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Ionizing Radiation: Dose Tolerability and Hormesis

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ABSTRACT

Hormesis is rarely mentioned in publications on radiation protection. Among environmental factors acting according to the hormesis model are numerous substances and chemical elements, light, ultraviolet and products of water radiolysis. By analogy with other environmental agents, an evolutionary adaptation to natural background radiation can be expected. The experimental evidence in favor of hormesis and adaptive responses to ionizing radiation is considerable, which means that experimental data are partly at variance with epidemiological studies. The main problems with the epidemiological research of low-dose low-rate exposures are potential bias and inter-study heterogeneity i.e. uneven quality of studies analyzed together in reviews and meta-analyses. The overestimation of medical consequences of the Chernobyl accident has been commented previously. Along with the elevated cancer risk, an increased risk of non-neoplastic diseases has been reported, whereas no plausible physiological mechanisms are known. This can be seen as a circumstantial evidence in favor of bias e.g. self-selection: dose-related differences in self-reporting and medical surveillance. Individuals knowing their higher doses or residing in more contaminated areas would be averagely more motivated to visit medical institutions, being at the same time given more attention, the diagnostics thus being more efficient in patients with higher dose estimates. The dose-effect relationships between low-dose low-rate exposures and non-neoplastic diseases call in question such relationships for cancer reported by the same and other scientists. Several examples of questionable reports and conclusions are discussed here along with the motives to overestimate medical consequences of low-dose low-rate exposures to ionizing radiation.

***Keywords:** dose limits, ionising radiation, radiation protection, carcinogens*

INTRODUCTION

This mini-review is an updated summary of several preceding papers (Jargin 2012-2018); its writing has been prompted by the fact that hormesis is rarely mentioned in publications on the radiation protection field including the UNSCEAR reports. At the same time, the linear no-threshold (LNT) hypothesis is continued to be discussed. The statements that the LNT hypothesis is unfalsifiable are unfounded: to reject the LNT, it would suffice to prove hormesis (Cardarelli and Ulsh 2018). Among environmental factors acting according to the hormesis model are numerous substances and chemical elements, light, ultraviolet and products of water radiolysis (Kaludercic et al. 2014; Le Bourg and Rattan 2014). By analogy with other environmental factors, an evolutionary adaptation to the natural background radiation can be reasonably assumed. The conservative nature of the DNA repair suggests that cells and organisms may have retained some capability to repair damage from higher radiation levels than the today's radiation background (Karam and Leslie 1999). The experimental evidence in favor of hormesis and adaptive responses to ionizing radiation is considerable (Scott 2008, 2014; Baldwin and Grantham 2015; Calabrese 2015; Alavi et al. 2016; Shibamoto and Nakamura 2018; Tang et al. 2017, Jargin 2018; UNSCEAR 1994, 2000), which means that experimental data are partly at variance with epidemiological studies.

The evidence against the LNT or in favor of radiation hormesis has been obtained also in a variety of human studies (Doss 2018; Shibamoto and Nakamura 2018; UNSCEAR 2017). In animal experiments, doses associated with carcinogenesis have been generally higher than average doses in Chernobyl, EURT (East Urals Radioactive Trace) cohorts and regular professional settings (UNSCEAR 1962, 1986, 1994, 2000; Mitchel 2009; Moskalev 1983; Braga-Tanaka et al. 2018; Rühm et al. 2018). Animal experiments with doses comparable to averages in the above-named populations might

appear unpromising as they would hardly bring any statistically significant results. Nevertheless this is the most reliable method to assess the probability of health-related effects of low dose low rate radiation: enhancing the number of animals to look for statistically significant deleterious or favorable (hormetic) effects expressed in the average life span. To make the experiments less expensive, it is unnecessary to examine individual animals and perform necropsies. It would suffice to maintain in equal conditions large animal groups and to register the life duration, which is known to be a sensitive endpoint attributable to radiation exposures (Braga-Tanaka et al. 2018). Such experiments, being simple and ethically acceptable, would objectively characterize the dose-response pattern. For such fundamental biological phenomena as hormesis and DNA repair, the data may be generalizable across species (Baldwin and Grantham 2015; Calabrese 2015). Further research could more precisely quantify radio sensitivity of different animal species thus facilitating extrapolations to humans (Higley et al. 2012).

The main problems of the epidemiological research of low-dose low-rate exposures are potential bias (Jaworowski 2010; Shibamoto and Nakamura 2018; Watanabe et al. 2008) and the inter-study heterogeneity (Little et al. 2010), especially the uneven quality and reliability of studies analyzed together in reviews and meta-analyses. The author agrees with Mark P. Little (2016) that studies of questionable reliability "should therefore probably not be used for epidemiologic analysis, in particular for the Russian worker studies considered here (Ivanov et al. 2006; Kashcheev et al. 2016; Azizova et al. 2015a; Moseeva et al. 2014)" and some others. The overestimation of medical consequences of the Chernobyl accident and EURT (East Urals Radioactive Trace) has been commented previously (Jargin 2012, 2013, 2018). Along with the elevated cancer risk, an increased risk of non-neoplastic diseases (circulatory, respiratory, gastrointestinal) has been reported by the same and other researchers e.g. (Azimzadeh et al. 2017; Azizova et al. 2010-2016; Ivanovo et al. 2006; Kashcheev et al. 2016; Krestinina et al. 2013; Moseeva et al. 2012, 2014; Rybkina and Azizova 2016). This can be seen as a circumstantial evidence in favor of bias e.g. self-selection: dose-related differences in self-reporting and medical surveillance, which is a known phenomenon (McGeoghegan et al. 2008; Zablotska et al. 2013). Individuals knowing their higher doses or residing in more contaminated areas would be averagely more motivated to visit medical institutions, being at the same time given more attention, the diagnostics thus being more efficient in patients with higher dose estimates. For example, the incidence of cerebrovascular diseases (CVD) was reported to be significantly higher among workers with total external γ-ray doses ≥0.2 Gy protracted over years compared to those exposed to lower doses (Azizova et al. 2011). In a later publication, the same was claimed for the doses ≥0.1 Gy (Azizova et al. 2015b), which can hardly be caused by radiation considering the dose comparisons in the next paragraph. The risk estimates by Azizova et al. (2011) were significantly higher than those in other studies (Rühm et al. 2019). The excess relative risk (ERR) for CVD per 1 Gy in the Mayak work force was reportedly even higher than that among A-bomb survivors in Japan (Azizova et al. 2010a; Moseeva et al. 2012), while for the ischemic heart disease (IHD) the mortality risk was comparable with that among A-bomb survivors (Azizova et al. 2012a), where the exposure was acute thus being presumably more efficient (Jargin 2016). Note that the self-selection and other bias could have been active also among A-bomb survivors. Finally, Krestinina et al. (2013) found higher cardiovascular risks in the Techa River cohort at several hundred mGy compared to risks calculated using the LNT-model (Rühm et al. 2019). In the author's opinion, conclusions pertaining to the dose and risk tolerability should not be made on the basis of such findings.

The average total γ-ray dose to male Mayak facility workers studied by Azizova et al. (2010b) and Moseeva et al. (2012) was ~0.91 Gy while ≥90% of the Techa river cohort received ≤0.1 Gy protracted over years (Krestinina et al. 2013). For comparison, some studies found no evidence for excess morbidity and mortality of IHD in women treated by radiotherapy for left vs. right-sided breast cancer (Vallis et al. 2002). An increased risk of heart disease has been associated with breast tumor doses of 40-50 Gy and meditational doses ≥40 Gy (UNSCEAR 2006). The BEIR (2006) Report concluded that "there may be some risk of cardiovascular morbidity and mortality for very high doses and high-dose-rate exposures". According to the UNSCEAR (2006), given the inconsistent epidemiological data and the lack of biologically plausible mechanisms, existing evidence is not sufficient to establish a causal

relationship between ionizing radiation and cardiovascular disease at doses ≤1-2 Gy. The latter figure is probably an underestimation as some epidemiological data are biased, while doses associated with functional or morphological cardiovascular changes in experiments have been generally higher (UNSCEAR 1962; Schultz-Hector 1992). Of note, for the mortality from all diseases other than cancer among younger A-bomb survivors there was an estimated threshold dose ~1.5 Sv (UNSCEAR 1994). Finally, evaluating the data on cardiovascular mortality, it should be taken into account that cardiovascular diseases tend to be over diagnosed post mortem in unclear cases e.g. in the former Soviet Union, which is a confounding factor (Jargin 2017).

The dose-effect relationships between low-dose low-rate exposures and non-neoplastic diseases call in question such relationships for cancer reported by the same and other scientists. Moreover, certain data indicating enhanced cancer risk after low-rate exposures appear doubtful. For example, a significantly increased risk of non-melanoma skin cancer was reported in the Mayak work force exposed to radiation at doses ≥2.0 Sv accumulated over prolonged periods (Azizova et al. 2018). For comparison, the Japanese A-bomb survivor non-melanoma skin cancer incidence dataset was consistent with a threshold at about 1 Sv (Little and Charles, 1997).

However, an observation bias was not excluded. The workers and probably also doctors knew the individual work histories, from which accumulated doses could be approximately inferred, potentially influencing the diagnostic thoroughness. The skin doses were unknown in the study by Azizova et al. (2018). The subjects were exposed mainly to γ-rays having a relatively high penetration distance in tissues, so that the absorbed doses in the skin must have been relatively low. Accordingly, the pre-malignant skin lesions and/or actinic keratoses were "very rare" in members of the study cohort (Azizova et al. 2018). It is known that radiation exposure is associated with premalignant epidermal changes; in particular, actinic keratosis can be caused by X-ray and radiotherapy (Gawkrodger 2004; Schmitt and Miot 2012). Considering the above, a causal relationship between radiation and skin tumors in the study by Azizova et al. (2018) appears questionable. Doubtful statements can be found also in preceding papers by the same authors:

"These data suggest that chronic external radiation enhances the risk for IHD" (Azimzadeh et al. 2017).

"It was shown that ionizing radiation is one of the promoters of the development of atherosclerosis" (Rybkina and Azizova 2016).

"It is concluded that this study provides evidence for an association of lower extremity arterial disease incidence with dose from external γ-rays" (Azizova et al. 2016).

"This study provides strong evidence of IHD incidence and mortality association with external γ-ray exposure and some evidence of IHD incidence and mortality association with internal alpha-radiation exposure" (Azizova et al. 2015c).

"A significant increasing trend in circulatory diseases mortality with increasing dose from internal alpha-radiation to the liver was observed" (Azizova et al. 2015d).

"The categorical analyses showed that CVD incidence was significantly higher among workers with total absorbed external γ-ray doses greater than 0.1 Gy compared to those exposed to lower doses and that CVD incidence was also significantly higher among workers with total absorbed internal alpha-particle doses to the liver from incorporated plutonium greater than 0.01 Gy compared to those exposed to lower doses" (Azizova et al. 2014a).

"Significant associations were observed between doses from external γ-rays and IHD and CVD incidence and also between internal doses from alpha-radiation and IHD mortality and CVD incidence" (Moseeva et al. 2014).

"Findings are that aortal atherosclerosis prevalence was higher in males and females underwent external γ-irradiation of total dose over 0.5 Gy, in males and females underwent internal alpha-irradiation from incorporated plutonium of total absorbed radiation dose in liver over 0.025 Gy" (Azizova et al. 2014b).

"There was a significantly increasing trend (ERR/Gy) of the IHD mortality with the total absorbed dose to liver from internal alpha-radiation due to incorporated plutonium" (Azizova et al. 2012b).

"A statistically significant increasing trend in CVD incidence with internal liver dose from plutonium alpha exposure was observed after adjustment for non-radiation factors and external exposure. ERR per Gy was 0.155 (95%

confidence interval 0.075-0.235). CVD incidence was statistically significantly higher among workers with a plutonium liver dose above 0.1 Gy… the incidence data point to higher risk estimates [in the Mayak work force] compared to those from the Japanese A-bomb survivors" (Moseeva et al. 2012).

As a systematic error or ideological bias is supposed, a question cui bono (to whose profit) should be discussed. It is known that CA has been exploited to strangle nuclear energy thus boosting fossil fuel prices. In more developed countries, antinuclear resentments are supported by Green movements, well in agreement with the interests of fossil fuel producers. Today, however, there are no alternatives to nuclear energy. In the long run, nonrenewable fossil fuels will become more expensive, contributing to the excessive population growth in fossil fuel producing regions and poverty elsewhere. The nuclear power is the cleanest, safest (if technology is on an appropriate level) and practically inexhaustible source to meet the global energy needs (Jaworowski 2010; Jargin 2019).

Further monitoring of exposed populations is important but will hardly clarify the matter. It can be predicted that the screening effect, increasing attention of people to their own health and biased research will result in the appearance of new reports on the elevated registered incidence (detection rate) of cancer and other diseases in populations exposed to the elevated radiation background, both anthropogenic and natural, which would prove no causal relationship. In conclusion, the dose limits for public and occupational exposures to ionizing radiation should be based mainly on the objective evidence from large-scale animal experiments. In the author's opinion, the current safety norms are exceedingly restrictive (Jargin 2018). Elevation of the limits should be accompanied by measures guaranteeing their observance. The magnitude of individual doses must be as low as reasonably achievable taking into account economical and societal considerations (Rühm et al. 2019). Strictly observed realistic safety norms would bring more benefit for the public health than excessive restrictions that would be violated in conditions of disregard for laws and regulations.

REFERENCES

[1] Alavi M, Taeb S, Okhovat MA, Atefi M, Negahdari F (2016) Look different: Effect of radiation hormesis on the survival rate of immunosuppressed mice. J Biomed Phys Eng. 6(3):139–146.

[2] Azimzadeh O, Azizova T, Merl-Pham J, Subramanian V, Bakshi MV, Moseeva M, Zubkova O, Hauck SM, Anastasov N, Atkinson MJ, Tapio S (2017) A dose-dependent perturbation in cardiac energy metabolism is linked to radiation-induced ischemic heart disease in Mayak nuclear workers. Oncotarget 8(6):9067–9078.

[3] Azizova TV, Muirhead CR, Druzhinina MB, Grigoryeva ES, Vlasenko EV, Sumina MV, O'Hagan JA, Zhang W, Haylock RG, Hunter N (2010a) Cerebrovascular diseases in the cohort of workers first employed at Mayak PA in 1948-1958. Radiat Res. 174(6):851–864.

[4] Azizova TV, Muirhead CR, Druzhinina MB, Grigoryeva ES, Vlasenko EV, Sumina MV, O'Hagan JA, Zhang W, Haylock RG, Hunter N (2010b) Cardiovascular diseases in the cohort of workers first employed at Mayak PA in 1948–1958. Radiat Res. 174(2):155–168.

[5] Azizova TV, Muirhead CR, Moseeva MB, Grigoryeva ES, Sumina MV, O'Hagan J, Zhang W, Haylock RJ, Hunter N (2011) Cerebrovascular diseases in nuclear workers first employed at the Mayak PA in 1948-1972. Radiat Environ Biophys. 50(4):539–552.

[6] Azizova TV, Muirhead CR, Moseeva MB, Grigoryeva ES, Vlasenko EV, Hunter N, Haylock RG, O'Hagan JA (2012a) Ischemic heart disease in nuclear workers first employed at the Mayak PA in 1948-1972. Health Phys. 103(1):3–14.

[7] Azizova TV, Moseeva MB, Grigor'eva ES, Muirhed CR, Hunter N, Haylock RG, O'Hagan JA (2012b) Mortality risk of cardiovascular diseases for occupationally exposed workers. Radiats Biol Radioecol. 52(2):158–166.

[8] Azizova TV, Haylock RG, Moseeva MB, Bannikova MV, Grigoryeva ES (2014a) Cerebrovascular diseases incidence and mortality in an extended Mayak Worker Cohort 1948-1982. Radiat Res 182(5):529–544.

[9] Azizova TV, Kuznetsova KV, Bannikova MV, Sumina MV, Bagaeva IaP, Azizova EV, Fot'eva NP, Krupenina LN (2014b) Prevalence of aortal atherosclerosis in workers underwent occupational irradiation. Med Tr Prom Ekol. (11):1–6.

[10] Azizova TV, Grigoryeva ES, Haylock RG, Pikulina MV, Moseeva MB (2015a) Ischaemic heart disease incidence and mortality in an extended cohort of Mayak workers first employed in 1948-1982. Br J Radiol. 88(1054):20150169.

[11] Azizova TV, Haylock R, Moseeva MB, Pikulina MV, Grigorieva ES (2015b) Cerebrovascular diseases incidence and mortality in an extended Mayak worker cohort:

1948-1982. Med Radiol Radiaton Safety (Moscow) 60(4):43–61.

[12] Azizova TV, Grigoryeva ES, Haylock RG, Pikulina MV, Moseeva MB (2015c) Ischaemic heart disease incidence and mortality in an extended cohort of Mayak workers first employed in 1948-1982. Br J Radiol. 88(1054):20150169.

[13] Azizova TV, Grigorieva ES, Hunter N, Pikulina MV, Moseeva MB (2015d). Risk of mortality from circulatory diseases in Mayak workers cohort following occupational radiation exposure. J Radiol Prot 35(3):517–538.

[14] Azizova TV, Bannikova MV, Grigorieva ES, Bagaeva YP, Azizova EV (2016) Risk of lower extremity arterial disease in a cohort of workers occupationally exposed to ionizing radiation over a prolonged period. Radiat Environ Biophys. 55(2):147–159.

[15] Azizova TV, Bannikova MV, Grigoryeva ES, Rybkina VL (2018) Risk of malignant skin neoplasms in a cohort of workers occupationally exposed to ionizing radiation at low dose rates. PLoS One 13(10):e0205060.

[16] Baldwin J, Grantham V (2015) Radiation hormesis: historical and current perspectives. J Nucl Med Technol 43(4):242–246.

[17] BEIR (2006) National Research Council. Health risks from exposure to low levels of ionising radiation: BEIR VII Phase 2. United States National Academy of Sciences. The National Academy Press, Washington.

[18] Braga-Tanaka I 3rd, Tanaka S, Kohda A, Takai D, Nakamura S, Ono T, Tanaka K, Komura JI (2018) Experimental studies on the biological effects of chronic low dose-rate radiation exposure in mice: overview of the studies at the Institute for Environmental Sciences. Int J Radiat Biol. 94(5):423–433.

[19] Calabrese EJ (2015) Model uncertainty via the integration of hormesis and LNT as the default in cancer risk assessment. Dose Response 13(4):1559325815621764.

[20] Cardarelli JJ 2nd, Ulsh BA (2018) It Is Time to Move Beyond the Linear No-Threshold Theory for Low-Dose Radiation Protection. Dose Response 16(3):1559325818779651.

[21] Doss M (2018) Are We Approaching the End of the Linear No-Threshold Era? J Nucl Med. 59(12):1786–1793.

[22] Gawkrodger DJ (2004) Occupational skin cancers. Occup Med (Lond). 54(7):458–463.

[23] Higley KA, Kocher DC, Real AG, Chambers DB (2012) Relative biological effectiveness and radiation weighting factors in the context of animals and plants. Ann ICRP. 41(3-4):233–245.

[24] Ivanov VK, Maksioutov MA, Chekin SY, Petrov AV, Biryukov AP, Kruglova ZG, Matyash VA, Tsyb AF, Manton KG, Kravchenko JS (2006) The risk of radiation-induced cerebrovascular disease in Chernobyl emergency workers. Health Phys. 90(3):199–207.

[25] Jargin SV (2012) Debate on the Chernobyl disaster: on the causes of Chernobyl overestimation. Int J Health Serv. 42(1):29–34.

[26] Jargin SV (2013) On the low-dose-radiation exposure in the Techa River Cohort and mortality from circulatory diseases. Radiat Environ Biophys. 52(3):419–420.

[27] Jargin SV (2016) Dose and dose-rate effectiveness of radiation: first objectivity then conclusions. J Environ Occup Sci. 5(1):25–29.

[28] Jargin SV (2017) Cardiovascular mortality in Russia: a comment. Cardiovasc Diagn Ther. 7(6):E13–E14.

[29] Jargin SV (2018) Hormesis and radiation safety norms: Comments for an update. Hum Exp Toxicol. 37(11):1233–1243.

[30] Jargin SV (2019) International Conflicts and Overpopulation. Current Politics and Economics of Northern and Western Asia 28(2-3). Nova Science Publishers, Inc.

[31] Jaworowski Z (2010) Observations on the Chernobyl Disaster and LNT. Dose Response 8:148–171.

[32] Kaludercic N, Deshwal S, Di Lisa F (2014) Reactive oxygen species and redox compartmentalization. Front Physiol. 5:285.

[33] Karam PA, Leslie SA (1999) Calculations of background beta-gamma radiation dose through geologic time. Health Phys. 77(6):662–667.

[34] Kashcheev VV, Chekin SY, Maksioutov MA, Tumanov KA, Menyaylo AN, Kochergina EV, Kashcheeva PV, Gorsky AI, Shchukina NV, Karpenko SV, Ivanov VK (2016) Radiation-epidemiological study of cerebrovascular diseases in the cohort of Russian recovery operation workers of the Chernobyl accident. Health Phys. 111(2):192–197.

[35] Krestinina LY, Epifanova S, Silkin S, Mikryukova L, Degteva M, Shagina N, Akleyev A (2013) Chronic low-dose exposure in the Techa River cohort: risk of mortality from circulatory diseases. Radiat Environ Biophys. 52(1):47–57.

[36] Le Bourg É, Rattan SI (2014) Hormesis and trade-offs: a comment. Dose Response 12(4):522–524.

[37] Little MP (2016) Radiation and circulatory disease. Mutat Res. 770(Pt B):299–318.

[38] Little MP, Charles MW (1997) The risk of non-melanoma skin cancer incidence in the Japanese atomic bomb survivors. Int J Radiat Biol. 71(5): 589–602.

[39] Little MP, Tawn EJ, Tzoulaki I, Wakeford R, Hildebrandt G, Paris F, Tapio S, Elliott P (2010) Review and meta-analysis of epidemiological associations between low/moderate doses of ionising radiation and circulatory disease risks, and their possible mechanisms. Radiat Environ Biophys. 49(2):139–153.

[40] McGeoghegan D, Binks K, Gillies M, Jones S, Whaley S (2008) The non-cancer mortality experience of male workers at British Nuclear Fuels plc, 1946-2005. Int J Epidemiol. 37:506–518.

[41] Mitchel RE (2009) The dose window for radiation-induced protective adaptive responses. Dose Response 8:192–208.

[42] Moseeva MB, Azizova TV, Muirhed CR, Grigor'eva ES, Vlasenko EV, Sumina MV, O'Hagan JA, Zang W, Haylock RG, Hunter N (2012) Risk of cerebrovascular disease incidence in the cohort of Mayak production association workers first employed during 1948-1958. Radiats Biol Radioecol. 52(2):149–157.

[43] Moseeva MB, Azizova TV, Grigoryeva ES, Haylock R (2014) Risks of circulatory diseases among Mayak PA workers with radiation doses estimated using the improved Mayak Worker Dosimetry System 2008. Radiat Environ Biophys. 53(2):469–477.

[44] Moskalev I (1983) Biological effects of low radiation doses. Institute of Biophysics, Moscow (in Russian).

[45] Rühm W, Azizova T, Bouffler S, Cullings HM, Grosche B, Little MP, Shore RS, Walsh L, Woloschak GE (2018) Typical doses and dose rates in studies pertinent to radiation risk inference at low doses and low dose rates. J Radiat Res 59(suppl_2):ii1–ii10.

[46] Rühm W, Breckow J, Dietze G, Friedl A, Greinert R, Jacob P, Kistinger S, Michel R, Müller WU, Otten H, Streffer C, Weiss W (2019) Dose limits for occupational exposure to ionising radiation and genotoxic carcinogens: a German perspective. Radiat Environ Biophys. doi: 10.1007/s00411-019-00817-x.

[47] Rybkina VL, Azizova TV (2016) The Influence of the Ionizing Radiation on the Development of Atherosclerosis. Radiats Biol Radioecol. 56(1):44–55.

[48] Schmitt JV, Miot HA (2012) Actinic keratosis: a clinical and epidemiological revision. An Bras Dermatol. 87(3):425–434.

[49] Schultz-Hector S (1992) Radiation-induced heart disease: review of experimental data on dose response and pathogenesis. Int J Radiat Biol. 61(2):149–160.

[50] Scott BR (2008) It's time for a new low-dose-radiation risk assessment paradigm - one that acknowledges hormesis. Dose Response 6(4):333–351.

[51] Scott BR (2014) Radiation-hormesis phenotypes, the related mechanisms and implications for disease prevention and therapy. J Cell Commun Signal. 8(4):341–352.

[52] Shibamoto Y, Nakamura H (2018) Overview of Biological, Epidemiological, and Clinical Evidence of Radiation Hormesis. Int J Mol Sci. 19(8).

[53] Tang FR, Loke WK, Khoo BC (2017) Low-dose or low-dose-rate ionizing radiation-induced bioeffects in animal models. J Radiat Res. 58(2):165–182.

[54] UNSCEAR (1962) Report to the General Assembly. Annex D: Somatic effects of radiation. United Nations, New York.

[55] UNSCEAR (1986) Report to the General Assembly. Annex B: Dose-response relationships for radiation-induced cancer. United Nations, New York.

[56] UNSCEAR (1994) Report to the General Assembly. Annex B: Adaptive responses to radiation in cells and organisms. United Nations, New York.

[57] UNSCEAR (2000) Report to the General Assembly. Annex B: Exposures from natural radiation sources. Annex G: Biological effects at low radiation doses. United Nations, New York.

[58] UNSCEAR (2006) Report to the General Assembly. Annex B: Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure. United Nations, New York.

[59] UNSCEAR (2006) Report to the General Assembly. Annex B: Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure. United Nations, New York.

[60] UNSCEAR (2017) Report to the General Assembly. Annex B: Epidemiological studies of cancer risk due to low-dose-rate radiation from environmental sources. United Nations, New York.

[61] Vallis KA, Pintilie M, Chong N, Holowaty E, Douglas PS, Kirkbride P, Wielgosz A (2002) Assessment of coronary heart disease morbidity and mortality after radiation therapy for early breast cancer. J Clin Oncol. 20(4):1036–1042.

[62] Watanabe T, Miyao M, Honda R, Yamada Y (2008) Hiroshima survivors exposed to very low doses of A-bomb primary radiation showed a high risk for cancers. Environ Health Prev Med. 13:264–270.

[63] Zablotska LB, Bazyka D, Lubin JH, Gudzenko N, Little MP, Hatch M, Finch S, Dyagil I, Reiss

RF, Chumak VV, Bouville A, Drozdovitch V, Kryuchkov VP, Golovanov I, Bakhanova E, Babkina N, Lubarets T, Bebeshko V, Romanenko A, Mabuchi K (2013) Radiation and the risk of chronic lymphocytic and other leukaemias among Chernobyl cleanup workers. Environ Health Perspect. 121(1):59–65.

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