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РАДІОІЗОТОПИ ЦЕЗІЮ І ДОСВІД ЦИТОГЕНЕТИЧНОЇ ДОЗИМЕТРІЇ ЗА АВАРІЙНИХ СИТУАЦІЙ

Представлено аналіз даних літератури та власних експериментальних досліджень стосовно радіаційних аварій з ^{137}Cs , шляхів його надходження та поведінки в організмі людини, застосування цитогенетичних показників у дозиметрії, досвіду оцінки дози потерпілих за умов зовнішнього опромінення та проблем цитогенетичної дозиметрії внутрішнього опромінення.

Ключові слова: радіоізотопи цезію, ^{137}Cs , радіаційні аварії, зовнішнє опромінення, внутрішнє опромінення, цитогенетична дозиметрія.

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RADIOISOTOPES OF CESIUM AND EXPERIENCE OF CYTOGENETIC DOSIMETRY IN EMERGENCY SITUATIONS

An analysis of data from the literature and own experimental studies related to radiation accidents with ^{137}Cs , the ways of its entry and behavior in the human body, cytogenetic indicators for exposure dosimetry, experience in assessing the dose of victims under conditions of external exposure, and the problem of cytogenetic dosimetry of internal exposure are presented.

Keywords: cesium radioisotopes, ^{137}Cs , radiation accidents, external exposure, internal exposure, cytogenetic dosimetry.

REFERENCES

1. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 2000. Report to the General Assembly. Vol. 1 (New York, UN, 2000) 654 p.
2. Toxicological profile for cesium. Agency for Toxic Substances and Disease Registry. (U.S., Department of Health and Human Services. Public Health Service, 2004) 306 p.
3. Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident. Report by the International Nuclear Safety Advisory Group. Safety Series No. 75-INSAG-1 (Vienna, IAEA, 1986) 106 p.
4. Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine. The Chernobyl Forum: 2003 - 2005. Second revised version (Vienna, IAEA, 2006) 55 p.
5. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. Report of the Chernobyl Forum Expert Group 'Environment' (Vienna, IAEA, 2006) 180 p.
6. Y.A. Izrael (Ed.) Chernobyl: Radioactive Contamination of the Environment (Leningrad: Gidrometeoizdat, 1990) 296 p. (Rus)
7. The Fukushima Daiichi Accident. Technical volume 1/5. Description and Context of the Accident (Vienna, IAEA, 2015) 238 p.
8. G. Nordberg, B. Fowler, M. Nordberg (Eds.). *Handbook on the Toxicology of Metals*. 4th ed. (Elsevier/Academic Press, 2014) 1542 p.
9. W. Penney et al. Report on the accident at Windscale No. 1 Pile on 10 October 1957. *J. Radiol. Prot.* 37(3) (2017) 780.
10. S. Jones. Windscale and Kyshtym: a double anniversary. *J. Environ. Radioactiv.* 99(1) (2008) 1.
11. The Radiobiological Accident in Goiânia (Vienna, IAEA, 1988).
12. A. Wojcik et al. Cytogenetic damage in lymphocytes for the purpose of dose reconstruction: a review of three recent radiation accidents. *Cytogenet. Genome Res.* 104(1-4) (2004) 200.
13. L.A. Ilyin et al. Early medical consequences of radiation incidents on the territory of the former Ukrainian SSR. *Meditina Truda i Promyshlennaya Ekologiya* 10 (2012) 10. (Rus)
14. A. Ghosh, A. Sharma, G. Talukder. Clastogenic effects of caesium chloride on human peripheral blood lymphocytes in vitro. *Toxicol. in Vitro* 7(2) (1993) 137.
15. R. Santos-Mello, T. Schmidt, E. Neuhauss. Induction of micronuclei by CsCl in vivo and in vitro. *Mutat. Res.* 446(2) (1999) 239.

16. S. Bangh et al. Prolonged QT and polymorphic VT with chronic cesium use. *J. Toxicol.-Clin. Toxic.* 39(5) (2001) 556.
17. N.S. Harik, C.D. Stowe, P.M. Seib. Cesium induced prolonged QT syndrome. *J. Invest. Med.* 50(1) (2002) 141A.
18. R. Santos-Mello, L.I. Deimling, A. Almeida. Induction of micronuclei in mouse polychromatic erythrocytes by the administration of non-radioactive CsCl by the oral and intraperitoneal route. *Mutat. Res.* 497(1-2) (2001) 147.
19. P. Olivier, D. Marzin. Study of the genotoxic potential of 48 inorganic derivatives with the SOS chromotest. *Mutat. Res.* 189 (1987) 263.
20. http://www.lnhb.fr/nuclides/Cs-137_tables.pdf
21. http://www.lnhb.fr/nuclides/Cs-134_tables.pdf
22. V.F. Kozlov. *Handbook of Radiation Safety* (Moskva: Energoatomizdat, 1991) 352 p. (Rus)
23. Age-Dependent Doses to Members of the Public from Intake of Radionuclides. Part 1. ICRP Publication 56. *Ann. ICRP* 20(2) (1989).
24. Age-Dependent Doses to Members of the Public from Intake of Radionuclides. Part 2. Ingestion Dose Coefficients. ICRP Publication 67. *Ann. ICRP* 23(3/4) (1993).
25. L.A. Beaugé, R.A. Sjodin. Transport of caesium in frog muscle. *J. Physiol.* 194(1) (1968) 105.
26. Y.I. Bandazhevsky. Chronic Cs-137 incorporation in children's organs. *Swiss. Med. Wkly.* 133(35-36) (2003) 488.
27. R.W. Leggett et al. A physiologically based biokinetic model for cesium in the human body. *Sci. Total Environ.* 317(1-3) (2003) 235.
28. *Le Césium: De l'environnement à l'Homme*. D. Robeau, F. Daburon, H. Métivier (Eds.) (EDP Sciences, 2000). 296 p.
29. D.R. Melo et al. A biokinetic model for ¹³⁷Cs. *Health Phys.* 73(2) (1997) 320.
30. Limits for Intakes of Radionuclides by Workers. ICRP Publication 30 (Part 1). *Ann. ICRP* 2(3-4) (1979) 133 p.
31. W. Müller, U. Scheffer. The metabolism and toxicity of caesium. In: *Radionuclide Metabolism and Toxicity*. P. Galle, R. Masse (Eds.) (Paris, Masson, 1982) p. 82.
32. *The Radiological Accident in Tammiku* (Vienna, IAEA, 1998) 70 p.
33. *The Radiological Accident in Lilo* (Vienna, IAEA, 2000) 120 p.
34. J.L. Lipsztein et al. Application of in vitro bioassay for ¹³⁷Cs during the emergency phase of the Goiânia accident. *Health Phys.* 60(1) (1991) 43.
35. J.L. Lipsztein et al. Studies of Cs retention in the human body related to body parameters and Prussian Blue administration. *Health Phys.* 60(1) (1991) 57.
36. R. Leggett. Biokinetic models for radiocaesium and its progeny. *J. Radiol. Prot.* 33(1) (2013) 123.
37. G. Schwartz, D.E. Dunning, Jr. Imprecision in estimates of dose from ingested ¹³⁷Cs due to variability in human biological characteristics. *Health Phys.* 43(5) (1982) 631.
38. J. Rundo, F.M. Turner. On the biological half-life of caesium in pregnant women and in infants. *Radiat. Prot. Dosim.* 41 (1992) 211.
39. A. Giussani et al. Eurados review of retrospective dosimetry techniques for internal exposures to ionising radiation and their applications. *Radiat. Environ. Bioph.* (59) (2020) 357.
40. N.A. Doggett, W.H. McKenzie. An analysis of the distribution and dose response of chromosome aberrations in human lymphocytes after in vitro exposure to ¹³⁷Cesium gamma radiation. *Radiat. Environ. Bioph.* 22(1) (1983) 33.
41. L. Padovani et al. Cytogenetic study in lymphocytes from children exposed to ionizing radiation after the Chernobyl accident. *Mutat. Res.* 319(1) (1993) 55.
42. S.M. Miller et al. Canadian Cytogenetic Emergency Network (CEN) for biological dosimetry following radiological/nuclear accidents. *Int. J. Radiat. Biol.* 83(7) (2007) 471.
43. V. Hadjidekova et al. The use of the dicentric assay for biological dosimetry for radiation accident in Bulgaria. *Health Phys.* 98(2) (2010) 252.
44. A.N. Balasem, A.S.K. Ali, J.J. Abdul-Khalil. The Yield of Micronuclei in Human Blood Lymphocytes Treated with Radioactive Caesium. *Radiat. Prot. Dosim.* 46(4) (1993) 295.
45. A.N. Balasem, A.S.K. Ali. Establishment of dose-response relationships between doses of Cs-137 γ -rays and frequencies of micronuclei in human peripheral blood lymphocytes. *Mutat. Res.* 259 (1991) 133.
46. K. Lijima K. Morimoto. Quantitative analyses of the induction of chromosome aberrations and sister-chromatid exchanges in human lymphocytes exposed to gamma-rays and mitomycin-C in combination. *Mutat. Res.* 263(4) (1991) 263.
47. K. Mikamo, Y. Kamiguchi, H. Tateno. Spontaneous and in vitro radiation-induced chromosome aberrations in human spermatozoa: application of a new method. *Prog. Clin. Biol. Res.* 340B (1990) 447.
48. K. Mikamo, Y. Kamiguchi, H. Tateno. The interspecific *in vitro* fertilization system to measure human sperm chromosomal damage. In: B.L. Gledhill, F. Mauro (Eds.) *New Horizons in Biological Dosimetry* (New York, Wiley-Liss, 1991) p. 531.
49. Y. Kamiguchi, H. Tateno, K. Mikamo. Micronucleus test in 2-cell embryos as a simple assay system for human sperm chromosome aberrations. *Mutat. Res.* 252(3) (1991) 297.
50. N.C. Arslan, C.R. Geard, E.J. Hall. Low dose-rate effects of cesium-137 and iodine-125 on cell survival, cell progression, and chromosomal alterations. *Am. J. Clin. Oncol.* 9(6) (1986) 521.

51. M. Bauchinger. Chromosome painting and biological dosimetry of absorbed radiation. In: *Radiation Research, 1895 - 1995: Proceedings of the Tenth International Congress of Radiation Research*. Würzburg, Germany, August 27 - September 1, 1995 (Germany, ICRR Society, 1995).
52. M.A Silva, M. Lemes, O.R. Santos. Study of chromosome aberrations induced in human lymphocytes following irradiation with ^{60}Co and ^{137}Cs in vitro. In: *4th Meeting on Nuclear Applications, Encontro Nacional de Aplicacoes Nucleares*, August 18 - 22, 1997, Pocos de Caldas, p. 129.
53. N.A. Maznyk, V.A. Vinnikov. Calibration dose-response relationships for cytogenetic biodosimetry of recent and past exposure to low dose gamma-radiation. *Ukrayins'kyy Radiolohichnyy Zhurnal* 12(4) (2004) 415.
54. *Cytogenetic Dosimetry: Applications in Preparedness for and Response to Radiation Emergencies* (Vienna, IAEA, 2011) 229 p.
55. Radiation protection. Performance criteria for service laboratories performing biological dosimetry by cytogenetics. ISO 19238:2023(en). 36 p.
56. *Cytogenetic Analysis for Radiation Dose Assessment*. Technical Reports Series No. 405 (Vienna. IAEA, 2001) 138 p.
57. G. Obe, Vijayalakmi (Eds.). *Chromosomal Alterations. Methods, Results and Importance in Human Health*. (Springer, 2007) 515 p.
58. K.H. Harada et al. Radiation dose rates now and in the future for residents neighboring restricted areas of the Fukushima Daiichi Nuclear Power Plant. *Proc. Natl. Acad. Sci. USA* 111(10) (2014) E914.
59. J. Depuydt et al. RENEБ intercomparison exercises analyzing micronuclei (Cytokinesis-block Micronucleus Assay). *Int. J. Radiat. Biol.* 93 (2016) 36.
60. C. Beinke et al. Adaption of the Cytokinesis-Block Micronucleus Cytome Assay for Improved Triage Biodosimetry. *Radiat. Res.* 185(5) (2016) 461.
61. Radiological protection. Performance criteria for laboratories using the cytokinesis block micronucleus (CBMN) assay in peripheral blood lymphocytes for biological dosimetry. ISO 17099:2014.
62. A.J. Sigurdson et al. International study of factors affecting human chromosome translocations. *Mutat. Res.* 652(2) (2008) 112.
63. E.A. Ainsbury et al. What radiation dose does the FISH translocation assay measure in cases of incorporated radionuclides for the Southern Urals populations? *Radiat. Prot. Dosim.* 159(1-4) (2014) 26.
64. E.A. Ainsbury et al. Uncertainty on radiation doses estimated by biological and retrospective physical methods. *Radiat. Prot. Dosim.* 178(4) (2018) 382.
65. E.J. Tawn, C.A. Whitehouse. Persistence of translocation frequencies in blood lymphocytes following radiotherapy: implications for retrospective radiation biodosimetry. *J. Radiol. Prot.* 23 (2003) 423.
66. C. Lindholm, A. Edwards. Long-term persistence of translocations in stable lymphocytes from victims of a radiological accident. *Int. J. Radiat. Biol.* 80(8) (2004) 559.
67. A.A. Edwards et al. Review of translocations detected by FISH for retrospective biological dosimetry applications. *Radiat. Prot. Dosim.* 113(4) (2005) 396.
68. U. Yadav et al. Multifaceted applications of pre-mature chromosome condensation in radiation biodosimetry. *Int. J. Radiat. Biol.* 96(10) (2020) 1274.
69. F. Darroudi et al. Detection of total- and partial-body irradiation in a monkey model: a comparative study of chromosomal aberration, micronucleus and premature chromosome condensation assays. *Int. J. Radiat. Biol.* 74(2) (1998) 207.
70. U. Yadav et al. Refined premature chromosome condensation (GO-PCC) with cryo-preserved mitotic cells for rapid radiation biodosimetry. *Sci. Rep.* 11(1) (2021) 1.
71. C. Lindholm et al. Premature chromosome condensation (PCC) assay for dose assessment in mass casualty accidents. *Radiat. Res.* 173(1) (2010) 71.
72. B. Rungsimaphorn, B. Kerkamnuaychoke, W. Sudprasert. Establishment of dose-response curves for dicentrics and premature chromosome condensation for radiological emergency preparedness in Thailand. *Genome Integr.* 7(8) (2016) 1.
73. U. Oestreicher et al. RENEБ intercomparisons applying the conventional Dicentric Chromosome Assay (DCA). *Int. J. Radiat. Biol.* 93(1) (2017) 20.
74. C.A. Oliveira et al. Design and operation of a whole-body monitoring system for the Goiânia radiation accident. *Health Phys.* 60(1) (1991) 51.
75. C.E. Brandão-Mello et al. Clinical and hematological aspects of ^{137}Cs : the Goiânia radiation accident. *Health Phys.* 60(1) (1991) 31.
76. E.T. Sakamoto-Hojo, A.T. Natarajan, M.P. Curado. Chromosome translocations in lymphocytes from individuals exposed to ^{137}Cs 7.5 years after the accident in Goiânia (Brazil). *Radiat. Prot. Dosim.* 86(1) (1999) 25.
77. J.G. Hunt, C.A.N. Oliveira. A method for estimating ^{137}Cs body burden under emergency conditions. *Radiat. Prot. Dosim.* 30(4) (1990) 275.
78. A.T. Ramalho et al. *Subsidies to Cytogenetic Dosimetry Technique Generated from Analysis of Results of Goiânia Radiological Accident*. Thesis (Brazil, 1993) 136 p. (Portuguese)
79. A.T. Ramalho, A.C. Nascimento. The fate of chromosomal aberrations in ^{137}Cs exposed individuals in the Goiânia radiation accident. *Health Phys.* 60(1) (1991) 67.

80. A.T. Ramalho, M.P. Curado, A.T. Natarajan. Lifespan of human lymphocytes estimated during a six year cytogenetic follow-up of individuals accidentally exposed in the 1987 radiological accident in Brazil. *Mutat. Res.* **331(1)** (1995) 47.
81. M. Sasaki, H. Miyata. Biological dosimetry in atomic bomb survivors. *Nature* **220** (1968) 1189.
82. C. Lindholm et al. Biodosimetry after accidental radiation exposure by conventional chromosome analysis and FISH. *Int. J. Radiat. Biol.* **70(6)** (1996) 647.
83. C. Lindholm et al. Persistence of translocations after accidental exposure to ionizing radiation. *Int. J. Radiat. Biol.* **74(5)** (1998) 565.
84. C. Lindholm et al. Intercomparison of translocation and dicentric frequencies between laboratories in a follow-up of the radiological accident in Estonia. *Int. J. Radiat. Biol.* **78(10)** (2002) 883.
85. J.N. Lucas et al. Rapid translocation frequency analysis in humans decades after exposure to ionizing radiation. *Int. J. Radiat. Biol.* **62(1)** (1992) 53.
86. J.N. Lucas et al. Stability of the translocation frequency following whole-body irradiation measured in rhesus monkeys. *Int. J. Radiat. Biol.* **70(3)** (1996) 309.
87. G. Dolphin. Biological dosimetry with particular reference to chromosome aberrations analysis. A review of methods. In: *Handling of Radiation Accidents. Proc. Int. Symp., Vienna, May 19 - 23, 1969. Proceedings Series (Vienna, IAEA, 1969)* p. 215.
88. A.T. Natarajan et al. Goiania radiation accident: results of initial dose estimation and follow up studies. *Prog. Clin. Biol. Res.* **372** (1991) 145.
89. L.K. Bezdrobna et al. Using the cytogenetic dosimetry for the control of potential over exposure of contractors enterprises staff of SSE ChNPP. *Nucl. Phys. At. Energy* **17(2)** (2016) 166. (Rus)
90. M.A. Pilinskaya. The results of selective cytogenetic monitoring of Chernobyl accident victims in the Ukraine. *Health Phys.* **71(1)** (1996) 29.
91. N. Maznyk, V. Vinnikov. Time-effect relationship for unstable chromosome exchange levels in Chernobyl clean-up workers. *Tsitolgiya i Genetika* **38(4)** (2004) 14. (Rus)
92. S. Alexanin et al. Chromosomal aberrations and sickness rates in Chernobyl clean-up workers in the years following the accident. *Health Phys.* **98(2)** 2010 258.
93. F. Granath et al. Retrospective dose estimates in Estonian Chernobyl clean-up workers by means of FISH. *Mutat. Res.* **369(1-2)** (1996) 7.
94. A.V. Sevan'kaev et al. Chromosomal aberrations in lymphocytes of residents of areas contaminated by radioactive discharges from the Chernobyl accident. *Radiat. Prot. Dosim.* **58(4)** (1995) 247.
95. N.O. Maznyk. Cytogenetic effects as a biological indicator of the action of ionizing radiation in low doses in the early and long term after exposure in the Chernobyl contingent. Thesis Abstract for the degree of Doctor of Sciences in Biology (Kyiv, Scientific Center of Radiation Medicine, Academy of Medical Sciences of Ukraine, 2005) 46 p. (Ukr)
96. J.N. Lucas et al. Rapid human chromosome aberration analysis using fluorescence *in situ* hybridization. *Int. J. Radiat. Biol.* **56(1)** (1989) 35.
97. I.E. Vorobtsova et al. Dependence of the frequency of stable and unstable chromosome aberrations on the irradiation dose of human lymphocytes in vitro. *Radiation Biology. Radioecology* **37(2)** (1997) 233. (Rus)
98. E.A. Dyomina et al. Biological effectiveness of ^{137}Cs gamma quanta at the chromosomal level of human peripheral lymphocytes. *Dopovidi Akademiyi Nauk Ukrayiny (Reports of the Academy of Sciences of Ukraine)* **2** (1992) 150. (Ukr)
99. E.A. Demina. Biological effectiveness of ^{137}Cs gamma radiation on the outcome of chromosomal aberrations in human peripheral blood lymphocyte culture. *Ukrayins'kyj Radiolohichnyj Zhurnal* **2** (1993) 107. (Ukr)
100. Yu.B. Kudryashov, Yu.F. Perov, A.B. Rubin. *Radiation Biophysics: Radio Frequency and Microwave Electromagnetic Radiation*. Textbook (Moskva: Fizmatlit; 2008). 184 p. (Rus)
101. O.M. Mikheev, Yu.V. Shilina. *Electromagnetic Radiation*. In: *Encyclopedia of Modern Ukraine*. I.M. Dzyuba, A.I. Zhukovskyi, M.H. Zheleznyak et al. (Eds.) Vol. 9 (Kyiv: Institute of Encyclopedic Research, National Academy of Sciences of Ukraine, 2009). (Ukr)
102. V.A. Kurochkina et al. “Dose – effect” calibration dependence by frequency of unstable chromosomal exchanges in human lymphocytes in acute gamma irradiation by ^{137}Cs in low doses for biological dosimetry. *Nucl. Phys. At. Energy* **22(2)** (2021) 167. (Ukr)
103. Radiation dose to patients from radiopharmaceuticals: A compendium of current information related to frequently used substances. ICRP Publication 128. *Ann. ICRP* **44(2S)** (2015) 325 p.
104. Occupational intakes of radionuclides: Part 1. ICRP Publication 130. *Ann. ICRP* **44(2)** (2015) 192 p.
105. The ICRP computational framework for internal dose assessment for reference adults: Specific absorbed fractions. ICRP Publication 133. *Ann. ICRP* **45(2)** (2016) 77 p.
106. Occupational intakes of radionuclides: Part 3. ICRP Publication 137. *Ann. ICRP* **46(3/4)** (2017) 491 p.
107. D.R. Melo et al. ^{137}Cs internal contamination involving a Brazilian accident, and the efficacy of Prussian Blue treatment. *Health Phys.* **66(3)** (1994) 245.
108. A.T. Ramalho, A.C.H. Nascimento, A.T. Natarajan. Dose assessments by cytogenetic analysis in the Goiânia (Brazil) radiation accident. *Radiat. Prot. Dosim.* **25(2)** (1988) 97.

109. One Decade After Chernobyl. Summing up the Consequences of the Accident. Proc. of an Int. Conf., Vienna, 8 - 12 April 1996 (Vienna, IAEA, 1996) 571 p.
110. V. Berkovski, G. Ratia, O. Nasvit. Internal doses to Ukrainian population using Dnieper river water. *Health Phys.* 71 (1996) 37.
111. S.L. Simon et al. A summary of evidence on radiation exposures received near to the Semipalatinsk nuclear weapons test site in Kazakhstan. *Health Phys.* 84(6) (2003) 718.
112. E. Shishkina et al. Reduction of measurement error of ^{90}Sr , ^{137}Cs and ^{40}K content in human body using the SICH91M whole body counter. *Instrumenty i Metody Izmereniya Radiatsii* 90 (2017) 25. (Rus)
113. S. Roch-Lefèvre et al. A mouse model of cytogenetic analysis to evaluate caesium 137 radiation dose exposure and contamination level in lymphocytes. *Radiat. Environ. Bioph.* 55 (2016) 61.
114. M.P. Little, B.E. Lambert. Systematic review of experimental studies on the relative biological effectiveness of tritium. *Radiat. Environ. Bioph.* 47 (2008) 71.
115. S. Roch-Lefèvre et al. Cytogenetic damage analysis in mice chronically exposed to low-dose internal tritium beta-particle radiation. *Oncotarget* 9 (2018) 27397.
116. G.P. Snegireva, T.I. Khaimovich, V.I. Nagiba. Estimation of the relative biological effectiveness of tritium based on the frequency of chromosomal aberrations in lymphocytes. *Radiation Biology. Radioecology* 50(6) (2010) 664. (Rus)
117. N. Vulpis. The induction of chromosome aberrations in human lymphocytes by in vitro irradiation with beta-particles from tritiated water. *Radiat. Res.* 97(3) (1984) 511.
118. N. Vulpis, G. Scarpa. Induction of chromosome aberrations by ^{90}Sr β -particles in cultured human lymphocytes. *Mutat. Res.* 63 (1986) 277.
119. E.J. Broome, D.L. Brown, R.E.J. Mitchel. Dose responses for adaption to low doses of ^{60}Co gamma rays and ^3H beta particles in normal human fibroblasts. *Radiat. Res.* 158(2) (2002) 181.
120. W. Deng et al. Biological dosimetry of beta-ray exposure from tritium using chromosome translocations in human lymphocytes analyzed by fluorescence in situ hybridization. *Radiat. Res.* 150(4) (1998) 400.
121. G. Ribas et al. Genotoxicity of tritiated water in human lymphocytes. *Toxicol. Lett.* 70(1) (1994) 63.
122. J.S. Prosser et al. The induction of chromosome aberrations in human lymphocytes by exposure to tritiated water *in vitro*. *Radiat. Prot. Dosim.* 4(1) (1983) 21.
123. G. Joksić, V. Spasojević-Tisma. Chromosome analysis of lymphocytes from radiation workers in tritium-applying industry. *Int. Arch. Occup. Environ. Health* 71(3) (1998) 213.
124. E.M. de Oliveira et al. Evaluation of the effect of ^{90}Sr beta-radiation on human blood cells by chromosome aberration and single cell gel electrophoresis (comet assay) analysis. *Mutat. Res.* 476(1-2) (2001) 109.
125. Relative biological effectiveness (RBE), quality factor (Q), and radiation weighting factor (W_R). ICRP Publication 92. *Ann. ICRP* 33(4) (2003) 121 p.
126. L.K. Bezdrobna et al. Simulation of conditions for external and internal exposure of human blood to low doses of ^{137}Cs radionuclide *in vitro* to study its genotoxicity. *Nucl. Phys. At. Energy* 21(2) (2020) 166.
127. T. Sato, K. Manabe, N. Hamada. Microdosimetric analysis confirms similar biological effectiveness of external exposure to gamma-rays and internal exposure to ^{137}Cs , ^{134}Cs , and ^{131}I . *Plos One* 9(6) (2014) e99831.
128. V.A. Kurochkina et al. Chromosome aberrations in human lymphocytes due to external and/or internal irradiation of blood samples by ^{137}Cs in model experiments *in vitro*. *Nucl. Phys. At. Energy* 22(3) (2021) 300. (Ukr)

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