Dosimetry in thyroid follicles due to low-energy electrons of iodine using the Monte Carlo method*

Dosimetria em folículos tireoidianos devido aos elétrons de baixa energia do iodo usando o método Monte Carlo

Laélia Campos[1], Frank da Silva[2]

Abstract **OBJECTIVE: To evaluate the absorbed dose in thyroid follicles due to low-energy electrons such as Auger and internal conversion electrons, besides beta particles, for iodine radioisotopes (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I) utilizing the Monte Carlo method. MATERIALS AND METHODS: The dose calculation was performed at follicular level, simulating Auger, internal conversion electrons and beta particles, with the MCNP4C code. The follicles (colloid and follicular cells) were modeled as spheres with colloid diameter ranging from 30 to 500 µm, and with the same density of water (1.0 g.cm^{-3}). RESULTS: Considering low-energy particles, the contribution of ^{131}I for total absorbed dose to the colloid is about 25%, while the contribution due to short-lived isotopes is 75%. For follicular cells, this contribution is still higher achieving 87% due to short-lived iodine and 13% due to ^{131}I. CONCLUSION: The results of the present study demonstrate the importance of considering low-energy particles in the contribution for the total absorbed dose at follicular level (colloid and follicular cells) due to iodine radioisotopes (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I).**
Keywords: Internal dosimetry; Short-lived iodines; Thyroid cancer; Monte Carlo method; MCNP.

Resumo **OBJETIVO: Avaliar a dose absorvida em folículos tireoidianos devido aos elétrons de baixa energia, como os elétrons Auger e os de conversão interna, além das partículas beta, para os radioisótopos de iodo (^{131}I, ^{132}I, ^{133}I, ^{134}I e ^{135}I) usando o método Monte Carlo. MATERIAIS E MÉTODOS: O cálculo da dose foi feito ao nível folicular, simulando elétrons Auger, conversão interna e partículas beta, com o código MCNP4C. Os folículos (colóide e células foliculares) foram modelados como esferas, com diâmetros do colóide variando de 30 a 500 µm. A densidade considerada para os folículos foi a da água (1,0 g.cm^{-3}). RESULTADOS: Considerando partículas de baixa energia, o percentual de contribuição do ^{131}I na dose total absorvida pelo colóide é de aproximadamente 25%, enquanto os isótopos de meia-vida física curta apresentaram contribuição de 75%. Para as células foliculares, esse percentual é ainda maior, chegando a 87% para os iodos de meia-vida curta e 13% para o ^{131}I. CONCLUSÃO: Com base nos resultados obtidos, pode-se mostrar a importância de se considerar partículas de baixa energia na contribuição para a dose total absorvida ao nível folicular (colóide e células foliculares) devido aos radioisótopos de iodo (^{131}I, ^{132}I, ^{133}I, ^{134}I e ^{135}I).**
Unitermos: Dosimetria interna; Iodos de meia-vida curta; Câncer de tireóide; Método Monte Carlo; MCNP.

Campos L, Silva F. Dosimetry in thyroid follicles due to low-energy electrons of iodine using the Monte Carlo method. Radiol Bras. 2008;41(6):403–407.

INTRODUCTION

The thyroid is a lobular endocrine gland located in the anterior portion of the neck, with a weight of 10 to 20 g for the adult man[(1)]. Each of the lateral thyroid lobes, connected by the isthmus, has a height of 4 to 6 cm, 2 cm transversely and 2 cm in thickness[(2)]. The functional unit of the thyroid is the follicle, formed by follicular cells and colloid. The follicle is sphere-shaped and its average diameter, in an adult man, is 200 µm, presenting however, an important variation in size, proportional to its functional activity. At rest, the follicles are large, with 200 to 500 µm in diameter, and in a hyperactivity state they are smaller, with 30 to 50 µm in diameter[(2)]. Follicular cells are joined by a basal membrane constituting a single layer that limits the colloid volume and have an average diameter of 10 µm. Colloid is a proteic substance that concentrates the iodines circulating in the blood, and incorporates thyroid hormones whose production is associated to the iodine intake by the organism[(2)]. Iodine is an essential element in the composition of hormones secreted by the thyroid, that play a determinant role in the metabolism of all cells in the organism[(3)] and, equally, in the growth process and development of the majority of organs[(4)], particularly the brain[(5)].

In case of accidents involving nuclear plants, large amounts of radioactive iodine isotopes are released in the environment and, due to its volatility and mobility, the exposure to these radioisotopes requires special attention regarding radioprotec-

* Study developed in the Department of Statistics and Information Technology at Universidade Federal Rural de Pernambuco (UFRPE), Recife, PE, Brazil.

1. PhD, Associate Professor II, Department of Statistics and Information Technology, Universidade Federal Rural de Pernambuco (UFRPE), Recife, PE, Brazil.

2. Master, Professor, Department of Statistics and Information Technology, Universidade Federal Rural de Pernambuco (UFRPE), Recife, PE, Brazil.

Mailing address: Dra. Laélia Campos. Departamento de Estatística e Informática, UFRPE. Rua Dom Manoel de Medeiros, s/nº, Dois Irmãos. Recife, PE, Brazil, 52171-900. E-mail: lpbcampos@gmail.com / l.campos@deinfo.ufrpe.br

Received March 31, 2008. Accepted after revision July 31, 2008.

tion[6,7]. In fact, the thyroid capacity of concentrating iodine makes such organ one of the most vulnerable in accidents of this nature[8]. Amongst the main types of thyroid cancer, papillary carcinoma represents from 60% to 80% of cases, and follicular carcinoma, from 10% to 20%[9]. These two types of carcinomas originate from the follicular cells. From the radioprotection standpoint, the most important radioactive iodine isotopes are ^{131}I and short half- life isotopes as follows: ^{132}I ($T_{1/2}$ = 2.38 h), ^{133}I ($T_{1/2}$ = 20.8 h), ^{134}I ($T_{1/2}$ = 52.5 min) and ^{135}I ($T_{1/2}$ = 6.7 h). Due to these iodine radioisotopes, dosimetry is of paramount importance[10,11].

Thus, the absorbed dose, defined as the average energy deposited by radiation per tissue mass unit or irradiated organ[12], is the most important physical magnitude in the assessment of risks associated with ionizing radiation contamination or exposure. However, retrospective dosimetry involving accidental internal contamination is not an easy task, generally due to the lack of information about exposure conditions. In the Chernobyl accident, adopted as a comparative example in the present study, the majority of direct dose measurements were made only approximately one month after the accident. Moreover, these measurements were only made for ^{131}I, while the short half-life iodine radioisotopes were not taken into consideration in the estimation of dose absorbed by the thyroid[8].

Some studies have reported results of dosimetry at cellular level of ^{131}I beta particles utilizing deterministic methods[13–15], while others have utilized Monte Carlo simulations for ^{131}I[16] and short half-life iodines[11]. However none of these studies has taken low energy particles, such as Auger electrons or internal conversion electrons, into consideration.

The adoption of Monte Carlo codes for calculating absorbed dose in organs and/or tissues of the human body[17,18] as well as in the cellular field[11] has been diffused worldwide, serving professionals involved in internal or external dosimetry, utilizing for such purpose, geometrical models (or phantoms) of organs and/or tissues to be studied[19].

In this context, the present study is aimed at assessing the absorbed dose in thyroid follicles due to low energy electrons, such as the Auger and internal conversion electrons, besides the beta particles for iodine radioisotopes (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I) by means of the Monte Carlo method.

MATERIALS AND METHODS

Modeling for the thyroidal follicle

The modeling of the thyroid follicles (consisting of colloid and follicular cells) was made with two concentrical spheres, with the internal sphere representing the colloid, and the region between the internal and external spheres (whose distance between internal and external radii was 10 µm) representing the follicular cells. Diameters utilized for the internal sphere (colloid) were the following: 30, 50, 80, 100, 200, 300, 400 and 500 µm. These values are justified by the diameter of the human thyroid follicles, that vary between 30 and 50 µm, when in hyperactivity state, while in rest state this variation is between 200 and 500 µm[2].

Simulation of thyroid follicle with the MCNP code

The code MCNP (*Monte Carlo N-Particle*) version 4C[20], which utilizes the Monte Carlo method for particles transportation, was adopted to simulate thyroid follicles contaminated by iodine radioisotopes. In the code input, the following parameters were described: follicle geometry, radioactive source distribution, energy decay spectrums of the Auger and internal conversion electrons, as well as the beta particles for each simulated iodine isotope. The water density (1.0 $g.cm^{-3}$) was considered as a parameter for colloid and follicular cells. For each diameter, the iodines (^{131}I, ^{132}I, ^{133}I, ^{134}I and ^{135}I) were simulated in a uniform manner within the colloid. The tables with the iodine energy decay spectrums and energy abundancy rates were obtained at the Brookhaven National Laboratory's (BNL) National Nuclear Data Center (http://www.nndc.bnl.gov; July/ 2008).

In the MCNP output, one has the energy deposited both in the colloid and in the follicular cells due to the iodine isotopes. Photons were not utilized in the simulation, as they do not contribute to the absorbed dose at cellular level.

RESULTS

The results of the simulations for the thyroid follicle model (colloid and follicular cells) are presented on Figures 1 thru 6. The graphs are plotted in logarithmic scale and correspond to dose in Gray per disintegration (Gy/dis) as a function of the simulated colloid diameter (µm). The points plotted in the graphs were individually obtained by means of a single simulation with specific physical and geometrical parameters.

Figures 1 and 2 present the results for the absorbed dose, respectively, in the colloid and follicular cells due to Auger electrons. Based on the graphs, one can observe that greatest contribution of absorbed dose due to Auger electrons comes from ^{131}I and next from ^{134}I, for all simulated diameters.

The results of dose due to internal conversion electrons are shown on Figures 3 and 4. One observes that the greatest dose contribution due to internal conversion electrons is initially due to ^{131}I, and as the follicle diameter increases, the ^{131}I contribution percentage tends to reach that of ^{134}I, until it becomes practically equal.

Figures 5 and 6 show absorbed doses due to beta particles. The contribution of the dose in the colloid is almost the same for all iodine isotopes (Figure 5) due to the beta particles, with a slightly higher contribution from ^{131}I, when compared with other isotopes. Observing Figure 6, one can affirm that all iodine isotopes have the same contribution to the deposited dose on follicular cells due to beta particles for all the simulated diameters.

The estimated relative errors generated by the MCNP code ranged from 0.06% to 1.7%, thus being within the confidence range, as established by this code.

Table 1 shows the total dose absorbed by the colloid (Gy/dis), considering the Auger electrons, internal conversion electrons and beta particles for all iodine isotopes and all simulated diameters, besides presenting the percentage of dose due to ^{131}I and short half-life iodines. Table 1 shows that the percentage of contribution of ^{131}I in the total dose absorbed by the

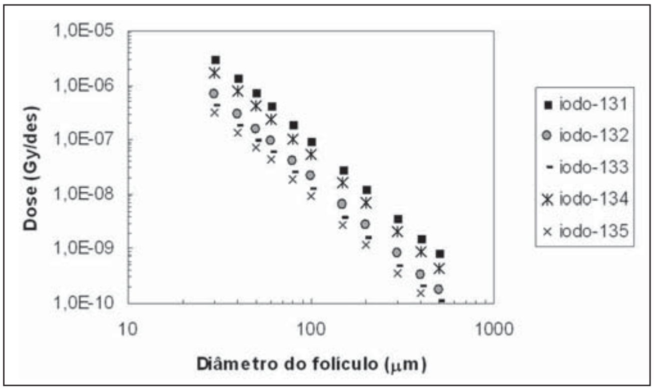

Figure 1. Absorbed dose in colloid due to Auger electrons.

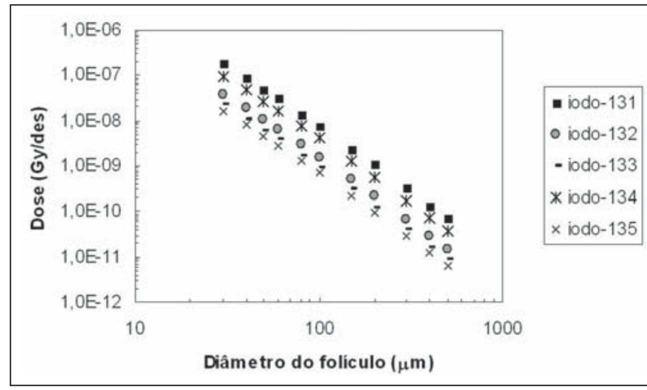

Figure 2. Absorbed dose in follicular cells due to Auger electrons.

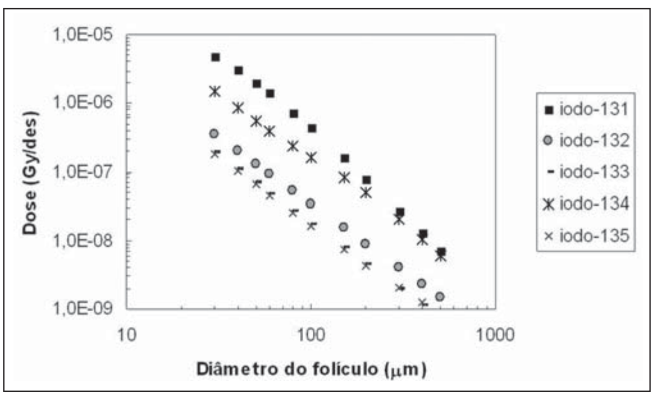

Figure 3. Absorbed dose in colloid due to internal conversion electrons.

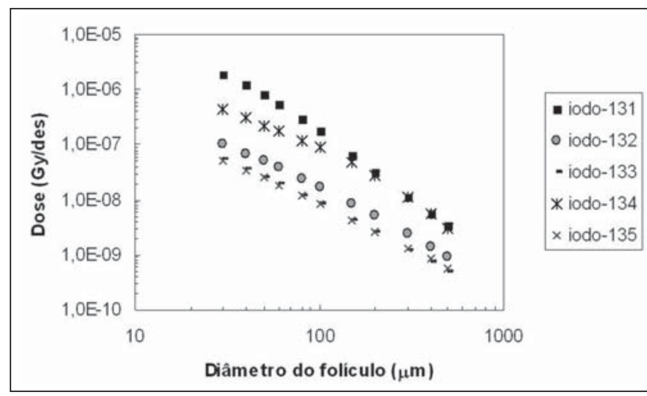

Figure 4. Absorbed dose in follicular cells due to internal conversion electrons.

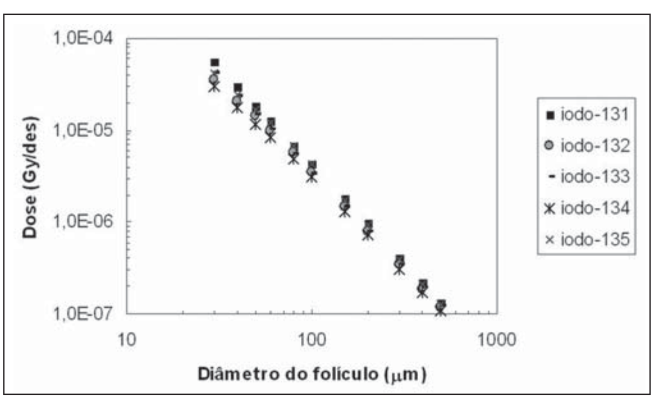

Figure 5. Absorbed dose in colloid due to beta particles.

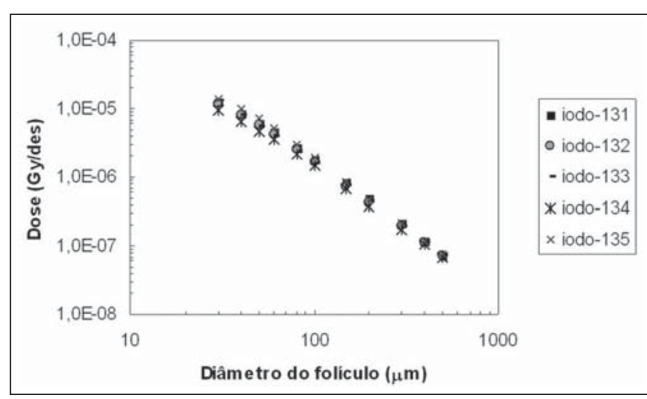

Figure 6. Absorbed dose in follicular cells due to beta particles.

colloid is, on average, 25%, while for the short physical half-life iodines this total percentage is 75% on average.

Table 2 shows the values of total dose absorbed by follicular cells (Gy/dis), considering Auger electrons, internal conversion electrons and beta particles, besides presenting the dose percentages due to ^{131}I (13%, on average) and percentages due to short physical half-life isotopes (87%, on average).

DISCUSSION

Figures 1 and 2 demonstrate the doses absorbed due to Auger electrons, with emphasis on the greater contribution for ^{131}I. The relevance of the Auger electrons in dosimetry has been neglected for several years, to a large extent because the energy absorbed by tissues due to these electrons is normally insignificant as compared with the total energy released in the radionuclide decay[21].

Auger electrons emissions produce a cascade of low energy electrons. Most of this energy is deposited within a few na-

Table 1 Total dose absorbed by colloid due to iodine isotopes.

Colloid diameter (μm)	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	(%) ^{131}I	(%) short $T_{1/2}$ iodines
30	6.37E-05	3.70E-05	4.23E-05	3.39E-05	4.20E-05	29	71
50	2.10E-05	1.44E-05	1.53E-05	1.26E-05	1.67E-05	26	74
80	7.77E-06	5.76E-06	5.59E-06	5.15E-06	6.82E-06	25	75
100	4.80E-06	3.60E-06	3.45E-06	3.28E-06	4.25E-06	25	75
200	1.07E-06	8.05E-07	8.13E-07	7.70E-07	9.22E-07	24	76
300	4.38E-07	3.45E-07	3.51E-07	3.30E-07	3.87E-07	24	76
400	2.32E-07	1.91E-07	1.94E-07	1.83E-07	2.11E-07	23	77
500	1.40E-07	1.20E-07	1.22E-07	1.16E-07	1.31E-07	22	78

Table 2. Total dose absorbed by follicular cells due to iodine isotopes.

Colloid diameter (μm)	^{131}I	^{132}I	^{133}I	^{134}I	^{135}I	(%) ^{131}I	(%) short $T_{1/2}$ iodines
30	1.45E-05	2.12E-05	2.20E-05	2.40E-05	2.40E-05	14	86
50	6.87E-06	9.78E-06	9.16E-06	1.14E-05	1.14E-05	14	86
80	3.05E-06	4.25E-06	3.92E-06	5.45E-06	4.91E-06	14	86
100	2.01E-06	2.80E-06	2.61E-06	3.83E-06	3.21E-06	14	86
200	5.23E-07	7.65E-07	7.37E-07	1.12E-06	8.58E-07	13	87
300	2.27E-07	3.54E-07	3.42E-07	4.68E-07	4.15E-07	13	87
400	1.23E-07	2.02E-07	1.98E-07	2.45E-07	2.46E-07	12	88
500	7.58E-08	1.31E-07	1.29E-07	1.47E-07	1.60E-07	12	88

nometers (nm), with a very high local dose. The most energetic Auger electron results from the transition to the K layer (25 to 27 keV), but most electrons are produced by transitions between exterior orbits, and therefore, present energies < 500 eV, with corresponding ranges < 25 nm. Auger electron emitting radionuclides are widely utilized in nuclear medicine and biomedical research. The Auger electrons effects have been evaluated by means of microdosimetry techniques[(22)].

Electrons carry only a small fraction of the energy released by decay, and make only a minor contribution for the total dose in the organ; however, Auger electrons may play a crucially significant role the determination of the cell damage magnitude, as the biological risks associated with Auger emission depend to a great extent on the local accuracy decay within the cell. Extracellular Auger electrons would be relatively harmless because of their limited range, but they may produce irreparable damage to any radiosensitive[(21)] structure.

The dose contributions to colloid and follicular cells due to internal conversion electrons are shown on Figures 3 and 4. Because of their lower range in the energy deposition, low energy electrons, such as the internal conversion ones, are widely utilized in the treatment of superficial tumors, and are also appropriate for intraoperative radiotherapy. The dense shower of short-range Auger electrons released by radionuclides, which decay by means of electron capture or internal conversion, results in biological damage, which is very dependent of the site of of decay within the cell[(23)].

Figures 5 and 6 show the doses absorbed by colloid and by follicular cells due to the beta particles. In radioimmunotherapy, preference is given to the treatment of deep tumors by beta particle emitting radionuclides. However, for the erradication of small groups of cancerigenous cells, Auger electron or alpha particle emitting radionuclides are considered as advantageous in the erradication of small cluster of cancer cells because of their ability to deposit radiation energy locally[(14)].

The percentage value of 75% of short physical half-life isotopes presented on Table 1, confirms the high contribution of dose absorbed by the colloid due to these isotopes, besides demonstrating that this percentage is even higher than the one reported in the literature[(11)], where no calculation with Auger and internal capture electrons is found. For the total dose absorbed by follicular cells (see Table 2), the percentage of the dose due to short half-life iodines is even higher, representing on average 87% of the total dose, while ^{131}I contributes with 13% on average. This result highlights the significant role of low energy particles in dose calculations at cellular levels, considering that in the present study the simulated Auger electrons present an energy range from 0.08 to 32 keV.

For low-energy beta particles emitting radionuclides, the conventional dosimetry frequently establishes an inappropriately estimated dose, i.e., the dose in individual cells within an organ may be much higher or much lower than the mean dose calculated for the organ as a whole, as conventional dosimetry establishes average radiation doses for specific organs or tissues, allowing a gross under- or overestimation of radiation exposure for individual cells.

Because of the low energy of Auger electrons and, correspondingly, their low range (from 1 nm to 1 μm), the biological effects of Auger emissions are highly dependent on their cellular and subcellular distribution. Conventional dosimetry utilized for a specific organ does not take into account the cell-by-cell heterogeneity, where the Auger emission will concentrate in the cell nucleus[24].

CONCLUSION

Based on the results obtained by Monte Carlo simulation, the importance of considering the contribution of low-energy particles such as Auger and internal conversion electrons to the total absorbed dose at follicular level (colloid and follicular cells) due to short half-life iodine isotopes (^{132}I, ^{133}I, ^{134}I and ^{135}I) and due to ^{131}I can be demonstrated. For the same number of disintegrations, the contribution percentage was at the order of 75% for the total absorbed dose by the colloid due to the short half-life iodines, and 25% for ^{131}I. For the follicular cells, these values reached 87% for the short half-life iodine isotopes and 13% for ^{131}I.

Acknowledgements

The authors wish to thank the Post Graduation Program in Biometry and Applied Statistics of the Universidade Federal Rural de Pernambuco (UFRPE), for its logistical support, and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Capes), within the Capes/Cofecub agreement, for the financial support.

REFERENCES

1. Cristy M. Reference man anatomical model. In: Raabe OG, editor. Internal radiation dosimetry. Madison: Medical Physics Pub Corp; 1994. p. 217–38.
2. Leclère J, Orgiazzi J, Rousset B, et al. La thyroïde: des concepts à la pratique clinique. 2nd ed. Paris: Elsevier; 2001.
3. Sterling K. Thyroid hormone action at the cellular level. In: Ingbar SH, Braverman LE, editors. Werner's The thyroid: a fundamental and clinical text. Philadelphia: JB Lippincott; 1986. p. 219–33.
4. Fisher DA. Thyroid hormone effects on growth and development. In: Delange F, Fisher DA, Malvaux P, editors. Pediatric thyroidology. Basel: Karger; 1985. p. 75–9.
5. Dussault JH. Action of thyroid hormones on brain development. In: Delange F, Fisher DA, Glinoer D, editors. Research in congenital hypothyroidism. New York: Plenum Press; 1989. p. 95–102.
6. Galle P. Toxiques nucléaires. 2nd ed. Paris: Masson; 1998.
7. International Commission on Radiological Protection (ICRP). Human respiratory tract model for radiological protection. ICRP Publication 66. Oxford: Pergamon Press; 1994.
8. United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). Sources, effects and risks of ionizing radiation. UNSCEAR Report 2000 to the General Assembly, with Annexes. New York: United Nations; 2000.
9. Schlumberger MJ. Papillary and follicular thyroid carcinoma. N Engl J Med. 1998;338:297–306.
10. Balonov M, Kaidanovsky G, Zvonova I, et al. Contributions of short-lived radioiodines to thyroid doses received by evacuees from the Chernobyl area estimated using early in vivo activity measurements. Radiat Prot Dosimetry. 2003;105:593–9.
11. Campos L, Amaral A, Colas-Linhart N, et al. Evaluation of absorbed dose in thyroid follicles due to short-lived iodines irradiation using the Monte Carlo method. Journal of Radioanalytical and Nuclear Chemistry. 2006;269:635–8.
12. International Commission on Radiation Units & Measurements (ICRU). Quantities and units in radiation protection dosimetry. ICRU Report 51. Bethesda: ICRU; 1993.
13. Bardiès M, Chatal JF. Absorbed doses for internal radiotherapy from 22 beta-emitting radionuclides: beta dosimetry of small spheres. Phys Med Biol. 1994;39:961–81.
14. Goddu SM, Rao DV, Howell RW. Multicellular dosimetry for micrometastases: dependence of self-dose versus cross-dose to cell nuclei on type and energy of radiation and subcellular distribution of radionuclides. J Nucl Med. 1994;35:521–30.
15. Li WB, Friedland W, Pomplun E, et al. Track structures and dose distributions from decays of ^{131}I and ^{125}I in and around water spheres simulating micrometastases of differentiated thyroid cancer. Radiat Res. 2001;156:419–29.
16. Champion C, Zanotti-Fregonara P, Hindié E. CELLDOSE: a Monte Carlo code to assess electron dose distribution – S values for ^{131}I in spheres of various sizes. J Nucl Med. 2008;49:151–7.
17. Campos L, Stabin M. Intravascular brachytherapy to prevent restenosis: dosimetric considerations. Cell Mol Biol (Noysi-le-grand). 2002;48:429–39.
18. Campos L, Stabin M. Internal dosimetry for radiation therapy in coronary arteries. Radiat Prot Dosimetry. 2002;101:423–6.
19. Fisher DR. From "micro" to "macro" internal dosimetry. In: Raabe OG, editor. Internal radiation dosimetry. Madison: Medical Physics Pub Corp; 1994. p. 61–80.
20. Briesmeister JF. MCNP™ – a general Monte Carlo N-particle transport code, version 4C. Manual LA-13709-M. Los Alamos: Los Alamos National Laboratory; 2000.
21. Ftáčniková S, Böhm R. Monte Carlo calculations of energy deposition on cellular, multicellular and organ level for auger emitters. Radiat Prot Dosimetry. 2000;92:279–88.
22. Persson L. Radiation protection issues of Auger electron emitters. Radiat Prot Dosimetry. 1996; 64:189–91.
23. Humm JL, Howell RW, Rao DV. Dosimetry of Auger-electron-emitting radionuclides: report No. 3 of AAPM Nuclear Medicine Task Group No. 6. Med Phys. 1994;21:1901–15.
24. Hofer KG. Dosimetry and biological effects of incorporated Auger emitters. Radiat Prot Dosimetry. 1998;79:405–10.