 26.07 ± 0.1% | 17.60 ± 0.2% | 0.675 ± 0.2% |
| Dual-point sources point (peaks) | 26.09 ± 0.2% | | 0.675 ± 0.3% |
| **Best Industries 2335 Pd-103** | | | **0.667 ± 3.7%** (Ref. 5 |
| Seed WAFAC | 7.138 ± 0.1% | 4.667 ± 0.2% | 0.654 ± 0.2% |
| Seed Point | 7.121 ± 0.2% | | 0.655 ± 0.3% |
| Dual-point sources WAFAC (Full) | 26.06 ± 0.1% | 17.27 ± 0.2% | 0.663 ± 0.2% |
| Dual-point source Point (Full) | 26.05 ± 0.2% | | 0.663 ± 0.3% |
| Dual-point source WAFAC (Peaks) | 26.05 ± 0.1% | 17.27 ± 0.2% | 0.663 ± 0.2% |
| Dual-point sources Point (Peaks) | 26.04 ± 0.2% | | 0.663 ± 0.3% |

or dual-point source geometry as appropriate. WAFAC and point distinguish calculations for the different measurement geometries as described in Sec. II.B. The table also contains the dose rate constants determined by Chen and Nath[5] using spectroscopic techniques.

Dose rate constant values in this table are comparable to those calculated by Taylor *et al.*[16] and also reported on the website of the Carleton Laboratory for Radiotherapy Physics[24] except for the $^{103}$Pd Theragenics 200 seed which has had some seed geometry description corrections to match the written description in the BrachyDose seed database. The dose rate constant value in the WAFAC and point calculations of the full seed geometry for both the $^{125}$I GE HealthCare/Oncura model 6711 and $^{103}$Pd Theragenics 200 seeds differ because of how the radioactive material is distributed in the respective seeds. Both seed models use a cylinder coated with radioactive material. In contrast, the $^{125}$I Imagyn IS-12051 and $^{103}$Pd Best Industries 2335 seeds use spheres as radioactive components which leads to no significant difference in the dose rate constant calculation regardless of the geometry (WAFAC or point). As observed by Williamson,[22,28] seed models whose radioactivity is distributed on the surface of radio-opaque materials with sharp corners will show an angle-dependent self-absorption at a distance. As expected, this phenomenon is not observed in the line source calculation and in all cases the WAFAC vs point air kerma calculations agree within the statistics of, at worst, 0.3%. Since the WAFAC calculations correspond to how air kerma strength is measured in practice, these are the values which should be used.

### III.C. Effect of scatter in the dose rate constant calculation

Table V shows the differences between the calculated normalized air kerma, dose per history, and dose rate constant calculated using either full or peaks-only spectra. These differences are usually within the statistical uncertainties of ≤0.2%, suggesting that suppressing scatter does not affect the calculations. The $^{125}$I GE HealthCare/Oncura model 6711

TABLE VI. Comparison between values for the dose rate constant of $^{125}$I and $^{103}$Pd seeds reported by Chen and Nath (Ref. 5) using the spectroscopic technique and corresponding Monte Carlo calculated values using only the peaks in the intensity ratio as initial spectrum and either a line source or dual-point source approximation and the WAFAC geometry. The table also shows values for the dose rate constant calculated with Monte Carlo simulation using the full seed model and the corresponding ratio to the Monte Carlo value corresponding to using the spectroscopic technique. The uncertainties on the Monte Carlo values represent the statistical component of uncertainty, calculated as one standard deviation.

| | Dose rate constant Λ (cGy/h/U) | | | | |
|---|---|---|---|---|---|
| | Line/dual-point[a] Source model | | | Full seed model | |
| | Chen and Nath (Ref. 5) | MC calc. | Diff. | MC calc. | $\frac{MC_{spec}}{MC_{full}}$ |
| $^{125}$**I**[b] | | | | | |
| GE 6711 | 0.960 ± 3.9% | 0.959 ± 0.2% | 0.1% | 0.928 ± 0.2% | 1.033 |
| Imagyn LS-12051 | 0.959 ± 3.8% | 0.956 ± 0.2% | 0.3% | 0.924 ± 0.2% | 1.035 |
| MBI SL-125 | 0.959 ± 3.9% | 0.953 ± 0.2% | 0.6% | 0.931 ± 0.2% | 1.024 |
| 6733 | 0.961 ± 3.7% | 0.954 ± 0.2% | 0.7% | 0.934 ± 0.2% | 1.021 |
| IsoAid IAI-125A | 0.962 ± 3.8% | 0.956 ± 0.2% | 0.6% | 0.925 ± 0.2% | 1.034 |
| Nucletron 130.002 | 0.962 ± 3.8% | 0.954 ± 0.2% | 0.8% | 0.917 ± 0.2% | 1.040 |
| Draximage LS-1(0.18) | 0.977 ± 3.8% | 0.962 ± 0.2% | 1.5% | 0.922 ± 0.2% | 1.043 |
| Implant Sciences 3500 | 1.004 ± 3.8% | 1.006 ± 0.2% | –0.2% | 0.994 ± 0.2% | 1.012 |
| Bebig/Thera I25.S06 | 1.019 ± 3.8% | 1.021 ± 0.2% | –0.2% | 1.013 ± 0.2% | 1.008 |
| OncoSeed 6702 | 1.024 ± 3.8% | 1.024 ± 0.2% | 0.0% | 1.007 ± 0.2% | 1.017 |
| NASI MED3631(0.125) | 1.017 ± 3.8% | 1.016 ± 0.2% | 0.1% | 0.995 ± 0.2% | 1.021 |
| Best 2301 | 1.021 ± 3.8% | 1.025 ± 0.2% | −0.4% | 0.999 ± 0.2% | 1.026 |
| STM 1251 | 1.024 ± 3.8% | 1.020 ± 0.2% | 0.4% | 0.992 ± 0.2% | 1.028 |
| IBt 1251L | 1.024 ± 3.8% | 1.017 ± 0.2% | 0.7% | 0.991 ± 0.2% | 1.026 |
| | | **Avg.** | **0.4%** | | **1.026** |
| $^{103}$**Pd**[c] | | | | | |
| Theragenics(0.099) | 0.678 ± 3.8% | 0.675 ± 0.2% | 0.4% | 0.685 ± 0.3% | 0.985 |
| NASI MED3633(0.125) | 0.676 ± 3.8% | 0.670 ± 0.2% | 0.9% | 0.665 ± 0.2% | 1.008 |
| Best 2335(0.155) | 0.667 ± 3.7% | 0.663 ± 0.2% | 0.6% | 0.654 ± 0.2% | 1.014 |
| IBt 1032P(0.155) | 0.664 ± 3.8% | 0.662 ± 0.2% | 0.3% | 0.669 ± 0.2% | 0.990 |
| Draximage Pd-1(0.183) | 0.661 ± 3.8% | 0.656 ± 0.2% | 0.8% | 0.627 ± 0.3% | 1.046 |
| IsoAid IAPd-103(0.113) | 0.676 ± 3.8% | 0.671 ± 0.2% | 0.7% | 0.661 ± 0.2% | 1.015 |
| | | **Avg.** | **0.6%** | | **1.010** |

[a]Seeds modeled as dual-point sources have the distance (in cm) from the seed center in parentheses after the name. Values provided by Jay Chen, June, 2012.
[b]Initial spectrum from NCRP Report 58. (Ref. 12)
[c]Initial spectrum from TG-43U1 (Ref. 2) although values are unchanged within statistics if the NNDC(2000) initial spectrum is used.

seed exhibits a 0.5% difference between the calculations with the full and peaks-only spectra. This difference is significantly less than other uncertainties in the spectroscopic technique for determining the dose rate constant.

### III.D. Effect of line and dual-point source approximations

Table V shows there is a systematic difference between the dose rate constants calculated using the real seed models vs the line or dual-point source models. Table VI presents a comparison of 20 dose rate constants from Chen and Nath[5] to our Monte Carlo calculated values using a line or dual-point source model or a full seed model. The average difference between the Chen and Nath values and the Monte Carlo line or dual-point source values is 0.5%. This close agreement is not surprising since the underlying approaches are in principle equivalent given that the measured and calculated spectra are very similar. The differences are much less than the reported uncertainties on the spectroscopic technique values.[4,5] A large fraction of the uncertainty in that hybrid technique comes from the uncertainty in the calculated values of the dose rate constant for monoenergetic photon energies and the close agreement with our results suggest these calculations have used the same cross sections as used in our Monte Carlo calculations. As a result, the relative uncertainties are reduced. Our Monte Carlo calculations demonstrate that the approximate methods used by Chen and Nath are very accurate within their framework of using the line or dual-point source approximations. However, the values of the dose rate constant for the line or dual-point source and real seed models differ on average by +2.6% (range from 0.8% to 4.0%) for the $^{125}$I seeds and 1.0% (range from −1.5% to +4.6%) for the $^{103}$Pd seeds. This systematic error is usually smaller than the reported uncertainty on the spectroscopically determined values of the dose rate constant,[5] but it should add to the uncertainty since it is independent of the sources of uncertainty currently taken into account.

We have looked for possible explanations of the differences in the full seed values vs the approximations based on isotropic radiation from the line or dual-point sources. Clearly, it must be related to the nonisotropic nature of the radiation in the full seed models which affects the absorbed dose calculations because of the change in the scatter conditions in the phantom. In contrast, the lack of isotropy does not affect the air kerma calculations. However, a plot of the ratio of the dose at (0°, 1 cm) to that at (90°, 1 cm) shows no clear correlation with the ratio of the full seed dose rate constants to those from the line source approximation. For the $^{125}$I seeds with significant silver content near the radioactivity, the values of the dose rate constant fall in a group with lower values and those without silver fall in a group with higher values of the dose rate constant. There is a very slight trend for the ratio of the full seed dose rate constants to those from the line source approximation to be higher for lower values of the dose rate constant. For the $^{103}$Pd seeds the same trend is much clearer. However, this does not really allow prediction of what the difference will be between the value of the dose rate constant with the full seed model vs the approximate model.

## IV. CONCLUSIONS

This project was initiated to see if the scatter component in the spectra from brachytherapy seeds has any effect on the spectroscopic method developed by Chen and Nath to determine the dose rate constant.[3–5] It was shown that use of just the major photon peaks is accurate to 0.5% or better.

While doing this, it was found that there are many different initial spectra available in the literature for $^{125}$I. Surprisingly, it is the oldest of these, from NCRP Report 58 (Ref. 12) which is similar to that recommended by NNDC in 2000, that provides significantly better agreement between the measured spectra from three different groups[5,8,9] for a wide variety of seed models and our Monte Carlo calculated emergent spectra. Our calculated spectra are in good agreement with the measured spectra for $^{125}$I seed models using the NCRP Report 58 initial photon spectrum (see Table I) but not when using the initial photon spectrum recommended by TG-43U1.[2]

A similar tendency is observed for the $^{103}$Pd seed models. Calculated spectra have better agreement with the measured spectra when using the initial spectrum provided by NNDC in 2000 (see Table II) instead of the one recommended by TG-43U1. In general, this work shows that when using initial spectra from NCRP Report 58 and NNDC in 2000 for $^{125}$I and $^{103}$Pd radionuclides, respectively, the Monte Carlo calculated photon energy spectra of brachytherapy seeds match those previously measured for three different groups.[5,8,9] Independently of any potential nuclear data update in the future, recommendations should be based on optimal agreement between measurements and calculations. Therefore, AAPM Task Group 43 should consider updating it's recommended initial spectra for $^{125}$I and $^{103}$Pd to those proposed here. Fortunately, these differences in the initial spectra for both radionuclides have little effect (less than the typical 0.2% statistical component of uncertainty) on the calculation of any parameters for use with the TG-43U1 formalism, in particular the dose rate constant.

Within the framework of using a line or dual-point source approximation for the seeds, our calculations verified the accuracy of the methods used by Chen and Nath to convert their measured spectra into a dose rate constant. However, the calculations also demonstrated that there are significant systematic errors (between $-1.5\%$ and $+4.6\%$) in using the line or dual-point source approximation rather than a full seed model. It would be tempting to use these Monte Carlo calculations to "correct" the spectroscopic values but in practice this reduces the spectroscopically determined values to being equivalent to the Monte Carlo calculated dose rate constant. This is because the correction factor is just the ratio of the Monte Carlo calculated value of the dose rate constant for the full seed divided by a similar calculation using a simple line source model. This suggests that the real value in measuring the spectra from the seeds is to verify the accuracy of Monte Carlo models of the seeds and to monitor manufacturing stability.

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