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30 years After the Chernobyl Nuclear Accident: Time for Reflection and Re-evaluation of Current Disaster Preparedness Plans

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ABSTRACT *It has been 30 years since the worst accident in the history of the nuclear era occurred at the Chernobyl power plant in Ukraine close to densely populated urban areas. To date, epidemiological studies reported increased long-term risks of leukemia, cardiovascular diseases, and cataracts among cleanup workers and of thyroid cancer and non-malignant diseases in those exposed as children and adolescents. Mental health effects were the most significant public health consequence of the accident in the three most contaminated countries of Ukraine, Belarus, and the Russian Federation. Timely and clear communication with affected populations emerged as one of the main lessons in the aftermath of the Chernobyl nuclear accident.*

KEYWORDS *Chernobyl nuclear accident, Radiation effects, Cancers, Radiation induced, Psychological effects, Disaster relief planning*

As we near the 30-year mark of the worst nuclear power plant accident known to mankind, it is an opportune time to pause and critically reflect upon lessons learned as well as to think how we could utilize this knowledge to improve current disaster preparedness and management plans. Chernobyl nuclear power plant's geographical location in Ukraine—less than 20 km from the borders of two other post-Soviet countries of Belarus and the Russian Federation, close to densely populated urban areas—could provide pertinent information for a variety of scenarios considered by public health officials in drawing nuclear disaster preparedness plans, particularly with regards to a "dirty" bomb.

The accident at the Chernobyl (Ukrainian spelling "Chornobyl") nuclear power plant on April 26, 1986, was due to a planned scientific experiment which went awry and resulted in the release of radioactive materials into the air for about 10 days.[1] Due to the prevailing wind patterns (in the Western and Northern directions in the first days after the accident and then in all directions), the long-range transport of various radionuclides caused serious contamination of the regions both close to the site of the accident but also throughout Europe. Scientific reports by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) have emphasized that three population groups in the three most affected countries had the highest levels of radioactive contamination and were at risk of long-term health effects from radiation exposures: (1) recovery operation workers ("liquidators" or "cleanup workers," $n = 530{,}000$); (2) evacuees from contaminated areas ($n = 115{,}000$); and (3) inhabitants of contaminated areas ($n = 6{,}400{,}000$).[2] The last group received low radiation doses equivalent to

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approximately one whole-body computed tomography (CT) scan.[2] In addition to these three groups, those living further away from the place of the accident both in the three most contaminated countries but also in Europe number almost 600 million people, with radiation exposure doses comparable to one annual background radiation dose.[2]

Risk projection studies conducted a decade after the accident estimated that about 9 to 10,000 deaths from leukemia, and solid cancers might be expected over life in the most exposed populations in Ukraine, the Russian Federation, and Belarus.[1] To date, epidemiological studies of the long-term effects of the Chernobyl accident have mainly focused on the three most severe health outcomes which emerged in the 30 years after the accident: (1) leukemia in cleanup workers; (2) cataracts and cardiovascular diseases (CVD) in cleanup workers; and (3) thyroid cancer and non-malignant diseases in those exposed as children and adolescents. Several recent reports have argued, however, that psychological consequences became the major health effect of the Chernobyl nuclear accident.[2,3] Below, we summarize the current knowledge of the long-term health effects for various population groups exposed in the aftermath of the Chernobyl accident and point to knowledge gaps as well as future directions for research.

LEUKEMIA IN CHERNOBYL CLEANUP WORKERS

Previous studies of radiation-exposed populations reported increased risks of leukemia associated with exposures to high doses of radiationr, [4] but several questions remained about the effects of exposures to low doses of radiation. Initial studies of Chernobyl cleanup workers reported increased incidence rates of leukemia,[5–7] but no increase was reported in the general population in contaminated areas.[8] Increased risks of leukemia, although not statistically significant, were reported from a study of Chernobyl cleanup workers from Belarus, Russia, and Baltic countries.[9] Similar findings were reported for Russian cleanup workers from the analysis based on the official reported doses and the Chernobyl Registry-based leukemia diagnoses.[10]

We recently reported the results of 20-year follow-up of a cohort of 110,000 cleanup workers from Ukraine.[11] A significant association between protracted radiation exposure at low doses and leukemia incidence was identified. The mean cumulative radiation doses were lower than reported for the atomic bomb survivors from Japan,[4] and the estimated radiation risks were lower, although comparable, given the range of statistical uncertainty. About 16 % of leukemia cases among Chernobyl cleanup workers was attributed to radiation exposure from cleanup activities in the Chernobyl 30-km zone.[11] Examination of the effects of non-radiation risk factors showed that increased risks of leukemia in this cleanup worker population could not be explained by lifestyle factors such as smoking and alcohol consumption or non-Chernobyl occupational exposures to pesticides and solvents, although there were some indications of increased risks due to petroleum exposures.[12] No associations with risk factors other than radiation were found for chronic lymphocytic leukemia (CLL).

Until recently, the majority of epidemiological studies of radiation-exposed populations, whether from occupational,[13] environmental, [4] or therapeutic exposures,[14–16] reported no radiation risk for CLL. The radiogenic risk for CLL has important public health implications because it is the most prevalent type of leukemia in Western populations.[17] In a reversal of previous findings, our study indicated elevated radiation risk estimates among cleanup workers for both CLL and non-CLL.[11] There is now an emerging consensus on CLL radiogenicity,[18–20] but the magnitude of risks remains unknown. We also recently reported that higher radiation doses and younger age at first exposure to radiation during Chernobyl cleanup work were associated with significantly shorter survival of CLL cases.[21] The median age at diagnosis was 57 years compared to the median age at diagnosis in the U.S. of 72 years.[22] Further investigations are needed to develop a better understanding of the association between radiation and CLL, which is the most common type of leukemia in this cleanup worker population.

CATARACTS AND CVD IN CHERNOBYL CLEANUP WORKERS

Cataracts are believed to be a deterministic effect of radiation exposure and their severity varies depending on the radiation dose.[23] The Ukrainian-American Chernobyl Ocular study reported a dose-related increase in the rate of cataracts in cleanup workers from Ukraine. [24] Importantly, the study challenged the previously suggested threshold of 1 gray (Gy) and reported a threshold of no more than 0.7 Gy. As a result of this singular investigation, the International Commission on Radiological Protection recommended a change in the threshold dose for the eye lens and dose limits for the eye for occupationally exposed persons from 1 to 0.5 Gy.[23] However, uncertainties in individual dosimetry and absence of confirmation studies in other cleanup worker populations temper the certainty of findings.

Previous studies of radiation-exposed populations indicated increased risks of the circulatory system, but the mechanism is not completely understood.[25] Radiation risks of CVD mortality have been reported for high-dose exposures above 0.5 Gy, but the evidence for lower doses is mixed.[26] To date, increased risks of CVD have been reported only for Russian Chernobyl cleanup workers based on data from the Russian National Medical and Dosimetric Registry and require further investigation.[27]

THYROID CANCER AND OTHER THYROID DISEASES

At the time of the Chernobyl accident, it was known that exposures to external ionizing radiation in childhood and adolescence were associated with increased risk of thyroid cancer,[4,28] but risks following internal exposure to radionuclides were much less well known. We established two parallel screening cohort studies in Ukraine and Belarus, with each involving about 12,000 subjects who were exposed to radioactive fallout, chiefly iodine-131 (^{131}I), from the Chernobyl accident as children or adolescents.[29] The cohorts have undergone periodic standardized screening for thyroid cancer and non-malignant diseases of the thyroid. The Ukranian[30–32] and Belarusian[33] studies have shown a significantly increased risk of thyroid cancer which was similar in magnitude to the risk associated with external radiation exposure.[4,28] Evidence from other smaller population-based case-control studies confirms a causal relationship between the observed increase in thyroid cancer risk and exposure to ^{131}I from the Chernobyl fall out.[34–36]

Research from our group has also introduced[37] and later confirmed[38] a novel idea that radioactive iodine contamination of those exposed as children and adolescents causes not only cancer but also benign tumors of the thyroid gland. Our studies also provided evidence on the importance of young age at exposure as a modifier of this risk.[38] The consistency in the results obtained from the two cohorts, in which benign follicular adenomas were ascertained by standardized examinations and pathology reviews,[39] strengthens the evidence of the radiation risks of this benign tumor. Future studies are needed to clarify the effects of radiation exposures on other non-malignant thyroid disorders for which the evidence has been mixed to date.[40–42]

PSYCHOLOGICAL EFFECTS

Initial delays by the Soviet government to provide timely information to the affected populations, seeming absence of disaster preparedness plans, and chaotic evacuations in the months after the accident at the power plant, created a climate of distrust and wide-spread frustration. In the years after the accident, sensationalist media reports about the health effects of radiation only increased the fears among those exposed. These effects were compounded by severe social and economic upheaval in the three countries most affected by the nuclear accident from the disintegration of the Soviet Union in 1991 and the subsequent disruption of existing government structures designed to deal with the nuclear accident consequences.

Several reports recently concluded that mental health effects were the most significant public health consequence of the accident.[2] Neuropsychological and psychological impairments associated with radiation exposure have been reported for those exposed as children, in particular poor self-rated health as well as clinical and subclinical depression, anxiety, and post-traumatic stress disorder.[3] The excess morbidity rate of psychiatric disorders among cleanup workers in the first year after a disaster was reported at 20 %,[3] and the rates of depression and post-traumatic stress disorder remained elevated decades later.[43] Many of the lingering effects were due to continuing worries about the adverse health effects of radiation exposures and to paucity of mental health care in affected regions. Future research is needed to clarify the incidence and prevalence of mental disorders in various exposure groups and the dose-dependent associations for individual mental health effects.

In summary, clinical and population-based studies conducted after the Chernobyl accident have provided unique insights into the associations between radiation exposures and long-term health risks of leukemia, CVD, and cataracts among cleanup workers and of thyroid diseases in those exposed as children and adolescents. While the long-term mental health effects were the most significant public health consequence of the accident, few scientific studies were conducted and no longitudinal studies. One of the main lessons of the aftermath of the Chernobyl nuclear accident is the recognition of importance of delivering timely information to the affected populations and of having clear communication strategies embedded in disaster preparedness and mitigation plans.[44] Based on the experiences after the Chernobyl accident and after other events, such as September 11 Terrorist Attacks in New York City,[45] it is imperative to integrate psychological support and psychiatric treatment for the affected populations with existing medical screening and treatment programs. Measures aimed at increasing resilience at the individual and population levels should be included in disaster preparedness, response, and management plans. Such plans should also include education and training of key personnel in health departments on actions to take with regards to risk communication, population needs assessment, establishment of treatment referral centers, and conduct of targeted outreach. The Chernobyl experience indicates that the psychological sequelae persist for a very long time, so future research should determine the radiation dose-response for mental health effects and the possible modifying effects of mitigating measures.

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