Spectra and air-kerma strength for encapsulated ^{192}Ir sources

Jette Borg and David W. O. Rogers[a)]
Institute for National Measurement Standards, National Research Council, Ottawa, Ontario K1A 0R6, Canada

(Received 4 May 1999; accepted for publication 16 August 1999)

The photon spectra in vacuum around four types of ^{192}Ir HDR brachytherapy sources are calculated using the Monte Carlo code EGS4 and the most recent spectral information on ^{192}Ir decay. The air-kerma strengths per unit activity are calculated based on the photon fluence around a bare ^{192}Ir source and around each of four types of encapsulated sources using recent mass energy-absorption coefficients. For the full spectrum the bare vs encapsulated difference is up to 23% due to the large air-kerma contribution from the unfiltered low-energy photons. For the penetrating part of the photon spectrum (>11.3 keV), the air-kerma strength per unit source activity on the transverse axis for a bare source is 2–15 % higher than for the encapsulated sources due to the attenuation and absorption in the core and the encapsulating material. The contribution to the air-kerma strength from photons scattered in the capsule and from bremsstrahlung are calculated to increase the air-kerma strength by 2–4% and 0.2–0.3%, respectively. Air-kerma strengths for a variety of sources agree well with previously reported results for sources from Nucletron International, Best Industries, Inc., and Alpha-Omega Services, Inc. In addition we present air-kerma strengths for the present model of the HDR source from Nucletron International and the source from Varian Associates, Inc. [S0094-2405(99)00211-4]

Key words: ^{192}Ir, brachytherapy sources, fluence spectra, air-kerma strength, Monte Carlo, EGS4

I. INTRODUCTION

The recommended method of specifying source strength for brachytherapy sources is in terms of air-kerma strength.[1,2] However, currently no primary standard exists for air kerma or exposure from high-dose rate (HDR) ^{192}Ir sources and these sources are calibrated using an interpolation technique.[3–5] As part of a project to develop an ion-chamber-based primary standard for ^{192}Ir HDR sources, detailed knowledge on the spectra outside different types of ^{192}Ir brachytherapy sources is required. A side result of the study of these spectra is that the air-kerma strength per unit source activity can be calculated and compared.

EGS4 Monte Carlo calculations of the photon spectra from different types of ^{192}Ir seed sources were performed by Thomason *et al.*[6,7] in 1989. Preliminary Monte Carlo calculations done at NRCC in Oct. 1992 to verify the spectra, and in particular to study the generation of photons with energy below 10 keV, did not confirm the contribution from the low-energy photons, which were present in the spectra calculated by Thomason *et al.* Since these could play an important role in a primary standard, further studies are required. In 1994, Büermann *et al.*[8] reported the air-kerma rate constants for the old microSelectron-HDR source and a bare ^{192}Ir source. For both the old and the new microSelectron source, the VariSource, and two types of seed sources, similar Monte Carlo calculations are performed with the latest spectral data for the ^{192}Ir nuclide published by Duchemin and Coursol[9] and values of the mass energy-absorption coefficients in air from Hubbell and Seltzer.[10] Furthermore, the contributions to the air-kerma strength from photons scattered in the core and the encapsulating material and from bremsstrahlung are calculated, and the influence of spectral bin size on the calculated air kerma is studied. This paper is a much shortened version of a more extensive internal report which is available online.[11]

II. SOURCES

Four types of ^{192}Ir sources are modelled—the seed sources manufactured by Best Industries, Inc., and by Alpha-Omega Services, Inc., the microSelectron-HDR source manufactured by Nucletron International, and the VariSource manufactured by Varian Associates, Inc. The new microSelectron-HDR source is assumed to consist of a 3.6 mm long cylinder with diameter 0.65 mm of pure Ir metal with the radioactive ^{192}Ir uniformly distributed in it. Around this core is a capsule with outer diameter of 0.9 mm made of AISI 316L steel, and connected to a 2.0 mm long (in the model) steel cable with diameter 0.7 mm. The old type of the microSelectron-HDR source is also modelled for comparison of the calculated air-kerma strength per unit source activity to the value reported by Büermann *et al.*[8] This source, with a design nearly identical to the source used by the GammaMed 12i afterloader, has a 3.5 mm long and 0.6 mm diameter core of pure Ir encapsulated in stainless steel.[8,12]

The ^{192}Ir core of the VariSource is 10.0 mm long with a diameter of 0.34 mm (private communication with Stavros Prionas, Varian Associates, Inc.). The encapsulation is Nitinol (55.8% wt Ni and 44.2% wt Ti) with a density of 6.42 g cm^{-3}. The diameter of the encapsulation is 0.6 mm and one end is covered by 0.1 mm Nitinol and the other end is attached to a 2.5 m long Nitinol wire. In the model the 2.5 m

Nitinol wire is reduced to 1.9 cm, since scatter from the total wire is insignificant.

The seed source from Best Industries, Inc., is 3.0 mm long, the core consisting of 30% Ir/70% Pt is 0.1 mm in diameter, and the cladding is 0.2 mm thick consisting of stainless steel.[2] The seed source from Alpha-Omega Services, Inc., is also 3.0 mm long, the core consisting of 10% Ir/90% Pt is 0.3 mm in diameter, and the cladding is 0.1 mm thick consisting of 99.9% Pt.[2] The total outer diameter of both types of seed sources is 0.5 mm. All types of stainless steel in the sources are approximated by the composition of AISI 304 steel.[12]

III. CALCULATIONS

The photon fluence around the sources is calculated using the NRCC user-code FLURZ which uses the EGS4 Monte Carlo system.[13] Each source is modelled as a cylindrical core region with the particles being emitted from homogeneously distributed points (using the uniform isotropically radiating cylinder source routine in FLURZ). The encapsulation is also cylindrical with the end caps for the microSelectron-HDR and VariSource being disks. Also part of the cable connected to the sources is modelled.

In the Monte Carlo calculations K-shell x-ray flourescence and Rayleigh scattering are taken into account in all regions. In the calculations with photons starting in the core the energy cutoff for electron transport is 2.0 MeV, which means that all energy transferred to electrons will be deposited at the point of the interaction and thus there are no radiative losses. Photons are followed till they reach the cutoff energy of 0.001 MeV.

From the fluence calculated using the EGS4 user-code FLURZ, the air-kerma per initial photon, K'_{air}, is calculated using the following discrete equation:

$$K'_{\mathrm{air}} = 1.602 \cdot 10^{-10} \sum_{E_{\min}}^{E_{\max}} \phi'(E_i) E_i \left(\frac{\mu_{en}(E_i)}{\rho} \right) \times \Delta E \quad [\mathrm{Gy}\,(\text{initial photon})^{-1}], \tag{1}$$

where E_i is the midpoint of each energy bin, $\phi'(E_i)$ $(\mathrm{MeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{photon}^{-1})$ is the differential photon fluence at energy E_i (MeV) per initial photon, $\mu_{en}(E_i)/\rho$ $(\mathrm{cm}^2\,\mathrm{g}^{-1})$ is the mass energy-absorption coefficient at energy E_i, and ΔE is the bin size. The factor 1.602×10^{-10} is required to convert K'_{air} from $(\mathrm{MeV}\,\mathrm{g}^{-1})$ into Gy. This equation ignores any distinction between the collision air kerma and the total air kerma since radiative losses are negligible ($<0.1\%$). On average one decay will result in the emission of 2.363 photons with energy in the interval from a few keV to 885 keV,[9] which includes photons directly following the β decay and also K- and L-shell x-rays. The air-kerma strength per unit source activity, S_k/A, in $(\mathrm{Gy}\,\mathrm{m}^2\,\mathrm{s}^{-1}\,\mathrm{Bq}^{-1})$ is calculated from:

$$S_k/A = K'_{\mathrm{air}}(d)\, d^2 (2.363 \pm 0.3\%), \tag{2}$$

or in $(\mathrm{U}\,\mathrm{Bq}^{-1})$

$$S_k/A = 3.6 \times 10^9 K'_{\mathrm{air}}(d)\, d^2 (2.363 \pm 0.3\%), \tag{3}$$

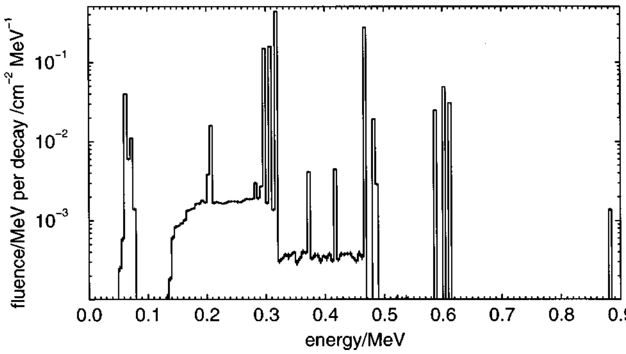

FIG. 1. Fluence spectrum for the new type of the microSelectron source. For fluence spectra for the other source types see Ref. 11 which also contains the data in digital format.

where d is the distance to the cylindrical axis of the source.

Choosing the proper bin size in the Monte Carlo calculations is important, since 88% of the photon energies for the bare ^{192}Ir spectrum happen to be in the upper half of 10 keV bins when divided into bins 0–10 keV, 10–20 keV,..., 890–900 keV. The kerma is calculated using the mass energy-absorption coefficient at the middle of the energy bins. This may cause a binning artifact due to the variation of the product of photon energy and mass energy-absorption coefficient within the bin. The binning artifact was studied for the stainless steel encapsulated seed source from Best Industries, Inc., for bin sizes of 10, 5, and 2 keV. Scoring in 5 keV bins instead of 10 keV bins increases the air-kerma rate by 0.6%, and scoring in 2 keV bins instead of 5 keV bins resulted in an additional increase of 0.04%. However, the smaller the bin size, the more memory is required. The bin size of 5 keV is chosen as a compromise between smallest binning artifact and an acceptable amount of memory. Photons with energy below 210 keV contribute less than 2% of the total air-kerma strength for the stainless steel encapsulated seed source. It is the photons with energy above 210 keV that cause the difference in air kerma for different bin sizes.

To estimate the effects of bremsstrahlung from the β decay within the source, we do a separate calculation in which the source is an isotropic source of electrons in the Ir core. We also estimate the bremsstrahlung from electrons set in motion by the source photons but these lead to a contribution to the air kerma of less than 0.05%. The photon fluence spectrum for bremsstrahlung from the β decay is scored in 10 keV bins, which will not result in a significant binning artifact, since the β spectrum is continuous. The electron transport for the calculation of bremsstrahlung is done with EGS4/PRESTA,[14] and a kinetic energy cutoff for electrons of 10 keV.

IV. RESULTS AND DISCUSSION

The fluence spectrum per decay calculated for the new microSelectron source type is shown in Fig. 1. Similar spectra are calculated for the VariSource and the two seed sources and more information is given in the detailed report.[11] The spectra are calculated with both air and vacuum

TABLE I. Air-kerma strength per unit source activity for different sources. The data are average values of the air-kerma strength per unit source activity based on fluence spectra at distances ranging from 2 to 50 cm, and they are calculated for lower cutoff energies of the fluence spectra of 11.3 and 60 keV for comparison with other reported values. The air-kerma strengths calculated in this work include the contribution from bremsstrahlung, which was not taken into account in the earlier results. The value of the total exposure-rate constant calculated by Glasgow and Dillman (Ref. 16) is corrected by 33.97/33.7, since the energy required to produce an ion pair in dry air has been re-evaluated since 1979 and their value was for humid air. The uncertainties are 1 standard deviation statistical uncertainties (note that some are given as absolute values and some as percent) except for the values from Büermann *et al.* (Ref. 8) which include uncertainties due to the interaction coefficients used in the Monte Carlo calculations (1%), uncertainty on the source geometry (0.5%), and uncertainty on the distribution of the activity within the core (0.5%).

Source	This work S_k/A $(10^{-8}\ \mathrm{U\,Bq^{-1}})$	Others S_k/A $(10^{-8}\ \mathrm{U\,Bq^{-1}})$
New microSelectron		
>11.3 keV	9.73±0.01	
>60 keV	9.70±0.01	
Old microSelectron		
>11.3 keV	9.79±0.02	
>60 keV	9.77±0.02	9.8±1.5%[8]
VariSource		
>11.3 keV	10.25±0.02	
>60 keV	10.22±0.02	
Best Industries		
>11.3 keV	10.70±0.02	10.8±0.1[6]
>60 keV	10.68±0.02	
Alpha-Omega		
>11.3 keV	9.92±0.02	9.95±0.14[6]
>60 keV	9.92±0.02	
Bare source		
>11.3 keV	11.23	11.20[16]
		11.23[6]
>60 keV	10.88	11.0±1%[8]

surrounding the sources, and for the encapsulated sources there is no significant difference between the spectra calculated in air and in vacuum.

In Table I the calculated values of air-kerma strengths per unit source activity are shown as an average of the values for distances ranging from 2 (5 cm for the VariSource) to 50 cm from the cylinder axis of the source. The uncertainty is 1 standard deviation based on the 5 calculated S_k/A values for these distances not taking into account their uncertainties. At these distances the geometry factor, i.e., the factor accounting for the source being a line and not a point, times d^2 is 1.0 within 0.4% except for the VariSource, where the distance to the source must be at least 4 cm for the source to be considered a point source.[15] The values in Table I also include bremsstrahlung contributions of 0.2% of the S_k/A values for the microSelectron-HDR source, the VariSource and the platinum encapsulated seed source (Alpha-Omega) and of 0.3% of the value for the stainless steel encapsulated seed source (Best Industries). The results of earlier work on the bare source, the old microSelectron source and the two seed sources are shown as well (these do not include the contribution from bremsstrahlung). The lower energies of the spectra, i.e., 11.3 keV and 60 keV, for the air-kerma calculation are used for comparison with earlier works. Photons of energy less than 11.3 keV are considered nonpenetrating.[16]

The air-kerma strengths per unit source activity for the old microSelectron-HDR source and for the bare source agree well with reported results from other authors within their stated uncertainties of 1–1.5%. For the new microSelectron-HDR source the air-kerma strength is 0.6–0.7% lower than for the old one. For the seed sources the air-kerma strengths calculated in this work are 0.3–1% lower than the results of Thomason *et al.* However, our values are expected to be about 1% higher than their results due to our added contribution from bremsstrahlung and because we scored in 5 keV bins and not in 10 keV bins. The difference is attributed to the differences in spectral data for the ^{192}Ir nuclide and in the (μ_{en}/ρ) values.

The Monte Carlo calculations include K-shell x-ray fluorescence but no L-shell x-rays. The energies of the K-shell x-rays are 76.1 and 78.4 keV for Ir and Pt, respectively, and 7.11 keV for stainless steel (mainly Fe). A calculation without x-ray fluorescence shows that the contribution to air-kerma strength from K-shell x-rays is about 0.2% for the microSelectron-HDR source. In Ir and Pt the L-shell x-rays have energies below 13.4 keV and 13.9 keV, respectively, and for the stainless steel the energy is below 0.85 keV. For stainless steel the L fluorescence yield is practically 0, and because of the low energy of the photons they will be absorbed within 1 cm of air and not show up in a measurement of air kerma. For L-shell x-rays from Ir and Pt no photons created in the core will pass through the encapsulation of the sources, and those created in the Pt encapsulation will have a high probability of undergoing a photoelectric interaction. The contribution from L-shell x-rays to the air-kerma strength is thus likely negligible.

V. CONCLUSIONS

The air-kerma strength per unit activity is calculated for a bare ^{192}Ir source, the microSelectron-HDR source, the VariSource, and stainless steel and platinum encapsulated seed sources at distances ranging from the surface of the source to 50 cm in both vacuum and air. The result for the microSelectron-HDR source (old type) is in agreement with the values from Büermann *et al.*[8] in 1994. The air-kerma strength per unit activity for the new type of microSelectron-HDR source is about 0.6–0.7% lower compared to the old type. For the seed sources the air-kerma strengths per unit source activity are less than 1% smaller than the exposure-rate constants calculated by Thomason *et al.*[6,7] in 1989. However, due to the bremsstrahlung contribution and the binning artifact, i.e., the difference between scoring in 10 keV bins instead of 5 keV bins, our values were expected to be about 1% higher than the values of Thomason *et al.* The differences in data for the primary ^{192}Ir spectrum and mass energy-absorption coefficients for dry air explain this difference.

The effect of bin size for scoring the fluence was studied to reduce the binning artifact as well as using an acceptable amount of memory. A bin size of 5 keV was found adequate.

For the penetrating part of the photon spectrum (>11.3 keV), the air-kerma strength for the bare source is 2–15% higher than for the encapsulated sources due to the attenuation and absorption in the core and the encapsulating material. The bremsstrahlung contribution to the air-kerma strength is calculated for the four sources and increases air kerma strength by 0.2–0.3%. Photons scattered in the source contribute 2–4% of the total air-kerma strength.

The contribution of the low-energy photons to the air-kerma strength was studied for the encapsulated sources. Eliminating photons with energy less than 60 keV decreases the air-kerma strength by 0.2–0.3% and eliminating the photons with energy less than 130 keV results in the air-kerma strength being reduced by 1%. The contribution from L-shell x-rays to the air-kerma strength is considered negligible.

The major purpose of this work is to provide reliable ''in-air'' spectra as presented in Fig. 1. These spectra are available in digital format online in Ref. 11.

ACKNOWLEDGMENTS

We are grateful to Jan Seuntjens, Ionizing Radiation Standards, NRCC, for ideas and discussions through this project and for commenting on this manuscript. We also wish to thank Stavros Prionas, Varian Associates, Inc., for providing us with information about the VariSource. Finally, we thank the referee for valuable comments on the paper. This work was supported by the National Institutes of Health through Grant No. R01 CA66852.

[a]Electronic mail: dave.rogers@nrc.ca; Tel: (613) 993-2715; Fax: (613) 952-9865

[1] AAPM TG–32, Specification of Brachytherapy Source Strength, AAPM Report 21, AAPM, New York, 1987.

[2] R. Nath, L. L. Anderson, G. Luxton, K. A. Weaver, J. F. Williamson, and A. S. Meigooni, ''Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43,'' Med. Phys. **22**, 209–234 (1995).

[3] S. J. Goetsch, F. H. Attix, D. W. Pearson, and B. R. Thomadsen, ''Calibration of ^{192}Ir high-dose-rate afterloading systems,'' Med. Phys. **18**, 462–467 (1991).

[4] M. J. Rossiter, T. T. Williams, and G. A. Bass, ''Air kerma rate calibration of small sources of ^{60}Co, ^{137}Cs, ^{226}Ra, and ^{192}Ir,'' Phys. Med. Biol. **36**, 279–284 (1991).

[5] F. Verhaegen, E. van Dijk, H. Thierens, A. H. L. Aalbers, and J. Seuntjens, ''Calibration of low activity ^{192}Ir brachytherapy sources in terms of reference air-kerma rate with large volume spherical ionisation chambers,'' Phys. Med. Biol. **37**, 2071–2082 (1992).

[6] C. Thomason, Dosimetry of Iridium-192 and Cesium-137 seed sources, Ph.D. thesis, University of Wisconsin, Madison, 1989.

[7] C. Thomason, T. R. Mackie, and M. J. Lindstrom, ''Effect of source encapsulation on the energy spectra of ^{192}Ir and ^{137}Cs seed sources,'' Phys. Med. Biol. **36**, 495–505 (1991).

[8] L. Büermann, H.-M. Kramer, H. Schrader, and H.-J. Selbach, ''Activity determination of ^{192}Ir solid sources by ionization chamber measurements using calculated corrections for self-absorption,'' Nucl. Instrum. Methods **A339**, 369–376 (1994).

[9] B. Duchemin and N. Coursol, Reevalution de l'^{192}Ir, Technical Note LPRI/93/018, DAMRI, CEA, France, 1993.

[10] J. H. Hubbell and S. M. Seltzer, Tables of X-ray mass Attenuation Coefficients and Mass Energy-Absorption Coefficients 1 keV to 20 MeV for Elements $Z=1$ to 92 and 48 Additional substances of Dosimetric Interest, Technical Report NISTIR 5632, NIST, Gaithersburg, MD 20899, 1995.

[11] J. Borg and D. W. O. Rogers, Monte Carlo Calculations of Photon Spectra in Air from ^{192}Ir Sources, NRC Report PIRS-629r (see http://www.irs.inms.nrc.ca/inms/irs/papers/PIRS629r/pirs629r.html), 1998.

[12] J. F. Williamson and Z. Li, ''Monte Carlo aided dosimetry of the microselectron pulsed and high dose-rate ^{192}Ir sources,'' Med. Phys. **22**, 809–819 (1995).

[13] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, The EGS4 Code System, Report SLAC-265, Stanford Linear Accelerator Center, Stanford, California, 1985.

[14] A. F. Bielajew and D. W. O. Rogers, PRESTA: The Parameter Reduced Electron-Step Transport Algorithm for electron Monte Carlo transport, National Research Council of Canada Report PIRS-0042, 1986.

[15] R. Wang and R. S. Sloboda, ''Influence of source geometry and materials on the transverse axis dosimetry of ^{192}Ir brachytherapy sources,'' Phys. Med. Biol. **43**, 37–48 (1998).

[16] G. P. Glasgow and L. T. Dillman, ''Specific γ-ray constant and exposure rate constant of ^{192}Ir,'' Med. Phys. **6**, 49–52 (1979).