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A Brief Review on Animal Research and Human Health Effects Following the Chornobyl Accident

Evgeniy Sidorik and Igor Yakymenko*

Laboratory of Biophysics, Institute of Experimental Pathology, Oncology and Radiobiology of NAS of Ukraine, Vasylkivska St., 45, Kyiv, Ukraine

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The Chornobyl (Chernobyl) nuclear power plant accident happened on April 26, 1986 in northern Ukraine, then a Soviet republic, was the biggest nuclear catastrophe in human history. The lessons of this catastrophe are extremely important for global nuclear safety and for nuclear medicine. This review concerns the results of complex animal research carried out on an experimental base of the Institute of Experimental Pathology, Oncology and Radiobiology of NAS of Ukraine in Chornobyl city since October 1986 as well as findings of more recent animal studies. Significant effects in animals exposed to radiation in the Chornobyl area, including reduction of lifespan, reduction of latent period of tumours, chronic oxidative stress, mutagenic effects and others are presented. On the other hand, we review the well-documented human health effects occurring years after the Chornobyl catastrophe. A comparison of human health effects and the findings of animal research following the Chornobyl accident reveals some similarities, but analysis of data from two such disparate groups requires utmost care.

Key words: Chornobyl catastrophe, low intensity ionizing radiation, biological effects, public health, cancer, non-cancer diseases

1. Introduction

The Chornobyl nuclear power plant (ChNPP) accident, which occurred on April 26, 1986 in Ukraine near the border of Belarus, was the biggest nuclear accident in human history. A systems test at reactor number four of the ChNPP has led to thermal explosions and destroyed the reactor and safety barriers. A direct impulse for the accident was the activation of the emergency reactor shutdown system that due to defective design of control and protection rods led to positive reactivity insertion and start of reactor power excursion[1, 2]. The reasons of the accident were analysed strictly in the years by many experts and institutions, and after the Chornobyl accident technological improvements were made to the RBMK reactor to warrant its safe operation[3]. The accident resulted in a huge amount of radionuclides released into the environment as a so called plume. Total radioactivity released was about 14 EBq and included both short-lived and long-lived radionuclides: ^{131}I (half-life of 8 days) ~1800 PBq; ^{133}I (half-life of 21 hours) ~2500 PBq; ^{137}Cs (half-life of 30 years) ~85 PBq; ^{134}Cs (half-life of 2 years) ~54 PBq; ^{90}Sr (half-life of 29 years) ~10 PBq; ^{89}Sr (half-life of 115 days) ~115 PBq; ^{238}Pu (half-life of 88 years) ~0.035 PBq; ^{239}Pu (half-life of 24,065 years) ~0.03 PBq;

*Igor Yakymenko: Laboratory of Biophysics, Institute of Experimental Pathology, Oncology and Radiobiology of NAS of Ukraine
Vasylkivska St. 45, Kyiv, 03022, Ukraine
E-mail: yakymenko@btsau.net.ua

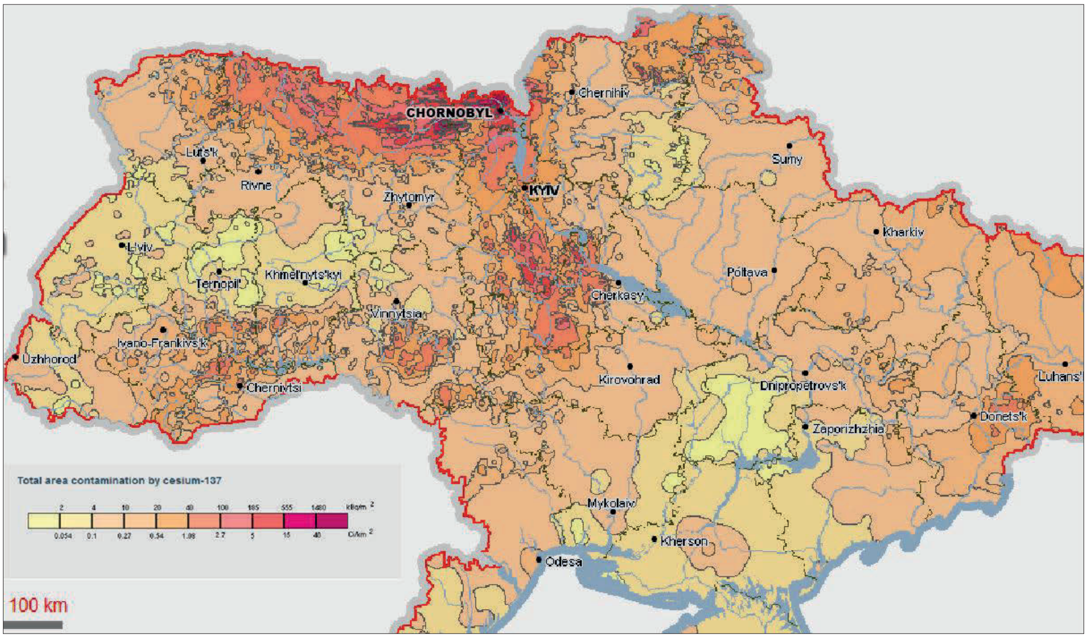

Fig. 1. Contamination of the territory of Ukraine by ^{137}Cs as of May, 1986[5].

^{241}Pu (half-life of 14.4 years) ~6 PBq and others[4]. Huge territories of the north hemisphere were contaminated following the Chornobyl accident. Thus, over 145,000 km^2 of the territories in Ukraine, Belarus, and Russia were contaminated by long-lived ^{137}Cs and ^{90}Sr exceeding 37 kBq/m^2 (Fig. 1). The most contaminated territories around the ChNPP (^{137}Cs deposition density exceeded 1,480 kBq/m^2) shortly after the accident have been segregated into the 30-km Chornobyl Exclusion Zone[5] (the Exclusion Zone, the Zone) and more than 130,000 people were evacuated from the Zone. More than 600,000 people, military and emergency workers, were employed during the first few years after the accident for decontamination of the territories of the Exclusion Zone. Most of them received equivalent doses of radiation ranged 50-250 mSv[4, 6]. The average thyroid dose to the evacuees was assessed at 490 mGy, the average thyroid dose to more than six million residents of the contaminated areas was assessed at about 100 mGy, and the average thyroid dose to pre-school children was about 200-400 mGy[1].

Today, a quarter of a century after the accident, the consequences of the disaster have been analyzed by global radiology community. Thus the International Conference “Twenty-five Years after Chornobyl Accident: Safety for the Future” held in Kyiv, Ukraine, in April 2011 has summoned scientists from all over the world involved into the studies of the Chornobyl accident consequences[7]. A wide spectrum of adverse effects of the Chornobyl fallout on public health has been derived from the long-term epidemiological research. This included not only thyroid cancer in children caused by radioactive iodine. Many findings indicate the host of other long-term public health effects, including cancer and non-cancer pathologies in categories of exposed people (see, for example, the comprehensive review from Prof R.Wakeford[8]).

On the other hand, animal research conducted in the Chornobyl Exclusion Zone during the first years after the accident and more recent studies in laboratory animals and wildlife inhabitants of the Exclusion Zone provided additional valuable information on biological/health effects of chronic exposure to Chornobyl fallout. Particularly, important data were obtained in a series of animal research carried out in experimental base of the Institute of Experimental Pathology, Oncology and Radiobiology of NAS of Ukraine (IEPOR) at Chornobyl city since October 1986. State of changes in the organs and tissues of animals, cancer and non-cancer diseases, and lifespan after long-term staying in the Chornobyl Exclusion Zone were assessed in these studies[9-13]. Subsequently, extremely important findings on long-term biological effects of Chornobyl radiation were made in studies of the wildlife in the Chornobyl area[14-16].

This review briefly analyses the results of animal research conducted on an experimental base in Chornobyl city since October 1986 and more recent animal studies in Chornobyl area. On the other hand, a review of the well-documented human health effects caused by the Chornobyl accident is included, to compare the results of animal research and human health effects. We suppose that such approach can be useful for comprehensive analysis of long-term public health effects following the chronic exposure to low intensity radiation.

Table 1. Specific activity of ^{134}Cs and ^{137}Cs in organs and tissues of rats of the Kyiv and Chornobyl groups[12)]

Organ	Group	Specific activity, x10^{-9} Ci/kg	
		^{134}Cs	^{137}Cs
Liver	Kyiv	3.51 ± 0.09	10.9 ± 0.20
	Chornobyl	14.0 ± 0.71	42.62 ± 0.99
Muscles	Kyiv	12.6 ± 0.20	38.0 ± 0.41
	Chornobyl	48.68 ± 0.72	144.16 ± 1.12
Bones	Kyiv	2.57 ± 0.09	8.08 ± 0.14
	Chornobyl	14.99 ± 0.52	47.63 ± 0.76
Blood	Kyiv	0.98 ± 0.16	3.54 ± 0.25
	Chornobyl	2.94 ± 1.34	14.76 ± 1.61

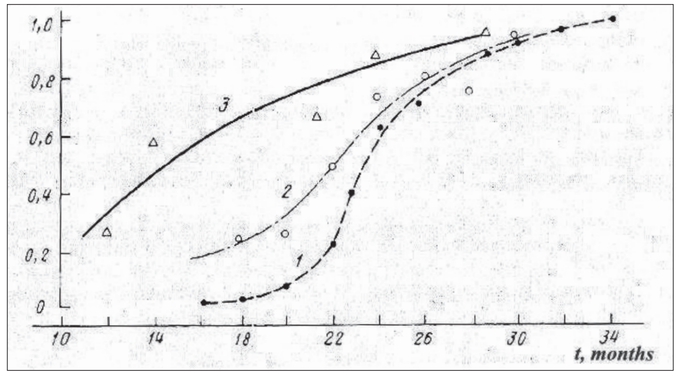

Fig. 2. Cumulative probability of malignant tumors latent periods in rats: 1 – the before-the-accident control; 2 – the Kyiv group; 3 – the Chornobyl group[17)].

2. Animal research

2.1. Research on test animals

Important results have been obtained in complex research during the first years after the accident in experimental base of IEPOR in Chornobyl city. This study was carried out since October 1986, just half a year after the accident. Design of the research was thoroughly described in a paper of a special issue of Radiobiology (Moscow)[12)]. Briefly, experimental group (the Chornobyl group) of white mature mongrel rats, 3 months old (n = 300) has been delivered into the experimental base in Chornobyl city, the Exclusion Zone, 10 km from ChNPP, in Oct 1986. Except of high external gamma radiation background (about 100 – 200 μR/h during Oct 1986-Oct 1987, and 75-100 μR/h during Oct 1987-Oct 1988), these animals were fed special forage contaminated of Chornobyl fallout. The first comparison group (the Kyiv group) was composed by matched animals kept in a vivarium of IEPOR, in Kyiv city (n = 260). These animals were fed standard forage. Kyiv is situated just about 100 km from ChNPP, and gamma radiation background in the vivarium of IEPOR exceeded the before-the-accident level as well. It was about 50-100 μR/h during Oct 1986-Oct 1987, and 25-50 μR/h during Oct 1987-Oct 1988[12)]. The second comparison group (the before-the-accident or historic control) “was extracted” from data of control animals in a vivarium of IEPOR in before-the-accident experiments (n = 220).

Radioactive contamination of animals' tissues, morphological and physiological parameters, biochemical and biophysical indexes, health effects, including carcinogenic effects, and lifespan has been assessed in the Chornobyl and Kyiv animals during the research[9-11, 17)].

An assessment of specific radioactivity of ^{134}Cs and ^{137}Cs in tissues of the Chornobyl and Kyiv group rats showed that the levels of contamination were about fourfold higher in the Chornobyl animals than in the Kyiv group (Table 1)[12)]. The total equivalent dose in the Chornobyl animals was assessed as 130 mSv/year in 1986-1987[18)]. The total equivalent dose in the Kyiv animals was about five times lower, but obviously much higher than in the before-the-accident animals.

Significant differences in health status of the Chornobyl group, Kyiv group and the before-the-accident animals were discovered. First of all, both the Chornobyl and the Kyiv group animals had a significantly lower life expectancy compared to the before-the- accident control[17)]. Life expectancy in the control rats at a vivarium of IEPOR before the accident was 28.2 ± 0.6 months, in the Kyiv group animals it was 21.6 ± 0.5 months, and in the Chornobyl group's animals it was 20.3 ± 0.8 months, i.e. the shorter survival was close to similar in animals of the Chornobyl and Kyiv groups. The main reasons of premature deaths in animals of these groups were pneumonia, ulcerative colitis, degeneration of liver, hyperplasia of lymph nodes. These findings have been partially confirmed in the other study at Chornobyl experimental base during 1995-2002 years[19)]. But in the latter study only the rats with total effective dose at 508 ± 40 mSv per year, mostly internal exposure to radionuclides in forage, had a significant decrease of life expectancy compared to the control (612 ± 19 days against 720 ± 23 days, respectively). Meanwhile, the animals with total effective dose at 51 ± 9 mSv/year and 17 ± 3 mSv/year had only a slight tendency to reduction of a life expectancy as compared to unexposed control.

Rats of the Chornobyl group displayed a considerable reduction of latent periods of malignant tumours compared to both the Kyiv group and the before-the-accident control[17)]. The first malignant tumour in the before-the-accident control was found at the age of 16 months (adenocarcinoma), in the Kyiv group at the age of 18 months (lymphosarcoma), but in Chornobyl animals the first two malignant tumours (adenocarcinomas) were detected at the age of 11 months (Fig. 2). The main types of cancer in all groups were mammary adenocarcinoma, carcinoma of the liver and lymphoma.

Significant changes were detected in the function of the hematopoietic system of animals of the Chornobyl group compared to the animals of Kyiv group and before-the-accident control[10, 18]. After the second month of location in Chornobyl city (at age of 5 months) the rats demonstrated a significant decrease of their leukocyte levels in the peripheral blood and a left shift of the leukogram to myeloblasts and undifferentiated blasts. During 3-8 months of staying in the Chornobyl Zone levels of circulating leucocytes of the rats decreased to about 50% of the control. In the Kyiv group animals, however, such a significant decrease in leucocyte levels was detected only at the age of 24 months. As well significant changes in levels of haemoglobin and red cells in the peripheral blood were revealed in the Chornobyl group after a few months of staying in the Chornobyl Zone[20]. The level of haemoglobin decreased more expressively than the quantity of red cells (state of hypochromic anemia) and after 8 months in the Zone it was consistently 60-70 % of the before-the-accident control. The Kyiv group rats had just a tendency to decreased levels of haemoglobin and red cells in blood at the age of 2 years. Additionally, a year after the exposure the levels of methemoglobin, a form of haemoglobin which cannot bind oxygen, in blood of the Chornobyl animals had increased significantly, almost fourfold, compared to the Kyiv group animals and the before-the-accident control[21]. Likewise, the level of transferrin, the main iron transport protein of plasma, and ceruloplasmin, the main antioxidant of plasma, were significantly decreased in the Chornobyl rats during a year of the exposure compared to the Kyiv group and the before-the-accident control.

Morphological and ultrastructural changes have been quantified in lungs of the Chornobyl group rats beginning from the 6-th month of keeping in the radioactive environment[9]. Changes were found both in the respiratory and the vascular connective tissues. In the lung tissues focal and diffuse lymphoid proliferations and, at later stages, lymphomatous changes were revealed. Data on the state of their respiratory system in the Kyiv group animals were not reported[9].

Considerable nonspecific changes in hepatocytes (fatty, vacuolar and parenchymatous degeneration, and hepatocyte necrobiosis) of the Chornobyl group rats throughout the total period of observation, since 6-th month of keeping in the Exclusion Zone, have been reported[11]. Coagulation necrosis of certain hepatocytes, Kupffer and endothelial cells, and development of microcholangiomas by the end of the 2-nd year were the most typical alterations.

During this research important data have been obtained by Electron Paramagnetic Resonance (EPR) method[22-25]. EPR signals with g value 2.03 (T = 77 K) in livers and kidneys of the exposed rats from Chornobyl city were detected a year after the exposure. This signal caused by nitrosyl complexes of nonheme Fe-S-proteins of electron transport chain (ETC) of mitochondria and indicates the disorders in ETC of mitochondria[23]. Particularly, nitrosyl complexes of nonheme Fe-S-proteins lead to a leak of electrons from ETC of mitochondria and result in a production of superoxide radicals[26]. Indeed, a significant, about fourfold, increase of superoxide radical levels in hepatocytes and kidney cells of rats of the Chornobyl group were detected 1-2 years after the exposure compared to the Kyiv group and the before-the-accident control[24]. A significant increase of hydroxyl radical levels in hepatocytes of the Chornobyl rats was detected during this period as well[24]. Additionally, disorders in the cytochrome P450 detoxification system of hepatocytes were revealed[22]. Both the levels of total cytochrome P450 and oxy-P450 in microsomes of hepatocytes of the Chornobyl group rats a year after the chronic exposure were significantly decreased compared to the Kyiv group animals. These disorders can lead to an additional production of superoxide radicals in cells[27].

Among the other important findings of this study a significant decrease of nonheme Fe- S-proteins level (EPR signal with g value 1.94) and formation of nitrosyl complexes of heme Fe-S-proteins (EPR signal with g value 2.01) were identified in adrenal glands of the Chornobyl rats a year after the exposure[23]. Both EPR signals herald the disorders in corticosteroid metabolism and were detected earlier in animals with cancers on hormonal imbalance background[23].

Significant changes were detected in activities of antioxidant defence enzymes in rats of the Chornobyl group[20]. Particularly, a significant chronic decrease in catalase activity was revealed in blood of the animals after a few months of exposure. Meanwhile a significant chronic decrease in peroxide resistance of red cell membranes were detected in these animals[20].

It must be noted here that in studying laboratory rats in Chornobyl city a significant reduction of body masses in young rats, as compared with the control, of a few generations was ascertained[18, 28]. Along with a significant increase in the mortality rate of young rats in the next generations, the body masses of one-month old rats have been fond reduced significantly, up to 50% of the control. A significant increase of chromosome aberration levels in bone-marrow cells of the second generation rats was determined, but not in parents or in the first generation of progenies in the Chornobyl group[28].

Obviously, these model studies had some significant limitations. First of all, it was a question of adequate control groups. Both the Kyiv control animals and the before-the- accident control had some drawbacks as a control. The Kyiv group animals actually had a rather significant radiation background and were not exactly unexposed control. The before-the-accident control was analyzed in different period of time, before the accident, that could lead to some mismatches. Nevertheless, the findings obtained give valuable information although need to be treated carefully. In general the findings are biologically plausible.

2.2. Research of wildlife

Significant long-term effects of the Chornobyl fallout on oxidative processes and antioxidant defence system in animal organisms were confirmed in more recent investigations of wildlife in the Chornobyl area[15, 16, 29]. In one field study during June 2000 and June 2002 an international team of researchers detected a significantly reduced level of antioxidants (retinol, carotenoids, α -tocopherol) in blood, liver and eggs of barn swallows of the Chornobyl area compared with data from an uncontaminated control area of Ukraine[15]. Additionally, the frequency of abnormal sperm parameters was almost an order of magnitude higher in Chornobyl male birds than in the control area and negatively correlated to antioxidant levels in blood and liver. Another field study conducted during 2003-2006 in the Chornobyl area and control study areas revealed a significant decrease of the concentrations of antioxidants (carotenoids, vitamins A and E) in eggs of great tits in the Chornobyl area compared to the less contaminated Ukrainian and French control study areas[16].

In 2007-2008 in the other field study plasma antioxidant capacity and concentration of reactive oxygen metabolites in plasma of barn swallows from colonies with variable background radiation levels in the Chornobyl region of Ukraine and Belarus were assessed[29]. Reportedly plasma concentration of reactive oxygen metabolites positively correlated with background radiation level. An index of oxidative stress was also larger in barn swallows exposed to high contamination levels.

Extremely important data showing effects of the Chornobyl fallout on brain development of wild birds were published recently[30]. Birds of 48 different species (n = 550) were caught and analyzed in 8 different points of the Chornobyl area during May-June 2010. A negative association between bird brain size and level of background radiation, independent of structural body size and body mass was quantified. The observed reduction in brain size in relation to background radiation corresponded to 5% across the range of a factor 5,000 in radiation level. The authors conclude that the findings reflect significant effects of low dose radiation on normal brain development and potentially on cognitive ability.

It has to be noticed that data obtained in wild birds in the Chornobyl area actually reflect the effects of the Chornobyl fallout exposure of many generations of birds and could not be transformed directly to humans.

Generally, animal research conducted in the Chornobyl area after the ChNPP accident provided unique and important observations on long-term biological effects of chronic radiation exposure. Significant changes/disorders in key metabolic processes of animal organism including development of chronic oxidative stress, mutagenic effects, disorders in blood and other tissues and organs, reduction of lifetime and latent period of tumors prove that chronic exposure to low intensity ionizing radiation is a heavy burden for animal organism.

3. Human health effects

3.1. Cancer incidence

It is recognized that thyroid cancer in children and adolescents exposed to ^{131}I increased dramatically years after the accident, mostly in Belarus and Ukraine[1], as shown in Fig. 3. Unfortunately, the optimistic prognoses on the likely rates of development of thyroid cancer caused by the Chornobyl fallout were incorrect[8], and more than 4000 cases of thyroid cancer caused by the accident were diagnosed up to the middle of 2000s[3]. A strong approximately linear relationship between thyroid cancer cases and individual thyroid doses was obtained, yielding an estimated excess relative risk of 5.25 per 1 Gy[31]. A prevalence of chronic thyroiditis in cohorts of affected children and adults was documented in Ukraine as well[4].

Leukaemia was one of the postulated cancers after the Chornobyl accident. Five years after the accident the European Childhood Leukaemia – Lymphoma Incidence Study did not reveal detectable relation of incidence of childhood leukaemia in Europe and the Chornobyl fallout[32]. It was quite the expected result for such a short period of analysis[8]. Later on, however, a significant increase in leukaemia risk with increasing radiation dose to the bone marrow was found in population-based case-control study (Apr 1986 – Dec 2000) among children from the contaminated territories of Ukraine, Belarus and Russia[33]. A significant association between Chornobyl-related radiation dose and increased risk of leukaemia was found in one Ukrainian-American case-control study within the cohort of Chornobyl clean-up workers (liquidators) from Ukraine between 1986 and 2000[34]. The excess relative risk of total leukaemia among clean-up workers was equal to 3.44 per 1 Gy in this study.

As for the other types of cancers, a significant twofold increase in risk of breast cancer among women from the most radiocontaminated territories (average cumulative dose of 40 mSv or more) compared with the least contaminated territories of Ukraine and Belarus was observed during 1997-2001 in ecological epidemiological study based on the national cancer registries of Ukraine and Belarus[35]. The increase was highest among women who were younger at the time of exposure. Meanwhile Chornobyl male clean-up workers from Latvia, who officially were documented as exposed to 1-50 cGy in 1986-1991, manifested a significantly increased cases in 2005 resulting in a twofold increased risk estimate of general cancer morbidity (SIR 2.01, 95% CI 1.44-2.74)[36]. Prostate cancer and lung cancer were the most frequent types of cancer in this cohort of men during this period.

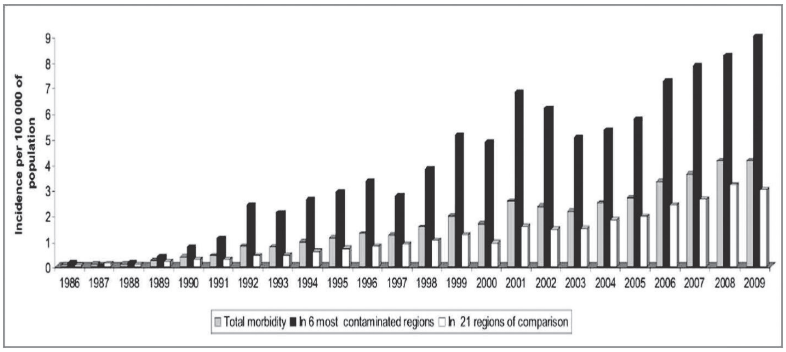

Fig. 3. Incidence of thyroid cancer per 100 000 of child population aged 0-14 at the time of the Chornobyl disaster[1].

3.2. Non-cancer health effects

The circulatory system disorders were/are among the public health risks from the Chornobyl fallout. The analysis of Russian National Medical and Dosimetric Registers of Chornobyl clean-up workers (61,017 people between 1986 and 2000 was observed) revealed statistically significant dose-dependent increased risks of ischemic heart diseases, essential hypertension and cerebrovascular diseases[37]. In this study the significant risk of cerebrovascular diseases as a function of average dose rate was associated with doses above 150 mGy: excessive relative risk, ERR per 100 mGy/d = 2.17.

A significant dose response was revealed for cataracts, specifically for posterior subcapsular cataracts, among Chornobyl clean-up workers from Ukraine (cohort of 8,607 people) 12 and 14 years after the accident[38]. "Posterior subcapsular or cortical cataracts characteristics of radiation exposure were present in 25% of the subjects[38]." The authors underline that the findings contradict the ICRP assumption of a 5-Gy threshold for detectable opacities and propose the evidence-based dose-effect threshold of less than 1 Gy.

Mental health effects are strongly associated with the public health consequences of the Chornobyl accident. Six years after the accident an epidemiological study of mental problems in the Gomel region, one of the most affected regions of Belarus, revealed psychiatric disorder in 35.8%, with especially high rates for affective (16.5%) and anxiety disorders (12.6%) among surveyed population. Dysthymia, general anxiety disorder, adjustment disorders made up 22.9% of the observed morbidity[39]. These findings were confirmed in subsequent research on a comparison level of Gomel region (affected) and Tver region (unaffected control) indicating population-based mental health disorders 6.5 years after the accident[40]. Scores of the self-report scales of psychiatric disorders were "consistently higher" in the affected region.

A significant prevalence of mental disorders in Chornobyl clean-up workers from Ukraine 18 years after the accident was determined with adequate means[41]. The depression rate among clean-up workers increased twice, the rate of post-traumatic stress disorder increased fourfold, and headache increased more than fivefold compared to the control incidences/prevalences. Level of exposure to radiation of clean-up workers was associated with severe headache, somatic complaints and post-traumatic stress disorder symptoms.

A disrupted development of the dominant hemisphere following prenatal irradiation caused by the Chornobyl accident was reported[42]. Thus children, exposed prenatally during the Chornobyl accident and examined at the age of 11 - 13 years, demonstrated lower full-scale and verbal IQ, IQ discrepancies with verbal decrement, disorganized EEG patterns, and interhemispheric inversion visual information processing compared to non-exposed classmates. In the other research scores of hyperactivity and attention-deficit/hyperactivity disorder were significantly higher among adolescents in 1998-2001, who were exposed *in utero* on contaminated territories of Ukraine during the Chornobyl accident and later emigrated to Israel[43].

3.3. Oxidative stress and mutagenic effects

Some studies indicate chronic oxidative stress as well as mutagenic effects in people exposed to the Chornobyl fallout. Increased oxidative stress with gene alteration in urinary bladder urothelium was identified in men who lived more than 13 years in highly radiocontaminated areas of Ukraine after the Chornobyl accident[44]. A significant increase in 8-hydroxydeoxyguanosine (8-OHdG) level was observed in men from highly contaminated area compared to less contaminated or clean area persons. Consistent levels of diene conjugates and malondialdehyde (oxidative stress markers) in red cells of women from radiocontaminated territories of Ukraine in 1994-1996 were significantly increased compared to the control[45]. At the same time, the activities of antioxidant enzymes (glutathione reductase, glutathione-S-transferase, and catalase) in red blood cells were significantly reduced in this cohort. Moreover, an increased level of DNA damages in leukocytes of Belorussian children from radiocontaminated territories was discovered (by alkaline comet assay) 10 years after the Chornobyl accident[46]. There was a significant relationship between the level of radiocontamination and DNA damage in leukocytes in that cohort. A significantly, fivefold, increased level of oxidative stress markers (lipid peroxides and hydroperoxides) in blood of Chornobyl clean-up workers from Latvia 14 and 24 years after the accident was ascertained[36, 47]. As well a significantly increased level of chromosome aberrations in lymphocytes in Chornobyl clean-up workers from Armenia 9 years after the accident was ascertained[48].

Thus, long-term public health effects, including both cancer and non-cancer diseases, caused by the Chornobyl accident have been proven nowadays. We cited here only some of the most reliable publications. Some other epidemiological and clinical research needs to be clarified or confirmed through avoidance of the problems of correct radiodosimetry shortly after the accident, problem of adequate control groups if any and size of the study subpopulations. Nevertheless, long-term public health effects in different cohorts of people exposed to the Chornobyl fallout time and again have been demonstrated in recent studies. It is important, that except of the clinical symptoms and diagnoses the different cohorts of affected persons reveal the objective features of chronic oxidative stress and mutagenic effects after low intensity radiation in the years after the accident. Obviously, it will serve a background for new radiation-related pathologies and diseases.

4. Discussion

A comparative analysis of the animal research findings and human health effects following the Chornobyl accident, which happened a quarter of a century ago, gives valuable information on persistent and irreversible biological effects of long-term exposure to low intensity radiation. First of all, generally speaking we can conclude some similarities in biological effects and disorders observed in animals and humans caused by the Chornobyl radiation. But for a correct analysis some principal differences in the animal research and the human health effects must be elucidated. The complexity of transforming observations from animal research findings on humans meets with a significant difference in lifespan, speed of metabolic processes, including repair processes, different sensitivity to ionizing radiation of animal species and humans[18]. For example, metabolic processes, including metabolism of radioisotopes of ^{131}I and ^{137}Cs, in rats are found to be 5-10 times faster than in humans[49]. Nevertheless, a significant similarity of radiobiological reactions in animal and human organisms is demonstrated. The main difference consists in time spans/speeds of different species reactions and recovery processes[49].

Additionally, it has to consider that there are differences in radiation backgrounds in animal research and epidemiological studies following the Chornobyl accident. The first research on test animals was started in the Chornobyl Zone in Oct 1986, half a year after the accident[12]. It means that test animals were exposed to a spectrum of Chornobyl radionuclides, excluding short-lived radionuclides, specifically ^{131}I. Another important thing is that the studies of wildlife in the Chornobyl area were conducted in significantly lower radiation background than it was during the very first period of time after the accident. On the other hand, the studies on wild birds actually present biological effects in several generations of chronically exposed animals to the low level radiation doses due to comparatively short real lifespan of many wild bird species. In contrast, for humans the first generation health effects were observed mainly up to now.

Taking these specificities in mind, nevertheless a strikingly similar demonstration of chronic oxidative stress both in animals[15, 24] and humans[44, 47] caused by long-term exposure to the Chornobyl fallout has been found. Meanwhile, it is generally accepted nowadays that a wide spectrum of disorders and diseases, including cancer, neurodegenerative diseases, aging processes closely connects with oxidative stress[50-52]. Increased levels of reactive oxygen species lead to oxidative damage of DNA[53, 54]. That is why significant mutagenic effects revealed years after the Chornobyl accident both in animals[15, 28] and humans[36, 46, 48] seem to be biologically plausible.

A wide spectrum of diseases was revealed both in test animals kept in the Chornobyl Zone[13, 20] and in affected sections/categories of people[31, 34, 37, 38, 41]. Some similarity can be found in a significant reduction of latent periods of cancers in exposed test animals[13] and unexpected fast development of thyroid cancer in exposed children[8]. There may be differences in that test animals were not exposed to ^{131}I and were not demonstrated to suffer from thyroid pathologies. But latent periods of other types of cancer (mammary adenocarcinoma, carcinoma of the liver, lymphoma) were reduced in exposed rats. This effect appears to be a specific effect of long-term/chronic exposure to low intensity ionizing radiation.

The recent findings on a significant reduction of brain size in the next generations of wild birds of the Chornobyl area[30] throw light on the question of the long-term effects of the Chornobyl fallout on human mental health. Thus, it remains a public health concern nowadays.

The question of a significant reduction of life expectancy in test animals in the Chornobyl Zone[17, 18] is still open, whereas a problem of accelerated aging of populations affected as a consequence of the Chornobyl accident is topical nowadays[1].

In summary, the animal research findings and human health effects following the Chornobyl nuclear accident reveal significant features of chronic oxidative stress, mutagenic effects, as well as cancer and non-cancer diseases and chronic persistent disorders. A comparison of the findings of animal research and long-term human health effects caused by Chornobyl fallout displays some similarities, but it requires caution. Meanwhile a quarter of a century after the Chornobyl accident a significant biological/health effects are still revealed both in affected categories of humans and wildlife inhabitants of the Chornobyl area.

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