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INFORMATION REPORT

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State of knowledge on the health consequences of a nuclear accident

Numerous research programs and epidemiological studies were and are being conducted on the health consequences for first responders, workers, and affected populations following the accidents at the Chernobyl nuclear power plant in 1986 and the Fukushima Daiichi nuclear power plant in 2011. This in-depth feature provides a summary of these studies.

It focuses primarily on the risks of thyroid cancer in people exposed to ionizing radiation during childhood and adolescence, but also covers other types of cancer and non-cancerous effects of exposure to ionizing radiation, particularly in workers involved in these two accidents.

1. THYROID CANCER AFTER A NUCLEAR ACCIDENT

The Chernobyl accident in 1986 and the Fukushima Daiichi accident in 2011 are the only two nuclear accidents classified at the maximum level of the International Nuclear Event Scale (INES), although contamination levels are much lower around the Fukushima Daiichi plant than around the Chernobyl plant.

To date, thyroid cancer in people exposed during childhood and adolescence is the main health effect demonstrated to be associated with radioactive fallout from the Chernobyl accident, due to iodine-131.

After the Fukushima Daiichi accident, based on the experience gained from the Chernobyl accident, systematic screening for thyroid cancer was established in Fukushima Prefecture for young people who were under 18 years of age at the time of the accident. At this time, about 10 years after the accident, it is still premature to say whether there is an increase in thyroid cancer due to the Fukushima Daiichi accident.

1.1. WHAT YOU NEED TO KNOW ABOUT THYROID CANCER

The thyroid is a gland located in the neck whose main function is to produce hormones from the iodine naturally present in food (fish, seafood, dairy...). These thyroid hormones are essential for the proper functioning of the body and, in the event of thyroid removal, hormone replacement therapy is prescribed for life.

The development of nodules in the thyroid gland is very frequent, in liquid form (cysts) or solid form. These thyroid nodules are generally benign, with only 10 to 15% of the nodules being cancerous in nature. Thyroid cancer occurs about three times more in women than in men, and the incidence of thyroid cancer varies from country to country: for example, in 2012, thyroid cancer rates per 100,000 women were 89 in South Korea, 20 in the United States, 15 in Italy, 13 in France, 8 in Finland and 6.5 in Japan. It is very rare before the age of 15 and represents less than 1% of all childhood cancers.

There are several types of thyroid cancer:

- differentiated cancers (papillary or follicular): papillary cancers are the most common, representing about 80% of thyroid cancers. They are mainly diagnosed between 30 and 50 years of age and have a good prognosis. Follicular cancers represent about 10% of thyroid cancers. Follicular cancers are generally not very aggressive and slow-growing.

- undifferentiated (anaplastic) cancers: they mainly occur in the elderly (about 1% of thyroid cancers), the prognosis is very poor, with a life expectancy of a few months.

- medullary (familial) cancers: the prognosis for medullary cancers is more reserved, with a 65% survival rate 10 years after diagnosis.

Typically, the process of diagnosing thyroid cancer begins because a patient has symptoms suggestive of thyroid cancer or because nodules are detected incidentally during a routine clinical examination.

Performing systematic ultrasound screening in a population that does not show clinical signs suggestive of thyroid cancer may reveal thyroid cancers that would not have progressed (usually very small) and would have never been diagnosed in the absence of screening. This is because thyroid cancer usually progresses slowly and only causes symptoms when it is in an advanced stage. These cancers diagnosed during screening correspond to what oncologists call indolent or quiescent cancers. Early detection of these cancerous nodules does not improve the health or survival of patients but may instead affect their quality of life due to medical treatment and/or surgical complications. **Thyroid cancer screening therefore leads to an over-diagnosis of thyroid cancer, i.e. the detection of cases for which there is no medical benefit from treatment.**

The thyroid gland is an organ that is particularly sensitive to ionizing radiation, especially after exposure in childhood. In individuals exposed to ionizing radiation during childhood, the risk of thyroid cancer varies according to the type of exposure (external or internal irradiation), the histological type of thyroid cancer (papillary, follicular...), the age at the time of exposure, the time elapsed since exposure, the presence of iodine deficiency, etc. The increase in this risk can be very high, up to a risk multiplied by 20 for a thyroid dose of 1 Gy according to some studies on external irradiation.

1.2. RISK OF THYROID CANCER DUE TO RADIOACTIVE FALLOUT FROM THE CHERNOBYL ACCIDENT

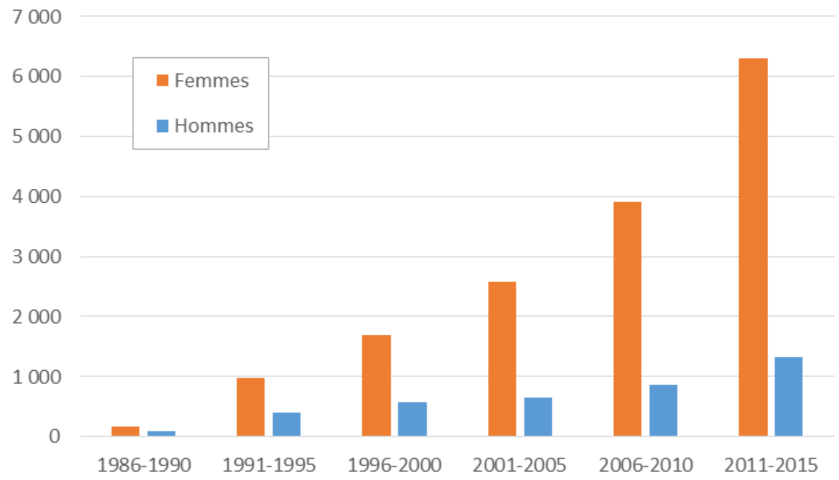
From the early 1990s, pediatric physicians in Belarus and Ukraine noted a significant increase in the number of thyroid cancers, mainly papillary cancers, in children and adolescents exposed to radioactive fallout after the Chernobyl accident. Subsequently, numerous studies showed that this increase was mainly due to radioactive iodine released during the accident, with the incidence of this cancer increasing with the radiation dose to the thyroid.

In order to better characterize the increased risk of thyroid cancer following exposure to radioactive iodine, thyroid screening including ultrasound imaging and clinical examination was implemented for approximately 13,000 children in Ukraine and 12,000 in Belarus (aged 18 years or less in 1986) for whom direct measurements of thyroid radiological activity could be made within 2 months after the Chernobyl accident. These screenings were carried out more than 10 years after the accident, once the increase in thyroid cancer incidence had been well established in young people aged 18 or younger at the time of the accident.

In Russia, an annual clinical examination of the population, supplemented by ultrasound or other imaging procedures, if necessary, was introduced in 1991 among the 110,000 residents of the most contaminated regions who were under 18 years of age at the time of the accident.

All these studies showed a significant increase in the risk of thyroid cancer in people exposed to radioactive fallout in childhood and adolescence, with a risk multiplied by 2.5 to 6 for a dose of 1 Gy depending on the studies. They also made it possible to estimate the respective share of screening and exposure to ionizing radiation in increasing the risk of thyroid cancer.

According to the report on thyroid cancer in Ukraine, Belarus and the most contaminated regions of Russia, published in 2018 by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), 19,233 cases of thyroid cancer were diagnosed in the period 1991-2015 in persons under 18 years of age at the time of the accident, almost 3 times more than in the period 1991-2005. In the latest period 2011-2015, a total of 7,630 new cases were diagnosed, 80% of which were women. This increase over time in the incidence of thyroid cancer in those under 18 years of age at the time of the accident is attributable to the rise in baseline cancer rates with age (the risk of cancer increasing spontaneously with age), exposure to ionizing radiation and improved medical detection methods. UNSCEAR has estimated that approximately 25% of these thyroid cancers are attributable to exposure to ionizing radiation (between 7% and 50% given the uncertainties).



Total number of thyroid cancers diagnosed between 1986 and 2015 in young people under 18 years of age in 1986 in Ukraine, Belarus and the most contaminated regions of Russia (Source: UNSCEAR 2018)

FOCUS: The risk of thyroid cancer due to radioactive fallout from the Chernobyl accident in France

In 2000, a study by IRSN and the French Public Health Agency estimated the theoretical number of thyroid cancers over the period 1991-2015 attributable to radioactive fallout from the Chernobyl accident among the 2.3 million children under the age of 15 living in eastern France in 1986. The estimate resulted in a very low number of thyroid cancers theoretically attributable to the radioactive fallout from the accident: between 7 and 55 excess cases.

This estimate was of the same order of magnitude as the uncertainty associated with the expected number of thyroid cancers in the absence of accidental exposure to iodine-131 in this population (889⍰ 60 spontaneous cases).

This observation is explained by the low doses due to the fallout from the Chernobyl accident in France (about 100 times less than those received by children in Belarus among whom an increase in the number of thyroid cancers has been detected). The study concluded that such an excess of cases would be very difficult to detect by an epidemiological study (Rogel et al. BEH 2016).

1.3. RISK OF THYROID CANCER AFTER THE FUKUSHIMA DAIICHI POWER PLANT ACCIDENT

Shortly after the accident at the Fukushima Daiichi nuclear power plant in 2011, based on the feedback from the Chernobyl accident, the Japanese government launched an extensive health monitoring program called the "Fukushima Health Management Survey". It includes the implementation of systematic screening for thyroid cancer by ultrasound for the 300,000 young people who resided in Fukushima Prefecture at the time of the accident.

Since 2014, follow-up thyroid check-ups are performed every 2 years in young people under the age of 20, and then every 5 years beyond this age. Compared to Chernobyl, radiation doses to the thyroid in young people in Fukushima were lower, in the order of a few mGy, with a maximum thyroid dose of about 60 mGy in children, 10 to 100 times less than the doses received after the Chernobyl accident.

Systematic screening implemented in Fukushima Prefecture shows a high rate of thyroid tumor nodules in children aged 18 years or younger at the time of the accident. The frequencies of tumor nodules are in the order of:

- 39/100,000 in the first screening campaign (prevalence of 116 cases among 300,476 children).
- 13/100,000 per year in the second campaign (incidence of 71 new cases in 2 years among 270,497 children).
- 7/100,000 per year in the third campaign (incidence of 31 new cases in 2 years among 217,921 children).
- 6/100,000 per year in the fourth campaign (incidence of 21 new cases in 2 years among 180,664 children). For this campaign, the number of cases is not yet consolidated and is likely to increase.

Fukushima Interpreting thyroid screening results in Fukushima Prefecture

A distinction must be made between the prevalence and incidence of thyroid nodules or cancers. Prevalence is the frequency of people with a disease at a given time, including both new and old cases. Incidence is the frequency of new cases of a disease over a given period of time.

As part of the systematic screening in Fukushima Prefecture, the first screening campaign from October 2011 to March 2014 provides prevalence data: as a result, some of the nodules identified may have been already present in individuals before the accident in March 2011. On the other hand, the 2nd, 3rd and 4th screening campaigns (as well as all those that will follow) provide incidence data: only new cases that have occurred since the previous screening campaign are identified. The results of the last three campaigns cannot therefore be directly compared with those of the first campaign. In the case of slowly progressing diseases, which is the case for thyroid cancer, prevalence is higher than incidence.

Most cases identified by systematic screening in Fukushima Prefecture are small tumor nodules with no clinical expression, i.e., no palpable neck lump, and no endocrine disruption. **These cases cannot be compared to those detected by a cancer registry that essentially records clinically expressed or incidentally discovered cases.** The frequency of tumor nodules detected by a screening campaign is therefore naturally much higher than that of cancers provided by a registry.

The increase in prevalence or incidence related to the routine nature of a screen is called a “screening factor”. For example, South Korea introduced ultrasound screening for thyroid cancer in adults in 1999: a comparison of the 1993 and 2011 figures shows that the observed rate of thyroid cancer was multiplied by a factor of 15 as a result of the introduction of this screening. Other work carried out in Ukraine after the Chernobyl accident has shown that systematic screening by ultrasound (but limited to a nodule diameter of 10 mm, twice as large as that of Fukushima) can lead to an increase in the observed incidence of thyroid cancer by a factor of 7. In a Russian study, over the period 1991-2013, it was estimated that the introduction of screening increased the incidence of thyroid cancer by a factor of 7 in those exposed in childhood and by 1.5 in those exposed in adulthood.

In order to make the comparison relevant, the data from the screening implemented in Fukushima Prefecture should be compared with those obtained in a screening campaign in non-exposed areas, using the same testing protocol as in Fukushima Prefecture. Thus, during the period 2011-2014, systematic thyroid cancer screening campaigns similar to the one in Fukushima were implemented in children aged 18 years or younger in three unaffected Japanese prefectures (Aomori, Hiroshima and Yamanashi prefectures). Data from these campaigns showed that the prevalence of thyroid nodules larger than 5 mm or cysts larger than 20 mm detected in young people by ultrasound in these prefectures was similar to the prevalence observed in Fukushima Prefecture.

Are the thyroid cancers in Fukushima due to radioactive fallout from the accident?

At this stage, given the effect of screening and the differences between prevalence and incidence, it is still premature to pronounce on a possible increase in post-accident thyroid cancer in children present in 2011 in Fukushima Prefecture at the time of the nuclear accident.

Studies published to date show no association between dose distribution and thyroid cancer frequency in Fukushima Prefecture (Ohira et al. 2020). UNSCEAR considers that future radiation-induced health effects (including a possible increase in the frequency of thyroid cancer) will be difficult to discern in Fukushima, given the low level of exposure to ionizing radiation (UNSCEAR 2021).

To date, there are several indications that the high frequency of thyroid tumor nodules observed in Fukushima Prefecture is related to the effect of screening rather than radiation (Bogdanova et al. Thyroid 2020):

- the age distribution of the observed cases is close to that classically observed in a non-exposed population (whereas the cases observed after the Chernobyl accident were much younger).
- a study published in the journal "Scientific Reports" in 2015 analyzed the oncogenic profile of 68 cases of thyroid cancer identified and operated in the framework of the systematic screening of Fukushima prefecture: the frequency of genetic alterations observed is similar to that observed in a non-exposed population (and very different from that observed after the Chernobyl accident).
- the prevalence of thyroid nodules observed in Fukushima Prefecture in the first screening campaign appears to be very close to that observed in Aomori, Hiroshima and Yamanashi Prefectures not exposed to the radioactive releases from the accident, where similar screening campaigns have been implemented.
- several modeling studies based on Ukrainian, Korean or Japanese data conclude that the effect of screening is compatible with the high prevalence of thyroid nodules recorded in Fukushima Prefecture.
- the estimated dose levels for children present in 2011 in Fukushima Prefecture are very low for most of them. Very few children received thyroid doses in excess of a few tens of mGy due to inhalation of radioactive iodine. At present time, the doses due to internal contamination of children have not been reconstructed individually (only a geographical distribution of absorbed thyroid doses by commune, estimated by UNSCEAR). But among the diagnosed cases for which the external dose was reconstructed, the highest estimated dose was of the order of 2 mSv. These doses are too low, in the current state of knowledge, to explain a detectable increase in the frequency of thyroid nodules.

In 2011, the clinical management of a thyroid tumor nodule in Fukushima Prefecture almost always consisted of complete or partial surgical removal of the thyroid. However, in recent years, considering that most nodules (even tumoral ones) are indolent and may remain unchanged for many years, clinical recommendations have evolved towards ultrasound monitoring of nodules with no severity criteria. Today, the position of the physicians of the Fukushima Medical University is to move towards a less systematic mode of screening and therapeutic management. In particular, they advise limiting surgical operations at the time of diagnosis, and more broadly proposing an individual follow-up to monitor the evolution of the nodules detected.

FOCUS: Recommendations for thyroid screening after a nuclear accident

As part of a European project on improving health and medical surveillance after a nuclear accident in which IRSN participated, the SHAMISEN Consortium (Nuclear Emergency Situations - Improvement of Medical And Health Surveillance: https://www.isglobal.org/en/-/shamisen) recommends considering systematic health screening after a nuclear accident only if it is duly justified, i.e. by ensuring that the screening will do more good than harm. Based on the experience of screening in Fukushima Prefecture, the Consortium does not recommend systematic thyroid cancer screening because the negative psychological and physical effects are likely to outweigh the potential benefits in affected populations. However, the Consortium does recommend that thyroid health surveillance be made available to those who request it, whether or not they are at increased risk of cancer, with appropriate information and support (Clero et al. Approx. Int 2021).

Subsequently, specific work on the value of systematic thyroid cancer screening was carried out in 2018 by an expert group from the International Agency for Research on Cancer (IARC, Thyroid monitoring after nuclear accident (TM-NUC) http://tmnuc.iarc.fr/en/), of which IRSN was a member. Consistent with the conclusions of the SHAMISEN Consortium, this expert group does not recommend systematic screening for thyroid cancer by ultrasound examination after a nuclear accident, in particular because of the risk of over-diagnosis. It recommends that consideration be given to offering a long-term thyroid monitoring programme for higher risk individuals after a nuclear accident, combined with detailed information on the risks of over-diagnosis for patients and families (Togawa et al. Lancet Oncol 2018).

The Japanese experience is rich in lessons. In 2011, the Fukushima Prefecture did not have a cancer registry. If this had been the case, it could have used this monitoring to quantify the incidence of cancers before and after the accident, and thus identify a possible resurgence of thyroid cancers. France set up a national children's cancer registry at the end of the 1990s, but the registries available for adults do not cover the entire territory. The SHAMISEN Consortium recommends the establishment of cancer registries, which help to estimate the health risk and to dialogue with civil society in the event of a nuclear accident.

2. OTHER CANCERS AND NON-CANCER EFFECTS AFTER A NUCLEAR ACCIDENT

2.1. CANCER RISKS FOR FIRST-RESPONDERS AND WORKERS AFTER A NUCLEAR ACCIDENT

Chernobyl accident

On April 26, 1986, reactor N°4 of the Chernobyl nuclear power station accidentally exploded during a technical test, causing a gigantic fire that was not definitively stopped until thirteen days later.

The 600 firefighters and workers of the power plant who intervened on the first day of the accident received the highest doses of ionizing radiation: two of them died immediately from burns and 28 died as a result of their irradiation in the first four months following the accident. A total of 134 first-responders and firefighters were diagnosed with acute radiation syndrome (ARS). Among the survivors, skin degeneration secondary to radiological burns and cataracts are the main sequelae observed today.

Following the accident, approximately 530,000 civilian and military personnel, known as "liquidators", were involved in the emergency response, containment and clean-up at the Chernobyl site and in the contaminated areas after the accident. Approximately 240,000 of them were present in 1986 and 1987, when doses were highest at the reactor site and in the surrounding 30-km zone. The average effective dose received by the liquidators between 1986 and 1990, mainly due to external irradiation, is estimated to be about 120 mSv (UNSCEAR 2011), but some liquidators who intervened in the first few weeks may have received doses greater than 1 Sv.

Studies based on detailed individual reconstruction of bone marrow dose have shown an increased risk of leukemia as a function of estimated dose among liquidators in the Baltic States, Belarus, Russia and Ukraine, including chronic lymphocytic leukemia generally considered to be non-radio-induced (Kesminiene et al. 2008, Romanenko et al. 2008, Zablotska et al. 2013). In Ukraine, an increased incidence of multiple myeloma and myelodysplastic syndrome was also observed in liquidators compared to the general population, but these results should be considered with caution as dose was not taken into account in the analysis (Bazyka et al. 2013).

An important question following the Chernobyl accident was whether exposure to iodine-131 could also lead to an increased risk of thyroid cancer in those exposed in adulthood (Hatch et al. 2017). Increases in thyroid cancer incidence have been observed among Russian (Ivanov et al. 2008) and Baltic workers (Rahu et al. 2013), particularly among those who worked in the first few months after the accident, when exposure to radioactive iodine could occur. A study of cohorts of Belarusian, Russian and Baltic liquidators (Kesminiene et al. 2012), using individual dose reconstruction, also found an increased risk of thyroid cancer. The risk was multiplied by 5 for a dose of 1 Gy received at the thyroid and this increase could not be explained only by thyroid screening campaigns and the increased attention of health professionals towards this pathology among liquidators.

Finally, a dose-related increase in the incidence of solid cancers among Russian workers in the national Chernobyl registry was observed (Kashcheev et al. 2015). Although the completeness of case identification is uncertain for this cohort, this observation is complemented by a similar increase in mortality due to solid cancers, a result for which there is no possible surveillance bias. The estimated risk of solid cancers is consistent with that obtained in recent studies of nuclear industry workers (Richardson et al. 2015) and compatible with extrapolations from studies of atomic bomb survivors from Hiroshima and Nagasaki (Ozasa et al. 2012).

Fukushima Daiichi Accident

In terms of the health consequences for workers, the accident at the Fukushima Daiichi nuclear power plant differs from the Chernobyl accident in many ways.

Approximately 25,000 workers were employed between March 2011 and October 2012 in emergency and remediation operations at the Fukushima Daiichi nuclear power plant site. The average effective dose of these workers in the first 19 months after the accident was about 12 mSv, 10 times less than that received by the Chernobyl liquidators. In Fukushima, 35% of the workers received a total dose of more than 10 mSv over this period and 0.7% received a total dose of more than 100 mSv. The maximum reported effective dose was 679 mSv (UNSCEAR 2014). No acute radiation syndrome or deaths that can be attributed to ionizing radiation exposure were observed among workers engaged in emergency work.

Given that the majority of workers have had low exposures, with effective doses of less than 10 mSv in the first year, and that less than 1% of workers received an effective dose of 100 mSv or more in the first year, **it is unlikely that an increase in the incidence of cancer (solid cancers, leukemia) due to ionizing radiation is noticeable.**

Since a small group of 13 workers received an absorbed dose to the thyroid estimated to be between 2 and 32 Gy, the possibility of thyroid cancer occurring in these workers cannot be excluded; however, the number of workers exposed to these high absorbed doses to the thyroid is probably too small to discern an increased incidence of this cancer. Preliminary results from an investigation involving ultrasound examinations of the thyroid of 627 emergency workers with an absorbed dose to the thyroid greater than 100 mGy and 1,437 workers with a lower dose to the thyroid show no significant difference in the incidence of thyroid disease between the two groups (IAEA 2015).

A cohort study (*Nuclear Emergency Workers Study*) was set up to provide a comprehensive assessment of the health of the workers at the Fukushima Daiichi site after the accident. Health information is collected through questionnaires and biological samples (blood, urine) (Kitamura et al. 2018; Yasui 2016). By the end of 2019, more than 6,700 workers had agreed to participate in the study.

2.2. NON-CANCEROUS PATHOLOGIES FOR WORKERS AND EXPOSED POPULATIONS

Cardiovascular and cerebrovascular pathologies

The pathologies of the circulatory system associated with exposure to ionizing radiation are mainly ischemic heart disease and cerebrovascular disease, mainly caused by atherosclerosis, which is characterized by the deposition of a plaque essentially composed of lipids (atheroma) on the walls of arteries. Eventually, these plaques can lead to damage to the arterial wall (sclerosis), lead to vessel obstruction or rupture, with consequences such as an acute myocardial infarction or stroke.

In 2006, an increased risk of cerebrovascular disease and ischemic heart disease related to ionizing radiation dose was observed in Russian liquidators (Ivanov et al. 2006), although no information was available to account for other risk factors for these diseases. The epidemiological monitoring of these liquidators, based on the national Chernobyl register, was extended for 12 years, until 2012, confirming the increase in the risk of cerebrovascular disease of the order of 50% by Gy (Kashcheev et al. 2016); again, no information was available on other risk factors, except for concomitant diseases such as diabetes. **A study of Ukrainian liquidators in the period 1986-1987 also revealed a dose-related increase in the risk of cardiovascular and cerebrovascular disease** (Krasnikova et al. 2013, 2014). However, these results need to be confirmed as the completeness and accuracy of the recording of these diseases and dose estimates is questionable, and although a number of non-radiation related risks were identified, confounding factors were not taken into account, with the exception of age.

A study published in 2018 looked at the risk of cardiac arrhythmia in children living in Russian territories contaminated by the fallout from the Chernobyl accident. This study was conducted as part of the EPICE (*Evaluation of Caesium-Induced Pathologies*) research program, launched by IRSN in 2009 in partnership with the clinical and biological diagnostic center of the city of Bryansk (Russia), to answer questions from scientists and associations about the health consequences of the Chernobyl accident on children.

For four years (2009-2013), approximately 18,000 children aged 2 to 18 were monitored for cardiac and radiological problems: electrocardiogram, cardiac ultrasound and measurement of body activity in caesium-137. For some children, a recording of cardiac electrical parameters (Holter) was performed over 24 hours, as well as an assessment of the main plasma cardiac markers. A cardiac arrhythmia was thus diagnosed in approximately 2,500 children. The prevalence of cardiac arrhythmia was not different between children in the contaminated and uncontaminated territories. In addition, the risk of cardiac arrhythmia did not increase with caesium-137 body contamination in the children. Thus, this study found no association between caesium-137 contamination and the risk of cardiac arrhythmia in children (Jourdain et al. 2018).

Cataracts

Cataracts are the most common cause of blindness in the world. Exposure to ionizing radiation from the lens of the eye is a known risk factor for the development of cataracts in humans. Other risk factors include aging, genetics (congenital cataracts), ultraviolet exposure, diabetes, high body marker index, smoking, alcohol consumption, prolonged use of corticosteroids and eye trauma.

An increased risk of cataract, particularly posterior subcapsular lens opacity, has been reported in a cohort of Ukrainian liquidators (Worgul et al. 2007). However, studies conducted to date do not conclude that there is a significantly increased risk of cataract due to methodological problems with statistical analysis of the data.

Cognitive and neurological effects

It is now well known that environmental and genetic factors, psychiatric disorders such as schizophrenia and depression, and the use of certain drugs can play a role in the development of neurological, cognitive and aging disorders such as Alzheimer's disease and senile dementia.

The study of the effects of exposure to ionizing radiation on neurological development and cognitive function has attracted considerable interest in recent years. However, research in this field is still rare.

After the Chernobyl accident, studies on Ukrainian liquidators exposed to an average dose of about 100 mGy showed an increased incidence of cognitive dysfunction, although the relationship between the nature of the effects and the radiation dose could not be established with certainty (Loganovsky et al. 2008; Bazyka et al. 2018).

A recent study conducted within the framework of the European CEREBRAD (*Cognitive and Cerebrovascular Effects Induced by Low Dose Ionizing Radiation*) project among 326 Ukrainian liquidators showed a higher prevalence of cognitive and psychological deficits in workers who received doses greater than 100 mGy, particularly in those who received doses greater than 500 mGy. Overall, this study suggests that cognitive deficit in humans, 25-30 years after irradiation, may be influenced by dose and age at the time of exposure.

An increase in rates of neurological pathology was also observed within 7 to 21 years after exposure to ionizing radiation in a cohort of about 40,000 people evacuated from the Chernobyl zone, particularly 12 to 21 years after exposure (Buzunov and Kapustynska 2018). Although the doses resulting from external exposure and the presence of long-lived radionuclides are relatively low, this study showed a statistically significant increase in the occurrence of neurological pathologies in individuals with high thyroid doses of iodine-131 between 300 and 750 mGy. However, further studies are needed to confirm a possible association between thyroid dose and the development of cognitive impairment in radiation-exposed individuals.

2.3. NON-RADIOLOGICAL HEALTH IMPACT OF A NUCLEAR ACCIDENT, IN PARTICULAR DUE TO EVACUATION

Health problems following a nuclear accident are not limited to the consequences of exposure to ionizing radiation.

Following the Fukushima Daiichi accident, the major problem in the first months was the health impact of the evacuation of the local population, especially among the most vulnerable people such as the elderly. Indeed, various problems emerged in the medium and long term as a result of this large-scale change in lifestyle: failures in medical infrastructure and services, social isolation, loss of motivation in life, intergenerational conflicts, disruption of diet leading to later diagnosis and management of diseases, aggravation of chronic diseases such as diabetes and psychological problems. The onset or aggravation of these problems are now attributed to a lack of social support and environmental changes rather than to individual perceptions of risk from exposure to ionizing radiation. The reorganization of health services and the provision of adequate human and material resources are essential to limit the negative impacts on the physical and mental health of populations affected by a nuclear accident (ICRP International Conference on Recovery After Nuclear Accidents. 2020).

A balanced consideration of these various interconnected health risks and the implementation of long-term countermeasures are therefore necessary to manage the health consequences of a nuclear accident.

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