The Overestimation of Medical Consequences of Low-Dose Exposure to Ionizing Radiation

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Cambridge Scholars Publishing

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This book first published 2019

Cambridge Scholars Publishing

Lady Stephenson Library, Newcastle upon Tyne, NE6 2PA, UK

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

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ISBN (10): 1-5275-2672-0
ISBN (13): 978-1-5275-2672-3

In memory of my father Vadim S. Yargin (1923-2012),
co-author of the “Handbook of Physical Properties of Liquids and Gases” edited by Begell House.

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INTRODUCTION

The Chernobyl accident has been exploited to strangle the worldwide development of atomic energy (Jaworowski 2010); but it was necessary for a certain period: nuclear technologies should have been prevented from spreading to overpopulated countries governed by unstable regimes, swarming with actual and potential terrorists. Today, there are no thinkable alternatives to nuclear energy: non-renewable fossil fuels will become more expensive, contributing to excessive population growth in fossil fuel producing countries and poverty elsewhere. The worldwide introduction of the nuclear power is a necessity, but it will be possible only after a concentration of authority in a powerful international executive. It will enable construction of nuclear power plants in optimally suitable places, regardless of national borders, considering all socio-political, geological and other conditions.

The overpopulation leads to poverty, overcrowding, pollution of air and water, etc. Ecological damage and depletion of non-renewable resources are proportional to the population size. Humankind can choose to check population growth by reducing the birth rate - instead of raising the death rate by means of wars, famine, and epidemics, as it was usual throughout the history. The ongoing industrial development of the previously underdeveloped countries is precarious because environment protection measures are observed less rigorously there and, most importantly, because of the large scale of this process, proportional to the population size. The exhaustion of fossil fuel resources and contamination of the environment provide another argument in favour of the nuclear energy: the cleanest, safest and practically inexhaustible means to meet the global energy needs (Jaworowski 2010). Producers of the fossil fuels are obviously interested in overestimation of biological effects of low-dose low-rate exposures to ionizing radiation to strangle the development of nuclear energy and maintain high prices for the fossil fuels (Jargin 2015).

The main purpose of this book was to analyse and to expose biases and hidden conflicts of interest in numerous scientific and supposed-to-be scientific publications overestimating medico-biological consequences of low-dose radiation thus causing harm to research, practice and economics (Jargin 2018).

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CHAPTER ONE

HORMESIS AND RADIATION SAFETY NORMS

Summary

Hormesis describes processes, where cells or organisms exhibit a biphasic response to increasing doses of a substance or condition; typically, low-dose exposures induce a beneficial response, while higher doses cause toxicity (Mattson and Calabrese 2010). Hormesis can be generally explained by evolutionary adaptation to the current level of a factor present in the natural environment or to some average from the past. This pertains also to ionizing radiation as the natural background has been decreasing during the time of life existence on the Earth. The DNA damage and repair are normally in a dynamic balance. The conservative nature of the DNA repair suggests that cells may have retained some capability to repair the damage from higher radiation levels than those existing today. According to this concept, the harm caused by a radioactive contamination would tend to zero with a dose rate tending to a wide range level of the natural radiation background. Existing evidence in favour of hormesis is substantial, experimental data being partly at variance with epidemiological studies. Potential bias, systematic errors and motives to exaggerate risks from the low-dose low-rate ionizing radiation are discussed here. In conclusion, current radiation safety norms are exceedingly restrictive and should be revised on the basis of scientific evidence. The elevation of limits must be accompanied by measures guaranteeing their observance.

Background

This chapter summarizes preceding articles on medico-biological effects of low-dose radiation coming to the conclusion that current radiation safety norms are exceedingly restrictive and should be revised to become more realistic and workable. The main goal is to emphasize the bias widespread in the epidemiological research on responses to radiation releases, which contributed to policy implementations perpetuating the use of the linear no-threshold theory (LNT) as the basis of radiation safety regulations. Current radiation safety norms are based on the LNT: extrapolations of a dose-response relationship down to low doses, where such relationships are unproven and can become inverse due to hormesis (Jaworowski 2010a, Prekeges 2003, Jolly and Meyer 2009, Cui et al. 2017, Mattson and Calabrese 2010, Sanders 2017). According to the current regulations, an equivalent effective dose to individual members of the public should not exceed 1 mSv/year. The dose limits for exposed workers are 100 mSv in a consecutive 5-year period, with a maximum of 50 mSv in any single year. For comparison, worldwide annual exposures to natural radiation sources are generally expected to be in the range 1-10 mSv; the estimated global average is 2.4 mSv (UNSCEAR 2000).

Recent assessments of the data on survivors of atomic explosions in Hiroshima and Nagasaki (A-bomb survivors) do not support the LNT and are consistent with hormesis (Doss 2016). For solid cancers and leukaemia, significant dose-response relationships were found among the A-bomb survivors exposed to ≤500 mSv but not ≤ 200 mSv (Little and Muirhead 1996, 1998, Heidenreich et al. 1997). The artificial neural network methods, applied to the data on A-bomb survivors, indicated the presence of thresholds around 200 mSv varying with organs (Sasaki et al. 2014, Sacks et al. 2016). The value 200 mSv has been mentioned in some reviews as a level, below which the cancer risk elevation is unproven (Heidenreich et al. 1997, González 2004). According to UNSCEAR (2010), a significant elevation was observed at doses ≥100-200 mGy. Among others, the underestimation of practical thresholds may result from biased epidemiological research.

The author agrees with Mark P. Little (2016) that potentially biased studies and those 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).” This recommendation may be extended onto some other studies discussed in this book. Moreover, the UNSCEAR evaluation of the low-dose radiation data seems to be prone to bias e.g. the overestimation of Chernobyl consequences; more details are in the next section. Today, when the literature is so abundant, research quality, bias and conflicts of interest must be taken into account defining inclusion criteria of studies into reviews.

Chernobyl accident

Using the LNT, the Chernobyl accident (hereafter accident) was predicted to result in a considerable increase in radiation-induced cancer. In fact, there has been no cancer increase proven to be a consequence of the radiation exposure except for the thyroid carcinoma in people exposed at a young age (UNSCEAR 2008, Raabe 2011, Anspaugh et al. 1988). Although the appearance of radiogenic thyroid cancers after the accident cannot be excluded, their number has been largely overestimated due to the following mechanisms. Prior to the accident, the registered incidence of paediatric thyroid malignancy was lower in the former Soviet Union (SU) compared to other developed countries apparently due to differences in diagnostic quality and coverage of the population by medical examinations (Lushnikov et al. 2006, Jargin 2017). Intensive screening in the contaminated territories after the accident detected not only small tumours but also advanced neglected ones accumulated in the population, misclassified as aggressive radiogenic cancers. Moreover, there was a pressure to be registered as Chernobyl victims to get access to benefits and health care provisions (Bay and Oughton 2005). It can be reasonably assumed that some patients from non-contaminated areas were registered as Chernobyl victims on the basis of wrong information. There was no regular screening outside the contaminated areas, so that such cases must have been averagely more advanced. These phenomena were confirmed by the fact that the "first wave" thyroid cancers after the accident were averagely larger and less differentiated than those diagnosed after 10 years and later (Williams et al. 2004, Nikiforov and Gnepp 1994), when the pool of neglected cancers was gradually exhausted by the screening while the registration reliability was improved. Admixture of old neglected cases explains the fact that Chernobyl-associated thyroid cancers tended to behave in an aggressive fashion. The following citation is illustrative: "The tumours were randomly selected (successive cases) from the laboratories of Kiev and Valencia... [The cancers were] clearly more aggressive in the Ukrainian population in comparison with the Valencian cases" (Romanenko et al. 2007). There is an explanation: averagely earlier cancer detection in Western Europe.

The misclassification of neglected advanced cases as aggressive radiogenic cancers gave rise to the concept that the tumours supposed to be radiogenic, at least those from the "first wave" after the accident, were more aggressive than sporadic ones (Williams et al. 2004, Zablotska et al. 2015, Fridman et al. 2015, Iakovleva et al. 2008). This had consequences for the practice: although approaches varied, the surgical treatment of supposedly radiogenic cases was recommended to be “more radical” (Rumiantsev 2009). After 1998-1999, the surgery in some institutions switched to a more aggressive approach (Iakovleva et al. 2008, Demidchik et al. 2006).

The following was recommended for Chernobyl-related paediatric thyroid carcinoma: “Radical thyroid surgery including total thyroidectomy combined with neck dissection followed by radioiodine ablation” (Demidchik et al. 2007) or external radiotherapy (40 Gy) (Mamchich and Pogorelov 1992). Some experts regarded subtotal thyroidectomy to be “oncologically not justified” and advocated total thyroidectomy with prophylactic neck dissection (Rumiantsev 2009, Demidchik et al. 1996, Demidchik and Kontratovich 2003, Lushnikov et al. 2003). Lesser resections were regarded to be “only acceptable in exceptional cases of very small solitary intrathyroidal carcinomas without evidence of neck lymph node involvement on surgical revision” (Demidchik et al. 2006).

It was written in a recent instructive publication that bilateral neck dissection must be performed in all thyroid cancer cases independently of the tumour size, histology and lymph node status (Demidchik and Shelkovich 2016). This approach is at variance with a more conservative treatment of papillary thyroid carcinoma applied also in the settings of a nuclear accident (Sugitani 2017). The sources (Segal et al. 1997, La Quaglia et al. 1988) were misquoted by Demidchik and Kontratovich (2003) advocating total thyroidectomy with bilateral neck dissection for all cases of paediatric thyroid cancer. The sources (Danese et al. 1997, Arici et al. 2002, Giuffrida et al. 2002) were cited in support of the statement: “The most prevailing opinion calls for total thyroidectomy regardless of tumour size and histopathology” (Demidchik et al. 2006). In fact, subtotal thyroidectomy was used or recommended in these studies, in some of them along with the total thyroidectomy (Danese et al. 1997, Arici et al. 2002, Giuffrida et al. 2002).

Note that many thyroid patients were young females potentially concerned with the cosmetic aspect. Moreover, the total thyroidectomy with neck dissection is associated with complications such as hypoparathyroidism and recurrent laryngeal nerve palsy (Demidchik et al. 1996, Bohrer et al. 2005, Henry et al. 1998, Rybakov et al. 2000). In this connection, the high suicide rate noticed among patients with Chernobyl-related thyroid cancer (Contis and Foley 2015, Fridman et al. 2014) might be explained as a consequence of decreased quality of life after the excessively radical surgery. Admittedly, other experts pointed out that ‘‘radiation history does not appear to significantly affect long-term treatment results, provided an appropriate, not principally different from that for sporadic thyroid cancer treatment and follow-up had been performed'' (Saenko et al. 2017).

Mechanisms of false-positivity have been discussed previously; among others, the misinterpretation of nuclear pleomorphism as a malignancy criterion of thyroid nodules occurred in the former SU of the 1990s (Jargin 2016). If a thyroid nodule is found by the screening, a fine-needle aspiration is usually performed. The thyroid cytology is accompanied by some percentage of inconclusive results, when histological examination is indicated. In the former SU of the 1990s, this percentage was relatively high due to the insufficient experience with paediatric material, suboptimal quality of specimens, shortage of modern literature etc. The surgical specimen is sent to a pathologist, who may be sometimes prone, after the in toto removal of the nodule, to confirm malignancy even in case of uncertainty (Jargin 2016). The fine-needle aspiration cytology was introduced into practice later than ultrasonography, which contributed to the overdiagnosis of malignancy especially during the 1990s.

The following citations from a Russian-language professional publication are illustrative: "Practically all nodular thyroid lesions, independently of their size, were regarded at that time in children as potentially malignant tumours, requiring an urgent surgical operation" or "Aggressiveness of surgeons contributed to the shortening of the minimal latency period" (Lushnikov et al. 2006). Note that the term "latency period" is unsuitable if the cause-effect relationship is unproven; in the above context the latency should be understood as the time between the radiation exposure and surgery.

Radio- and cancerophobia contributed to the overdiagnosis of cancer. The number of detected nodules was additionally increased due to the iodine deficiency in the contaminated territories with the enhanced incidence of goitre and nodular lesions found by the screening providing more opportunities for the false-positive diagnoses. Frozen sections were sometimes used, which is suboptimal for histological diagnostics of thyroid nodules.

The facts discussed in this section seem to be camouflaged in the UNSCEAR reports. As mentioned above, the registered incidence of thyroid cancer in children and adolescents prior to the accident had been lower in the former SU than in other developed countries i.e. there was a pool of neglected cases. This is not clearly perceptible from UNSCEAR reports because the increased incidence 4-5 years after the accident was compared not with the pre-accident data but with those from the first years after the accident, when the registered incidence already started to increase (UNSCEAR 2008). Health checkups were started in the contaminated areas of Russia in 1986, while the risk of TC in children was known. Similar actions were conducted in Belarus and Ukraine. In Ukraine, the local cancer registry was established in 1987 in the radio-contaminated areas, which probably contributed to a better cancer detection and hence to the increase in the registered incidence.

Another example: the number of registered thyroid cancers in Ukraine prior to the accident as per UNSCEAR (2008) is higher than corresponding data published by IARC (Parkin et al. 1999): 39 cases for the period 1982-1985 vs. 25 cases for 1981-1985. These higher figures were published with references to "communications to the UNSCEAR Secretariat" (UNSCEAR 2008) and the paper by Tronko et al. (2002). However, this article could be found neither in online databases, nor on the website of the International Journal of Radiation Medicine (edited in Kiev): http://www.physiciansofchernobyl.org.ua/magazine/eng/index.html (accessed 22 May 2018), nor in libraries. According to the personal communication from the UNSCEAR Secretariat (22 October 2013), the UNSCEAR was provided with hard copies of this paper. Apparently, the paper by Tronko et al. (2002) has never been accessible to the international scientific community. The biased attitude within UNSCEAR may be conveyed by certain experts pushing through a prescribed notion.

East Urals Radioactive Trace

A tendency to exaggerate causal relationships between radiation and some diseases in the Techa river and Mayak facility cohorts, usually discussed in the context of the East Urals Radioactive Trace (EURT), has been noticed recently (Jargin 2014). In earlier papers no increase in cancer incidence was reported at doses ≤520 mSv or among all studied workers of the Mayak facility. Existence of a threshold was held possible, the keynote being the absence of significant radiation-related abnormalities in the EURT cohorts (Buldakov et al. 1990, Okladnikova et al. 2000, Tokarskaya et al. 2002, Kostyuchenko and Krestinina 1994). It was noticed that excessive absolute risk of leukaemia had been 3.5 times lower in the Techa river cohort than among A-bomb survivors i.e. the risk from acute exposure was higher than that from protracted ones (Akleev et al. 2001, 2004). Later on, the attitude has apparently changed. The same researchers pointed out a similar level of cancer risk in the EURT cohorts and among A-bomb survivors (Akleev and Krestinina 2010, Krestinina et al. 2013a, Ostroumova et al. 2008). An unofficial directive could have been behind this metamorphosis; potential motives are discussed in Chapter 11. Moreover, increased risks of non-malignant diseases - cardiovascular, respiratory, digestive - have been reported by the same and other scientists in the EURT and Chernobyl cohorts (Ivanov et al. 2006, Kashcheev et al. 2016, Azizova et al. 2010a, 2011, 2013, 2014a-c, 2015a,b, Moseeva et al. 2012, 2014, Krestinina et al. 2013b, Yablokov 2009a). For example, the incidence of cerebrovascular disease was significantly elevated among Mayak workers with a total external dose ≥0.1 Gy protracted over years (Simonetto et al. 2015). This is indicative of a bias, in particular, of dose-dependent self-selection, noticed also by other researchers in radiation-exposed cohorts (McGeoghegan et al. 2008, Zablotska et al. 2013). It can be reasonably assumed that individuals with higher dose estimates were on average more interested in medical examinations. In the health care system of the former SU, thoroughness of medical examination has often depended on a patient's initiative. According to a personal communication (2014) with the EURT expert Ludmila Krestinina, members of the EURT cohorts were preoccupied with monetary compensations. Most probably, individuals with higher dose estimates or those residing in more contaminated areas were more insistent at examinations, visited medical institutions more frequently, being at the same time given more attention. As a result of the screening effect, observation bias, dose-dependent selection and self-selection, diagnostics would be a priori more efficient in patients with higher doses, especially of diseases without local symptoms such as leukaemia; therefore, epidemiological studies alone e.g. (Little et al. 2018) do not prove causality for low doses.

Besides, a recall bias can cause a systematic error in case-control studies: cases would recollect facts related to the exposure better than controls, thus contributing to an overestimation of doses among the cases. For example, a study that compared self-reported questionnaires with medical reports in patients with thyroid cancer and controls indicated that the patients were nearly twice as likely as controls to report x-ray exposures even though the medical records demonstrated the exposures to be comparable (Jorgensen 2013).

UNSCEAR (2010) could not draw any conclusions about direct causal relationships between doses ≤1-2 Gy and excess incidence of cardiovascular as well as other non-malignant diseases, while physiological mechanisms are unclear. The above figure ≤1-2 Gy seems to be an underestimation due to systematic errors in the epidemiological research. There is some cardiovascular risk associated with high-dose high-rate exposures; for example, patients treated by radiotherapy at doses ≥40 Gy to parts of the heart may develop heart disease later in life. Some sources discuss also lower doses (NAS 2006, Baselet et al. 2016, Darby et al. 2010), which are still much higher than averages in the Chernobyl and EURT cohorts. The doses associated with cardiovascular damage in animals have also been higher than those in the above-named cohorts (UNSCEAR 1962, Schultz-Hector 1992). The mean total dose to male Mayak workers in a study reporting an increase in cerebrovascular diseases was 0.91 Gy protracted over years (Moseeva et al. 2012); over 90% of the Techa river cohort in a study of circulatory conditions received doses ≤0.1 Gy (Krestinina et al. 2013b). A relationship of atherosclerosis and cerebrovascular diseases with radiation was reported in Mayak workers exposed to external irradiation at total doses ≥0.5 Gy and/or to internal α-radiation from incorporated plutonium at liver doses ≥0.025 Gy protracted over years (Azizova et al. 2010a, 2014a). The excess relative risk (ERR) for cerebrovascular diseases among Mayak facility workers was reported to be even higher than that in A-bomb survivors (Moseeva et al. 2012), where the self-selection bias could have been active as well. It is known that correlations do not necessarily prove causality being caused by bias or irrelevant factors. The cause-effect relationships for non-cancer outcomes for the low dose levels are improbable a priori. Demonstration of relationships between low-dose low-rate exposures and non-neoplastic diseases cast doubt on the analogous relationships with cancer found in epidemiological studies by the same and other researchers using similar methods (Azizova et al. 2010b, Krestinina et al. 2007, 2013a, Sokolnikov et al. 2008, 2015, Ivanov et al. 2004, Yablokov 2009b).

Hormesis and radiation safety norms

Hormesis describes processes, where a cell or organism exhibits a biphasic response to increasing doses of a substance or condition; typically, low-dose exposures induce a beneficial response, while higher doses cause toxicity (Mattson and Calabrese 2010). Among hormetic factors are various substances and chemical elements, vitamins, light, ultraviolet, ionizing radiation and products of water radiolysis, as well as different kinds of stress (Kaludercic et al. 2014, Le Bourg and Rattan 2014). For factors that are present in the natural environment, hormesis can be explained by an adaptation to a current environmental level or some average from the past. This pertains also to ionizing radiation. The LNT is based on the concept that cells are altered by ionizing radiation: the more tracks pass through cell nuclei, the higher would be the risk of malignant transformation. This concept does not take into account that DNA damage and repair are normally in a dynamic equilibrium. The natural background radiation has been decreasing over the time of life existence on the Earth. The conservative nature of the DNA repair suggests that cells may have retained some capability to repair damage from higher radiation levels than those existing today (Karam and Leslie 1999).

The evolutionary adaptation to ionizing radiation was explained by the increased synthesis of DNA repair enzymes, activated endogenous radioprotective mechanisms, achieved e.g. by accumulation of sulfhydryl compounds and antimutagens, as well as an increase of the reserve of off-cycle cells (Burlakova et al. 2016). Hormesis is assumed to work on the molecular (stimulating DNA repair) and cellular levels; corresponding studies were reviewed by Jolly and Meyer (2009), Jaworowski (2010a), Mattson and Calabrese (2010). Eukaryotic cells display an adaptive response that enhances their radio-resistance after a low-dose priming irradiation (Marples and Skov 1996). So, the repair of DNA damage is enhanced in cells irradiated with a priming dose of 0.25 Gy followed by 2 Gy compared with those irradiated with 2 Gy only (Le et al. 1998). Doses 50-75 mGy significantly enhanced proliferation of cultured cells via activation of signaling pathways (Liang et al. 2011). Furthermore, the bystander effect (a biological response of a cell resulting from an event in a nearby cell) may play a role in radiobiological responses to low dose irradiation. A review by Mitchel (2004) concluded that below 100 mGy, the bystander effect reduced rather than increased the risk of radiation-induced damage and hence of genetic instability. Details of these mechanisms are beyond the scope of this book.

Existing evidence in favour of hormesis is substantial (Scott 2008, Baldwin and Grantham 2015, Calabrese 2015, Alavi et al. 2016), which means that experimental data are partly at variance with epidemiological studies. Among others, there is evidence in favour of hormetic effects of low-dose radiation such as activation of DNA repair and apoptosis, suppression of inflammation and protection from inflammatory diseases, stimulation of anticancer and other immunity. There is experimental evidence that low-dose exposure slows ageing and prolongs life (Scott 2014). Admittedly, not all experiments supported hormesis e.g. showing life lengthening of exposed mice (Tanaka et al. 2003). Other studies did report life lengthening under similar conditions (Caratero et al. 1998).

In animals, doses associated with carcinogenesis have been higher than those in the Chernobyl and EURT cohorts, amounting to hundreds or thousands mGy (UNSCEAR 1986, 2000, Mitchel 2009, Moskalev 1983, Braga-Tanaka 2018). It should be mentioned that radiation hormesis was demonstrated also for synergistic interactions. For example, residential radon and some professional exposures may protect against lung cancer in smokers; in the Mayak facility cohort, radiation hormesis apparently protected not only against spontaneous lung cancer but also against that associated with the cigarette smoking (Sanders and Scott 2006). In vitro, eukaryotic cells show adaptive responses enhancing their radioresistance after a low-dose priming irradiation (Jolly and Meyer 2009, Klammer et al. 2012, Ojima et al. 2011, Nenoi et al. 2015); the mechanisms are outside the scope of this book.

For such ancient biological phenomena as hormesis and DNA repair, the data may be generalized across species (Baldwin and Grantham 2015, Calabrese 2015). Further research could quantify radiosensitivity of different animal species thus enabling more precise extrapolations to humans (Higley et al. 2012).

The benefit from a moderate exposure to ionizing radiation was reported in A-bomb survivors (Luckey 2008), although these data might be not free from bias due to a better monitoring of the survivors. Occupational exposures were reported to be associated with better health (Prekeges 2003, Jolly and Meyer 2009), which at least in part can be explained by the healthy worker effect. Cancer mortality was found to be lower in high-elevation areas, where the natural radiation background is enhanced due to a higher intensity of the cosmic radiation (UNSCEAR 2010, Prekeges 2003, Hart 2010). There are many places in the world where the dose rate from natural background radiation is 10-100 times higher than the average e.g. 260 mGy/year in Ramsar, Iran; yet no higher incidence of cancer or other radiation-related diseases has been found in such areas (Sacks et al. 2016). Those living in Mississippi receive ~2 mGy per year from natural radiation, while those living in Colorado receive ~8 mGy per year. Nevertheless, epidemiological studies demonstrated that the cancer rate mortality in Colorado is 30% less than in Mississippi after correcting for confounding factors (Sanders 2017). The screening effect and increasing attention of people to their own health may result one day in an increase of the registered cancer incidence in areas with high natural radiation background, which would prove no causal relationship. The most promising way to gather reliable information on low dose effects would be large-scale animal experiments. However, the integrity of all participants is needed for that. A mixture of reliable und unreliable studies assessed together remains a problem of reviews and meta-analyses. Large-scale experiments must be made possibly inexpensive. In our opinion it is unnecessary to examine each mouse, perform necropsies (Little 2018, Tran and Little 2017) etc. It would suffice to maintain in equal conditions large murine populations - unexposed and exposed to different dose rates - and to register the average life duration. Such an experiment, being simple and relatively inexpensive, would objectively characterize the dose-response pattern and hormesis.

Conclusion

Summarizing the above and previously published arguments (Jargin 2011, 2016, 2017), the harm caused by radioactive contamination would tend to zero with a dose rate tending to a wide range level of the natural radiation background. Within a certain range, the dose-effect relationship may become inverse due to hormesis. A graph, plotted on the basis of experimental data, with a sagging of the dose-effect curve below the background cancer risk within the range 0.1-700 mGy (Fig. 7-1), was presented in the review by Mitchel (2009). Low doses should be analysed separately from higher doses (Rozhdestvenskii 2008, 2011) to prevent unfounded LNT-based prognostications e.g. of millions of victims from nuclear accidents (Bertell 2006).

With regard to radiation safety regulations, a new approach is needed - to determine the threshold dose using large-scale animal experiments and establish regulations to ensure that doses are kept well below the threshold level (Doss 2016). In our opinion, current radiation safety norms are exceedingly restrictive and should be revised to become more realistic and practical. An elevation of limits must be accompanied by measures guaranteeing their observance, and by openness of dosimetric data. No contraindications have been found to an elevation of the total doses to individual members of the public up to 5 mSv/year (Jargin 2018). The dose rate would thus remain within the range of the natural background. Considering that development of nuclear technologies is needed to meet the global energy needs (Jaworowski 2010b), a doubling of limits for professional exposures should be considered as well. Strictly observed realistic safety norms will bring more benefit for the public health than excessive restrictions that might be neglected in conditions of disrespect for laws and regulations. Note that disregard of written instructions was among the causes of the Chernobyl accident (Beliaev 2006, Semenov

1995). The worldwide development of nuclear technologies will be possible only after a concentration of authority in the most developed parts of the world, the science-informed harmonization of global radiation regulatory standards and globalized control of the nuclear industry.

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