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A discretized approach to determining TG-43 brachytherapy dosimetry parameters: case study using Monte Carlo calculations for the MED3633 ^{103}Pd source

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Abstract

It is of interest to discern the energy-dependence of American Association of Physicists in Medicine (AAPM) TG-43 brachytherapy dosimetry parameters. Using Monte Carlo calculation geometry and techniques (MCNP), dependence of these parameters was calculated as a function of photon energy, in general, and for the MED3633 ^{103}Pd source using a discretized approach. Results were weighted and summed to determine the total contribution for comparison with the ^{103}Pd source literature. Comprehensive 2-D results are discussed, and the level of agreement with other assessments are presented. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Discretization; Monte Carlo calculations; TG-43; ^{103}Pd; Brachytherapy

1. Introduction

Using Monte Carlo calculations, it is possible to discern the contribution of separate photon energies to each of the AAPM TG-43 brachytherapy dosimetry parameters (Nath et al., 1995). This approach allows one to ascertain the energy dependence of each parameter, and readily permits revamping of dosimetry parameters should data on radiation energies or abundances be revised. Proof of principle is demonstrated using the MED3633 ^{103}Pd source produced by North American Scientific Incorporated (NASI). This source is one of the two ^{103}Pd sources that satisfy the American Association of Physicists in Medicine (AAPM) recommendations for publication of at least one complete set of experimental measurements and at least one complete set of Monte Carlo calculations of brachytherapy dosimetry parameters as outlined in TG-43 (Williamson et al., 1998). Wallace and Fan (1999) reported results for the MED3633 using TLDs, and Li et al. (2000) used a diode and Monte Carlo calculations, and these publications demonstrate good agreement among results for all TG-43 dosimetry parameters. While it was a necessity for the experimental measurements, results from both of these studies were obtained through integrating results over all photon energies. In this study, the ^{103}Pd spectrum was characterized as nine photons with energies ranging from 20–497 keV. Monte Carlo methods were used to calculate: $\dot{D}(r_0, \theta_0)$, $F(r, \theta)$, $g(r)$, and Λ as a function of energy; calculation of $G(r, \theta)$ was independent of photon energy. This technique, which discretizes energy, may be used for other poly-energetic photon-, electron-, or neutron-emitting sources, and may also be used for other radiological parameters of interest such as μ/ρ (Rivard et al., 1999).

2. Materials and methods

Impact of capsule orientation on TG-43 dosimetry parameters was first examined by Rivard (2001). These results indicated that "realistic" modeling of the MED3631-A/M ^{125}I source capsule orientation may be

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well-approximated using the "diagonal" capsule orientation. This is due to the high (96.4%) weighting of the "diagonal" orientation in comparison to the "vertical" orientation (3.6%), and also due to general similarity among their TG-43 dosimetry data. Since the dimensions of both the titanium capsule and internal components (ion exchange resin beads and gold–copper radiographic markers) of the MED3631-A/M ^{125}I source are identical to the MED3633 ^{103}Pd source, the aforementioned approximation also holds true for the MED3633 source. Consequently, only the "diagonal" capsule orientation was modeled in this study, and presumed to well-approximate results for a "realistic" capsule orientation. Since the MED3633 has identical bead-marker dimensions as the MED3631-A/M ^{125}I source with negligible geometric impact of isotope distribution (volume or surface), $G(r, \theta)$ for the MED3633 ^{103}Pd source was identical to that for the MED3631-A/M source (Rivard, 2001). Based on analysis of specific activities presented for the MED3631-A/M source, no Pd material was included in the MED3633 Monte Carlo source model. The computer system, Monte Carlo calculation geometry and techniques (MCNP), and all mass densities and compositions have already been described in great detail (Briesmeister, 1997; Rivard, 2001). The only differences were:

1. surface distribution of ^{103}Pd on the ion exchange resin bead instead of ^{125}I volume distribution,
2. technique used to calculate air kerma strength, and
3. ^{103}Pd source photon energy spectrum from Table 1 (Browne and Firestone, 1986).

Transport was also performed for unencapsulated point sources with photon energies ranging from 50 to 661.6 keV to quantify the energy-dependence of both Λ and $g(r)$, that is, $\Lambda(E)$ and $g(r, E)$. Calculation of air kerma strength, S_K, for low-energy (^{125}I and ^{103}Pd) photon-emitting brachytherapy sources is usually complicated by the presence of characteristic X-rays produced by the titanium capsule. These X-rays have energies of 4.505, 4.511 and 4.932 keV for the $K_{\alpha 2}$, $K_{\alpha 1}$, and $K'_{\beta 1}$ lines with normalized yields of 50.3%, 100%, and 20.1%, respectively; the average of these lines may be approximated as 4.56 keV (Shihab-Eldin et al., 1986). S_K was initially calculated with contribution from photons of all energies and without removing attenuation by air; these two effects were accounted for as follows:

1. titanium X-ray contribution to S_K was corrected by introducing a 5 keV cut-off, and
2. attenuation and scatter as a function of distance from the source was calculated independently for each of the nine photon energies using the extrapolation method described in detail by Williamson (2000).

For calculations of the nine S_K values and the total S_K value, the order in which these two corrections were applied did not matter.

Table 1
^{103}Pd photon source model. Source photons with energies less than 5 keV, and source electrons, were ignored due to their negligible chance of penetrating the titanium capsule

Photon energy (keV)	Photons per disintegration (%)
20.074	22.4
20.216	42.3
22.717	10.4
23.312	1.94
39.755	0.0683
62.51	0.00104
294.95	0.0028
357.46	0.0221
497.054	0.00401
20.74 keV avg.	77.14% total

3. Results and discussion

3.1. Radial dose function

Carlsson and Ahnjesö (2000) examined dosimetry of mono-energetic photons in water using the collapsed-cone superposition algorithm as a means to understand the impact of brachytherapy scatter dose. Due to the scatter-to-primary ratio, $g(r)$ maximizes at $\sim$100 keV because of the ratio of Compton scattering to total cross-sections in water at this photon energy. Using EGS4, $g(r)$ peaked at 1.6 at 8 cm and 1.03 at 3 cm for 100 and 350 keV photons, respectively, with $g(10) = 0.85$ for 662 keV photons. Both these depths and the 350 keV $g(3)$ value were in close agreement with data presented in Table 2. However, their 100 keV $g(8)$ value of 1.6 was $\sim$17% greater than that determined herein. This may be due in part to differences in water cross-section data. Radial dose functions for each of the ^{103}Pd photon energies are individually presented in Table 3. The weighted average $g(r)$ for ^{103}Pd was fit within $\pm 2\%$ to a fifth order polynomial from $r = 0.25$ to 10 cm with parameters given below.

$$a_0 = 1.490;\ a_1 = -5.471\times10^{-1};\ a_2 = 4.309\times10^{-2};$$

$$a_3 = 7.873\times10^{-3};\ a_4 = -1.457\times10^{-3};\ a_5 = 6.376\times10^{-5}.$$

Upon comparison of $g(r)$ for ^{103}Pd sources examined by various investigators in Table 4, it is evident there was relatively good agreement over all radial distances. Luxton and Jozsef (1999) also calculated energy dependence of $g(r)$ in water, i.e., $g(r, E)$. Though their data was presented graphically, general agreement with results presented in Table 2 was obtained.

Table 2
$g(r, E)$ in a 30 cm diameter water phantom and $\Lambda(E)$ for unencapsulated, mono-energetic, photon-emitting point sources

r (cm)	Photon energy (keV)												
	50	100	150	200	250	300	350	400	450	500	550	600	661.6
0.10	0.811	0.874	0.94	0.962	0.976	0.988	0.992	0.994	0.996	1.002	1.008	1.016	1.022
0.15	0.821	0.885	0.942	0.964	0.978	0.989	0.993	0.995	0.997	1.001	1.007	1.013	1.018
0.20	0.829	0.896	0.945	0.967	0.979	0.990	0.993	0.995	0.997	1.001	1.006	1.011	1.016
0.25	0.838	0.905	0.948	0.969	0.980	0.991	0.994	0.996	0.998	1.001	1.005	1.009	1.014
0.30	0.847	0.912	0.952	0.972	0.982	0.992	0.995	0.997	0.998	1.001	1.004	1.007	1.011
0.40	0.872	0.922	0.958	0.975	0.985	0.993	0.996	0.998	0.999	1.000	1.003	1.005	1.009
0.50	0.893	0.931	0.964	0.979	0.987	0.994	0.997	0.998	0.999	1.000	1.002	1.003	1.008
0.75	0.948	0.963	0.980	0.990	0.991	0.997	0.998	0.999	1.000	1.000	1.001	1.002	1.004
1.50	1.088	1.057	1.036	1.025	1.015	1.010	1.007	1.005	1.003	1.001	0.998	0.995	0.993
2.00	1.150	1.111	1.064	1.043	1.027	1.014	1.010	1.004	1.003	0.999	0.997	0.994	0.991
3.00	1.245	1.210	1.116	1.074	1.044	1.022	1.013	1.004	1.001	0.995	0.989	0.984	0.980
4.00	1.290	1.287	1.161	1.099	1.056	1.029	1.015	1.003	0.994	0.985	0.981	0.978	0.974
5.00	1.287	1.341	1.182	1.104	1.056	1.022	1.005	0.989	0.979	0.970	0.961	0.954	0.947
6.00	1.257	1.372	1.197	1.108	1.054	1.016	0.997	0.980	0.968	0.957	0.948	0.939	0.930
7.00	1.204	1.384	1.198	1.099	1.041	1.004	0.982	0.964	0.952	0.937	0.930	0.921	0.914
8.00	1.131	1.367	1.182	1.083	1.021	0.979	0.959	0.939	0.927	0.914	0.906	0.898	0.891
9.00	1.039	1.333	1.155	1.056	0.991	0.951	0.929	0.911	0.898	0.886	0.877	0.871	0.865
10.00	0.947	1.284	1.112	1.013	0.955	0.917	0.895	0.878	0.867	0.856	0.849	0.841	0.834
12.50	0.693	1.064	0.943	0.871	0.828	0.800	0.788	0.777	0.771	0.765	0.762	0.758	0.753
Λ, this work	1.304	1.260	1.193	1.156	1.144	1.130	1.125	1.117	1.113	1.109	1.105	1.102	1.096
Λ, Luxton and Jozsef (1999)	1.336	1.266	1.200	1.166	1.145	1.130	1.125	1.114		1.117		1.114	
Λ, Chen and Nath (2001)	1.300	1.259	1.193	1.159		1.133		1.122		1.114		1.107	

Table 3
$g(r, E)$ and $\Lambda(E)$ for the MED3633 ^{103}Pd source[a]

r (cm)	Photon energy (keV)									Weighted average
	20.074	20.216	22.717	23.312	39.755	62.51	294.95	357.46	497.054	
0.25	1.375	1.362	1.191	1.169	0.878	0.847	0.983	0.994	0.997	1.336
0.30	1.360	1.346	1.182	1.154	0.882	0.861	0.987	0.991	1.000	1.321
0.35	1.337	1.325	1.176	1.149	0.894	0.871	0.989	0.994	1.001	1.302
0.40	1.315	1.305	1.165	1.140	0.901	0.881	0.992	0.995	1.009	1.283
0.50	1.269	1.260	1.148	1.127	0.927	0.905	0.994	0.997	1.005	1.243
0.60	1.215	1.209	1.123	1.107	0.943	0.928	0.997	0.998	1.003	1.196
0.75	1.132	1.128	1.077	1.067	0.963	0.949	0.998	0.999	1.001	1.120
1.00	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.25	0.873	0.875	0.919	0.927	1.024	1.044	1.005	1.002	1.000	0.882
1.50	0.763	0.768	0.845	0.859	1.049	1.086	1.009	1.004	0.999	0.780
1.75	0.663	0.669	0.772	0.791	1.065	1.124	1.011	1.005	0.996	0.686
2.00	0.577	0.584	0.703	0.726	1.075	1.162	1.015	1.007	0.994	0.603
2.50	0.427	0.436	0.576	0.606	1.087	1.231	1.022	1.009	0.993	0.459
3.00	0.315	0.323	0.466	0.499	1.086	1.288	1.026	1.010	0.991	0.347
4.00	0.169	0.176	0.303	0.334	1.049	1.368	1.028	1.006	0.980	0.197
5.00	0.0918	0.0966	0.196	0.222	0.980	1.408	1.024	0.998	0.966	0.114
7.00	0.0243	0.0262	0.0750	0.0912	0.809	1.405	0.999	0.969	0.931	0.0357
10.00	0.0034	0.0039	0.0173	0.0229	0.541	1.217	0.918	0.890	0.854	0.0073
Λ	0.644	0.655	0.795	0.830	1.217	1.293	1.108	1.106	1.102	0.672

[a] Shown are the nine photon energies and their weighted average with weighting based on photon abundances from Table 1 and performed before r_0 normalization. As expected, the weighted average $g(r)$ data behaved as a single monoenergetic 20.74 keV photon source within 0.3% (2σ) over the full radial range of 0.25–10.00 cm.

Table 4
$g(r)$ and Λ for NASI MED3633 and Theragenics Model 200 ^{103}Pd sources[a]

r (cm)	MED3633				Model 200	
	TLD by Wallace and Fan (1999)	Diode by Li et al. (2000)	MCPT by Li et al. (2000)	MCNP in this work	TG-43	MCPT by Williamson (2000)
0.25				1.336		1.279
0.50	1.275	1.345	1.243	1.243	1.29	1.231
0.75	1.132		1.125	1.120		
1.50	0.769	0.772	0.770	0.780	0.765	0.764
2.00	0.580	0.551	0.583	0.603	0.576	0.570
3.00	0.318	0.362	0.325	0.347	0.310	0.312
4.00	0.174		0.177	0.197	0.165	0.169
5.00	0.102		0.098	0.114	0.0893	0.0918
7.00	0.045		0.028	0.0357		
10.00				0.0073		0.00633
Λ	0.70	0.721	0.677	0.672	0.568	0.655

[a] Measurements of Λ in 1999 were made using TLDs and a diode and are corrected by +3.2% for instabilities in WAFAC calibrations. The weighted average $g(r)$ and Λ for the MED3633 calculated herein was taken from Table 2. Results of calculations by Williamson (2000) are for an effective ^{103}Pd thickness of zero, which matches the methodology used herein.

3.2. Dose rate constant

Calculated $\Lambda(E)$ results are presented in the bottom of Table 2. It would appear from these data that $\Lambda(E)$ monotonically decreases as energy increases. Chen and Nath (2001) have previously calculated $\Lambda(E)$ using analytical techniques and with more energy points. Their results indicate $\Lambda(E)$ peaks at approximately 60 keV and decreases to 0.649 at 20 keV. Upon comparison with their results at common energies, differences of 0.3% were generally obtained. Comparison with data by Luxton and Jozsef (1999) in Table 2 also indicated excellent agreement. At the higher energies, differences between results may be due to the break-down of our approximation of dose and kerma equivalence. For these unencapsulated point sources, there were no Ti X-ray contributions, and consequently, the impact of photons <5 keV to S_K was negligible. However, significance of contributions to S_K by photons <5 keV for the nine mono-energetic sources using the MED3633 geometry varied as a function of $\dot{K}(d)$. The impact of Ti X-ray contributions decreased as photon energy increased and as d increased. For example, contributions to $\dot{K}(d)$ by photons <5 keV for the 20.074 keV photon source were 6.0% and 2.6% at 20 and 175 cm, respectively. The weighted average for the ^{103}Pd photons yielded $_{\text{MED3633}}\Lambda = 0.672\,\text{cGy}\,\text{h}^{-1}\,\text{U}^{-1}$.

Wallace and Fan (1999) measured $_{\text{MED3633}}\Lambda = 0.68\,\text{cGy}\,\text{h}^{-1}\,\text{U}^{-1}$ using TLDs in a water-equivalent phantom. Li et al. (2000) measured $_{\text{MED3633}}\Lambda = 0.714$ and $0.682\,\text{cGy}\,\text{h}^{-1}\,\text{U}^{-1}$ using a diode calibrated to Nycomed–Amersham ^{125}I sources, models 6702 and 6711, respectively, in which the calibration is traceable to NIST. In 1999, Li et al. (2000) also calculated $0.677\,\text{cGy}\,\text{h}^{-1}\,\text{U}^{-1}$ using MCPT. Based on corrections to calibrations made using the WAFAC in 1999, TLD and diode results need to be increased by 3.2%. While there were no reported shifts in 1999 WAFAC calibrations for the Nycomed–Amersham ^{125}I sources, this method of cross-calibration with different seed types or different isotopes is not recommended due to propagation of errors and unknown uncertainties. Compared with these three previously reported results for ^{103}Pd MED3633 Λ, our calculated value was on average 5% less than their measured values and within 1% of their calculations using MCPT. For comparison, Λ values for the Theragenics Model 200 seed are also presented. Using Chen and Nath's analytical technique and the average photon energy of 20.74 keV from Table 1, $_{\text{MED3633}}\Lambda = 0.70$ is obtained. This value is in good agreement with experimental and calculative results.

3.3. Anisotropy

Table 5 presents the energy dependence of $F(r, \theta)$ for all nine ^{103}Pd photon energies and their weighted average. Clearly $F(r, \theta)$ for the higher-energy photons exhibited less anisotropy. Table 6 presents $\phi_{an}(r)$ and $\bar{\phi}_{an}$ for all nine photon energies and their weighted average. As a function of photon energy, $\phi_{an}(r)$ values increased at a given radius. Upon dividing each $\phi_{an}(r)$ value by $\bar{\phi}_{an}$ for a given photon energy, all nine datasets became coincident and were readily fit to Eq. (1) with

Table 5
$F(r, \theta)$ derived using Monte Carlo methods for the MED3633 for various discretized photon energies. Clearly the lower-energy sources have greater anisotropy. Also presented is their weighted average, based on contributions from each mono-energetic photon source at $\theta = 90^{\circ}$

r(cm)	F(r, θ)																		
	0	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°
20.074 keV																			
0.25	0.766	0.768	0.822	0.887	0.932	0.956	0.977	1.001	1.010	1.000	0.990	0.976	0.948	0.914	0.852	0.762	0.598	0.589	0.758
0.50	0.629	0.600	0.650	0.753	0.837	0.896	0.944	0.978	0.995	1.000	0.988	0.964	0.923	0.869	0.795	0.676	0.514	0.475	0.631
1.00	0.535	0.567	0.632	0.741	0.822	0.891	0.940	0.974	0.996	1.000	0.997	0.971	0.933	0.873	0.794	0.675	0.524	0.458	0.567
2.00	0.577	0.563	0.642	0.743	0.823	0.889	0.939	0.973	0.993	1.000	0.993	0.971	0.934	0.877	0.797	0.685	0.542	0.468	0.592
5.00	0.597	0.576	0.659	0.759	0.839	0.896	0.942	0.976	1.004	1.000	0.996	0.979	0.938	0.885	0.806	0.701	0.577	0.494	0.566
10.00	0.771	0.588	0.688	0.728	0.804	0.880	0.915	0.952	0.986	1.000	0.991	0.999	0.912	0.872	0.791	0.684	0.556	0.516	0.667
20.216 keV																			
0.25	0.818	0.772	0.823	0.888	0.933	0.957	0.978	1.000	1.011	1.000	0.990	0.975	0.948	0.914	0.855	0.764	0.602	0.590	0.798
0.50	0.628	0.603	0.653	0.757	0.839	0.897	0.945	0.979	0.997	1.000	0.989	0.965	0.925	0.871	0.798	0.680	0.520	0.480	0.648
1.00	0.527	0.571	0.637	0.745	0.824	0.893	0.941	0.975	0.996	1.000	0.996	0.972	0.934	0.876	0.797	0.679	0.528	0.463	0.569
2.00	0.575	0.568	0.646	0.747	0.826	0.891	0.939	0.972	0.993	1.000	0.993	0.971	0.934	0.880	0.801	0.690	0.548	0.474	0.577
5.00	0.582	0.579	0.665	0.763	0.841	0.899	0.944	0.977	1.004	1.000	0.997	0.979	0.940	0.887	0.806	0.707	0.582	0.504	0.585
10.00	0.892	0.567	0.678	0.728	0.817	0.859	0.912	0.947	0.982	1.000	0.979	0.962	0.898	0.864	0.785	0.689	0.578	0.486	0.558
22.717 keV																			
0.25	0.895	0.813	0.845	0.896	0.932	0.961	0.978	0.999	1.009	1.000	0.992	0.971	0.950	0.919	0.875	0.794	0.668	0.654	0.847
0.50	0.643	0.648	0.704	0.797	0.862	0.912	0.949	0.979	0.996	1.000	0.991	0.972	0.936	0.894	0.837	0.738	0.596	0.536	0.722
1.00	0.628	0.622	0.695	0.792	0.861	0.911	0.951	0.977	0.995	1.000	0.998	0.978	0.948	0.900	0.841	0.746	0.610	0.529	0.617
2.00	0.611	0.628	0.710	0.803	0.866	0.916	0.955	0.981	0.997	1.000	0.995	0.979	0.952	0.908	0.844	0.760	0.631	0.549	0.614
5.00	0.615	0.658	0.735	0.812	0.875	0.923	0.961	0.983	1.002	1.000	1.001	0.981	0.954	0.912	0.851	0.772	0.668	0.583	0.631
10.00	0.729	0.663	0.754	0.814	0.876	0.917	0.955	0.972	0.986	1.000	0.994	0.973	0.936	0.898	0.850	0.781	0.666	0.597	0.648
23.312 keV																			
0.25	0.891	0.819	0.849	0.899	0.934	0.963	0.976	0.998	1.005	1.000	0.991	0.970	0.951	0.919	0.879	0.800	0.681	0.662	0.837
0.50	0.674	0.656	0.712	0.805	0.867	0.915	0.950	0.980	0.997	1.000	0.990	0.972	0.938	0.898	0.845	0.748	0.611	0.550	0.685
1.00	0.621	0.631	0.707	0.802	0.867	0.916	0.953	0.979	0.996	1.000	0.997	0.978	0.950	0.907	0.849	0.758	0.626	0.547	0.609
2.00	0.650	0.641	0.723	0.814	0.876	0.920	0.958	0.981	0.996	1.000	0.996	0.980	0.954	0.912	0.853	0.772	0.649	0.566	0.603
5.00	0.632	0.674	0.744	0.826	0.883	0.929	0.962	0.985	1.000	1.000	0.999	0.981	0.957	0.915	0.858	0.783	0.685	0.602	0.627
10.00	0.770	0.689	0.757	0.827	0.878	0.916	0.970	0.972	1.000	1.000	0.993	0.979	0.945	0.907	0.858	0.786	0.679	0.595	0.617
39.755 keV																			
0.25	0.919	0.908	0.912	0.929	0.951	0.973	0.984	1.005	1.015	1.000	0.998	0.978	0.973	0.961	0.943	0.884	0.852	0.830	0.892
0.50	0.735	0.763	0.826	0.891	0.927	0.950	0.973	0.990	0.997	1.000	0.998	0.988	0.972	0.952	0.925	0.882	0.807	0.731	0.801
1.00	0.682	0.760	0.832	0.900	0.932	0.956	0.974	0.990	0.997	1.000	1.003	0.992	0.981	0.961	0.935	0.890	0.825	0.756	0.732
2.00	0.744	0.796	0.861	0.916	0.941	0.963	0.978	0.993	0.997	1.000	1.000	0.995	0.984	0.967	0.944	0.909	0.854	0.785	0.783
5.00	0.824	0.850	0.902	0.936	0.957	0.976	0.986	0.996	1.003	1.000	0.999	0.995	0.985	0.970	0.950	0.927	0.886	0.844	0.828
10.00	0.851	0.880	0.911	0.939	0.964	0.977	0.988	0.994	0.998	1.000	1.000	0.991	0.981	0.976	0.951	0.926	0.895	0.859	0.854
62.51 keV																			
0.25	1.002	0.933	0.942	0.951	0.961	0.977	1.000	1.005	1.017	1.000	1.001	0.994	0.989	0.983	0.968	0.933	0.886	0.868	0.895
0.50	0.694	0.810	0.867	0.917	0.949	0.961	0.983	0.998	0.995	1.000	0.999	0.996	0.976	0.966	0.943	0.913	0.854	0.800	0.831
1.00	0.787	0.803	0.872	0.923	0.949	0.966	0.982	0.992	0.995	1.000	0.999	0.994	0.988	0.975	0.959	0.925	0.880	0.806	0.732
2.00	0.766	0.831	0.895	0.936	0.956	0.972	0.984	0.992	0.997	1.000	1.000	0.999	0.990	0.978	0.964	0.941	0.902	0.845	0.783
5.00	0.860	0.901	0.933	0.959	0.972	0.983	0.993	0.998	1.001	1.000	1.001	0.999	0.990	0.985	0.975	0.959	0.935	0.898	0.882
10.00	0.918	0.926	0.948	0.967	0.978	0.985	0.994	0.997	1.001	1.000	1.000	0.997	0.993	0.982	0.970	0.962	0.943	0.918	0.969
294.95 keV																			
0.25	1.013	1.001	0.996	0.994	1.002	1.003	1.000	1.001	1.007	1.000	1.011	0.998	1.000	1.004	0.996	0.998	0.988	0.985	0.969
0.50	0.932	0.947	0.971	0.987	0.991	0.994	1.002	0.998	0.998	1.000	1.002	1.001	1.000	0.997	0.990	0.988	0.959	0.939	0.922
1.00	0.912	0.930	0.969	0.980	0.993	0.995	0.999	0.996	0.998	1.000	1.001	0.996	0.998	0.994	0.989	0.987	0.964	0.935	0.905

Table 5 (*continued*)

r(cm)	$F(r, \theta)$																		
	0	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°	110°	120°	130°	140°	150°	160°	170°	180°
2.00	0.920	0.938	0.968	0.986	0.990	0.992	0.998	0.996	0.998	1.000	0.999	0.994	0.998	0.993	0.991	0.986	0.969	0.938	0.913
5.00	0.928	0.949	0.976	0.986	0.997	0.998	0.999	1.000	1.000	1.000	0.999	0.991	0.997	0.993	0.990	0.985	0.971	0.950	0.929
10.00	0.947	0.958	0.980	0.988	0.993	0.996	0.998	1.002	0.999	1.000	1.000	1.000	1.000	0.995	0.992	0.987	0.974	0.961	0.950
357.46 keV																			
0.25	1.017	1.008	1.006	0.998	1.009	1.006	1.001	1.001	1.012	1.000	1.013	0.994	1.004	1.009	1.000	1.005	1.006	1.007	0.869
0.50	0.958	0.962	0.979	0.990	0.993	0.997	1.000	1.002	0.999	1.000	1.002	1.003	1.001	1.000	0.994	0.992	0.966	0.953	0.942
1.00	0.927	0.947	0.978	0.986	0.996	0.994	0.999	0.995	0.996	1.000	1.000	0.999	0.998	0.995	0.992	0.991	0.973	0.950	0.923
2.00	0.941	0.953	0.977	0.992	0.994	0.995	0.998	1.000	1.000	1.000	1.001	0.999	1.000	0.998	0.995	0.991	0.979	0.955	0.928
5.00	0.983	0.991	0.994	0.998	0.999	0.999	0.999	1.001	1.002	1.000	1.001	1.001	0.999	0.996	0.994	0.989	0.979	0.963	0.945
10.00	0.940	0.968	0.986	0.991	0.994	0.997	0.997	1.000	1.000	1.000	1.001	0.998	0.998	0.995	0.992	0.991	0.980	0.964	0.958
497.054 keV																			
0.25	1.024	1.018	1.017	1.013	1.011	1.005	1.000	1.003	1.002	1.000	1.007	0.994	1.001	1.009	1.012	1.015	1.018	1.025	0.868
0.50	0.976	0.980	0.993	0.994	0.997	0.998	1.000	0.998	1.002	1.000	1.001	1.003	1.000	1.006	0.995	0.997	0.976	0.967	0.946
1.00	0.965	0.969	0.984	0.991	0.994	0.998	0.999	0.996	0.999	1.000	0.999	0.998	1.000	0.996	0.995	0.994	0.985	0.972	0.952
2.00	0.954	0.972	0.985	0.994	0.995	0.997	0.999	0.997	0.999	1.000	0.999	0.999	1.000	0.997	0.998	0.994	0.987	0.971	0.964
5.00	0.965	0.980	0.989	0.995	0.996	0.997	0.999	0.998	1.000	1.000	1.000	1.000	0.999	0.997	0.995	0.993	0.987	0.976	1.001
10.00	0.972	0.979	0.991	0.996	0.997	0.998	0.998	0.998	1.000	1.000	0.999	0.999	0.998	0.996	0.992	0.994	0.988	0.976	1.008
Weighted average																			
0.25	0.831	0.778	0.825	0.886	0.933	0.956	0.976	1.004	1.008	1.000	0.995	0.977	0.951	0.914	0.861	0.768	0.617	0.606	0.782
0.50	0.632	0.609	0.660	0.762	0.841	0.899	0.946	0.980	0.998	1.000	0.989	0.967	0.926	0.875	0.805	0.690	0.532	0.487	0.668
1.00	0.546	0.580	0.645	0.753	0.830	0.895	0.943	0.974	0.995	1.000	0.999	0.972	0.937	0.880	0.803	0.691	0.541	0.472	0.581
2.00	0.584	0.579	0.658	0.759	0.835	0.896	0.942	0.974	0.994	1.000	0.994	0.972	0.938	0.884	0.810	0.704	0.563	0.486	0.593
5.00	0.600	0.607	0.688	0.781	0.851	0.906	0.950	0.979	1.003	1.000	0.998	0.980	0.945	0.894	0.822	0.729	0.614	0.530	0.617
10.00	0.812	0.677	0.764	0.802	0.863	0.905	0.944	0.967	0.988	1.000	0.985	0.982	0.934	0.906	0.843	0.770	0.666	0.605	0.652

Table 6
$\phi_{an}(r)$ and $\bar{\phi}_{an}$ or all nine photon energies with their weighted average based on abundances from Table 1[a]

r (cm)	20.074	20.216	22.717	23.312	39.755	62.51	294.95	357.46	497.054	Weighted average
0.25	1.252	1.254	1.271	1.287	1.316	1.331	1.376	1.379	1.384	1.257
0.30	1.114	1.116	1.136	1.140	1.185	1.203	1.248	1.252	1.258	1.119
0.35	1.046	1.048	1.068	1.072	1.116	1.135	1.176	1.179	1.181	1.050
0.40	0.998	0.999	1.021	1.025	1.073	1.086	1.126	1.127	1.129	1.002
0.50	0.957	0.959	0.980	0.985	1.029	1.047	1.078	1.079	1.088	0.962
0.60	0.931	0.932	0.953	0.956	1.004	1.016	1.050	1.054	1.056	0.935
0.75	0.912	0.914	0.935	0.940	0.988	1.005	1.032	1.034	1.038	0.917
1.00	0.898	0.899	0.923	0.927	0.972	0.986	1.015	1.017	1.019	0.903
1.25	0.893	0.895	0.917	0.922	0.968	0.981	1.004	1.007	1.010	0.899
1.50	0.891	0.893	0.916	0.920	0.967	0.980	1.002	1.005	1.007	0.897
1.75	0.890	0.892	0.915	0.919	0.966	0.979	1.001	1.003	1.005	0.896
2.00	0.889	0.891	0.914	0.918	0.967	0.978	0.999	1.001	1.003	0.895
2.50	0.889	0.890	0.914	0.918	0.967	0.978	0.997	0.999	1.000	0.895
3.00	0.889	0.890	0.915	0.919	0.967	0.979	0.996	0.997	0.999	0.896
4.00	0.889	0.890	0.915	0.919	0.968	0.981	0.995	0.997	0.999	0.897
5.00	0.889	0.891	0.915	0.919	0.970	0.982	0.995	0.997	0.998	0.898
7.00	0.891	0.892	0.916	0.920	0.971	0.984	0.994	0.996	0.998	0.903
10.00	0.892	0.893	0.918	0.922	0.972	0.986	0.994	0.995	0.997	0.917
$\bar{\phi}_{an}$	0.892	0.893	0.916	0.921	0.968	0.980	1.002	1.004	1.007	0.899

[a] Note that this average is differs slightly from the weighted sum of each integral of each $\phi_{an}(r)$ and $\bar{\phi}_{an}$ since weighting was performed on the absorbed energy from each of the nine photon sources, not the ratio of absorbed doses. Upon dividing each of the nine $\phi_{an}(r)$ results by their respective $\bar{\phi}_{an}$, the $\phi_{an}(r)/\bar{\phi}_{an}$ data became independent of photon energy and was readily fit to Eq. (1).

Table 7
^{103}Pd 1-D anisotropy functions and anisotropy constants for the NASI MED3633 and Theragenics Model 200 sources[a]

	MED3633	MED3633	MED3633	Model 200
r (cm)	Wallace and Fan (1999)	Li et al. (2000)	This work	TG-43
0.25			1.257	
0.30			1.119	
0.35			1.050	
0.40			1.002	
0.50			0.962	
0.60			0.935	
0.75			0.917	
1.00	0.954	0.927	0.903	0.921
1.25			0.899	
1.50			0.897	0.889
1.75			0.896	
2.00	0.912	0.919	0.895	0.820
2.50			0.895	
3.00	0.971	0.916	0.896	0.834
4.00	0.971	0.927	0.897	
5.00	0.928	0.917	0.898	0.888
10.00			0.917	
$\bar{\phi}_{an}$	0.948	0.925	0.899	0.903

[a] All values for $\bar{\phi}_{an}$ were obtained by using a $1/r^2$ weighting for $\phi_{an}(r > 1)$ data.

errors $<1\%$.

$$\frac{\phi_{an}(r)}{\bar{\phi}_{an}} = e^{(6.53r)^{-2.3}}. \quad (1)$$

This type of coincident behavior has been previously demonstrated by Rivard (2000) for 3-D characterization (r, L, diam) of the geometry function on the transverse-plane where geometry functions for sources with varying active lengths collapsed to a single function when examining dimensionless distance. Table 7 presents the MED3633 weighted average $\phi_{an}(r)$ and $\overline{\phi}_{an}$ values for comparison with results by Wallace and Fan (1999), Li et al. (2000), and TG-43 by Nath et al. (1995). Results generally demonstrated better than 5% agreement over all radii.

4. Summary

Using an energy discretization technique to discern the energy dependence of various TG-43 dosimetry parameters, good agreement was obtained upon comparing weighted average results with those obtained by other investigators for the MED3633 ^{103}Pd source. In addition to this clinically relevant example, energy dependence of $g(r)$ and Λ was assessed over the 50–661.6 keV photon energy range. Comparisons of these results with those obtained by others also demonstrated good agreement. The impact of encapsulation on $g(r)$ and Λ was minimal, and decreased as energy increased. As expected, anisotropy also decreased as energy increased. An energy-independent equation for $\phi_{an}(r)/\bar{\phi}_{an}$ was derived for the MED3633 ^{103}Pd source, and may be extended to include other brachytherapy source types or radioisotopes.

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