Dose rate constants for ^{125}I, ^{103}Pd, ^{192}Ir and ^{169}Yb brachytherapy sources: an EGS4 Monte Carlo study

1998 Phys. Med. Biol. 43 1557

(http://iopscience.iop.org/0031-9155/43/6/014)

Phys. Med. Biol. **43** (1998) 1557–1566. Printed in the UK PII: S0031-9155(98)88552-7

Dose rate constants for ^{125}I, ^{103}Pd, ^{192}Ir and ^{169}Yb brachytherapy sources: an EGS4 Monte Carlo study

Ernesto Mainegra†, Roberto Capote‡ and Ernesto López

Departamento de Física, Centro de Estudios Aplicados al Desarrollo Nuclear, Calle 30#502, e/5ta y 7ma, Miramar, La Habana, Cuba

Received 20 October 1997, in final form 12 January 1998

Abstract. An exhaustive revision of dosimetry data for ^{192}Ir, ^{125}I, ^{103}Pd and ^{169}Yb brachytherapy sources has been performed by means of the EGS4 simulation system. The DLC-136/PHOTX cross section library, water molecular form factors, bound Compton scattering and Doppler broadening of the Compton-scattered photon energy were considered in the calculations. The absorbed dose rate per unit contained activity in a medium at 1 cm in water and air-kerma strength per unit contained activity for each seed model were calculated, allowing the dose rate constant (DRC) Λ to be estimated. The influence of the calibration procedure on source strength for low-energy brachytherapy seeds is discussed. Conversion factors for ^{125}I and ^{103}Pd seeds to obtain the dose rate in liquid water from the dose rate measured in a solid water phantom with a detector calibrated for dose to water were calculated. A theoretical estimate of the DRC for a ^{103}Pd model 200 seed equal to 0.669 ± 0.002 cGy h^{-1} U^{-1} is obtained. Comparison of obtained DRCs with measured and calculated published results shows agreement within 1.5% for ^{192}Ir, ^{169}Yb and ^{125}I sources.

1. Introduction

Accurate brachytherapy dosimetry requires knowledge of the dose rate constant (DRC) Λ as well as the relative dose distribution. In the past ten years experimental and theoretical studies on the dosimetry of brachytherapy sources have been undertaken intensively. Nath *et al* (1995) reviewed studies for ^{125}I seed models 6711 and 6702, ^{192}Ir with stainless steel cladding and the ^{103}Pd seed model 200. As was stated, there is still an open question concerning the DRC value of the ^{103}Pd seed model 200, because 'the Monte Carlo simulations of Williamson (1991) did not accurately reproduce the measured DRC for ^{103}Pd sources in solid water'. Moreover there is an 7.5% disagreement between two available measurements of this quantity (Meigooni *et al* 1990, Chiu-Tsao and Anderson 1991). ^{169}Yb has recently been introduced for brachytherapy applications as an alternative to radioisotopes such as ^{192}Ir, and possibly ^{125}I and ^{103}Pd (Battista and Mason 1994). The appropriate value of the DRC for ^{169}Yb seeds is also controversial. Piermattei *et al* (1992, 1995), MacPherson and Battista (1995) and Perera *et al* (1994) reported measured DRCs of 1.52, 1.34, 1.25 and 1.21 cGy h^{-1} U^{-1} respectively, covering a range of more than 25%. More recently, Das *et al* (1997) reported a measured value of 1.21 cGy h^{-1} U^{-1}.

In the present study we use a theoretical approach to characterize the distribution of absorbed dose around commercially available ^{125}I seed models 6711 and 6702, ^{192}Ir platinum

† E-mail address: mainegra@ceaden.edu.cu
‡ E-mail address: rcapote@infomed.sld.cu

and stainless-steel covered 3 mm seeds, ^{169}Yb seed models X1267 and 8, and the ^{103}Pd seed model 200. Monte Carlo calculations were performed using the EGS4 code system (Nelson *et al* 1985, Nelson and Rogers 1988). The most recent photon cross section compilation, the DLC-136/PHOTX cross section library (RSIC 1993) contributed by the National Institute of Standards and Technology (NIST) and implemented for EGS4 use by Sakamoto (1993), was employed in the calculations. Bound Compton scattering and Doppler broadening of the Compton-scattered photon energy were considered in the calculations by including the Low-Energy Photon-Scattering (LSCAT) expansion for the EGS4 Code (Namito *et al* 1994, 1995). Molecular form factors from Morin (1982) for coherent scattering in water were also included. In addition, our Monte Carlo EGS4 user code was used to calculate the air-kerma strength per unit activity for each seed model, allowing clinically relevant absolute absorbed dose rates in water to be estimated. The dose rate constant (DRC) Λ for a specific source design is defined as the dose rate to water medium per unit air-kerma strength S_k at 1 cm from the source centre on the transverse axis in a water phantom (ICWG 1990). This quantity is fundamental in clinical dosimetry calculations and includes the effects of source geometry, the spatial distribution of radioactivity, encapsulation and self-filtration within the source and scattering in water surrounding the source. The numerical value of this quantity also depends on the standardization measurements to which the air-kerma strength calibration of the source is traceable.

This paper presents DRC values for seven types of commonly used brachytherapy seeds derived from extensive Monte Carlo calculations. The air-kerma strengths S_k were evaluated in a vacuum simulation (excluding all source spectrum radiation below 10 keV and following photons inside the detector until their energy dropped under the PCUT value of 1 keV) except for the ^{125}I 6711 and 6702 seeds. For the latter S_k was calculated by simulating the free-air chamber calibration measurements performed at NIST (Loftus 1984). Radial dose functions and anisotropy distributions in water and solid water derived from the present calculations will be presented in an additional paper.

2. Materials and methods

2.1. Dose calculation formalism

We follow the dose calculation formalism proposed originally by the Interstitial Brachytherapy Collaborative Working Group (ICWG 1990) to predict the two-dimensional dose distribution around a cylindrically symmetric source using only measured data, although it can be equally well used with theoretically calculated data. This formalism was expanded to all brachytherapy sources by the AAPM Radiation Therapy Committee Task Group no 43 (Nath *et al* 1995). In this formalism the symbol S_k denotes the quantity air-kerma strength, a measure of brachytherapy source strength which is specified in terms of air-kerma rate at the point along the transverse axis of the source ($\theta_0 = \pi/2$) in free space. It is defined as the product of air-kerma rate at a calibration distance, d, in free space $K_r(d)$, measured along the transverse bisector of the source, and the square of the distance (d^2):

$$S_k = \dot{K}_r(d)d^2. \tag{1}$$

The dose rate constant, Λ, is the dose rate per unit source strength at a reference point taken here to be 1 cm from the source centre on its transverse bisector:

$$\Lambda = \dot{D}(r_0, \theta_0)/S_k. \tag{2}$$

For a definition or more detailed description of the formalism the reader is referred to the Task Group 43 report (Nath *et al* 1995) or the paper by Williamson and Nath (1991).

2.2. Brachytherapy sources and phantoms

For the sources studied the basic sizes and materials of the core and capsules (cladding) used in the calculations were taken as follows: ^{125}I and stainless steel covered ^{192}Ir seeds as described by Williamson (1991), Pt covered ^{192}Ir wires (0.1 mm thick cladding) as described by Nath *et al* (1995), ^{103}Pd seed mod.200 as described by Chiu-Tsao and Anderson (1991), ^{169}Yb model X1267 as described by Piermattei *et al* (1995) and ^{169}Yb mod.8 as described by Das *et al* (1997). Energy spectra of source photons are taken from the NUDAT database (BNL 1996). In this study a cylindrical phantom was used. A brachytherapy source was located in the centre of the phantom with its long axis coincident with the phantom central axis. Phantom materials included air, water and solid water. The composition by weight of solid water was taken from Williamson (1991) and is stated to be hydrogen 8.0%, carbon 67.22%, nitrogen 2.4%, oxygen 19.84%, calcium 2.32%, and chlorine 0.13%. Its density was taken as 1.015 g cm^{-3}. An additional calculation, for low-energy seeds, with a liquid water thin ring detector embedded in a solid water phantom was done to obtain the solid water to water correction factor. The dose calculation grid was so dimensioned that on the transverse and longitudinal axes a width of 0.02 cm under 0.1 cm, between 0.1 cm and 2.0 cm a width of 0.1 cm, beyond 2 cm and under 10 cm a width of 0.5 cm and a width of 2 cm over 10 cm were used.

2.3. Monte Carlo calculations

The EGS4 Monte Carlo system (Nelson *et al* 1985, Nelson and Rogers 1988) has been extensively adopted by workers in medical physics. It is a well documented and tested public domain code. The EGS4 system consists of the data preprocessing code PEGS4 and the particle transport code EGS4. Simulated photon interactions included pair production, photoelectric absorption, Compton and Rayleigh scattering and production of K-edge characteristic x-rays. In addition, a user code should be written by the user to initiate geometry, scoring, inputs and outputs. In our work user code DOSRZ (Bielajew and Rogers 1989) was employed in which a plane-cylinder geometry model is provided. In order to incorporate algorithms for the binding correction to Compton scattering (Namito *et al* 1994, 1995), for consideration of molecular water form factors (Morin 1982, Leliveld *et al* 1995) and to simulate the complex geometric structure of the seeds in detail all EGS4 codes were modified.

An analogue dose estimator was employed, since we adopted the original scheme of scoring deposited energy in each shell and averaging it over the mass of the cylindrical shell. Electrons were not transported and the cut-off energy for photon transport in all calculations was 1 keV (PCUT = 0.001 MeV). The 'importance sampling' technique was used, in which photons were not allowed to undergo photoelectric absorption, but were forced to scatter at each interaction site. The resulting bias in the dose estimator was removed by reducing the weight of the scattered photon by the branching ratio $(\sigma_{\mathrm{Compton}}+\sigma_{\mathrm{pair}})/(\sigma_{\mathrm{Compton}}+\sigma_{\mathrm{pair}}+\sigma_{\mathrm{photo}})$ (coherent scattering in the EGS4 system is treated in an independent way as a correction) and scoring a deposited energy equal to the photon energy times the initial photon weight reduced by the ratio $\sigma_{\mathrm{photo}}/(\sigma_{\mathrm{Compton}}+\sigma_{\mathrm{pair}}+\sigma_{\mathrm{photo}})$. Photon histories were terminated by Russian roulette if their relative weights fell below a cut-off of 0.05 for water/solid water simulations. For air-kerma calculations, particles heading to the detector were split into 100 daughter particles with weight 1/100; in any other case, particles emerging from the source were discarded. Russian roulette was played after splitting photons and histories were terminated if their relative weight felt below a cut-off of 0.005. The ring detector region for vacuum simulations was located 100 cm away from the source in the transverse axis direction. The inner and outer radii of the ring were 99.5 and 100.5 cm respectively and height of the ring was equal to 1 cm. The outer diameter of the simulation geometry is 40 cm for liquid/solid water and for air-kerma strength S_k calculations in air of the ^{125}I seed models 6702 and 6711 an extra air ring of 10 cm was set behind the detector. Statistical uncertainty in all regions of interest for DRC calculations was below 0.5% for water and solid water media and below 1% for an air medium. All quoted calculation errors are only statistical within one standard deviation.

3. Results and discussion

3.1. ^{125}I seeds

Table 1 compares our theoretically calculated DRC with previously published results. DRC values obtained by us using the original photon cross section compilation (DLC-15) supplied with EGS4 and those obtained by Williamson (1988) using photon cross section compilation DLC-7F, are also reported. They show excellent agreement and reinforce the need to use up-to-date photon cross section libraries, since they can affect DRC values. As mentioned before, air-kerma strength was calculated by simulating the free-air chamber calibration measurements performed at NIST (Loftus 1984). From those computed values of S_k, correction factors for attenuation in air of 0.001 490 cm^{-1} and 0.001 486 cm^{-1} were obtained for the seed models 6702 and 6711 respectively in excellent agreement with the 0.0015 cm^{-1} value measured by Loftus (1984) and the value of 0.0014 cm^{-1} calculated by Williamson (1991).

Table 1. Dose rate constants for ^{125}I seeds.

Author (cross section library)	Air-kerma strength	Phantom material	Λ(cGy h^{-1} U^{-1}) model 6702	Λ(cGy h^{-1} U^{-1}) model 6711
Williamson (1988) (DLC-7F)	S_k in air	Atomic water	0.962	0.909
This study (DLC-15)	**S_k in air**	**Atomic water**	**0.960 ± 0.040**	**0.889 ± 0.010**
	S_k in vacuum	**Atomic water**	**0.826 ± 0.020**	**0.726 ± 0.010**
Mason *et al* (1992)	S_k in vacuum	Atomic water	0.823 ± 0.040	—
	S_k in air	Atomic water	0.933 ± 0.040	—
Wang and Sloboda (1996) (DLC-99)	S_k in air	Atomic water	—	0.895 ± 0.004
Williamson (1991) (DLC-99)	S_k in air	Liquid water	0.932	0.877
		Solid water	0.899	0.841
This study (DLC-136)	**S_k in air**	**Liquid water**	**0.933 ± 0.002**	**0.888 ± 0.002**
		Solid water	**0.908 ± 0.004**	**0.858 ± 0.004**
Piermattei *et al* (1988)	Measurements	MS11(water)	—	0.890
Luxton *et al* (1990)	Measurements	PMMA	—	0.984
Luxton (1994) (correction)	—	Liquid water	—	0.879
NCI contract group				
Nath *et al* (1990)	Measurements	Solid water	0.903	0.855
Weaver *et al* (1989)	Measurements	Solid water	0.923	0.832
Chiu-Tsao *et al* (1990)	Measurements	Solid water	0.932	0.853
ICWG average	—	Solid water	0.919	0.847

Applying air attenuation correction factors and averaging over all distances, we obtained the DRC values showed in table 1. Calculated DRC values for the solid-water medium agree with the average of the ICWG measurements within 1.5% and 1.4% and with Williamson's (1991) calculations within 1.2% and 0.01% for the model 6711 and 6702 seeds respectively. In addition, our calculations are in agreement with Luxton's (1994) corrected DRC value obtained from Lucite-medium measurement (Luxton 1990) for the 6711 seed, agreeing within 1.0%.

It is known that NIST air-kerma strength standard for ^{125}I seeds is currently under revision since it overestimates the penetrating component of the air-kerma strength by 9–10% because the air attenuation corrections were allowed to be dominated by the Ti K-edge characteristic x-rays (Williamson 1991). We have obtained a DRC value of 0.826 cGy h^{-1} U^{-1} for the ^{125}I model 6702 seed, using air-kerma strength calculated in a vacuum. This value is in excellent agreement to within 0.4% with the one obtained by Mason *et al* (1992) and should be considered a theoretical constant based on a fundamental geometry with a vacuum between the source and detector, and is fully consistent with the AAPM definition (Williamson and Nath 1991). This result confirms that the current NIST correction for air attenuation does not properly yield the air-kerma rate in free space as stated by Williamson (1991). It is worth noticing that Ti K-edge characteristic x-rays were included in our vacuum calculations as well as in Mason *et al* (1992). We performed air-kerma strength calculations for the model seed 6702 in a vacuum, neglecting characteristic x-ray production. A DRC value of 1.009 cGy h^{-1} U^{-1} was obtained agreeing within 0.7% with the 1.0017 and 1.0022 values obtained in air neglecting x-ray fluorescence by Mason *et al* (1992) and Williamson (1991) respectively. Differences between calculations simulating NIST air-kerma strength standard for ^{125}I seeds, developed by Loftus (1984), and calculations performed in a vacuum arise from the fact that 4.5 keV characteristic x-rays are attenuated rapidly in air and travel unimpeded in a vacuum.

3.2. ^{192}Ir sources

Table 2 shows measured and theoretical calculated DRC values for both types of iridium seed. The DRC values obtained in this work with either type of encapsulation are indistinguishable within given statistical uncertainties. In contrast to ^{103}Pd and ^{125}I, the Monte Carlo estimates of the ^{192}Ir DRC for liquid and solid water media are nearly identical confirming previous experimental (Meli *et al* 1988, Thomason and Higgins 1989) and theoretical studies (Williamson 1991). The agreement between Monte Carlo results and experimental data is excellent, well below the 1% limit.

3.3. ^{103}Pd seed model 200

Chiu-Tsao and Anderson (1991) published absolute dose rate distributions measured in a solid water phantom for this seed. Their data are presented as the product of distance squared and dose rate per unit source strength in units of cm^2 cGy h^{-1} mCi^{-1}. This product has the value 0.680 cm^2 cGy h^{-1} U^{-1} at a distance of 1 cm on the transverse axis. By definition this value is the measured DRC for the ^{103}Pd seed model 200 in solid water. Meigooni *et al* (1990) reported a value of DRC for ^{103}Pd equal to 0.735 ± 0.03 cGy h^{-1} U^{-1}. Both measurements were normalized by an air-kerma strength derived from the vendor's contained activity specification and deviate by 7.5%. The most likely explanation for this difference is poor reproducibility and systematic error of the vendor's activity measurement procedures. Another possible explanation for this discrepancy might be that Chiu-Tsao

Table 2. Dose rate constants for ^{192}Ir sources.

Author (Cross section library)	Air-kerma strength	Phantom material	Λ(cGy h^{-1} U^{-}1)
This study (DLC-136) 3 mm seed with SS clad	**S_k in a vacuum**	**Liquid water**	$\mathbf{1.105 \pm 0.008}$
This study (DLC-136) 3 mm ^{192}Ir wire with Pt clad	**S_k in a vacuum**	**Liquid water**	$\mathbf{1.111 \pm 0.006}$
This study (DLC-136) 1 mm ^{192}Ir wire with Pt clad	**S_k in a vacuum**	**Liquid water**	$\mathbf{1.125 \pm 0.007}$
Williamson (1991) (DLC-99)	S_k in air	Liquid water	1.110 ± 0.002
		Solid water	1.121 ± 0.003
Wang and Sloboda (1996) (DLC-99)	S_k in a vacuum	Liquid water	1.113 ± 0.001
Meisberger *et al* (1968)	Measurement	Water	1.118
NCI contract group			
Nath *et al* (1990)	Measurement	Solid water	1.120 ± 0.030
Weaver *et al* (1989)	Measurement	Solid water	1.111 ± 0.017
Chiu-Tsao *et al* (1990)	Measurement	Solid water	1.100

and Anderson (1991) used homemade solid water, which may have had a slightly different composition than the commercial material used in the Meigooni *et al* (1990) work (Nath *et al* 1995). In this study we computed absorbed dose in a liquid water detector embedded in a solid water phantom and S_k was calculated in a vacuum, considering photon emission above 10 keV and without Ti x-ray fluorescence emission. A DRC value in solid water of 0.639 ± 0.002 cGy h^{-1} U^{-1} was obtained, being 6% smaller than Chiu-Tsao's experimental value. Our above mentioned solid water result assumes a detector calibrated for dose to water. A calculation in a solid water phantom which does not consider such a calibration yielded a DRC value of 0.677 ± 0.002 cGy h^{-1} U^{-1}, agreeing with the Chiu-Tsao and Anderson (1991) experimental value within 0.4%. Calculations in a liquid water medium produced a DRC value of 0.669 ± 0.002 cGy h^{-1} U^{-1}.

We should also stress that ^{103}Pd has no air-kerma standard yet, only the vendor's 'apparent' activity constancy standard. However, its relationship to air-kerma is unknown. Therefore a direct comparison of measured and calculated absolute dose rates will be only meaningful when a standard calibration procedure is implemented.

3.4. ^{169}Yb seeds

This is one of newest brachytherapy sources in use. A number of recent studies have been performed that allow comparison of dosimetric results for ytterbium prototype seeds (Mason *et al* 1992, Perera *et al* 1994, Piermattei *et al* 1995, MacPherson and Battista 1995, Das *et al* 1997). Table 3 compares our DRC values for type 8 and X1267 sources with previously published results for a variety of prototype ^{169}Yb seed designs. The phantom material used in the measurements was solid water. For ^{169}Yb, which has average emission energy around 93 keV, solid water is, on theoretical grounds, an excellent liquid-water substitute. For air-kerma calculations in vacuum only spectral lines with energy above 10 keV were considered.

Spherical ion chambers used for ytterbium source strength calibration are made of air equivalent plastic (C552 or similar). They have a 0.5 to 1 mm wall thickness and a 2 mm build-up cap thickness, therefore they are not sensitive to photons below 10 keV. The calculated DRC values for type 8 and X1267 seeds agree with the average value 1.21 of the

Table 3. Dose rate constant for ^{169}Yb seeds.

Author (cross section library)	Air-kerma strength	Seed type	Λ(cGy h^{-1} U^{-1})
This study(DLC-136)	**S_k in vacuum** $E > 10$ keV, no Ti x-ray	**Type 8**	$\mathbf{1.170 \pm 0.010}$
This study(DLC-136)	**S_k in vacuum** $E > 10$ keV, no Ti x-ray	**Type X1267**	$\mathbf{1.191 \pm 0.007}$
Perera *et al* (1994)	Measurement	Type 6	1.250 ± 0.050
	S_k in air	Type 6	1.225 ± 0.006
Mason *et al* (1992)	S_k in vacuum	Types 4 and 5	1.190 ± 0.050
MacPherson and Battista (1995)	S_k in air	Types 6 and 8	1.250 ± 0.050
	Measurement	Type 8	1.340 ± 0.100
Piermattei *et al* (1992)	Measurement	Type 6	1.520 ± 0.090
Piermattei *et al* (1995)	Measurement	Type X1267	1.200 ± 0.050
	S_k in air	Type X1267	1.210 ± 0.050
Wang and Sloboda (1996)	S_k in vacuum	Type 8	1.171 ± 0.006
	$E > 10$ keV	Type X1267	1.194 ± 0.006
		Type 5	1.193 ± 0.005
Das *et al* (1997)	S_k in air	Type 8	1.204 ± 0.004
	Measurement	Type 8	1.210 ± 0.070

most recent measurements (Piermattei *et al* 1995, Das *et al* 1997) based on direct ionometric measurements of air-kerma strength within 1.8%, well in the statistical uncertainty limits of the calculations. In addition, our calculations are in excellent agreement with previous Monte Carlo calculations by Mason *et al* (1992), MacPherson and Battista (1995), Piermattei *et al* (1995), Wang and Sloboda (1996) and Das *et al* (1997).

3.5. Solid water to water correction factors

It is well known that the solid phantom measurements requires conversion to dose rate in a water medium from dose rate in a non-water phantom to a detector calibrated for dose to water. Uncertainties in dose conversion factors are larger in low-energy brachytherapy dosimetry for sources such as ^{125}I and ^{103}Pd, which have an average emission energy between 20 and 30 keV. Williamson (1991) had already shown such a difference on iodine seeds. Luxton (1994) used a simple model based on a point source approximation to obtain the solid phantom to water dose rate conversion factors. Employing a methodology proposed by Luxton (1994), but using realistic seed models, the correction factors needed to obtain DRC (in liquid water) from measurements in a solid water phantom with liquid water calibrated detectors were calculated. Correction factors for DRC were obtained by simulating a solid water phantom with a single ring of liquid water detector (1 mm thickness) centred at 1 cm in the transverse axis direction. Experimental data and correction factors for low-energy ^{103}Pd and ^{125}I seeds are shown in table 4.

For the ^{103}Pd seed model 200 a correction factor equal to 1.048 was used by TG43 (Nath *et al* 1995) as obtained by Williamson (1991), which is in excellent agreement with our and Luxton's (1994) values. For other values of the correction factor the overall agreement between our values and Luxton's (1994) results is also excellent. That means that solid water to liquid water correction factor practically does not depend on the internal structure of the seed, as was suggested by Luxton (1994). Moreover there is almost no dependence on the consideration of binding effects in Compton scattering and molecular interference effects

Table 4. Application of solid water phantom correction factors to published measurements of DRC for ^{125}I and ^{103}Pd brachytherapy seeds. Monte Carlo liquid water DRC obtained in this work are shown for comparison.

Seed type	Author	Measured Λ (cGy h^{-1} U^{-1})	Correction factor (this study)	Corrected Λ (cGy h^{-1} U^{-1}) (this study)	Correction factor (Luxton 1994)	Corrected Λ (cGy h^{-1} U^{-1}) (Luxton 1994)
^{125}I (6711)	Nath *et al* (1990)	0.85	1.038	0.882	$(1.056*0.913)^{-1}$ =1.038	0.882
^{125}I (6711)	Weaver *et al* (1989)	0.835	1.038	0.866	1.038	0.866
^{125}I (6711)	Chiu-Tsao *et al* (1990)	0.853	1.038	0.885	1.038	0.885
^{125}I (6711)	ICWG average	0.846	1.038	0.878	1.038	0.878
^{125}I (6711)	**This study, Monte Carlo liquid water DRC**			**0.888 (0.877 Williamson (1991))**		
^{125}I (6702)	Nath *et al* (1990)	0.90	1.028	0.925	$(1.064*0.917)^{-1}$ =1.025	0.923
^{125}I (6702)	Weaver *et al* (1989)	0.926	1.028	0.952	1.025	0.949
^{125}I (6702)	Chiu-Tsao *et al* (1990)	0.932	1.028	0.958	1.025	0.955
^{125}I (6702)	ICWG average	0.919	1.028	0.945	1.025	0.942
^{125}I (6702)	**This study, Monte Carlo liquid water DRC**			**0.933 (0.932 Williamson (1991))**		
^{103}Pd(200)	Chiu-Tsao *et al* (1991)	0.68	1.047	0.712	$(1.014*0.940)^{-1}$ =1.049	0.713
^{103}Pd(200)	Meigooni *et al* (1990)	0.735	1.047	0.769	1.049	0.771
^{103}Pd(200)	**This study, Monte Carlo liquid water DRC**			**0.669**		

in coherent scattering in water, probably because correction factors for DRC are defined at 1 cm. At this still small distance from the seed the influence of binding corrections on the dose rate is negligible as was demonstrated by Wang and Sloboda (1996).

4. Conclusions

An exhaustive evaluation of dose rate constants of commercially available ^{125}I seed models 6711 and 6702, ^{192}Ir platinum and stainless-steel covered 3 mm seeds, ^{169}Yb seed models X1267 and 8, and ^{103}Pd seed model 200 has been presented. The accuracy of a Monte Carlo EGS4 simulation in the energy range from 20 to 254 keV was validated by comparing its predictions with a large set of experimental data and theoretical calculations of well characterized ^{125}I and ^{192}Ir seeds. The agreement of our Monte Carlo calculations with experimental measurements, as well as with other Monte Carlo simulations, within 1.5% and 1% for ^{125}I and ^{192}Ir respectively, enhances confidence in the reliability of Monte Carlo simulation as a dose-computation tool, allowing us to study other, less measured, brachytherapy sources. When a new NIST standard for ^{125}I seeds correcting the influence of low-energy contaminant radiation is released, excellent agreement between experimental results in air, corrected for attenuation in air, and calculations in a vacuum should be expected.

Our DRC value for the ^{103}Pd seed model 200 calculated in a liquid water detector embedded in a solid water medium using theoretical air-kerma strength evaluated in a vacuum is equal to 0.639 ± 0.002 within 6% of the Chiu-Tsao and Anderson (1991) TLD measurements and 15% below the Meigooni *et al* (1990) value, both in solid water. In contrast, the value of 0.677 ± 0.002 cGy h^{-1} U^{-1} obtained for a solid water detector is in very close agreement with the Chiu-Tsao and Anderson (1991) experimental value. Our calculated DRC value in water is only a theoretical estimate. Comparison with experimental values can only then be done when a well defined calibration standard for this source is established.

Calculated DRC values for ^{169}Yb seeds type 8 (1.170 ± 0.010) and X1267 (1.191 ± 0.007) agree with the average value 1.21 of the most recent measurements (Piermattei *et al* 1995, Das *et al* 1997) based on direct ionometric measurements of air-kerma strength within 3%.

Correction factors needed to obtain DRC (in liquid water) from measurements in a solid water phantom with liquid water calibrated detectors were tabulated for low-energy brachytherapy seeds ^{125}I and ^{103}Pd. This correction factor practically does not depend on the internal structure of the seed and there is almost no dependence on the consideration of binding effects in Compton scattering and molecular interference effects in coherent scattering in water.

Acknowledgments

We are grateful to Professor Dr J F Williamson, Professor Dr A Piermattei, Dr M C Schell, Dr A S Meigooni, Dr A Bielajew, and Dr R Wang for useful comments and discussion of relevant problems. We also express our gratitude to Dr Y Namito who kindly provided us with the LSCAT extension to the EGS4 system.

References

Battista J and Mason D 1994 New radionuclides for brachytherapy *Brachytherapy from Radium to Optimization* ed R F Mould, J J Batterman, A A Martínez and B L Speiser (Nucletron)

BNL (Brookhaven National Laboratory) 1996 *NUDAT Database* (last update 31/01/96)

Bielajew A F and Rogers D W O 1989 *DOSRZ User Code, EGS4 Distribution Package*

Chiu-Tsao S T and Anderson L L 1991 Dose rate determination for I-125 seeds *Med. Phys.* **18** 449–52

Chiu-Tsao S T, Anderson L L, O'Brien K and Sanna R 1990 Thermoluminescent dosimetry for Pd-103 (mod.200) in solid water phantom *Med. Phys.* **17** 817–25

Das R K, Meigooni A S, Mishra V, Langton M A and Williamson J F 1997 Dosimetric characteristics of the Type 8 ytterbium-169 interstitial brachytherapy source *J. Brachytherapy Int.* **13** 1

ICWG (Interstitial Collaborative Working Group) 1990 *Interstitial Brachytherapy: Physical, Biological, and Clinical Considerations* ed L L Anderson, R Nath and K A Weaver (New York: Raven) pp 21–32

Leliveld C J, Maas J G, Bom V R and Van Eijk C W E 1995 *IEEE Medical Imaging Conf. (San Francisco, 26–28 October)*

Loftus T P 1984 Exposure standardization of iodine-125 seeds used for brachytherapy *J. Res. NBS* **89** 295–303

Luxton G 1994 Comparison of radiation dosimetry in water and in solid phantom materials for I-125 and Pd-103 brachytherapy sources: EGS4 Monte Carlo study *Med. Phys.* **21** 631–41

Luxton G, Astrahan M A, Findley D O and Petrovich Z 1990 Measurement of dose-rate from exposure calibrated I-125 seeds *Int. J. Radiat. Oncol. Phys.* **18** 1199–207

MacPherson M S and Battista J J 1995 Dose distribution and dose rate constant for new ytterbium-169 brachytherapy seeds *Med. Phys.* **22** 89–96

Mason D L D, Battista J J, Barnett R B and Porter A T 1992 Ytterbium-169: calculated physical properties of a new radiation source for brachytherapy *Med. Phys.* **19** 695–703

Meigooni A S, Sabnis S and Nath R 1990 Dosimetry of palladium-103 brachytherapy sources for permanent implants *Endocuriether. Hypertherm. Oncol.* **6** 107–17

Meli J A, Meigooni A S and Nath R 1988 On the choice of phantom material for dosimetry of Ir-192 sources *Int. J. Radiat. Oncol. Biol. Phys.* **14** 487–594

Morin L R M 1982 Molecular form factors and photon coherent scattering cross section of water *J. Phys. Chem. Ref. Data.* **11** 1091–8

Namito Y, Ban S and Hirayama H 1994 Implementation of Doppler broadening of Compton scattered photon into the EGS4 code *Nucl. Instrum. Methods* A **349** 489–94

——1995 LSCAT: Low-energy photon scattering expansion for the EGS4 code *KEK Internal Report* 95-10, National Laboratory for High Energy Physics, Tsukuba-shi, Ibaraki-ken, Japan

Nath R, Anderson L L, Luxton G, Weaver K A, Williamson J F and Meigooni A S 1995 Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group 43 *Med. Phys.* **22** 209–34

Nath R, Meigooni A S and Meli J A 1990 Dosimetry on transverse axes of I-125 and Ir-192 interstitial brachytherapy sources *Med. Phys.* **17** 1032–40

Nelson W R, Hirayama A and Rogers D W O 1985 The EGS4 system version 4 *Stanford Linear Accelerator Center Report* SLAC-265

Nelson W R and Rogers D W O 1988 *Monte Carlo Transport of Electrons and Photons* ed T M Jenkins, W R Nelson and A Rindi (New York: Plenum) pp 287–306

NUDAT 1996 *NUDAT Database* (National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY)

Perera H, Williamson J F, Zuofeng Li, Mishra V and Meigooni A S 1994 Dosimetric characteristics, air kerma strength calibration and verification of Monte Carlo simulation for a new ytterbium-169 brachytherapy source *Int. J. Radiat. Oncol. Biol. Phys.* **28** 953–70

Piermattei A, Arcovito G and Andreasi Bassi F 1988 Experimental dosimetry of I-125 new seeds (mod.6711) for brachytherapy treatments *Phys. Med.* **1** 59–70

Piermattei A, Arcovito G , Azario L, Rossi G, Soriani A and Montemaggi A 1992 Experimental dosimetry of Yb-169 prototype 6 for brachytherapy treatments *Phys. Med.* **8** 163–9

Piermattei A, Azario L, Rossi G, Soriani A, Arcovito G, Ragona R, Galelli M and Taccini G 1995 Dosimetry of Yb-169 seed model X1267 *Phys. Med. Biol.* **40** 1317–30

RSIC 1993 *Radiation Shielding Information Centre Data Package* DLC-136/PHOTOX, Photon Interaction Cross Section Library contributed by National Institute of Standards and Technology

Sakamoto Y 1993 *Proc. Third EGS4 User's Meeting in Japan (KEK Proceedings 93-15)*

Thomason C and Higgins P 1989 Radial dose distribution of Ir-192 and Cs-137 seed sources *Med. Phys.* **16** 254–7

Wang R and Sloboda R 1996 EGS4 dosimetry calculations for cylindrically symmetric brachytherapy sources *Med. Phys.* **23** 1459–65

Weaver K A, Smith V, Huang D, Barnett C, Schell M C and Ling C C 1989 Dose parameters of I-125 and Ir-192 seed sources *Med. Phys.* **16** 636–43

Williamson J F 1988 Monte Carlo evaluation of specific dose constant in water for I-125 seeds *Med. Phys.* **15** 686–94

——1991 Comparison of measured and calculated dose rates in water near I-125 and Ir-192 seeds *Med. Phys.* **18** 776–86

——1995 as stated in *Med. Phys.* **22** 215 (Nath *et al* 1995)

Williamson J F and Nath R 1991 Clinical implementation of AAPM Task Group 32 recommendations on brachytherapy source strength specification *Med. Phys.* **18** 439–48