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The Consequences of the 1986 Chernobyl Nuclear Disaster are Still Felt Today

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Abstract

This review summarizes publications on medical and biological effects of low-dose radiation. Potential bias in epidemiological research is analyzed. Consequences of Chernobyl accident and radiocontamination in the Urals are discussed in some detail. Thyroid cancer was rarely diagnosed in children and adolescents in the former Soviet Union prior to the accident. The mass screening after the accident found not only small tumors but also advanced neglected cancers misinterpreted as aggressive radiogenic malignancies. The latter gave rise to the concept that cancer in exposed individuals is more aggressive than in the general population, which caused overtreatment. Children at schools and preschools were easily available for screening; mass examinations were performed under conditions of high expectancy of thyroid cancer, which resulted in overdiagnosis. Some patients from non-contaminated areas were registered as Chernobyl victims. After the accident, numerous poorly substantiated publications appeared, whereas spontaneous diseases in clean-up workers or residents of contaminated areas were a priori regarded to be radiogenic. The accident has been exploited to strangle the worldwide development of atomic energy for boosting of fossil fuel prices. Later on, consequences of contaminations in the Urals have been overestimated as well. Radiation safety standards are exceedingly restrictive and should be revised to become more realistic and workable. Elevation of the limits must be accompanied by measures guaranteeing their observance. Strictly observed realistic safety norms will bring more benefit for the public health than excessive restrictions that would be neglected in countries with prevailing disrespect for laws and regulations. Of note, negligence and disregard of written instructions was among the causes of the Chernobyl catastrophe. In conclusion, consequences of the Chernobyl accident are still felt: some countries continue dismantling nuclear power plants, thus strengthening their economic dependence on Russia.

Introduction

Since many years we have tried to demonstrate that certain scientists have overestimated medical consequences of low-dose exposure to ionizing radiation [1,2]. The overestimation contributed to the strangulation of nuclear energy, supporting appeals to dismantle nuclear power plants (NPPs), which agrees with the interests of fossil fuel producers. The use of atomic energy is on the agenda today due to increasing energy needs of the humankind. Health risks and environmental damage are maximal for coal and oil, lower for natural gas and much lower for atomic energy - the cleanest, safest and practically inexhaustible energy resource [3,4]. 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. Exhaustion of fuel resources and contamination of the environment provide another argument in favor of nuclear energy.

This review summarizes preceding publications on medical and biological effects of low-dose low-rate radiation coming to the conclusion that current radiation safety regulations are exceedingly restrictive and should be revised to become more realistic and workable. The goal is to emphasize the bias in some epidemiological research on responses to radiation exposures, which contributed to the use of linear no-threshold (LNT) model: extrapolations of a dose-response relationship down to low doses, where such relationships are unproven. The overestimation of cancer risk using the LNT model resulted in high costs with no medical benefit [5]. The experimental evidence in favor of radiation hormesis, i.e. beneficial effect of low-dose exposure within some dose range, is considerable [6-10]. There are large datasets that demonstrate thresholds in the dose-response relationship for cancer induction [5]. Some assessments of the data from studies of survivors of atomic explosions in Hiroshima and Nagasaki (A-bomb survivors) do not support LNT and are consistent with hormesis [11]. For solid cancers and leukemia, significant dose-response relationships were found among A-bomb survivors exposed to ≤500 mSv but not ≤ 200 mSv [12-14]. The artificial neural network methods, applied to the data on A-bomb survivors, indicated the presence of thresholds around 200 mSv varying with organs [15,16]. The value 200 mSv has been mentioned in some reviews as a level, below which the cancer risk elevation is unproven [12,17]. According to the UNSCEAR, a significant increase of cancer risk was observed at doses ≥100-200 mGy [18]. This latter figure may be an underestimation due to bias in the epidemiological research. The author agrees with Mark P. Little that results of biased research should therefore probably not be used for epidemiologic analysis, in particular the Russian worker studies considered here [19-23]. This recommendation may be extended onto some other studies discussed in this review.

Chernobyl accident

The average individual effective doses, received by six million residents of areas recognized as contaminated after the Chernobyl accident (hereafter accident) during the period 1986-2005 were around 9 mSv, which means that "most of the workers and members of the public were exposed to low level radiation comparable to, or at most a few times higher than, the annual natural background levels" [24]. It was estimated that individual external and internal doses received by residents of Kiev during the first year after the Chernobyl accident were about 3 mSv and 1.1 mSv respectively [25], thus being

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comparable with the global average annual doses from the natural radiation background (2,4 mSv). According to another estimation, the average whole-body annual individual dose to the residents of Kiev from all sources of exposure was ≤10 mSv in 1986, decreasing thereafter [26]. Nevertheless, patients from Kiev were repeatedly studied together with residents of contaminated areas in "exposed" cohorts [27,28].

The worldwide annual exposures to the natural background radiation vary widely; they are generally expected to be in the range 1-10 mSv but are higher in some densely populated areas [5,24,29,30]. High natural radiation background is not known to be associated with any increase in health risks [18,30,31], leaving apart the separate topic of radon and lung cancer at a cumulative exposure level of about 250 mSv [32]. Human data on doses and dose rates, comparable with or a few orders of magnitude above the natural background, show no measurable change in cancer frequency [5]. The average individual doses from the background radiation for some countries are presented in the monograph [33]. This matter should have been elucidated in the publications where patients from different countries were compared; otherwise, exposures in a control group can turn out to be not significantly different from those in "exposed" cohorts [27,28]. A comparison with controls from Europe should have included dose estimates from diagnostic radiology extensively used in the West. Computed tomographic (CT) examination causes an effective dose 2-20 mSv, while the doses from interventional CT procedures usually range within 5-70 mSv. Organs in the beam can receive 10-100 mGy (usually 15-30 mGy) per single CT sequence [34].

Misunderstanding can arise from the paper by Balonov, containing the following phrase in the abstract: "Apart from the dramatic increase in thyroid cancer (TC) incidence among those exposed at a young age and some increase of leukemia and solid cancer in most exposed workers, there is no clearly demonstrated increase in the somatic diseases due to radiation" [35]. This is misquoting. In the Chernobyl Forum publication [36] cited by Balonov [35], leukemia and solid cancers (other than TC) are not discussed. In another Chernobyl Forum publication, it is stated that "apart from the dramatic increase in TC incidence among those exposed at a young age, there is no clearly demonstrated increase in the incidence of solid cancers or leukemia due to radiation in the most affected populations" and further "there have been many post-Chernobyl studies of leukemia and cancer morbidity in the populations of contaminated areas in the three countries. Most studies, however, had methodological limitations and lacked statistical power. There is no convincing evidence at present that the incidence of leukemia or cancer (other than thyroid) has increased in children, those exposed in utero, or adult residents of the contaminated areas" [37]. In the Report of the UN Chernobyl Forum Expert Group "Health", it was commented that "there is currently no evidence to evaluate whether a measurable risk of leukemia exists among the exposed as adults in the general population... With regard to liquidators, there is clearly a need to clarify the existing observations" and further "there is no evidence of increased risk of non-thyroid solid cancers resulting from Chernobyl" [38]. The same, in principle, is said in the text of Balonov's article [35]. The above-cited statement from the open access abstract is substantiated neither in the article text nor in the Chernobyl Forum publications referred to in this article titled "The Chernobyl Forum: major findings and recommendations" [35]. Furthermore, the counterpart of the "the most exposed workers or liquidators" [35] in the general population, middle-aged men from the working class, are incompletely covered by medical services, so that regular medical checkups of liquidators have predictably resulted in an increase in the registered incidence of various diseases. These considerations, as well as bias due to the dose-dependent self-reporting of patients [39], pertain also to another study [40], where national statistics for leukemia were used as external control for a cohort of liquidators. Further discussion of leukemia among liquidators is in [41].

Thyroid lesions

Based on the LNT concept, Chernobyl was predicted to result in a considerable increase in radiation-induced malignancy. In fact, there has been no cancer increase proven to be a consequence of the radiation exposure except for the thyroid cancer (TC) in people exposed at a young age [24]. The precipitous elevation of TC detection rate, started ~4 years after the accident, could be predicted neither from studies of A-bomb survivors nor from experiences with radiotherapy. Although the appearance of radiogenic TCs 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 pediatric thyroid malignancy was lower in the former Soviet Union (SU) than in other developed countries apparently due to differences in diagnostic quality and reliability of medical checkups [2,42]. It is known by insiders that yearly preventive examinations (so-called dispensarizations), performed during the Soviet time at schools, universities, many factories and institutions, were sometimes rather a formality, missing various diseases. Obviously, thyroid nodules in children were missed prior to the accident. Targeted screening in the contaminated territories in condition of high cancer expectancy found not only small tumors but also advanced neglected cancers. Moreover, there was pressure to be registered as Chernobyl victims to get access to benefits and health care provisions [43]. 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 TCs after the accident tended to be larger and less differentiated than those diagnosed after 10 years or later" [44,45]. The pool of neglected TCs was gradually exhausted while the diagnostic reliability improved. Admixture of old neglected cases explains the fact that Chernobyl-associated TCs were often described as highly aggressive. The following citation is illustrative: "The tumors 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" [46]. An explanation is the earlier cancer detection in Europe.

The following statement can be misunderstood: "With regard to the size of the primary tumor, 77% were greater than 1 cm, suggesting that these were not incidental thyroid cancers detected by aggressive screening" [47]. As discussed above, mass screening detected not only small incidental tumors but also advanced TCs. This predictable phenomenon was confirmed by the fact that the first wave TCs after the Chernobyl accident were on average larger and structurally less differentiated than those detected later [45]. It is sometimes objected

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that the screening cannot account for age-related differences: the incidence increase of Chernobyl-related TC was recorded mainly among people exposed at a young age. In fact, there is an explanation: children at schools and preschools are easily available for screening; mass examinations were performed by not always perfectly trained teams, in conditions of high expectancy of thyroid cancer.

As discussed above, TC was rarely diagnosed in children and adolescents in the former SU prior to the accident: in Belarus during the years 1981-1985, the absolute number of TCs diagnosed in children under 15 years was 3, and the corresponding annual rate per million children under 15 years was 0.3; for Ukraine, correspondingly, 25 and 0.5. For the northern regions of Ukraine contaminated after the accident, these figures were correspondingly 1.0 and 0.1 [48]. Even lower pre-accident TC incidence rates were published by the International Agency for Research on Cancer (IARC): "In the whole of Belarus, by 1995, the incidence of childhood TC had increased to 4 cases per 100000 per year compared to 0.03-0.05 cases per 100000 per year before the accident" [49]. The pre-accident incidence rates quoted above are low in comparison with other developed nations [50,51]. TC is the most frequent tumor of endocrine glands in children and adolescents; its incidence was estimated to be 2-5 per million per year [52]. Based on the cases diagnosed during 2000-2004, the US Cancer Registry SEER reported an annual age-adjusted incidence rate 8.5 per 100.000; ~2.1% of the cases diagnosed under the age 20 [52], which corresponds to the annual incidence rate in the latter age group ~1.8 per million. Corresponding data from a regional Tumor Registry in Würzburg, Germany, are given in the same article, where age-adjusted incidence rate per 1 million for the age under 20 years was 2.0 [52].

The UNSCEAR 2008 Report compared the enhanced TC incidence after the Chernobyl accident not with the pre-accident level but with the years 1986-1990 (Annex D, pp. 60-61), when the incidence had already increased to ~5 cases/million. In particular, it is stated: "The background rate of TC among children under the age 10 years is approximately 2 to 4 cases per million per year" [24], which is much higher than the pre-accident rates quoted above [48,49]. The number of the registered cases in Ukraine presented by the UNSCEAR (25 cases in the period 1981-1985 [24]) was given with the reference to [53]. However, the publication [53] was found neither in online databases, nor on the Journal website, nor in libraries. According to a written communication from the UNSCEAR Secretariat (22 October 2013), the UNSCEAR was provided with hard copies of this paper. Apparently, the article [53] has never been available to the international scientific community. All that looks like camouflage of the low registered incidence of pediatric TC prior to the accident.

The detection rate of pediatric TC tends to be higher in more developed countries [51], obviously in consequence of better diagnostics. Comparing the figures presented above, it is evident that there was a pool of neglected TCs in Belarus and Ukraine prior to the Chernobyl accident. In the Russian Federation (RF), TC was started to be registered as a separate entity only in 1989 [42], when the screening had been started and detection rate of TC began to rise. Admittedly, the TC incidence increase after the Chernobyl accident was so dramatic that an increase in the background incidence rate by several cases per million per year would have limited impact on the interpretation of the elevation as a consequence of the accident. If the background annual incidence of pediatric TC was just 2-4 cases per million, then the maximum size of the pool of undiagnosed TC would be 30-60 cases per million. If these cases were all diagnosed during the period of 5 years after the rapid incidence rise (1991-1995), then the maximum incidence rate, if increased only due to this mechanism, would be only 8-16 cases per million per year. The reported figures were higher: in Belarus among residents exposed as children and adolescents (aged ≤18 years in 1986) the TC incidence was between 30 (men, 1991-1995) and 120 (women, 2001-2005) cases per million per year [24,54]. Obviously, other mechanisms such as the false-positivity, registration of latent, dormant, questionable TC, microcarcinomas and tumors of uncertain malignant potential as cancers, as well as false registration of non-exposed patients as Chernobyl victims, have additionally contributed to the increase. The ability of the screening to enhance the registered TC incidence many times was known before the accident [3].

Furthermore, iodine deficiency in contaminated areas and goiter associated with it have contributed to the high registered incidence, as more thyroid nodules were found by the screening, providing more opportunities for false-positive diagnoses. Frozen sections instead of paraffin-embedded ones were sometimes used, which is suboptimal for histological diagnostics of thyroid nodules. The data on verifications by expert commissions of post-Chernobyl pediatric TC in Russia are discussed below and in the book [2]. False-positive cases, not covered by verifications, have remained undisclosed.

Nearly all pediatric TCs after the accident were of papillary type often with solid and follicular tissue components [49]. A reason thereof is obvious for an ex-Soviet pathologist: the diagnosis of follicular TC often requires numerous high-quality histological sections from the capsular area of a nodule to find an invasion, which was not always done because of technical reasons and insufficient awareness of minimally-invasive follicular carcinoma. Therefore, follicular TC tended to be under-diagnosed. Furthermore, it is known that more advanced papillary TCs often contain solid and follicular structures. The high prevalence of such tissue components in the post-Chernobyl papillary TC is another argument in favor late diagnostics. Finally, about the absence of significant TC increase among children born after the accident: the data pertaining to them originated from a later period, when the diagnostic quality improved, radiophobia subsided, and there were no motives to artificially enhance the figures. In the author's opinion, based also on interviews with pathologists and other medics involved in the diagnostics of Chernobyl-related tumors, trimming of data in a desired direction contributed to the overestimation of Chernobyl consequences. Circumstantial evidence thereof is a large number of papers with obviously unrealistic results and conclusions, some of them commented previously [2,55].

The chromosomal rearrangement of the tyrosine kinase proto-oncogene RET/PTC3 was found to be more frequent in TCs of *non-exposed* (residing outside the contaminated areas) patients from Ukraine than in TCs from France: 64.7 vs. 42.9% [56], most probably thanks to earlier tumor detection in France. Remarkable data were reported about thyroid adenoma, a benign condition with different pathogenesis: the RET rearrangements were found in 57.1 % of non-exposed patients from Ukraine and not in a single adenoma from

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France. An explanation is in the same article: at a re-examination, in 8 from 14 of the adenomas from Ukraine (but in no one from France) were found groups of cells with "limited nuclear features of papillary cancers" [56], which sounds unusual for a practical pathologist and indicates diagnostic uncertainty. Interestingly, significant LNT-type dose-response relationship was found not only for TC but also for follicular thyroid adenoma [39], a benign lesion with different pathogenesis. This is another reason to doubt the cause-effect relationships between radiation and TC after Chernobyl.

Another example is the study comparing 359 papillary TCs from exposed patients and the control: TCs from 81 patients born ≥9 months after the accident [57]. The "study population included a substantial number of papillary TCs occurring after ≤100 mGy," where development of radiogenic cancer would be improbable as per the dose comparisons presented in this review. The study reported "…radiation dose-related increases in DNA double-strand breaks in human TCs developing after the Chernobyl accident… non-homologous end-joining (NHEJ) the most important repair mechanism… increased likelihood of fusion versus point mutation drivers" [57]. These findings are not surprising: DNA damage tends to accumulate along with the tumor progression. Double-strand breaks with error-prone repair contribute to the genome diversity in cancer cells [58]. The NHEJ repair pathway is potentially mutagenic. At the same time, no association of exposure with transcriptomic and epigenomic markers was found [57]. This indicates that the latter markers are to a lesser extent associated with the neoplastic progression than DNA lesions. As for patients born after the accident (the control group) [57], the data pertaining to them originated from a later period, when the quality of diagnostics improved while the reservoir of advanced neglected cancers was exhausted by the screening. Therefore, the average stage and grade of TCs in the exposed group must have been a priori higher than among the controls [57]. The causative role of low-dose radiation such as "a dose-dependent carcinogenic effect of radiation derived primarily from DNA double-strand breaks" [57] in the studied population remained unproven. It was rightly noted that the "increased detection of pre-existing papillary TCs in the population that may not become clinically evident until later, if at all, due to intensive screening and heightened awareness of thyroid cancer risk in Ukraine" [57]. This concept was discussed also earlier [59].

The report with participation of Edward D. Williams stated that "The exposed and unexposed tumors from the same geographical area are essentially identical morphologically and in their degree of aggressiveness… childhood papillary TC (PTC) from Japan were much more highly differentiated ($p<0.001$), showed more papillary differentiation ($p<0.001$) and were less invasive ($p<0.01$) than Chernobyl tumors" [60]. Later on, in articles by the same authors without E.D. Williams, the accents have been modified: "Childhood Japanese PTC differed from Ukrainian PTC by more pronounced invasive properties… higher morphological aggressiveness of PTC in young Japanese patients" [61]. In a more recent paper, Bogdanova et al. acknowledged that Ukrainian "radiogenic" or "radiation-related" PTC "had a solid-trabecular growth pattern and displayed morphological features of aggressive biological behavior" [62] without any satisfactory proof that the tumors in the studied residents of Kiev, Chernigov and Zhitomir provinces were indeed caused or influenced by radiation. What was different about inhabitants of these regions were the screening with detection of neglected cases and some over-diagnosis, radiation phobia with increased self-reporting, and registration of some unexposed patients as Chernobyl victims.

After the accident, numerous poorly substantiated publications appeared, where spontaneous diseases in Chernobyl clean-up workers or residents of contaminated areas were claimed to be radiogenic without any satisfactory proof; more details and references are in [2,55]. If earlier papers were unreliable, some later ones by the same or other authors might be unreliable as well (despite more skilful formulation), because the motives have generally remained unchanged. For an inside observer it is evident that behind some papers from the former SU, overestimating Chernobyl consequences, was a directive, which had been not unusual for the Soviet science. Research topics were assigned to scientists, while "expected results" were discussed at scientific councils, sometimes being, in fact, prescribed in advance. Desired research results could be "recommended" in advance, which was favored by the authoritative management style, ingrained also in the science and medicine. Motives for overestimation of Chernobyl consequences have been obvious: it facilitated preparation of numerous dissertations, financing and international aid. Moreover, the Chernobyl accident has been exploited to strangle the worldwide development of atomic energy for boosting of fossil fuel prices [3].

Diagnostics

Mechanisms of the overdiagnosis were discussed in more detail in the book [2]. One of them is as follows. If a thyroid nodule is found by the screening, a fine-needle aspiration biopsy (FNAB) is usually performed. Cytology of thyroid is associated with a considerable percentage of uncertain conclusions, when histological verification is indicated. Patients were referred for surgery if the cytology was suspicious. Most operations consisted of a complete or partial thyroidectomy [63]. The surgical specimen was sent to a pathologist, who could be sometimes prone, after the in toto removal of a nodule, to confirm malignancy even in case of some uncertainty. FNAB was introduced into practice later than ultrasonography, which additionally contributed to the overdiagnosis during the 1990s.

Gross dissection of surgical specimens was often made with blunt autopsy knives, without rinsing instruments and the board with water, which could result in tissue deformation, contamination of the cut surface by cells and tissue fragments as well as other artefacts [64], hardly distinguishable from malignancy criteria. This probably contributed to the high frequency of tumor cells found in blood vessel lumina (45 % of cases) reported in post-Chernobyl papillary TC [65]. In many laboratories, celloidin embedding was used, not allowing reliable evaluation of nuclear changes in papillary thyroid carcinoma, in particular, the ground-glass nuclei, which is an important diagnostic criterion. Pathologists in Russia, having experience with thyroid tumors from radiocontaminated areas, pointed out the "low quality of histological specimens, impeding the assessment of nuclei" [66]. The Head pediatric oncologist of Russian Federation Vladimir Poliakov pointed out shortage of cytologists, especially those having experience with pediatric material (written communication 2009). In the 1990s, some diagnostic criteria for TC were missing in the used manuals and monographs in Russian. Foreign handbooks of cytology were rare at workplaces.

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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 tumors, requiring an urgent surgical operation" and "Aggressiveness of surgeons contributed to the shortening of the minimal latency period" [42]. Of note, 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. These quotes demonstrate that the high expectancy contributed to the overdiagnosis and overtreatment of TC.

Overtreatment of TC

High aggressiveness, invasiveness or poor differentiation of TC in patients from contaminated areas was reported by many studies, some of them referenced in [67]. The authors of the latter paper found no enhanced aggressiveness of TC in a cohort of patients with TCs developed after radiotherapy [67]. The misclassification of advanced neglected cases as aggressive radiogenic cancers gave rise to the concept that malignancies in exposed individuals are more aggressive than in the general population [65,68,69]. This had consequences for the practice: surgical treatment of supposedly radiogenic cases was recommended to be "more radical" [70]. Indeed, after 1998, thyroid surgery in some institutions became more radical [69,71]. Guidelines recommended "total thyroidectomy (TT) combined with neck dissection followed by radioiodine ablation" [51] and irradiation with 40 Gy [72]. Certain experts generally recommended TT with neck dissection for TC [73]. Less radical surgery was regarded to be "only acceptable in exceptional cases of very small solitary intra-thyroidal carcinomas without evidence of neck lymph node involvement on surgical revision" [71]. It was written in an instructive publication that bilateral neck dissection must be performed for TCs independently of tumor size and histological structure [74]. This approach is at variance with a more conservative treatment also in the settings of a nuclear accident [75]. The sources [76-78] were misquoted to support the recommendation: "The most prevailing opinion calls for TT regardless of tumor size and histopathology" [71]. In the quoted publications not TT but subtotal resection is discussed. Along the same lines, the sources [78-80] were misquoted in the article [73].

The "excessive thyroid surgery activity" on contaminated territories with overdiagnosis and overtreatment of TC and "large number" of post-surgery complications was recognized by Russian Health Ministry in 1998 [81]; but the overtreatment continued, especially in Belarus. The Health Minister ordered a morphological revaluation of surgical specimens of patients from Bryansk province born after 1968 [81]. The verification detected false-positivity: "Diagnosis of TC was confirmed in 79,1 % of cases (federal level of verification: 354 cases) and 77,9 % (international level: 280 cases)" [82]. Considering general propensity to manipulate statistics [83], these figures may be an underestimation.

In a later study, 69% of post-Chernobyl pediatric TC patients underwent TT; among them, radioiodine was administered in 69% of the cases [84]. As per the same article, in patients diagnosed with TC after the Fukushima Daiichi accident, hemithyroidectomy was applied in 92% and TT in 8% of the cases only. In another study, "given the presence of radiation exposure in the patients' histories", TT was performed in 405 out of 465 (87.1%) papillary thyroid *microcarcinomas* [emphasis added] with postoperative radioiodine therapy in 76.1% of the cases. Neck dissection was performed in ~50%. Recurrences were diagnosed only in 1.3% of the cases (median follow-up 5.2 years). The authors acknowledged that microcarcinomas were "rather indolent" and advised "more frequent organ-preserving surgeries vs. TT even for potentially radiogenic papillary thyroid microcarcinomas" [85]. The long-term overall survival of post-Chernobyl TC patients was found to be excellent: during the 1990-2014 period, 1.9% (21 pediatric patient) with TC died, among them only 2 from progressive carcinoma while 7 TC patients committed suicide [84]. According to a most recent paper, ten-year follow-up of thyroid tumors diagnosed after the Chernobyl accident revealed a disease-specific mortality rate of ≤1% [86]. In another study, 7 suicides were reported among 936 surgically treated TC patients in Belarus (1990-2005) [87]. Many patients diagnosed with radiogenic TC were young females, for whom esthetic consequences would be of importance. Analogously, radical thyroidectomy was applied in TC patients exposed to radiation in the Urals [88].

The author agrees with the following conclusions: "After the Chernobyl and Fukushima nuclear accidents, thyroid cancer screening was implemented mainly for children, leading to case over-diagnosis"; "The existence of a natural reservoir of latent thyroid carcinomas, together with advancements in diagnostic practices leading to case overdiagnosis, explain, at least partially, the rise in TC incidence in many countries"; "Total thyroidectomy, as performed after the Chernobyl accident, implies that patients must live the rest of their lives with thyroid hormone supplementation. Additional treatment using radioactive iodine-131 therapy in some cases may result in potentially short- or long-term adverse effects" [89].

Epidemiologists warned against false-positive diagnoses of malignancy in thyroid nodules. Experts argued that the worldwide increase in the TC incidence has been caused by the screening, improvements of medical surveillance and technological advancements in diagnostics. Indeed, "the extent to which opportunistic thyroid cancer screening is converting thousands of asymptomatic persons to cancer patients without any known benefit to them needs to be examined carefully" [90]. Health-related and social (stigmatization as a cancer patient) adverse effects of surgical hyper-radicalism are known. The risk of complications associated with thyroid surgery (nerve injuries, hypoparathyroidism and others) is proportional to the extent of thyroidectomy [91]. The rate of adverse effects was additionally elevated because of insufficient qualification of some surgeons engaged after the Chernobyl accident in conditions of a high workload [92]. In particular, performing subtotal thyroidectomy instead of TT may be a better choice in order to preserve parathyroid function [93]. Elective neck dissection is usually performed in patients with clinically evident nodal disease although there is no general agreement on this matter [91,93]. Of note, TT would have unfavorable consequences in conditions of irregular supply of thyroxin e.g. in the areas of military conflicts.

Renal and bladder lesions

In the studies by Romanenko et al., the patients were subdivided according to the soil contamination: 1st group - 5-30 Ci/km^2 (185-1110 kBq/m^2); 2nd group - 0.5-5 Ci/km^2 (18.5-185 kBq/m^2)

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[94]. Individual whole body lifetime doses as a function of the soil contamination were estimated as follows: for the range 185-555 kBq/m^2 - 5-20 mSv; for 555-1480 kBq/m^2 - 20-50 mSv [33]. For the period 1986-2000 the dose range was from 2 mSv in towns located in black soil areas with the contamination level 40-600 kBq/m^2 to 300 mSv in villages with podzol sandy soil and contamination level about 600-4000 kBq/m^2 [36]. The doses in the period 2001-2056 were considerably lower. For comparison, the standard (70 years) lifetime dose from the average natural radiation background (2.4 mSv/year) is 170 mSv, with a typical range 70-700 mSv for different regions [36]. These comparisons indicate that the term "chronic, long-term, low doses of ionizing radiation" [27,94-97] is not generally applicable to the residents of contaminated areas after the Chernobyl accident.

The statement "Recent studies have shown that during the period subsequent to the nuclear Chernobyl accident (April 1986), an increase in morbidity (4.7 to 9.8 per 100.000 of the total population), aggressiveness, and proliferative activity of renal cell carcinomas from Ukrainian patients is recognized" [28] was endorsed by a self-reference [95] and another reference to a report by the Ukrainian Ministry of Health. However, no cancer incidence increase, apart from TC in patients exposed at a young age, was proven to result from Chernobyl exposures [24,98]. As discussed above, among causes of the registered TC incidence increase were improved medical surveillance and regular examinations [24]. Morphologic and molecular-genetic differences between renal cancers from contaminated and non-contaminated areas were probably caused by differences in the tumor grade and stage between the compared cohorts: cancers from Ukraine tended to be more advanced and hence less differentiated than controls from Spain [27,28]. This, in turn, was caused by an earlier detection of malignancies in Spain. Of note, surgeons might overuse nephrectomy if they read that renal-cell carcinoma from contaminated territories is on average more aggressive, while surrounding parenchyma contains "proliferative atypical nephropathy with tubular epithelial nuclear atypia and carcinoma in situ" [99].

The false-positivity is a probable explanation also for the fact that in different groups of men with benign prostatic hyperplasia (BPH) and women with chronic cystitis, from contaminated areas and Kiev, severe urothelial dysplasia and carcinoma in situ (CIS) were found by bladder biopsy as frequently as in 56-92 % of all random cases [94,96,97]. The random selection mode was repeatedly pointed out: "The Institute of Urology (Academy of Medical Sciences of Ukraine) in Kiev during 1994-2006 collected all BPH patients who underwent suprapubic prostatectomy and all these patients were included in our study in different years without exception, along with a small number of females with chronic cystitis" [94].

The following was stated about patients with BPH studied by bladder biopsy: "Irradiation cystitis with multiple foci of severe urothelial dysplasia/CIS and some invasive transitional cell carcinoma were observed in 96/66, 76/56 and 56/8 % of patients in groups I, II and III respectively" (the group III was from non-contaminated areas) [100]. In the Handout by the same authors, distributed at the XXIII International Congress of the International Academy of Pathology (IAP) on the 15-20 October 2000 in Nagoya, the following was written: "Histologically the different forms of proliferative cystitis, which were frequently combined and had features of irradiation cystitis with multiple areas of severe dysplasia and carcinoma in situ (CIS), sometimes associated with small transtional-cell carcinoma, occurred in 97% of patients from the radio contaminated areas of Ukraine." Such a high prevalence of severe dysplasia and CIS in randomly selected BPH patients is obviously unrealistic. It should be stressed that overdiagnosis entailed overtreatment including repeated cystoscopies with "mapping" biopsies. Apparently, the "Chernobyl cystitis" [94,101], characterized by urothelial dysplasia and CIS as well as "reactive epithelial proliferation associated with hemorrhage, fibrin deposits, fibrinoid vascular changes, and multinuclear stromal cells" [101] was in some cases caused by repeated cystoscopies, mapping biopsies and electrocoagulation.

In the studies of bladder lesions [94,96,97], the differences between the exposed and unexposed groups could have been caused by a selection mode and quality of specimens. Some images were published repeatedly [94,102], reproduced and commented [103]. Looking at the illustrations in the earlier articles by the same authors [104,105] (reproduced in [103]), it seems that overdiagnosis of dysplastic and neoplastic bladder lesions took place also earlier. Histological images of bladder mucosa and thyroid from widely used Russian-language handbooks, conductive to false-positivity, were reproduced and commented [2,106].

Radioactive contamination in the Urals

Consequences of radiocontamination in the Urals have been generally more serious than after the Chernobyl disaster. The difference is that the latter was an accident, but the former has been contamination lasting over 70 years with several accidents in between. Apart from professional exposures, the disposal of radioactive substances into the river Techa, the 1957 Kyshtym accident and dispersion by winds from the lake Karachai in 1967, led to exposures of residents. The East Urals Radioactive Trace (EURT) cohort included people exposed after the Kyshtym accident. Considerable contamination with dumping of radioactive waste into the Techa river occurred in the period 1949-1956.

In earlier publications by Russian researchers, no cancer incidence increase was reported in the cohorts with average exposures below 0.5 Sv or generally among employees of the Mayak Production Association (MPA) [107-112]. The absolute risk of leukemia per 1 Gy and 10000 man-years was reported to be 3.5-fold lower among residents of Techa riverside villages compared to A-bomb survivors. This was reasonably explained by a higher efficiency of the acute exposure compared to chronic and protracted ones. Later on, the same researchers started reporting similar risks for cancer and other diseases in the Techa river, MPA and EURT cohorts, on one hand, and A-bomb survivors on the other hand [113-115]. Analogously, an earlier study found a decrease in the cancer mortality in the EURT cohort compared with the general population [110]. A review confirmed the same level of both cancer and all-cause mortality in the EURT cohort vs. control [108]. In a later report on the same cohort, the authors avoided direct comparisons but fitted their data into a linear model. The configuration of dose-response curves in this paper is inconclusive but nonetheless the authors claimed an elevated cancer risk in the EURT population [116]. An unofficial directive was apparently behind this ideological shift noticed in the period 2005-2007. Manipulations with statistics have been not unusual

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[83,106,117]. Potential motives included financing, international aid, publication pressure, stirring anti-nuclear protests in other countries and strangulation of atomic energy aimed at the boosting of fossil fuel prices. Several articles from the former SU about medical and ecological consequences of low-dose low-rate radiation have common features: large volume, abundant details and mathematical computations, but no clear insight into medical and ecological consequences.

Increased risks of cardiovascular diseases were claimed for Chernobyl, MPA, Techa and EURT cohorts, whereas average doses have been comparable with the natural radiation background. There are many populated areas where dose rates from the natural background are 10-100-fold higher than the global average (2.4 mSv/year) with no proven health risks [5,118]. The doses have been protracted over decades: studied MPA workers were first employed in the years 1948-1982. For example, the mean dose of Cradiation was 0.54 Gy in men and 0.44 Gy among women in the MPA cohort study, where the incidence of arteriosclerosis in lower limbs correlated with the radiation dose [119]. Average doses in the Techa river cohort were 34-35 mGy while the follow-up was since the 1950s [120], so that the dose rates were compatible with the natural background in some populated areas. Apparently, the Techa river data do not possess sufficient statistical power to determine the dose response shape. In particular, the uncertain and biased statistics are unsuitable for computations of the Dose and Dose Rate Effectiveness Factor (DDREF). Earlier Russian publications stressed the higher biological efficiency of acute exposures compared to chronic and fractionated ones [107]; later on, the same researchers recommended the use of DDREF = 1.0, which implies that acute and chronic exposures are equally efficient [121]. This recommendation is evidently unfounded for dose rates compatible with the natural radiation background.

In earlier reports, cardio- and cerebro-vascular mortality in the MPA cohort did not depend on the external dose [122,123] (commented [124]). Reported dose-dependence of the incidence can be explained by greater diagnostic thoroughness in people with higher doses leading to registration of mild conditions. In a later paper based on the MPA cohort, an increased excess relative risk (ERR/Gy) of death from ischemic heart disease was claimed for the dose range 5-50 mGy/year [125]. Recent review by A.N. Koterov [126] has apparently been influenced by relevant comments cited by the same author previously [127]; further commented [128]), trying, however, to shift responsibility for overestimation of low-dose effects onto foreign authors: "In most sources, 2005-2021 (publications by M.P. Little with co-workers, and others) reveals an ideological bias towards the effects of low doses of radiation … In selected M.P. Little and co-authors sources for reviews and meta-analyses observed both absurd ERR values per 1 Gy and incorrect recalculations of the risk estimated in the originals at 0.1 Gy" [126]. Note that publications co-authored by Mark P. Little [129,130] used the data provided by Russian colleagues. Of note, Koterov mistranslated some cited phrases with a change of meaning in his Russian-language publication [127], commented previously [128,131].

It has been rightly noted in the recent review that the "diagnosis (by a physician knowing the patient's history) could vary with dose"; and the "inter-study variation in unmeasured confounders or effect modifiers" [130]. Early and borderline conditions would be more often diagnosed in people with higher doses due to more thorough examinations and the patients' attention to their own health (selection and self-selection bias). "The markedly elevated mortality and morbidity rates of circulatory disease in the Russian population compared with other developed countries" [129] has been explained by unfounded diagnoses. At least in Russia, there is a tendency: the lower the diagnostic quality, the higher the portion of cardiovascular diseases among causes of death both after autopsies and in people dying at home without post mortem examination [132].

Among members of the MPA cohort who received Cgamma-rays doses more than 0.1 Gy, the incidence of circulatory diseases was found to be higher than in subjects exposed to lower doses [133,134]. The excess relative risk (ERR/Gy) of cerebro-vascular conditions in MPA employees was reported to be even higher than among A-bomb survivors [133,135], where dose-dependent selection could have taken place like in other epidemiological studies. Of note, some data assessments in A-bomb survivors are compatible with hormesis [11,13,136,137]. For cancers, a dose-response association was found among A-bomb survivors who received doses ≤0.5 Sv but not ≤0.2 Sv [12-14]. An example: the data about renal cancer in males indicated hormesis: U-formed dose-response curve with negative ERR estimates at low doses [137]. A preceding article by the same researchers also showed different shapes of dose-response curves for males and females [138]. Other studies found no significant risks for kidney cancer from low doses [139-141]. Apparently, epidemiological data have too many uncertainties to reliably characterize dose-effect relationships at low-to-moderate doses; animal experiments would be more informative.

Furthermore, significantly increased risk of non-melanoma skin cancer was reported in MPA employees exposed to radiation ≥2.0 Sv accumulated over prolonged periods [135]. An observation bias cannot be excluded in the latter study. The workers and some medical personnel knew the individual work histories, wherefrom the doses could be inferred, possibly having impact on the diagnostic quality. The subjects were exposed mainly to gamma-rays having a relatively high penetration distance in tissues, so that the absorbed doses within the skin must have been relatively low. Accordingly, the premalignant skin lesions and actinic keratoses were "very rare" in the subjects [135]. Radiation exposure is associated with premalignant epidermal changes; in particular, actinic keratoses are often induced by radiotherapy. Therefore, a cause-effect relationship between radiation and skin tumors in the study [135] is improbable.

The risk estimates by Azizova et al. [142] were considerably higher than in other research [143]. For example, in MPA workers with Cgamma-rays doses ≥0.1 Gy, the incidence of circulatory diseases was claimed to be higher than in those exposed to lower doses [133,134]. Cause-effect relationships are improbable at such a low dose level, taking into account the dose comparisons presented in this review. The UNSCEAR could not reach a final conclusion on causality between exposures below 1-2 Gy and cardiovascular diseases [144]. Cardiovascular risks have been discussed here to stress the unreliability of risk assessments in the Urals, which pertains also to cancer.

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Hormesis and radiation safety regulations

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 [145]. Among hormetic factors are various substances and chemical elements, light, ultraviolet, ionizing radiation and products of water radiolysis [146,147]. 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 hypothesis 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 in a dynamic equilibrium. The natural background radiation has been decreasing over 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 [148]. Evolutionary adaptation to ionizing radiation was explained by the increased synthesis of DNA repair enzymes and activated endogenous radioprotective mechanisms. In particular, low-dose exposures are conductive to hormesis by triggering DNA repair and antioxidant response, which protects chromosomes from mutations. Moreover, experimental evidence has demonstrated that low doses enhance immunity [149]. For such ancient biological mechanisms as hormesis and DNA repair, the data may be generalized across species [6,150]. Further research could quantify radiosensitivity of different animal species thus enabling more precise extrapolations on humans [151].

The benefit from a moderate exposure to ionizing radiation was observed among A-bomb survivors [136]. Occupational exposures were reported to be associated with better health [152,153], which can be explained at least in part by the healthy worker effect. Cancer mortality was found to be lower in high-elevation areas, where the natural radiation background is enhanced [18,152,154]. The residents of Mississippi receive ~2 mGy per year from natural radiation, while in Colorado the annual dose is ~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 [155]. 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. 150-400 mSv/year in Ramsar, Iran [5]; yet no higher incidence of cancer has been reliably detected in such areas [15].

In future, the screening effect and attention of people to their own health may result in an increase in registered cancer incidence in areas with elevated radiation background, which would prove no causal relationship. A mixture of reliable und unreliable data assessed together remains a problem of reviews and meta-analyses. The most promising way to reliable information on low dose effects would be large-scale animal experiments. It is unnecessary to examine each mouse and perform necropsies [156,157]. It would suffice to maintain in equal conditions large populations, exposed to different dose rates, and to register the average life duration. Such experiments would objectively characterize the dose-response pattern and hormesis.

Finally, a few words about dentistry. Dental diagnostic X-rays were reported to be associated with an increased risk of meningioma [158,159] but not of malignant brain tumors (gliomas) [159]. Malignant gliomas grow rapidly; meningioma grows slowly, it may persist over many years without symptoms or produce mild transitory pains e.g. trigeminalgia sometimes perceived as toothache, provoking a patient to go to the dentist, hence more dental X-rays. Furthermore, meningioma may be associated with seizures [159]. Such patients would undergo diagnostic X-rays within the scope of the examination for epilepsy and, again, go more frequently to a dentist because of injuries to teeth or oral mucosa. Therefore, association between dental X-rays and meningioma can be explained by more frequent visits to dentists. Slow non-invasive growth of a benign tumor over many years is an argument against the cause-effect relationship with radiation because many X-rays would be performed when the tumor already exists. A carcinogenic effect has never been proven for the dose levels associated with routine diagnostic X-rays including the cone beam CT applied in dentistry [34,160]. The above considerations pertain also to vestibular schwannoma reported to be associated with dental x-rays [161]. Remarkably, an enhanced schwannoma risk was found also in people who started using cell phones before the age of 20 years [161]. As discussed previously, there is neither compelling evidence nor theoretic plausibility for the concept that radio-frequency electromagnetic fields are more harmful than infrared radiation, which is ubiquitous and harmless up to the thermal damage. The reported association may be caused by selection, self-selection and recall bias [162]. The bias must be stronger in case of ionizing radiation than for electromagnetic fields as the general public is informed about carcinogenicity of the former. All said, the following conclusion should be agreed with: “Protection from ionizing radiation is as important as the diagnostic benefit to patients” [159], among other things, because exposures may be unpredictable and their effects can accumulate. Fortunately, radiation exposures associated with dental x-rays have decreased over the last decades.

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 thresholds [11], as low as reasonably achievable taking into account economical and societal considerations [143]. Admittedly, irradiation may act synergistically with other noxa. Many factors can contribute to carcinogenesis, including viruses, chemicals, diet, hormones, and genetic predisposition [163], whereas synergism with ionizing radiation cannot be excluded. Therefore, the petition to remove the phrase “As low as reasonably achievable” (ALARA) from the radiation safety regulations [164] is hardly justified, as exposures are unpredictable during a human life, while their effects may accumulate. The principle ALARP (as low as reasonably practicable) seems to be more realistic and workable than the ALARA.

Apparently, current radiation safety standards [165] are excessively restrictive and should be revised to become more realistic and practical. An elevation of limits must be accompanied by measures guaranteeing their observance. No contraindications have been found to an elevation of the total doses to individual members of general public up to 5 mSv/year. The dose rate would thus remain within the range of the natural background. Considering that development of

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nuclear technologies is required to meet the global energy needs, 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 countries with prevailing disrespect for laws and regulations. Of note, negligence and disregard of written instructions was among the causes of the Chernobyl accident [33,166,167].

Dose and dose rate effectiveness factor (DDREF)

DDREF is used for the adjustment of risk at acute radiation exposures to continuous (low dose rate) ones [168]. This section comments on the discussion of DDREF = 2.0, recommended by the International Commission on Radiological Protection [169-171]. The topics of threshold, hormesis and DDREF are interrelated with the LNT hypothesis. Only LNT is discussed below, but the same arguments pertain to other no-threshold models. In particular, the linear-quadratic model does not agree with all experimental data [172]. As discussed above, the LNT concept does not take into account that DNA damage and repair are permanent processes in dynamic equilibrium reached in the long term. There is an ecologically based argument against the LNT hypothesis: given the evolutionary prerequisite of the best fitness, living organisms must have been adapted by the natural selection to a background level of ionizing radiation [173].

Evidently, if a dose is split into fractions, a biological system would have time for repair. With the dose protraction or fractionation, the damage caused by a given track would less frequently interact with that induced by a subsequent track, resulting damage thus being lower [174]. Biological effects of high linear energy transfer (LET) radiation were reported to have a small or no dose rate dependence in contrast to the low-LET radiation, where lowering of the dose rate can significantly reduce the biological impact [156,175-177]. The dependence between LET values and relative biological effectiveness is non-linear with a peak at higher LET levels. Comparing low-LET and high-LET radiation, the latter is characterized by a higher effectiveness causing more damage per unit of absorbed dose: the cell death can be produced by a few tracks or a single one [174,177,178]. Moreover, the high-LET radiation, being a minor component of the natural radiation background except for radon, has probably induced less adaptation of internal organs other than lungs. This might explain why lowering the dose rate of low-LET radiation generally reduces carcinogenic effectiveness while the rate lowering of high-LET radiation does not [175,179,180].

In the study of A-bomb survivors, it was concluded that the estimated lowest dose range with a significant excess relative risk (ERR) for solid cancers was 0 to 0.20 Gy, while a dose-threshold analysis indicated no threshold [181]. This conclusion was doubted as the analysis had a priori restricted possible functional forms using only linear and linear-quadratic dose-response dependences [7,182,183]. If a more generalized functional form was used, the lower bounds of 95% confidence intervals were below zero for low doses. This does not prove existence of a threshold, but demonstrates that the data variability is too high to conclude that the threshold is zero [7,183]. Fitting of mathematical models is of limited value for determining whether a threshold and a cause-effect relationship exist; understanding of mechanisms and verification by reliable methods are necessary, which is true also for chemical carcinogens [184,185].

Doses comparable with those in A-bomb survivors, and dose rates varying by factors 100-1000, produced in experiments DDREF values 1-10 or higher with a central value ~4.0 [175]. A comprehensive review concluded that DDREF is ≥2.0 [5]. A range of models suggested that protracted exposures are between 2.0 and infinity times safer than acute exposures at comparable doses [172], the latter being compatible with the threshold model. A threshold is a point on a dose-response graph; but hormesis is a continuum. Therefore, hormesis must be easier to prove than the threshold as such. It was argued that an LNT-predicted risk might exist but too small to be detected, rendering the LNT hypothesis unfalsifiable [186]. Of note, to reject the LNT, it suffices to prove hormesis.

Discussion

Unrealistic laws and regulations are often violated, which contributes to disrespect for the law in general. Today's radiation safety standards are based on the LNT hypothesis: extrapolation of dose-response relationships down to minimal doses, where such relationships are unproven and can be inverted due to hormesis. Several publications about Chernobyl and EURT are discussed in this review because of inadequate use of the term "long-term low-dose exposure to ionizing radiation", which was sometimes, in fact, only a moderate elevation of the radiation background. It is difficult to determine with certainty the level of exposure, below which there is no appreciable cancer risk for humans [187]; it appears to be 200 mSv or more. Accordingly, a recent review designated doses up to 200 mGy as low [149]. This latter value is given as not associated with proven risks also in preceding reviews [12,17]. For solid cancers, a significant dose-response relationship was found among A-bomb survivors exposed to ≤500 mSv but not to ≤200 mSv; analogous data were reported also for leukemia [13,14,30]. According to the UNSCEAR, statistically significant elevation of cancer risk is observed in epidemiological studies at the doses ≥100-200 mGy [18]. There were also reports on dose-response relationships at lower doses [188-190], but substantiation was questioned [30]. The practical thresholds can be even higher because of bias in epidemiological research on stochastic effects of low doses [144,191].

Epidemiological data fail to demonstrate harmful effects of ionizing radiation after exposures to doses ≤100-200 mSv [173]. A detrimental action of radiation may disappear at low doses and dose rates being replaced by protective effects. In small animals, minimal doses associated with elevated cancer risk are in the range of hundreds or thousands of mGy [30,192-194], thus being higher than corresponding doses reported in epidemiological studies. Certainly, the knowledge about effects of low doses and hormesis is incomplete. The most promising way to obtaining reliable data are large-scale animal experiments.

Conclusion

A concluding point is that radiation safety standards are exceedingly restrictive and should be revised [195] to become more realistic and workable. Elevation of the limits must be accompanied by measures guaranteeing their observance. We found no valid contraindications to a fivefold elevation of equivalent effective doses

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to individual members of the public up to 5 mSv/year. Considering the global need for the nuclear energy production, doubling of the limits for professional exposures should be considered as well, bearing in mind the main goal of the radiation safety regulations: maximizing the ratio of benefits to risks and protecting people from health risks [196].

The consequences of the 1986 Chernobyl nuclear disaster are still felt today. The accident soured perception of nuclear power in the United States and other parts of the world. The scale of the U.S. nuclear power program's collapse was described as "appalling". Fortunately, there has been "nuclear renaissance" in the 21st century (with unexpected turns during the Obama administration) [197]. Following the Chernobyl impact, some countries, Germany in the first place, started dismantling their NPPs, thus strengthening their economic dependence on Russia. The decision of the Bundestag on 30 June 2011 to phase out nuclear power paved the way for an end to the commercial use of nuclear energy. The dismantling of nuclear facilities is a complex affair; the work may span decades exceeding the building time, exemplified by the NPP Kahl [198]. The cost of dismantling each NPP may reach into billions of dollars [199]. The Fukushima accident triggered another crisis of confidence in nuclear energy in the West but not in the RF. At the same time, Russian nuclear industry is regarded to be the global leader in terms of contracts to build NPPs in foreign countries [200]. There is no opposition against nuclear power in the Russian population; in fact, there is no real opposition whatsoever. Today there are no alternatives to nuclear power. Hopefully, fusion power, which is intrinsically safer, will be used in future for generation of energy [201]. Natural energy sources like wind, solar, geothermal, hydroelectric power, combustible renewables and waste will make a contribution, but their share in the global balance is too small. Chernobyl accident has been exploited to strangle worldwide development of the nuclear power thus boosting fossil fuel prices. In more developed countries, antinuclear resentments have been supported by "Green" activists, well in agreement with the interests of fossil fuel producers. The Ukraine war and threats to use nuclear weapons are directly or indirectly applied to boost fossil fuel prices. Obviously, durable peace is needed for the development of nuclear energy because NPPs are war targets. The worldwide use of nuclear energy will be possible after a concentration of authority within a powerful international executive based in most developed parts of the world, leaving aside political disputes and rivalries.

Conflict of interest

The author declares no conflict of interest.

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