Calculation of Air Kerma Rate Constants for 39 Commonly Used Nuclides

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Abstract

The nuclide air kerma rate constant Γa is crucial data for dose and shielding calculations. The calculation of Γa requires the conversion coefficient from fluence to air kerma rate Ka/Φ and information on photons from nuclide decay. In 2020, the International Commission on Radiation Units and Measurements (ICRU) published Report No. 95, which recommended new Ka/Φ values. To verify the changes in nuclide values after the update of fundamental data, the air kerma rate constants of 39 commonly used nuclides in medicine, industry, and agriculture were calculated using theoretical and Monte Carlo methods, and a comparative analysis of different interpolation methods and threshold selections was performed. The following conclusions were obtained: cubic spline, log-log Lagrange interpolation, and linear-log Lagrange interpolation methods have minimal impact on the calculation of Γa; threshold selection is very important for the calculation of Γa, and for some nuclides, the calculation differences under different threshold conditions are significant; it is recommended that a 10 keV threshold be used for nuclear medicine dose estimation, and a 20 keV threshold be selected for other situations; the difference between theoretical calculation and MCNP simulation calculation is small, and both can be used for the calculation of this constant.

Full Text

Preamble

Calculation of Air Kerma Rate Constants for 39 Commonly Used Radionuclides

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Abstract

The radionuclide air kerma rate constant, denoted as a_G, is a crucial parameter in dose assessment and shielding calculations. Its computation requires the conversion coefficient from photon fluence to air kerma rate (a_K/F) along with detailed nuclear decay photon data. In 2020, the International Commission on Radiation Units and Measurements (ICRU) published Report 95, which recommended updated values for a_K/F. To verify the impact of these fundamental data revisions on a_G values, we calculated the air kerma rate constants for 39 radionuclides commonly used in medical, industrial, and agricultural applications using both theoretical and Monte Carlo methods, and conducted comparative analyses of different interpolation methods and threshold selections.

Our findings indicate that interpolation methods—including cubic spline, log-log Lagrangian, and linear-log Lagrangian—have minimal influence on a_G calculations. However, threshold selection proves critically important, with some nuclides showing substantial calculation differences across different threshold values. We recommend using a 10 keV threshold for nuclear medicine dose estimation and a 20 keV threshold for other applications. The differences between theoretical calculations and MCNP simulations are small, demonstrating that both approaches are suitable for determining these constants.

Keywords: air kerma rate constant; air kerma; conversion coefficient

1. Calculation Methods

1.1 Air Kerma Rate Calculation Formula

The air kerma rate at a point in air from a radiation source depends on photon energy, source activity, distance from the source, and source geometry. The calculation typically employs Equation (1):

$$a_K = \frac{A \cdot a_G}{r^2}$$

where A represents the source activity, a_G is the air kerma rate constant for a point source, and r is the distance from the source to the calculation point. The inverse square law relationship assumes an isotropic point source and neglects source self-shielding and scattering effects.

1.2 Air Kerma Rate Constant Calculation Formula

The air kerma rate constant a_G is calculated using Equation (2):

$$a_G = \sum_i p_i \cdot E_i \cdot \left(\frac{a_K}{F}\right)_i$$

where p_i denotes the branching ratio for photons with energy E_i, and $(a_K/F)_i$ represents the conversion coefficient from fluence to air kerma for energy E_i. The constant k converts units to Gy and Bq, with units of $\mathrm{Gy} \cdot \mathrm{m}^2 \cdot \mathrm{Bq}^{-1} \cdot \mathrm{s}^{-1}$ for a_G.

1.3 Theoretical Calculation of a_G

Theoretical a_G values were computed according to Equation (2) using the latest a_K/F data from ICRU Report 95 and decay data from the IAEA official website. The calculation considered all gamma-ray photons, characteristic X-ray photons, internal conversion photons, and orbital electron capture photons from nuclear decay. Three interpolation methods were employed to determine conversion coefficients at discrete photon energies: log-log Lagrangian interpolation (DLI), linear-log Lagrangian interpolation (LLL), and cubic spline interpolation (CPI). To investigate the relationship between threshold selection and a_G values, calculations were performed using both 10 keV and 20 keV thresholds.

1.4 Simulation Calculation Method

Monte Carlo simulations of a_G values were conducted using MCNP6 software. An idealized massless isotropic point source was modeled to simulate the theoretical a_G values, excluding source self-shielding effects. A small sphere with 1.5 cm radius was positioned 100 cm from the source. Combined photon and electron transport was simulated using the F4 tally card together with de and df cards to calculate the air kerma rate constant, with ICRU data employed for the de and df cards.

2. Calculation Results

The calculated a_G values for different threshold selections, fundamental data sources, and interpolation methods are presented in Table 1 . Rows 2, 3, and 4 specify the fundamental data source, interpolation method, and threshold selection used in the calculations. Columns 3 and 4 list the a_G values obtained from theoretical calculations and simulations, respectively. Columns 6 and 8 present the calculation results from Li Shijun and Ninkovic M M, while columns 10 and 12 show results for 20 keV threshold and CPI interpolation, respectively. Column 14 displays percentage differences (C), calculated according to Equation (3):

$$C = \frac{|a_{G1} - a_{G2}|}{a_{G2}} \times 100\%$$

where a_{G1} and a_{G2} represent air kerma rate constants for the same nuclide obtained through different methods or sources.

3. Results Analysis

3.1 Comparison with Previous Studies

Compared with Li Shijun's calculations, 26 nuclides show percentage differences within 5%, 7 nuclides differ by 5-10%, and 5 nuclides (Fe-52, Tm-170, Eu-152, Pu-238, Am-241) differ by more than 10%. Comparison with Ninkovic M M' s results reveals 22 nuclides within 5% difference, 3 nuclides in the 5-10% range, and 7 nuclides exceeding 10% difference (Fe-52, Co-57, Se-75, I-123, Eu-152, Hg-197, Am-241).

Potential sources of these discrepancies include differences in fundamental decay data, conversion coefficient selections, interpolation methods, and threshold choices. Since fundamental decay data and conversion coefficients are continuously updated, they inevitably affect a_G calculations. The following analysis focuses specifically on the impacts of interpolation methods and photon energy thresholds, as theoretical and simulation results show minimal differences.

3.2 Influence of Interpolation Methods

Current domestic and international calculations of a_G primarily employ three interpolation methods: DLI, LLI, and CPI. Using identical decay data and photon thresholds, we calculated a_G for all 39 nuclides with these different methods. As shown in Table 1, the percentage difference between LLI and DLI is approximately zero when rounding to one decimal place, and CPI results are consistent with DLI. These findings demonstrate that interpolation method selection has minimal influence on a_G calculations.

3.3 Influence of Energy Thresholds

Comparisons were made between a_G values calculated using DLI with 10 keV and 20 keV thresholds. The results, presented in Table 1, show percentage differences exceeding 10% for Co-57, Se-75, Tc-99m, Hg-197, and Pu-238. Examination of the decay data reveals that these nuclides emit photons in the 10-20 keV range that contribute significantly to a_G calculations: Co-57 emits 14.4 keV photons (40% contribution), Se-75 emits 10.5, 11.8, 11.9, and 14.9 keV photons (71% contribution), Tc-99m emits 18.3 and 18.4 keV photons (19% contribution), Hg-197 emits 11.4 keV photons (89% contribution), and Pu-238 emits 16.7 keV photons (99% contribution).

While other nuclides also emit photons between 10-20 keV, these contributions are relatively minor, resulting in smaller differences between threshold calculations. This indicates that scientific threshold selection is necessary for certain nuclides. According to Ninkovic M M, photons below 20 keV are typically neglected in general health physics, but must be considered in nuclear medicine because they contribute significantly to dose at close distances. Therefore, a_G calculations must be tailored to the specific application: a 10 keV threshold is recommended for nuclear medicine dose estimation, while a 20 keV threshold is appropriate for industrial and agricultural applications.

3.4 Theory vs. Simulation

The percentage differences between theoretical and simulation results are consistently small, with 33 nuclides differing by less than 1% and 6 nuclides in the 1-3% range. These minor differences are acceptable for dosimetric constant calculations in medical, industrial, and agricultural applications.

4. Conclusion

This study presents updated a_G calculations for 39 commonly used radionuclides based on conversion coefficients from ICRU Report 95 and the latest decay data from the IAEA website. The results demonstrate that a_G values depend critically on nuclear decay data, which requires continuous updating as new measurements become available. Photons in the 10-20 keV energy range contribute substantially to a_G values, making threshold selection essential. We recommend a 10 keV threshold for nuclear medicine dose estimation and a 20 keV threshold for industrial and agricultural applications. The small differences between theoretical calculations and MCNP6 simulations confirm that both methods are reliable. The a_G values reported herein, based on the most current data, provide more accurate parameters for precise dose calculations for patients, nuclear workers, and radiation environments.

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Note: Figure translations are in progress. See original paper for figures.