TECHNICAL REPORT

A semi-analytic approach to determine dose rate constant of brachytherapy sources in compliance with AAPM TG 60 formalism

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Abstract

Values of dose rate constant (DRC) in compliance with AAPM TG 60 formalism recommended for intravascular brachytherapy (IVBT) were calculated for different point isotropic mono-energetic photon sources in the energy range E = 20-1000 keV using a semi-analytic model. Based on these DRC values, DRC of some existing models of ^{192}Ir and ^{125}I brachytherapy sources were then calculated using (1) bare energy spectra and (2) a single energy parameter which represents mean energy (photon number weighted or air-kerma weighted) for bare and actual sources or the most probable energy of the spectra (energy line with the highest probability of emission) of the investigated sources (^{192}Ir and ^{125}I). Applicability of the semi-analytic approach was examined by also computing the values of DRC of the investigated sources using MCNP Monte Carlo simulation code (Version 3.1) that involved modeling of the sources accurately. A comparison of values of DRC resulting from MCNP calculations with those resulting from the semi-analytic approach showed that for ^{192}Ir sources the agreement was within 0.40 % and for ^{125}I sources it was within 2.3 %.

Key words dose rate constant, semi-analytic approach, brachytherapy, Monte Carlo method, MCNP

Introduction

Accurate brachytherapy dosimetry requires the knowledge of dose rate constant (DRC) as DRC is one of the key parameters of the dose calculation protocols, AAPM TG 43[1] and AAPM TG 60[2], recommended for conventional brachytherapy and intravascular brachytherapy (IVBT) applications, respectively. For conventional brachytherapy, DRC should be determined at r = 1 cm from the source centre along the transverse axis of the source whereas for IVBT it should be determined at r = 0.2 cm. A number of publications have been devoted to dosimetry studies of gamma emitting seeds and wires and are discussed in detail in the literature[1,2]. It may be noted that ^{125}I, ^{192}Ir and ^{103}Pd are the possible photon emitting radionuclides recommended for IVBT applications[2]. Recently, Wang and Li[3] have reported dose parameters in compliance with AAPM TG 60 formalism[2] recommended for IVBT for a stainless steel (SS) encapsulated ^{192}Ir source.

More recently, Chen and Nath[4] have proposed a semi-analytic approach to determine DRC of ^{125}I, ^{103}Pd, ^{192}Ir and ^{169}Yb brachytherapy sources in compliance with AAPM TG 43 formalism[1]. For the numerical calculation of DRC, the authors used energy-absorption build-up factors in water published by Angelopoulos et al[5] and the investigated sources were assumed to be point isotropic. The present study employs a similar approach[4], but derives DRC in compliance with AAPM TG 60 formalism[2], for some existing models of ^{125}I and ^{192}Ir sources. The energy-absorption build-up factors in water (at r = 0.2 cm) required for the numerical calculation of DRC in the present study were generated by using Monte Carlo method. In order to examine the applicability of this approach we also computed the values of DRC for the investigated sources using the Monte Carlo method that involved modeling of the sources accurately. The well-established coupled neutron and photon Monte Carlo simulation code MCNP (Version 3.1)[6] was used in the study. The MCNP code includes a geometric modeling system that allows the source and calculation geometry to be modeled.

Materials and methods

Benchmark study

The applicability of MCNP simulation code[6] to various photon energies was checked in the present study by

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calculating the values of DRC (in units of $cGyh^{-1}U^{-1}$; 1 U = 1 $cGycm^2h^{-1}$) in compliance with AAPM TG 43 formalism[1], for various point isotropic mono-energetic photon sources in the energy range E = 20-1000 keV, and also for brachytherapy sources MicroSelectron ^{192}Ir HDR (old version) and Pharma Seed^{TM} ^{125}I seed (model BT-125-I). A comparison of our DRC values obtained for E = 20-1000 keV with those reported by Chen and Nath[4] showed an agreement between 0.30 % and 2 %. For the MicroSelectron ^{192}Ir HDR source, we have obtained the DRC value of 1.113 ± 0.10 % against the value 1.115 ± 0.5 %, reported by Williamson and Li[7] using MCPT Monte Carlo simulation code. Similarly, for ^{125}I source (model BT-125-I), a DRC value of 0.961 ± 0.06 % obtained in the present study is in good agreement with the value 0.950 ± 3 %, reported by Popescu et al[8] using PTRAN Monte Carlo simulation code. Hence, we can conclude that MCNP[6] can satisfactorily be used for the photon energies that are considered in the present study.

Calculation of DRC using a semi-analytic model

In the present study we calculated DRC for various point isotropic mono-energetic photon sources, $\Lambda_p(E)$, in the energy range E = 20-1000 keV, by using the following general formula proposed by Chen and Nath[4]:

$$\Lambda_p(E) = \left[\mu_{en}(E)/\rho\right]_{air}^{wat} e^{-\mu(E)r} r^{-2} [B_{en}\{\mu(E)r\}]_{wat} \quad (1)$$

where $\left[\mu_{en}(E)/\rho\right]_{air}^{wat}$ is the ratio of mass-energy-absorption coefficient of water to that of air for the photon energy E, $\mu(E)$ is the linear attenuation coefficient of water in unit of cm^{-1} for E, $[B_{en}\{\mu(E)r\}]_{wat}$ is the energy-absorption build-up factor in water at position r, where r = 0.2 cm in compliance with AAPM TG 60 formalism[2]. The factors $\left[\mu_{en}(E)/\rho\right]_{air}^{wat}$ and $e^{-\mu(E)r}$ (at r = 0.2 cm) appearing in equation (1) were calculated using Hubbell and Seltzer data[9]. The factor $[B_{en}\{\mu(E)r\}]_{wat}$ at r = 0.2 cm for each E was calculated as follows:

$$[B_{en}\{\mu(E)r\}]_{wat} = [K_T(r,E)]_{wat} / [K_P(r,E)]_{wat} \quad (2)$$

where $[K_T(r,E)]_{wat}$ is the total kerma (primary + scatter) in water scored (in units of $cGyPhoton^{-1}$) in a spherical shell segment at r = 0.2 cm in a 15 cm diameter liquid water sphere using the MCNP simulation code[6] and $[K_P(r,E)]_{wat}$ is the kerma in water due to a primary photon calculated using the following analytic expression:

$$[K_P(r,E)]_{wat} = \frac{1}{4\pi r^2} k.E.\left[\mu_{en}(E)/\rho\right]_{wat} e^{-\mu(E)r} \quad (3)$$

where $\left[\mu_{en}(E)/\rho\right]_{wat}$ is the mass-energy-absorption coefficient of water for the energy E and k is the conversion factor to express $[K_P(r,E)]_{wat}$ in units of $cGyPhoton^{-1}$.

The assumption made in equation (1) is that charged particle equilibrium exists at r = 0.2 cm, so that water-kerma at r = 0.2 cm approximates the dose. This may not be the case at r = 0.2 cm for a point isotropic mono-energetic photon source of higher energy. However, for the energy spectra corresponding to the investigated brachytherapy sources, approximating water-kerma to dose at r = 0.2 cm, should not introduce significant error in the numerical calculation of DRC. It was shown by Wang and Li[3] that for radial distances greater than 1 mm from the ^{192}Ir source(c) referred to below, the approximation is good to better than 2 %. It may also be noted that in the study carried out by Angelopoulos et al[10] in respect of a new ^{192}Ir HDR VariSource (model VS2000), it was mentioned that for distances greater than 1 mm from the source, water-kerma approximates dose.

In order to enable calculation of DRC for poly-energetic point isotropic photon sources, $\Lambda_p(E)$ for the mono-energetic photons determined from equation (1) was fitted to a 6th order polynomial function of $\log_{10}(E)$:

$$\Lambda_p(E) = \sum_{j=0}^{6} a_j [\log_{10}(E)]^j \quad (4)$$

Hence, for a poly-energetic point isotropic photon source with a known energy spectrum, DRC can be calculated by using the following expression[4]:

$$\Lambda_p = \frac{\sum_i f_i E_i [\mu_{en}(E_i)/\rho]_{air} \Lambda_p(E_i)}{\sum_i f_i E_i [\mu_{en}(E_i)/\rho]_{air}} \quad (5)$$

where f_i denotes the number of photons emitted with E_i per nuclear disintegration, E_i is the energy emitted by the source in unit of MeV per photon, $[\mu_{en}(E_i)/\rho]_{air}$ the mass-energy-absorption coefficient of air[9] for the photon energy E_i and $\Lambda_p(E_i)$ is evaluated at E_i using the equation (4).

In the present study, we considered the following existing models of ^{192}Ir and ^{125}I brachytherapy sources for deriving DRC: (a) SS encapsulated MicroSelectron ^{192}Ir HDR (both old/new versions), (b) Platinum (Pt) encapsulated ^{192}Ir seed source (Alpha-Omega, Bellflower, CA), (c) SS encapsulated ^{192}Ir seed source (Best Industries, Springfield, VA), (d) Titanium (Ti) encapsulated ^{125}I seed source (model BT-125-I), and (e) Ti encapsulated ^{125}I seed source (model 6711).

The energy spectrum of ^{192}Ir considered in the Monte Carlo calculations ranges between 61.49 keV and 884.54 keV[11] and that of ^{125}I was taken from ICRP report No. 38[12].

It should be noted that equation (5) is strictly applicable to a point isotropic source. Hence, for the above-mentioned brachytherapy sources, the geometry factor (the factor accounting for the source being a line and not a point), $G(r,\pi/2)$, at r = 0.2 cm along the transverse axis of the sources needs to be taken into account for evaluating DRC. This is because $G(r,\pi/2) \neq 1/r^2$ at r = 0.2 cm, for the investigated sources. Thus, DRC for the actual brachytherapy sources considering the bare energy spectra, Λ_{spm}, can be calculated using the following equation:

$$\Lambda_{spm} = \Lambda_p G(r = 0.2cm, \pi/2) r^2 \quad (6)$$

It may be noted that evaluation of Λ_{spm} involves equations (4) and (5). The value of $[\mu_{en}(E_i)/\rho]_{air}$ at each E_i required for numerical calculation of equation (5) was calculated in the present study by using the polynomial coefficients, b_i,

($\log[\mu_{en}(E)/\rho]_{air} = \sum_{i=0}^{8} b_i[\log_{10}(E)]^i$) reported by Chen and Nath[4].

An easier estimation of DRC was also obtained in the present study without involving detailed energy spectra i.e. just by using a single energy parameter representing either mean energy (photon number weighted, E_N, or air-kerma weighted, E_{AK}, emitted from the actual sources) as described by Chen and Nath[4], or the most probable energy of the spectrum (energy line with the highest probability of emission), E_{MPE}, as considered in the present study, as follows:

$$\Lambda_{E^*} = \Lambda_p(E^*)G(r = 0.2cm, \pi/2)r^2 \quad (7)$$

Here $\Lambda_p(E^*)$ is evaluated at E^* using the relation (4) and E^* refers to E_N or E_{AK} or E_{MPE}, as the case may be. We used E_{MPE} = 27.47 keV for ^{125}I (50.68 % of the total emission) and E_{MPE} = 316.51 keV for ^{192}Ir (36.94 % of the total emission).

The mean energies, E_N and E_{AK} corresponding to the bare and the actual investigated sources were calculated (using MCNP code) from the following relations, respectively:

$$E_N = \int E\phi(E)dE \Big/ \int \phi(E)dE \quad (8)$$

$$E_{AK} = \int E^2\phi(E)[\mu_{tr}(E)/\rho]_{air}dE \Big/ \int E\phi(E)[\mu_{tr}(E)/\rho]_{air}dE \quad (9)$$

where E is the energy of the photon; $\phi(E)$ is photon number per unit energy interval; and $[\mu_{tr}(E)/\rho]_{air}$ is mass-energy transfer coefficient of air[9] for the energy E.

Computation of DRC involving accurate modeling of sources

Applicability of the semi-analytic model was examined by computing DRC of the investigated sources using MCNP simulation code, which involved modeling of the sources accurately. Computation of DRC using MCNP, Λ_{MCNP}, needed computation of the following:

(a) dose rate at r = 0.2 cm along the transverse axis of the sources, D(r = 0.2 cm, π/2), in a 15 cm diameter liquid water sphere, and

(b) air-kerma strength in free space, S_k , along the transverse axis of the sources in a 500 cm diameter void sphere.

Λ_{MCNP} was then calculated according to the following definition[2]:

$$\Lambda_{MCNP} = \frac{D(r = 0.2cm, \pi/2)}{S_K} \quad (10)$$

Both D(r = 0.2 cm, π/2) and S_k were calculated for content source activity of A_c = 1 Bq.

For the sources investigated the basic sizes and materials of the core and capsules (encapsulation) used in the Monte Carlo calculations were taken as follows: old version of MicroSelectron ^{192}Ir HDR source as described by Williamson and Li[7], new version of MicroSelectron ^{192}Ir HDR source as described by Daskalov et al[13], Pt encapsulated ^{192}Ir seed source as described in the AAPM TG 43 report[1], SS encapsulated ^{192}Ir seed source as described by Wang and Li[3], Ti encapsulated ^{125}I (model 6711) as described by Williamson[14] and Ti encapsulated ^{125}I (model BT-125-I) as described by Popescu et al[8].

In the Monte Carlo calculations between 1 x 10^7 and 4 x 10^7 photon histories were simulated and the photon cut-off energy was chosen at 5 keV. The statistical uncertainties resulting from MCNP calculations lay between ±0.01% and ±0.07% (relative standard error expressed as % corresponding to 1 σ of the mean). In the case of ^{125}I sources contribution from Ti characteristic K x-rays (4.5 keV) resulting from photoelectric absorption of primary ^{125}I x-rays in the Ti capsule was suppressed for the numerical calculation of DRC, which is in accordance with the air-kerma strength 1999 standard, $S_{k,1999std}$, for ^{125}I sources[15].

Results and discussion

Air-kerma strength and mean energy

Table 1 presents the values of air-kerma strength per unit content source activity, S_k/A_c (in units of UBq^{-1}) and mean energy (E_N and E_{AK}) calculated for the investigated sources. Also shown in this Table are the values of S_k/A_c published by Borg and Rogers[16] for ^{192}Ir sources. The values of S_k/A_c and mean energy presented for the ^{125}I sources (models BT-125-I and 6711) excluded the contribution from Ti characteristic K x-rays. The contribution from this x-ray was found to be nearly 20 % and 18.7 % of the total S_k/A_c of the models BT-125-I and 6711, respectively.

The small variation in the mean energies of a given source with source type is due to change in the attenuation and scattering properties of primary photons with source materials (source core and encapsulation).

Energy dependence of DRC of point sources

The energy dependence of $\Lambda_p(E)$ ((equation (1)) is due to the behaviour of three contributing quantities to $\Lambda_p(E)$ namely $[B_{en}\{\mu(E)r\}]$, $[\mu_{en}(E)/\rho]_{air}^{wat}$, and $e^{-\mu(E)r}$. Table 2 presents values of the product of these three contributing quantities to $\Lambda_p(E)$ for E = 20-1000 keV. Also presented in this Table are the actual and fitted values of $\Lambda_p(E)$ determined from equation (1) and equation (4), respectively. It may be noted that the values in column 4 of Table 2 are calculated using the polynomial coefficients, a_j, presented in Table 3. The error introduced in the fitting (which is responsible for the differences between the DRCs for the same energy in Table 2) varied between 0.02 % and 0.33 %. It is observed that except for the energy E = 20 keV, the product of $e^{-\mu(E)r}$, $[B_{en}\{\mu(E)r\}]_{wat}$ and $[\mu_{en}(E)/\rho]_{air}^{wat}$ has yielded a value greater than unity and reached a maximum value of 1.1291 for E = 100 keV. The factor r^{-2} has the value of 25. Hence, the value of $\Lambda_p(E)$ is always greater than 25 for E > 20 keV and has a maximum value of 28.228 for E = 100 keV.

Applicability of semi-analytic model

Table 4 presents the values of DRC of the investigated brachytherapy sources resulting from the semi – analytic

Source type	Air-kerma strength per Bq, S_k/A_c		Mean energy (keV)	
	Present work X10^{-8} UBq^{-1}	[a] Published values X10^{-8} UBq^{-1}	Number weighted, E_N	Air-kerma weighted, E_{AK}
^{192}Ir Sources:				
Bare source	10.92	10.88	365	398.61
MicroSelectron (old)	9.85	9.77	358.37	398.11
MicroSelectron (new)	9.79	9.70	358.93	398.91
Alpha-Omega	10.02	9.92	358.59	398.49
Best Industries	10.73	10.68	360.26	396.71
^{125}I Sources:				
Bare Source	3.53		28.40	28.14
Model BT-125-I	2.04		27.14	26.20
Model 6711	2.12		27.27	26.54

[a]Borg and Rogers[16]

Table 1. *Values of air-kerma strength per unit content source activity, S_k/A_c, and mean energy (E_N and E_{AK}) presented for the investigated sources (statistical uncertainties lay between ±0.03% and ±0.06%). Also presented are the published values of S_k/A_c for ^{192}Ir sources (all values have statistical uncertainty of ± 0.02 which is an absolute value corresponding to 1 σ of the mean).*

E (keV)	$e^{-\mu(E)r}[B_{en}\{\mu(E)r\}][\mu_{en}(E)/\rho]_{air}^{wat}$	Actual DRC Equation (1)	Fitted DRC Equation (4)
20	0.9760	24.401	24.418
30	1.0581	26.451	26.366
40	1.0834	27.086	27.147
50	1.0995	27.488	27.559
60	1.1114	27.786	27.806
80	1.1264	28.159	28.065
100	1.1291	28.228	28.170
150	1.1246	28.115	28.174
200	1.1211	28.027	28.069
300	1.1143	27.857	27.864
400	1.1115	27.788	27.755
500	1.1103	27.757	27.721
600	1.1086	27.715	27.725
800	1.1078	27.695	27.749
1000	1.1084	27.710	27.688

Table 2. *Values of the product of three contributing quantities and DRC presented for various mono - energetic point isotropic photon sources.*

j	Coefficient a_j
0	-361.14766
1	1073.1006
2	-1253.91758
3	787.11636
4	-277.61796
5	51.85025
6	-3.99164

Table 3. *Coefficients for the polynomial fit of $A_p(E)$*

model (equations (6) and (7)) and accurate modeling of the sources using MCNP (equation (10)) and also the values of geometry factor, G(r, π/2) at r = 0.2 cm. It was observed that the values of DRC calculated for ^{192}Ir sources using E_N and E_{AK} of bare ^{192}Ir source in equation (7) are indistinguishable from the corresponding values presented in Table 4 (based on E_N and E_{AK} of the actual ^{192}Ir sources). This is because DRC is almost independent of energy in the range E = 300–1000 keV (Table 2). However, the use of E_N and E_{AK} of bare ^{125}I sources in equation (7) yielded slightly larger DRC values (21.98 and 21.95 respectively, for model BT-I-125 and 22.42 and 22.39 respectively, for model 6711) than those presented in Table 4 (based on E_N and E_{AK} of the actual ^{125}I sources). This is because DRC is sensitive to energy in the energy range E = 20-30 keV (Table 2). A comparison of DRC values resulting from the semi-analytic approach and those resulting from MCNP showed that for ^{192}Ir sources the agreement was within 0.40 % and for ^{125}I

Geometry factor	Geometry factor G(r=0.2 cm,π/2)	Semi-analytic model Eqn (6) using bare spectrum	Eqn (7) using E_N	E_{AK}	E_{MPE}	Accurate modeling Eqn (10) using MCNP
^{192}Ir Sources:						
MicroSelectron (old)	20.5380	22.84	22.82	22.80	22.87	22.84
MicroSelectron (new)	20.3560	22.63	22.62	22.60	22.67	22.54
Alpha-Omega	21.4500	23.85	23.84	23.82	23.89	23.76
[a]Best Industries	21.4500	23.85	23.84	23.82	23.89	23.85
^{125}I sources:						
Model BT-125-I	20.9944	21.94	21.83	21.71	21.87	22.23
Model 6711	21.4137	21.94	22.29	22.19	22.31	22.68

[a]Published value is 23.76 ± 0.06 (Wang and Li)[3]

Table 4. *DRC of investigated brachytherapy sources (statistical uncertainties lay between ±0.04% and ±0.07%).*

sources it was within 2.3 %. It is interesting to note that even a single energy parameter E_N or E_{AK} (corresponding to either the bare or the actual source) or E_{MPE} of the spectra is sufficient to determine DRC. It may be noted that the DRC values obtained in the present study in respect of a SS encapsulated ^{192}Ir source (Best Industries) showed an excellent agreement with the value 23.76 ± 0.06, reported by Wang and Li[3] using EGS4/PRESTA Monte Carlo simulation code.

Conclusion

The semi-analytic model described in the present study has been found to be applicable for deriving DRC of some existing models of ^{192}Ir and ^{125}I brachytherapy sources in compliance with AAPM TG 60 formalism recommended for IVBT applications. It is observed that a single energy parameter representing mean energy (photon number weighted or air-kerma weighted) of either the bare or the actual source or the most probable energy of the spectrum is sufficient to determine DRC. We conclude that this approach would be an efficient tool for an accurate evaluation of DRC of photon emitting brachytherapy seeds with energy spectra in the range 20-1000 keV when the assumption of water - kerma approximating the dose at r = 0.2 cm holds good.

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