

The Chernobyl Catastrophe Consequences on Human Health



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THE DIFFICULT TRUTH ABOUT THE CHERNOBYL CATASTROPHE: THE WORST EFFECTS ARE STILL TO COME

For millions of inhabitants of the planet the explosion of the fourth block of the Chernobyl Nuclear Power Plant on the 26th of April 1986 divided their life into two parts: pre and post Chernobyl. All mixed into the word “Chernobyl” are technocratic adventurism and the heroism of liquidators, human solidarity and the cowardice of leaders (frightened to warn their citizens about the terrible outcomes and, by that, strongly increasing the number of innocent victims), the sufferings of many and the self-interest of others. Chernobyl brought into our lives new terminology, such as “liquidators”, the “children of Chernobyl” and “Chernobyl AIDS”.

In the past twenty years it has become clear, that nuclear energy conceals dangers, in some aspects, even greater than atomic weapons: the ejecta from this one reactor exceeded the radioactive contamination caused by the nuclear weapons used at Hiroshima and Nagasaki by one hundred times. It has become clear that one nuclear reactor can contaminate half of the Earth and that no longer, not in one single country, could citizens be assured that the state will have the forethought and wisdom to protect them from nuclear misfortunes. The fate of thousands of soldier-liquidators was sealed by the phrase in one of the documents of the former USSR Ministry of Defence dated 9th July 1987. “... the fact of the proximity of work performed on the core [on liquidation] should not be reflected, nor the total radiation dose, if they [liquidators] did not reach the degree of radiation sickness...”.

The "Chernobyl' Forum" - a group of specialists, including the representatives of the IAEA, the UN Scientific committee on the influence of atomic radiation, the WHO, other UN programs, as well as the World Bank and the staff of some of the state organizations of Belarus, Russia and Ukraine presented a report, "Health Effects of the Chernobyl Accident and Special Health Care Programs" on the threshold of the Chernobyl anniversary, in September 2005. The basic conclusions of the medical portion of the report of the "Chernobyl Forum" are that 4,000–9,000 people died, or will die, from radiogenic cancer (which against the background of spontaneous cancers "will be difficult to identify"). That report indicates that 4,000 cases of childhood radiogenic cancers of the thyroid gland were resolved via medical operations. That report acknowledges that certain increases in the cataracts of liquidators and children from the contaminated regions have been discovered. The report concludes, generally, that the consequences of the catastrophe "for the people's health proved to be not so significant, as they were first considered to be".

A more objective point of view was well-expressed by the UN General Secretary, Kofi Annan: "...the exact number of victims may never be known, but 3 million children require treatment and...many will die prematurely...Not until 2016, at the earliest, will be known the full number of those likely to develop serious medical conditions...because of delayed reactions to radiation exposure...many will die prematurely...".

Radioactive fall-outs from Chernobyl clouds touched many territories, where more than three billion people live. More than 50% of these territories across 13 European countries were dangerously contaminated by radionuclides from Chernobyl (and in 8 further countries - more than 30 % of their territories). It will be the fate of many future generations to suffer the echoes of Chernobyl in these countries according to inexorable statistical and biological laws.

In reality, the number of childhood thyroid cancers caused by Chernobyl in Belarus, Ukraine and Russia is much greater than is indicated by the IAEA and/or the WHO. It is also impossible to consider those having undergone medical operations as having been "cured" - for in reality they will have had their health compromised by disruptions of their hormonal and immune systems and by living on medication. Thyroid cancer is only one of many pathologic changes in this organ under the effect of the radiation. For each case of cancer there are many tens of cases of other diseases of this important endocrine gland. Disturbances of health, connected with radiogenic changes in the thyroid gland, already touched not several, but many tens of thousands of individuals. In the following 30-50 years they will touch many thousands more.

The worsening of health related to radiation exposure from the Chernobyl accident (especially – in children's health), in the "Chernobyl" territories of Belarus, Ukraine and Russia is without scientific doubt. Dozens of diseases are explicable neither by the effect of the screening methodologies, nor by social and economic factors.

I will not repeat here the content of the following report, but I will highlight some of the reasons for such serious differences in the estimation of the consequences of the Chernobyl catastrophe between the side of the atomic energy industry and from the side of many independent experts. Some former Soviet officials have not only forbidden doctors to connect current diseases with the Chernobyl irradiation, but have also classified some Chernobyl-related materials, making these materials difficult, and at times impossible, to obtain. In order to overcome these political manipulations, a rigorous scientific approach has been applied in the assessment and selection of material provided in this report. Statistically significant variances of the health of the population in the affected territories, with identical ethnic, psychological, geographical, social and economic characteristics (which are differentiated only by the exposure to the Chernobyl irradiation) are explained via the consequences of the Chernobyl catastrophe.

The following report, in its concentrated form, presents to the English speaking reader material that was previously difficult to access (published in Belarus, Russian and Ukrainian literature). There are many scientific studies on the consequences of the Chernobyl catastrophe on health, published in these three countries but to date, little of this information has been available via Western journals. It should be noted that since 1959 there has been an understanding between the IAEA and the WHO, that the WHO will "coordinate" its position with the IAEA on atomic-related health issues. With the valuable assistance of many independent specialists from Russia, Ukraine, Belarus and many other countries, I hope that this report will be among many further objective examinations of the true scale of the Chernobyl catastrophe to be published in the near future.

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EXECUTIVE SUMMARY

The 20th anniversary of the Chernobyl disaster in 2006 is largely marked by a critical need for continued study of the far-reaching consequences of this serious event. Twenty years ago, the term ‘peaceful atom’ disappeared in the dark cloud above the burning nuclear reactor number four of the Chernobyl nuclear power plant in the former Soviet Union. The most significant and wide-ranging technological catastrophe in the history of humankind occurred in a small Ukrainian town on the Pripyat river. Overnight, the name of Chernobyl became known to the whole world.

Twenty years later, several million people (by various estimates, from 5 to 8 million) still reside in areas that will remain highly contaminated by Chernobyl’s radioactive pollution for many years to come. Since the half-life of the major (though far from the only) radioactive element released, caesium-137 (¹³⁷Cs), is a little over 30 years, the radiological (and hence health) consequences of this nuclear accident will continue to be experienced for centuries to come.

This truly global event had its greatest impacts on three neighbouring former Soviet republics, namely the now independent countries of Ukraine, Belarus, and Russia. The impacts, however, extended far more widely. More than half of the Caesium-137 emitted as a result of the explosion was carried in the atmosphere to other European countries. At least fourteen other countries in Europe (Austria, Sweden, Finland, Norway, Slovenia, Poland, Romania, Hungary, Switzerland, Czech Republic, Italy, Bulgaria, Republic of Moldova and Greece), were contaminated by radiation levels above the 1 Ci/m² (or 37 kBq/m²) limit used to define areas as ‘contaminated’. Lower, but nonetheless substantial quantities of radioactivity linked to the Chernobyl accident were detected all over the European continent, from Scandinavia to the Mediterranean and Asia.

Despite the documented geographical extent and seriousness of the contamination caused by the accident, the totality of impacts on ecosystems, human health, economic performance and social structures remains unknown. In all cases, however, such impacts are likely to be extensive and long lasting. Drawing together contributions from numerous research scientists and health professionals, including many from the Ukraine, Belarus and the Russian Federation, this report addresses one of these aspects, namely the nature and scope of the long-term consequences for human health.

The range of estimates of excess mortality resulting from the Chernobyl accident spans a wide range depending upon precisely what is taken into account. The most recent epidemiological evidence, published under the auspices of the Russian Academy of Sciences, suggests that the scale of the problems could be very much greater than predicted by studies published to date. For example, the 2005 IAEA report predicted that 4000 additional deaths would result from the Chernobyl accident. The most recently published figures indicate that in Belarus, Russia and the Ukraine alone the accident resulted in an estimated 200,000 additional deaths between 1990 and 2004.

Overall, the available data reveal a considerable range in estimated excess mortalities resulting from the Chernobyl accident, serving to underline the uncertainties about the full impact of the Chernobyl accident.

This report includes data, which has not been published before in the international arena. In combination with the extensive body of literature which has been published to date, these data indicate that official industry figures (e.g. the IAEA 2005 evaluation) for morbidity (incidence of disease) and death arising as a direct result of the radioactive contamination released from Chernobyl may grossly underestimate both the local and international impact of the incident.

Four population groups appear to have experienced the most severe health effects:

1. accident clean-up workers, or ‘liquidators’, including civilian and the military personnel drafted to carry out clean-up activities and construct the protective cover for the reactor;
2. evacuees from dangerously contaminated territories inside the 30-km zone around the power plant;
3. residents of the less (but still dangerously) contaminated territories; and
4. children born into the families from all of the above three groups.

Some of the key findings relating to cancer and non-cancer illnesses are summarised below.

Cancer

Today it is clear that the pollution from Chernobyl has indeed caused a large-scale increase in cancers. In particular, cancers are notably more common in populations from the highly contaminated regions and among the ‘liquidators’ (highest radiation exposure) in comparison with reference (relatively unexposed) groups. In ‘liquidators’ from Belarus, for example, incidences of kidney, urinary/bladder and thyroid cancer were all significantly higher for the period from 1993 to 2003 than in a comparable reference group. Leukaemia was significantly higher in ‘liquidators’ from the Ukraine, in adults in Belarus and in children in the most contaminated areas of Russia and Ukraine.

Other examples (though this list is far from exhaustive) include:

- Between 1990 and 2000, a 40% increase in all cancers in Belarus was documented, with higher increases (52%) in the highly contaminated Gomel region than in the less contaminated regions of Brest (33%) and Mogilev (32%).
- In Russia, cancer morbidity in the highly contaminated Kaluga and Bryansk regions was higher than across the country as a whole. For example, in heavily contaminated areas of Bryansk region, morbidity was 2.7 times higher than in less contaminated territories of the region.
- In contaminated areas of the Zhytomir region of Ukraine, the number of adults with cancer increased almost threefold between 1986 and 1994, from 1.34% to 3.91%.

Thyroid cancer

Thyroid cancer increased dramatically in all three countries, as expected because of the release of large quantities of radioactive iodine from the Chernobyl catastrophe. For example, incidence in the highly contaminated Bryansk region in the period 1988-1998 was double that for Russia as a whole, and triple that figure by 2004. Estimates in excess possibly of 60, 000 additional cases have been predicted for Ukraine, Belarus and the Russian Federation alone.

Children who were 0-4 years old at the time of exposure were particularly vulnerable to this cancer. Before the accident, occurrence of thyroid cancer among children and adolescents averaged 0.09 cases per 100 000. After 1990, the frequency of occurrence rose to 0.57-0.63 per 100 000. The peak of thyroid cancer morbidity among those who were children and teenagers at the moment of the catastrophe is predicted to occur in 2001-2006.

The cancer of the thyroid gland caused by Chernobyl appeared to be unusually aggressive, with early and rapid progression to form secondary tumours in the lymph glands and lungs, which worsened the prognosis and frequently demanded multiple surgical interventions to address.

Given the particularly long latency periods, which can be associated with thyroid cancer, new Chernobyl-induced cases may be expected to emerge for decades to come. Long-term monitoring of 'at-risk' populations, including those which received relatively low doses, will be essential to allow timely and effective medical intervention.

Leukaemia

Higher rates of acute leukaemia among Belarusian 'liquidators' were first observed in 1990-91. From 1992, significant increases in the incidence of all forms of leukaemia were detectable in the adult population of Belarus as a whole. In the Ukraine, the frequency of malignant blood cancers was significantly higher than for the pre-catastrophe period in the four most highly contaminated parts of Zhytomyr and Kiev regions, both during the first four years and during the sixth year after the catastrophe.

Childhood leukaemia in Tula region in the post-Chernobyl period significantly exceeded the average rates for Russia, especially in children aged 10-14. In Lipetsk, cases of leukaemia increased 4.5 times from 1989 to 1995. Some data suggest increased risk of leukaemia even for children exposed in the womb.

Other cancers

An increase in cancer of the respiratory passages in women has been observed in the most contaminated areas of Kaluga region. From 1995 onwards, excesses of cancers of the stomach, lungs, breast, rectum, colon, thyroid gland, bone marrow and lymph system have also been detected in the southwestern areas of that region. In the Tula region, unusually high rates of bone cancer and cancers of the central nervous system were detectable in children during the period from 1990-1994.

In the most contaminated territories, of the Ukraine the incidence of breast cancer remained fairly stable, and rather lower than in surrounding areas, throughout the period from 1980-1992. However, from 1992 onwards, incidences of breast cancer in the contaminated territories began to rise. Significant increases in the incidence of urinary/bladder cancers has also been detected in the contaminated territories of Ukraine in recent years.

Non-Cancer illnesses

The identified changes in the incidence of cancerous diseases reported from studies of populations exposed to radiation arising from the Chernobyl accident are only one aspect of

the range of health impacts reported. In addition, significant increases in non-cancer illnesses amongst the exposed populations have also been reported although given the scale of the exposure, the number of studies is relatively very few.

Despite difficulties in deriving absolute cause-effect relationships and the relative paucity of data given the substantial international impact of the Chernobyl release, the various reports are enough to make it quite clear that morbidity and mortality based only on projected and observed changes in cancerous disease rates amongst these populations could considerably underestimate the full scope and scale of the impacts upon human health.

Respiratory system

Exposure of the respiratory systems of humans to radioactive materials released by the Chernobyl accident took place through two major pathways. In the early phases of radioactive release the formation of variously sized aerosol solid and liquid “hot particles” together with radionuclides in gaseous form meant that the inhalation pathway was the most significant. Subsequently, external irradiation from deposited material was considered the most significant route of respiratory system exposure.

Amongst the evacuees from the 30-km zone examined in Belarus, cases of respiratory morbidity almost doubled. Such morbidity accounted for around a third of the problems observed in evacuees and in those adults and adolescents who continued to dwell in the contaminated territories. In children, respiratory problems accounted for nearly two thirds of documented morbidity. In Russia a positive correlation was observed between respiratory problems in newborn children and the levels of radioactive pollution in the localities in question.

Ukrainian Ministry of Health statistics document a rise in cases of unspecified chronic bronchitis and emphysema from around 300 per 10,000 population in 1990 to over 500 per 10,000 in the adult and adolescent population, in 2004. Over the same period, bronchial asthma morbidity almost doubled to reach 55.4 cases per 10,000 population.

The most comprehensive studies reported appear to be those of liquidators involved in securing and cleaning the site subsequent to the incident. In this group, chronic obstructive pulmonary disease in the form of chronic obstructive bronchitis and bronchial asthma have been reported as leading reasons for mortality, morbidity and invalidity. In these cases the follow up studies have allowed a comprehensive health observations to be linked with reconstructed radiation dose profiles.

This has allowed the progression of reported problems to be documented in some detail. This group provides a relatively rare example of a population group impacted by the radiation release, which was followed up in some detail.

Digestive system

There is some evidence of digestive system disorders being more frequent amongst individuals exposed to Chernobyl radiation. A survey carried out in 1995 suggested that morbidity from such disorders was 1.8 times higher amongst Belarus evacuees and inhabitants of the contaminated territories than for the Belarus population as a whole. Between 1991 and 1996 the reported incidence of peptic ulcer increased in the Belarus population increased by almost 10%.

In the Ukraine, more comprehensive reports exist. During 1988-1999 a doubling of digestive system morbidity was observed in the population still living in contaminated areas. Digestive system problems reported among adult evacuees from Prypyat' city and in the 30-km zone were more common than in the rest of the population. Indices of digestive system morbidity among those living in the strict radiation control zones were higher than for the Ukrainian population at large. This was also the case for children in whom digestive system disease rose over two-fold between 1988 and 1999 to 10.1 per 10,000. Amongst children there was a clear tendency towards increased reporting of digestive organ pathology and similar findings were made for children exposed *in utero*. Again, incidence doubled. Digestive system disorders were reported as the most common cause of ill health in children living in the contaminated territories.

Blood vascular system

Exposure to radioactive pollution from Chernobyl has been linked not only with malignant blood and lymphatic diseases, but also with non-malignant conditions of the blood vascular system, which are likely to have been more readily diagnosed as a result of the attention directed at these body organ systems in connection with their sensitivity to malignant diseases.

In Belarus, ten years after the Chernobyl accident, blood diseases generally increased, with a greater increase reported in the contaminated areas. Disturbance of white blood cell counts has also been reported from the population sub-groups living in the Russian territories affected by Chernobyl fallout.

The most extensive and holistic studies appear to have been carried out in the Ukraine. Generalised early atherosclerosis and coronary heart disease developed more commonly in evacuees from 30-km zone and those living in areas polluted with radionuclides as compared to the general population. In the contaminated territories blood system morbidity rose by an estimated factor of between 10 and 15 times between 1988 and 1999.

In a relatively uncommon cross border study, haemorrhagic conditions and congenital jaundice in newborn babies were monitored in several of the areas exposed to Chernobyl radiation in Belarus, Ukraine and the Russian Federation. These were found to be 4.0 and 2.9 times more common, respectively, than in the uncontaminated areas surveyed.

Musculo–Skeletal and Cutaneous Systems

Specific data on musculo-skeletal and connective tissue system responses to radiation exposure resulting from the Chernobyl accident are relatively rare. This is undoubtedly due in part to the fact that these body organ systems are not *per se* regarded as critically vulnerable systems

Nonetheless, data reported from contaminated areas in Belarus and the Ukraine suggests that reported musculo-skeletal complaints increased markedly. Foetal skeletal examinations also revealed incorporation of ¹³⁷-Cs in bones and a greater than expected occurrence of abnormalities.

A cross-border study of neonatal health conducted in several of the contaminated territories suggested an increasing trend of musculo-skeletal development deficiencies.

Hormone/endocrine status

In 1993, more than 40% of children surveyed in the Gomel region of Belarus had enlarged thyroid glands while in the Ukraine damage to the thyroid gland was observed in 35.7% of 3 019 adolescents from the Vinnitsk and Zhytomyr regions who were 6-8 years old at the time of the accident. In this study, primary functional reaction of the thyroid gland was observed in 1986-1987 subsequent to the accident followed by chronic autoimmune thyroiditis (1990-1992) and clinical realization of disease in 1992-1993. Among these children, 32.6% developed an obvious pathology of the thyroid gland compared with 15.4% in the control group.

Reported morbidity due to endocrine system disease, nutritional disorders, metabolism and immune disorders in evacuees from the exclusion zone as well as the population of the contaminated territories was more than twice as high as among the entire Belarus population. In 1995, cases per 100 000 were 2 317 (evacuees) and 1 272 (population of contaminated zone) compared to the national average of 583.

Occurrence of endocrine system diseases in children living in Chernobyl-contaminated parts of the Tula region in Russia increased five-fold by 2002 as compared to the pre-accident period. Morbidity in the adult population living in the highly contaminated Southwest territories of Bryansk region exceeds the regional average by some 2.6 times.

It seems that a generalised response in the individuals living in contaminated areas was increased endocrine system activity, which only stabilised 5-6 years after leaving these areas. In Russian areas affected by the radioactivity from Chernobyl generalised disturbances in the production and balance of sex hormones was described while a persistently increased level of autoimmune endocrine illness - autoimmune hyroadenitis, thyrotoxicosis and diabetes – was observed from 1992 onwards in the Ukrainian contaminated territories.

Overall, endocrine system pathology is a highly important and significant impact observed in those populations exposed to Chernobyl radiation. Given the importance of the endocrine system in the modulation of whole body function, it is not surprising that other dysfunctions have also been observed.

Abnormalities of immune function

Generalised immune responses

The immune system is one system modulated by endocrine function. Accordingly, abnormalities of the immune system can be expected where the endocrine system is disturbed. In addition, ionizing radiation can directly affect components of the immune system.

In Belarus, a study of the immune system status of 4 000 men exposed to small, but long term, doses of radiation, showed that chronic radiation exposure leads to loss of the immune system's ability to resist development both of infectious and non-infectious diseases. Surveys of cellular and humoral immunity in Gomel region of Belarus showed that immune changes developing in children chronically exposed to radiation depend on the radionuclides involved: different effects were found with exposure to radiologically equivalent levels of strontium, caesium and other radionuclides.

Decreased immunity was manifest in reductions in the numbers of leukocytes, the activity of T-lymphocytes and killer cells as well as in thrombocytopenia and various forms of anaemia, which were observed in the Chernobyl-affected territories of Russia. By 2002, the frequency of immune and metabolic effects in children from parts of Tula region contaminated with Chernobyl fallout increased 5-fold compared to the pre-Chernobyl level.

In the Ukraine the most unfavourable changes were observed in children with high *in utero* doses of thyroid irradiation (over 200 cGy). Among such children, 43.5% developed immune deficiency compared with 28.0% in the control group

Infectious diseases

Interference with the immune system can impact upon the occurrence and severity of infectious diseases in the wider population. Some of the statistics gathered post-Chernobyl suggest that radiation exposed populations may be more vulnerable to disease.

It was found that congenital infections occurred 2.9 times more often than before the accident in newborns whose mothers came from radiation-contaminated parts of the Polesky district of Kiev region (up to 20-60 Ci/km²), the Chechersky district of Gomel region (5-70 Ci/km²), Mtsensky and Volkhovsky districts of Orel region (1-5 Ci/km² and 10-15 Ci/km²)

Between 1993 and 1997, greater frequency of viruses of hepatitis B and C as well as greater spread of viruses D and G were discovered among 2 814 adults and adolescents who suffered from the Chernobyl radiation in Vitebsk region of Russia. This could ultimately lead to increased mortality from cirrhosis and primary liver cancer. Incidence of viral hepatitis in highly contaminated parts of the Gomel and Mogilev regions more than 6-7 years after the accident was double the average level in Belarus

Elsewhere in Russia, an increase in cryptosporidia infections was found in the Bryansk region. Children in contaminated areas were more frequently affected with pneumocystosis (56.3% against 30% in the reference group).

Genetic abnormalities & Chromosomal aberrations

The frequencies of chromosomal aberrations in areas of the Ukraine, Belarus and Russia that were contaminated by Chernobyl fallout are noticeably higher than the global average.

Frequency of aberrant cells and chromosomal aberrations per 100 lymphocytes in contaminated areas of Ukraine and Belarus reached up to three times the global average. In Russia, frequency of chromosomal aberrations increased 2 to 4-fold in inhabitants of territories with contamination levels over 3 Ci/km², while a study of a number of Ukrainian residents before and after the Chernobyl accident revealed a 6-fold increase in frequency of radiation-induced chromosome changes, a phenomenon which also seems to be carried over to their children. Chromosomal aberrations thought to be attributable to Chernobyl have been recorded as far away as Austria, Germany and Norway.

Increases in chromosome mutation frequency often correlate with increased incidence of a variety of illnesses. For example, increased chromosomal aberrations in lymphocytes have been found to coincide with diagnosed levels of psycho-pathologic challenge and secondary immunosuppression in 88% of 'liquidators' surveyed.

Urogenital and reproductive system

During 1988-1999, diseases of the urogenital system more than doubled in populations still living in the most contaminated territories of the Ukraine. A 3-fold growth in internal inflammatory diseases, disturbances of the menstrual cycle and benign ovarian tumours was reported in exposed women. In other contaminated regions, both infertility and male impotence have reportedly become more frequent since the accident. Structural changes in the seminiferous tubules and disturbance of sperm production were reported in three-quarters of men surveyed in the Kaluga region of Russia.

More than 8-10 years after the accident, the threat of interrupted pregnancy became more frequent in evacuees from the 30km zone and those living in the contaminated territories. In highly exposed groups in the Ukraine, more than half of pregnant women suffered complications during pregnancy (including pre-eclampsia, anaemia, foetoplacental failure), while in control group, complications occurred in only 10%. Similarly, risk of inhibited foetal development was observed in 35% of radiation risk group women, three times higher than in the general population, while complications during childbirth were experienced by over three-quarters of the radiation risk group, more than twice that in the control group. Accumulation of radionuclides in the placentas of women living in the most contaminated areas correlated with numerous indicators of poor placental development and consequent reductions in birth-weights of babies.

Impacts are unlikely to have been limited to Russia, Belarus and Ukraine alone. Across Western Europe and Scandinavia (including Greece, Hungary, Poland, Sweden, Norway, Hungary, Finland and Germany), studies have identified *in utero* exposure to Chernobyl radiation as possible contributory factor in spontaneous abortions, low birth weight and reduced infant survival.

Premature Ageing

The apparent 'biological' age of people living in known radiation-contaminated areas of Ukraine has increased disproportionately in the years since the accident, with assessed 'biological' age now exceeding calendar age by as much as 7-9 years. In a study of 306 'liquidators', this discrepancy was estimated at between 5 and 11 years. In the most contaminated territories of Belarus, average age at death for victims of heart attack was 8 years lower than for the general population.

Sense organs

In contaminated areas around Chernobyl, disorders of the eyes such as cataracts (including in newborn infants), and other problems were encountered with greater frequency than in neighbouring, cleaner regions. Although the greatest risks occur at the highest exposures, there is no known threshold of radiation dose below which risk of cataracts is not increased. Similarly, other eye problems which occur naturally in all populations at some level, such as retinal degradation, have been reported with increased frequency in irradiated populations.

Neurological and Psychological disorders

Even comparatively low levels of ionizing radiation can lead to some level of damage to the central and peripheral nervous systems. Assessing the full extent of the neurological damage resulting from the releases of radionuclides from Chernobyl is, therefore, a very difficult task.

However, in ‘liquidators’ from Russia, for example, neurological diseases were the second most common group of diseases recorded, accounting for 18% of all morbidity. Neurological and psychiatric disorders among adults in radiation-contaminated territories of Belarus were also considerably more frequent than normal (31.2% compared to 18.0%).

Increases in nervous system and mental disorders have also been reported in children from some contaminated areas of Belarus, including lowering of IQ, though their relationship to direct measures of radiation exposure is not always clear-cut.

Conclusions

Clearly the overall body of evidence concerning human health impacts of the radiation released by the Chernobyl accident is highly diverse and complex but of great significance. Many of the features of the accident and its consequences, such as uncertainty regarding total quantities of radionuclides released, uneven distribution of radioactivity, concomitant and sequential effects of multiple radioisotope exposures, as well as limitations in medical monitoring, diagnosing, forecasting and treating diseases, make it altogether unique, thus rendering many previously applied standards and methods inapplicable. Complete evaluation of the human health consequences of the Chernobyl accident is therefore likely to remain an almost impossible task, such that the true extent of morbidity and mortality resulting may never be fully appreciated.

At the same time, however, this sheer range of health impacts described, combined with the variety of ways in which they have been detected and quantified, underscore the need for any proper evaluation to consider all available data and to reflect the diversity of both lethal and non-lethal effects. Any description which attempts to present the consequences as a single, ‘easy to understand’ estimation of excess cancer deaths (such as the figure of 4 000 much publicised by bodies such as the IAEA during 2005) will therefore inevitably provide a gross oversimplification of the breadth of human suffering experienced. Moreover, much of the evidence presented in the current report indicates that such figures may also greatly underestimate the scale of impacts as outlined earlier in the text.

Many uncertainties remain. In particular there are still very few estimates of non-cancer mortalities attributed to Chernobyl, while long latency periods for development of cancers (in

some cases greater than 40 years) inevitably mean that new cases are likely to emerge well in to the future. The health impacts on the children of the exposed are evident and will continue throughout their lifetimes, and possibly through those of their own children. The substantial gaps in available data, combined with some large discrepancies between estimates for incidences and excesses of certain cancers and other diseases, prevent any single, robust and verifiable assessment of overall human health consequences from being performed, leaving fundamental questions unanswered.

Two important conclusions can, nevertheless, be drawn.

Firstly, it is vital that a far more extensive body of data, including those presented in this report, be considered by the international community in coming to conclusions regarding the scale and extent of the impact on human health. In particular, the reasons for the wide discrepancies between the highest estimates and those accepted by the IAEA and WHO must be investigated with some urgency.

Secondly, in the absence of a properly co-ordinated and international approach to monitoring incidences and trends in both cancer and non-cancer morbidity throughout the region impacted, and with particular emphasis on the most contaminated populations in the Ukraine, Belarus and the Russian Federation, a huge (though hopefully unique) opportunity to learn fully the long-term consequences of such a disaster has been missed. Moreover, it seems inevitable also that opportunities to intervene at earlier stages with appropriate programmes of medical surveillance, treatment and care have also been lost.

In terms of an holistic understanding of the implications of a large-scale nuclear accident for human health, it seems that we are little further ahead than we were before the Chernobyl explosion 20 years ago. It is therefore vital also to continue, and even increase, research efforts in this field. Far from being a convenient time to draw a line of firm conclusions under the disaster and move on, its 20th anniversary should be seen as signal to redouble international efforts to identify and monitor long-term impacts and, as far as possible, alleviate the suffering of the millions still effected.

The Chernobyl accident, while having some features in common with other global catastrophic events, is so far unique. We can only hope it remains so. This generation saw its beginning, but it is unlikely that we will see its end.

THE CHERNOBYL CATASTROPHE CONSEQUENCES ON HUMAN HEALTH

1.1. General hazards associated with the nuclear power industry

The health and environmental effects of the nuclear fuel cycle, from ore extraction to waste disposal, have been documented for over half a century. Because of the long recognized ability of ionizing radiation to induce various types of cancer, many of the studies of health effects have been focused on this group of diseases. In addition, however, non-cancerous effects from acute exposure have been identified, such as burns and radiation sickness, as well as genetic effects on offspring of workers in the industry thought to be caused by chronic exposure.

In the conversion and fuel enrichment process, chemical agents are also widely used. Some of these, for example acids, may also produce adverse skin and respiratory effects. Milling of uranium ore entails respiratory exposures to dusts and toxic heavy metals, as well as to radioactive decay products derived from the ore. If an acid leach process is used in the process of milling the ore into fine particles, millers may also be at increased risk of reactive airway dysfunction syndrome, a problem associated with inhaling acid mists. A significant occupational risk of contracting lung cancer was identified early in the history of the uranium mining and milling industries. This was linked with increased exposure to alpha radiation from radon inhaled by workers (BEIR VI 1999).

There are numerous opportunities for accidents and spills during fuel transportation, reactor operations and waste management that may expose workers and nearby residents. During power plant operation, workers are monitored for potential radiation exposure from routine operations, spills, leaks and unexpected incidents. Studies of power plant workers have been done in the UK, Canada, the U.S., France, and several other countries, and are summarized in numerous reports (Cardis *et al.* 2005, BEIR VII 2005). There have been some studies of communities near nuclear facilities that have showed increased leukaemia, especially in children and young adults (Beral *et al.* 1993). Results reported from the general population have been questioned, largely because of a lack of individual exposure measurements, but the reported epidemiological data are certainly consistent with effects seen in power plant workers which indicate that power plant workers have experience increased mortality due to leukaemia and to other cancers.

The 1986 Chernobyl nuclear plant accident was a big departure from the general context of health concerns within the nuclear the industry as a whole. The quantities of radioactivity released in the accident were unprecedented as were the human exposures, both short and long term to the released radioactive materials. The effects were widespread and most profound in Ukraine, Belarus, and Russia where the most serious contamination occurred. But significant radiological impacts were also reported from neighbouring countries in Central Europe and countries of the Northern Hemisphere generally. In the Chernobyl accident radioactive material was released through a powerful explosion that carried debris into the upper atmosphere for hundreds and thousands of kilometres. Children and adults from the general population were exposed to radioactive iodine and mixed fission products both directly from fallout and indirectly through the food chain. The environmental contamination continues to the present day into the foreseeable future. Vast areas around the damaged power plant remain uninhabitable due to radioactive contamination.

The human (and wider ecological) impacts of the Chernobyl accident have proven to be both short and long term. Significant early health impacts were identified, but subsequently, the longer term impacts have revealed themselves. This report, based upon the work of a number of scientists and drawing upon work published in the academic literature describes the health impacts of the Chernobyl accident.

1.2. General overview – Morbidity, Mortality, the Main Health Problems

The global impact of Chernobyl accident exceeds that of any other accident either in the nuclear industry or in industry as a whole. Many billions of dollars have been spent over the last 20 years in the countries most affected by the radioactive contamination, which resulted: Ukraine, Belarus, and Russia. Some 350,000 people have been relocated from the most affected areas. Nonetheless, in excess of five million people currently continue to reside in the contaminated areas, and outside these areas many millions of others have been exposed to lower levels of radioactivity released in the accident. The health impacts of these exposures have been evaluated and estimated by various research teams. These studies have produced a spectrum of numbers and a diversity of opinions about the true human health impacts of the accident.

The short-term to medium-term human impacts of Chernobyl included thirty or more deaths in power plant workers immediately following the explosion, several thousand cases of thyroid cancer, primarily in children in Ukraine and Belarus, and a variety of cancer and non-cancer health effects, within the group of emergency workers (liquidators) and the population resident in other areas.

The first official predictions of the health consequences of the explosion of the reactor in the 4th block of the Chernobyl NPP on April 26th, 1986 were dismissive. They predicted only very few additional cancer cases. 20 years after the accident it is clear that the possible impacts have extended widely across the Northern Hemisphere and could affect many millions of people. According to Yablokov (2006) the most vulnerable population groups include:

- 1) The more than 100,000 residents evacuated in 1986 from contaminated areas of Belarus, Russia and Ukraine.
- 2) Those who received significant doses of radiation in the first days and weeks after the accident including people living in territories with radioactive contamination levels of more than 1 Ci/km² (up to 3,2 million in the Ukraine, up to 2,4 million in Russia, up to 2,6 million in Belarus with another 0,5-0,8 million in Sweden, Norway, Bulgaria, Romania, Austria, southern Germany and other European countries).
- 3) Liquidators (the persons involved in damage limitation/control and clean-up at the power station and in the contaminated territories). These are estimated at: around 740,000 persons from the Ukraine, Russia and Belarus and an additional 80,000-90,000 from Moldova, the Baltic States, the Caucasus, and from Middle and Central Asia.
- 4) Children whose parents belong to the first three groups: estimated at nearly 2 million to date.

- 5) The people in the former USSR but also in Sweden, Norway, UK and a number of other countries in Europe - in order of several hundred thousands - who consumed and continue to consume foodstuffs contaminated as a result of the accident.
- 6) The people living in all areas where fallout from the Chernobyl accident occurred. This number is difficult to estimate but totals several hundred million people in Europe, North America and Asia.

The gathering of accurate data about impacts of the accident was considerably impeded by a blanket of official secrecy thrown over the event, which persisted until May 1989. Moreover, for the first three years after the accident it appears that the authorities falsified medical data, permanently corrupting the data set. This was accompanied by an absence of authentic medical statistics in the former USSR. As a result, the primary epidemiological consequences of the accident will probably never be clear. The uncertainties extend to the inventory of radioactive materials emitted from the damaged reactor. Official Soviet data admit to 50 million Ci while a recent review (Fairlie & Sumner, 2006) suggests that the figure could be many times in excess of this. Even though manipulation of data may be a thing of the past, it is questionable as to whether sufficient resources have been directed by national and international agencies at evaluating the full health consequences given the unprecedented scale of events at Chernobyl. There is a vital need to continue to monitor longer term health impacts as they emerge in the exposed populations and to try and unravel the various causal relationships involved in adverse health outcomes.

Despite the large numbers of people exposed to radiation from the accident, a number of other circumstances exist which make it very difficult to identify and assign causal relationships to data sets documenting radiation levels and consequent health impacts. Some of these are detailed in a recent review (Yablokov, 2006) and include:

- 1) The highly uneven distribution of radioactive fallout over affected areas;
- 2) Poor understanding of the behaviour and impact of various of the short-lived radionuclides in the early period after the release (e.g. ^{133}J , ^{135}J , ^{132}Te);
- 3) Poor understanding of the fate and effects of “hot particles”;
- 4) The complexity of environmental radiochemistry and radiobiology of the mixture of radionuclides released by the explosion;
- 5) Poor understanding of the differing specific radiological impacts of the different isotopes under identical conditions of radiation density;
- 6) Poorly characterised distribution of internal and external radiation doses over the affected areas.

All these factors conspire to undermine the validity of reconstructed radiation doses and dose rates, and in turn compromise the possibilities for establishing robust dose-response relationships with strong correlations to particular health effects. The difficulties in characterising and resolving these issues have led in classic fashion to “absence of evidence of impact” being interpreted widely as “evidence of absence of impact”. This is noticeable, for example, in the report of Chernobyl Forum Expert Group “Health” 2005. The significance

of the emitted radiation for human health is heavily downplayed and much made of the lack of scientific “proof” of widespread human health impacts.

Considerable insight into the true public health impacts of the Chernobyl event can be gathered by consideration of data which exist for comparisons of population groups over the same period after the accident, and comparisons of population groups from similar geographical and socio-economic backgrounds, subject to differing radiation levels. Overall it appears that since 1986, in the former territories of the USSR, life expectancy has noticeably decreased, with increases in infant mortality and mortality rates in older age groups. While there is no proof that these general observations are linked to the Chernobyl accident, analysis of data from particular territories contaminated by the accident reveals links with the accident and adverse health outcomes.

For example several studies have shown that in the contaminated areas of Ukraine, Belarus and Russia there has been a generalised increase in mortality in comparison with neighbouring areas (See: Grodzinsky, 1999; Omelyanets, *et al.* 2001; Kashirina, 2005; Sergeeva *et al.* 2005). An increase in the numbers of stillborn children, apparently correlated with contamination levels, has been noted for some areas of the Ukraine (Kulakov *et al.* 1993) and Belarus (Golovko & Izhevsky, 1996), in early studies. In contaminated territories of Russia the number of reported miscarriages has increased noticeably. One estimate of radiation related miscarriages and stillbirths in the Ukraine puts the total number at 50,000 or more (Lipik, 2004). Since 1987, an increase of infant and child mortality has been noted in the polluted areas of the Ukraine (Omelyanets & Klementev, 2001) and in Russia (Utka *et al.* 2005). Elsewhere, in some European countries increased perinatal mortality has been attributed to the Chernobyl accident (Korblein 1997).

Cancer mortality has also been monitored in the radioactively contaminated areas. Between 1986 and 1998 the cancer mortality rate increased from 12% over the Ukraine as a whole to between 18% and 22% in the contaminated areas and in the population evacuated from such areas subsequent to the accident (Omelyanets *et al.* 2001; Golubchikov *et al.* 2001). Also in the Ukraine, mortality of men from prostate cancer has risen by a factor of 1.3 in the country as a whole, while in the contaminated territories the factor was between 1.5 and 2.2.

Increased incidence of cancerous diseases and other serious radiation related impacts would undoubtedly result in excess mortalities in the populations in question. A precise determination of such a figure for the Chernobyl incident is hampered both by a lack of empirical data and by an apparent unhealthy politicization of the data, which do exists.

One of the lowest estimates of additional cancer deaths likely to occur as a result of the radioactive releases is that of 4,000 published by the International Atomic Energy Agency (IAEA, 2005) known for its pro-nuclear industry stance. By contrast other estimates of additional mortality have been published which greatly exceed this estimate. Early estimates (Anspaugh *et al.* 1988) predicted 17,400 excess cancer deaths over a 50-year period, with 63% of these occurring outside the USSR, mostly elsewhere in Europe. A figure of 32,000 excess deaths from all causes was considered defensible by one epidemiological researcher (Scherbak 1996). A more recent study (Mousseau *et al.* 2005), indicates that the accident will result in 9,335 excess cancer deaths (excluding thyroid cancer) in the next 95 years.

Notwithstanding the acknowledged difficulties in retrospective dose reconstruction following the incident, this has been attempted. Calculations of individual and collective exposure doses for the population of Belarus and all other countries polluted by the Chernobyl accident have been recently published (Malko 2006). Based on the current data in the official Belarusian health statistics and his estimates of radiation exposure in various regions of Belarus, this researcher estimates that the Chernobyl accident could result in an additional 31,400 thyroid cancer cases and 28,000 solid tumours other than thyroid between 1986 and 2056 in Belarus alone (Table 1.2.1.). This estimate predicts 93,080 total excess cancer deaths associated with the Chernobyl accident in all the affected countries, ten times more than the estimate of Mousseau *et al.* (2005).

Pathology	Morbidity		Mortality	
	Belarus	All countries	Belarus	All countries
Thyroid cancer	31,400	137,000	3,140	13,700
Other solid cancers	28,300	123,000	16,400	71,340
Leucosis	2,800	12,000	1,880	8,040
Total	62,500	270,000	21,420	93,080

Table 1.2.1. Estimates of morbidity and mortality caused by solid cancers and leucosis in 1986-2056 as a result of the Chernobyl accident

Affected populations	Estimated period (years)	Illnesses considered	Mortality	Range	Comments	Reference/ source
1, 5 (for Russia)	NA	All	Max. 145	NA		Minatom 2002
1, 3, 4	NA	Solid cancers, leukaemia	4,000	NA	Conclusion did not fit with the Chernobyl Forum 2005 although the same methodology was used	IAEA 2005
1, 3, 4, 5	95 10	Solid cancers, leukaemia	9,335	NA	95 years for all solid cancers 10 years for leukaemia	Report of Chernobyl Forum Group "Health" 2005 ¹
6	95	All cancers (excluding thyroid cancers)	9,335	NA		Mousseau <i>et al.</i> 2005
8	50	All illnesses	17,400	NA		Anspaugh <i>et al.</i> 1988
8	NA	Cancer and non-cancer illnesses	32,000	NA		Shcherbak 1996
8	70	Thyroid cancer, other solid cancers and leucosis	93,080	46 000-150 000	For all deaths figure should be doubled but uncertainty is up to 100%	Malko 2006
5	15	All	210,000	Not applicable for the whole region. For Russia - 55,000-65,000 (95 %)	From 1990 till 2004, based on Russian statistical data	Khudoley <i>et al.</i> 2006
8	NA	All cancers	475,368	NA	For group 6 - 212150, for group 7 - 244786	Goffman 1990
8	NA	Acute radiation exposure and all cancers (without thyroid)	NA	905 016 to 1 809 768		Bertell 2006
8	70 Years	All cancers	Up to 6,000,000	NA	Estimations are based on own attributed risk model, Belarus – up to 25 000 per year	ECRR, 2003

Table 1.2.2. Some estimations of mortality caused by Chernobyl Catastrophe

Affected populations: 1. Liquidators 1986-1987; 2. Other liquidators; 3. Evacuees; 4. Residents of highly contaminated areas; 5. Residents of other contaminated areas in Ukraine, Belarus and Russia; 6. Population of Ukraine, Belarus, Russia; 7. Population of countries other than Russia, Ukraine and Belarus; 8. Global population.

*Notes: For calculations, latency of solid cancers was not applied. Uncertainties in risk factor are also significant, but cannot be resolved. For 95% probability lower and higher boundaries of relative attributed risk can vary by 60 times (0,007-0,47) (Krestinina *et al.* 2005), for 90% probability – by 6 times (1,2-8,8). It is also important to note that uncertainties in risk factors and collective dose estimates could raise this figure to as many as 260 000 deaths.*

¹ Uncertainties in dose estimation can be up to factor 5 (where identifiable at all).

The trends in general mortality can be illustrated using figures from Belarus (based on the data published on the official government Belarus website <http://stat.med.by/>). These show that in the period from 1990 to 2004 general mortality has risen by 43% from 6,5 to 9,3 per 1 000 of general population. In absolute numbers, this equates to 109,582 in 1990 rising to 140,084 in 2004. Cancer mortality increased from 17 683 to 18 818 correspondingly. Over the same time period the percentage of patients newly diagnosed with malignant tumours at any site has grown from 0,26% to 0,38% (an increase of 46,2%), while in the Gomel region, the region of Belarus most affected by the accident, these diagnoses increased from 0,25% to 0,42% (an increase of 68%).

These data are illustrative but part of a wide range of opinions, and estimates expressed around the issue of the impact of Chernobyl and human health outcomes. Factors contributing to the high levels of speculation and general uncertainty include:

- discrepancies in calculations of the amount of radioactive materials released into the environment, and exclusion of a number of the radioactive isotopes from evaluations (see above);
- various approaches to determining the doses of exposure, with or without taking into account internal exposure of thyroid, lungs, gastrointestinal tract, urogenital organs, bones and bone marrow following selective accumulation of certain radionuclide in these organs/tissues;
- absence of an adequate dose-effect coefficient;
- variation in numbers of the affected people “included” into these calculations. For example, the number of liquidators in all countries has been quoted as 200 000 by IAEA (2005) report, whereas 305 639 liquidators were officially listed in the State Register of Ukraine (SRU) for that country alone in 2005 and 400 000 liquidators are reported by Shcherbak (1996), Yablokov (2006) refers to more than 800,000 such individuals;
- not taking into account countries other than Belarus, Russia, and Ukraine that were polluted after Chernobyl accident despite the fact that, according to De Cort & Tsaturov (1996), European countries with areas contaminated by ^{137}Cs of Chernobyl origin at the levels of 1-5 Ci/km² include ten other countries all over the continent: from Sweden and Finland in the North to Italy and Greece in the South;
- exclusion of data presenting non-oncological diseases, even though numerous research reports have proven that such diseases, including disorders of cardiovascular, respiratory, digestive, nervous and other systems;
- lack of adequately trained personnel and/or diagnostic supplies for conducting medical diagnostic procedures after the accident in the former USSR;
- errors in reporting the epidemiological data in the post-Soviet countries;
- mismanagement of vital statistics databases in these countries.

This list can be supplemented with other relevant points. For example, given that the latency period for solid tumours can exceed 40 years (Sinclair 1996), the picture for oncological morbidity and mortality linked to Chernobyl is far from complete. Moreover, the combination of radiation with other harmful factors (mechanical trauma, biological or chemical agents) have been shown experimentally as well as clinically to significantly increase effects of radiation exposures (Pellmar & Ledney 2005). This, on the one hand, highlights the possibility of a situation where low doses of radiation exposure on the background of other factors such as chemical pollution or other factors in or around Chernobyl, such as physical exhaustion and psychological stress, can produce much more harmful effects than radiation alone. On the other hand, enhancement of the effects of non-radiological stressors by

Chernobyl radiation would lead to highly increased rates of non-cancerous diseases in people affected by Chernobyl. It should also be mentioned here that morbidity and mortality from any disease depends on the level of healthcare in each country, and, therefore, projections based on accepted benchmarks of Western medicine would not be appropriate for the post-Soviet countries with generally poor levels of healthcare.

The health effects of Chernobyl are by no means limited to oncological diseases. Links between many diseases other than cancer and radiation exposure have been established (Preston *et al.* 2003). In fact, the health victims of Chernobyl have increasingly been suffering from various diseases affecting all the major body systems: cardiovascular, neurological, hormone/endocrine, respiratory, gastrointestinal, immune, etc. Mortality of the exposed population from non-cancerous causes related, directly or indirectly to Chernobyl exposure, could be much higher than from cancer alone.

The death toll from Chernobyl has always been viewed as one of the most meaningful ways of expressing the significant outcome of the incident and, as such, it has been the subject of vigorous scientific and political discussions. Estimations range from dozens (see table 1.2.2.) to millions of additional deaths worldwide. However, it is widely acknowledged that neither the available data nor current epidemiological methodology allow holistic and robust estimations of the death toll caused by the Chernobyl accident. The existing research, even excluding extreme figures, indicates a death toll of anywhere between 10,000 and –200,000 additional cancer deaths. Indeed, the most recent epidemiological evidence, (Khudoley *et al.*) indicates that the scale of the problems could be very much greater than predicted by many studies published to date. For example, the 2005 IAEA report predicted that 4000 additional deaths would result from the Chernobyl accident. The most recently published figures indicate that in Belarus, Russia and the Ukraine alone the accident could have resulted in an estimated 200,000 additional deaths in the period between 1990 and 2004.

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2. CANCER IN UKRAINE, BELARUS & RUSSIA

Cancer is one of the best-known manifestations of radiation exposure. Despite this, initial predictions following the huge release of radiation from the Chernobyl power plant were anodyne and reassuring:

R. Gale: "...any possibility of cancer illnesses arising in the effect of the Chernobyl accident is infinitesimal ... It may happen that no cases will be stated, or their quantity will be such that they shall not be able to be determined... I hope that will be no additional cases of cancer illnesses".

L.A. Buldakov: "There is the background morbidity and no additional cases should be found".

Taken from a translated conversation of California University professor Robert Gale with the Deputy Director of Biophysics Institute of the Health Ministry of the USSR professor L.A. Buldakov several months after the Chernobyl catastrophe (Dyachenko et al. 1996).

The risk of fatal cancer due to the Chernobyl accident has been evaluated at around 5% per 1 Gy (UNDR, UNICEF, UN-OCHA & WHO 2002). This is much lower than the 1988 UNSCEAR estimate of lifetime risk of fatal cancer of 10-12% per Sv (Sinclair 1996), but the UNSCEAR figure would have been based on data from populations such as those exposed to radiation from the atomic bombings in Japan (ICRP 1966), nuclear tests (Sinclair 1996) and patients exposed to radiation via medical diagnostics and therapeutic procedures. However, these populations were exposed to different radioisotopes and studied over a longer time period than those exposed after Chernobyl, two factors which may, among other, affect the accuracy of overall predicted cancer outcomes.

Today it is clear that the radioactive contamination from Chernobyl has indeed caused a large-scale increase in malignant neoplasms. Cancer rates in critical populations of the three most affected countries, Belarus, Russia and Ukraine are significantly elevated. The following research summary, while not exhaustive, gives an indication of the scale of the problem.

Belarus

In the most contaminated areas of Belarus, total morbidity from cancer increased sharply after the Chernobyl accident as can be seen from Figure 2.1. Approximately 26 000 cases of radiation-induced malignant neoplasms (including leukaemia) were recorded in Belarus in the period from 1987-1999, of which approximately 11,000 cases were fatal (Malko 2002). The most recent estimates (Malko 2006) are that the total cancer incidence (all solid cancers and leukaemias) in Belarus over the 70 years from 1986 to 2056 could range up to 62 500, with as many as 21 420 deaths resulting from these cancers.

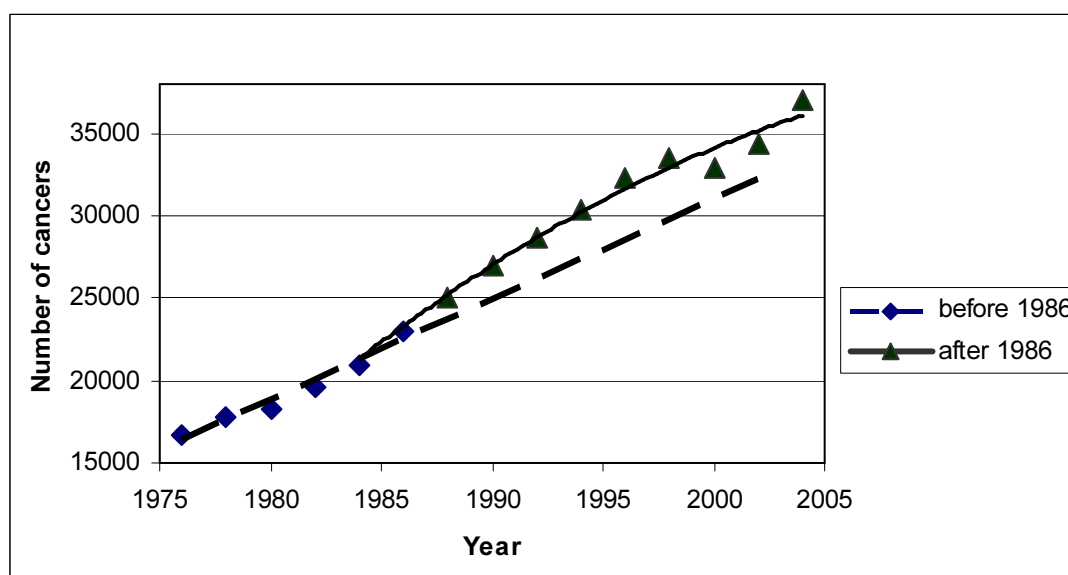


Figure 2.1. Newly diagnosed cases of cancer in Belarus 1975-2005. Based on data from Matsko (1999) and the Belarusian Centre of Scientific Medical Information of the Health Ministry of the Republic of Belarus (<http://stat.med.by/>).

Between 1990 and 2000, there was a 40% increase in all cancers in Belarus (Okeanov *et al.* 2004). A survey of the district impacted by Chernobyl-derived radiation showed the greatest increase to be in the highly contaminated Gomel region (Matsko 1999). The increase here was (52%), and was lower in the less contaminated regions of Brest (33%) and Mogilev (32%) (Okeanov *et al.* 2004).

¹³⁷ Cs, Ci/km ²	Gomel region		Mogilev region	
	1977-1985	1986 -1994	1977 -1985	1986 - 1994
< 5	181.0±6.7	238.0±26.8	248.8±14.5	306.2±18.0*
5-15	176.9±9.0	248.4±12.5**	241.8±15.4	334.6±12.2***
>15	194.6±8.0	304.1±16.5**	221.0± 8.6	303.9± 5.1**

Table 2.1. Malignant cancer incidence (per 100 000) in the contaminated territories of Belarus: before and after the Chernobyl catastrophe (Konoplya & Rolevich 1996). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Okeanov *et al.* (2004) studied the cancer risk in Belarusian liquidators. The cohort numbered 71,840 (representing 790,249 person-years over the course of the study). This total comprised 57,440 men (631,844 person-years) and 14,400 women (158,405 person-years). The population of Vitebsk region, the part of Belarus which received the least fallout of long-lived radionuclides, was used as a control. All tumours among liquidators living in Vitebsk region and in people who moved there from contaminated areas were excluded from the research.

Morbidity was analysed using standard indicators and truncated age-standardised rates (TASR) for the ages of 20 to 85 and over.

Over the time period 1993-2003, a statistically significant increase in morbidity due to malignant neoplasms was observed among liquidators, but such morbidity also increased in the reference region. Consequently, comparison within the liquidators' cohort and in the reference area was conducted upon the basis of average levels of standardized indicators of morbidity and upon the value of the associated regression coefficient, which specifies the rate of morbidity increase.

Comparison of average values of the standardized indicators for the period from 1993 to 2003 showed that the morbidity amongst liquidators due to malignant neoplasms at all sites, including kidney, urinary bladder and thyroid cancers was significantly higher than morbidity in the reference group (Table 2.2). Regression coefficients were higher for the liquidators than for the general population of the Vitebsk region, indicating a higher rate of morbidity among the liquidators.

Tumour site	Morbidity indicator (per 10 ⁵)		Regression coefficient per year	
	Liquidators	Controls	Liquidators	Control
All sites	422.2±20.6	366.4±5.3	13.15±5.29	4.69±1.10
Stomach	41.1±3.4	42.9±1.2	1.99±0.92	-0.99±0.19
Colon	19.1±2.1	16.1±0.4	1.14±0.59	0.24±0.12
Lungs	55.6±5.4	53.6±1.2	3.78±1.26	-0.38±0.31
Kidney	15.7±1.9	10.8±0.5	1.78±0.27	0.68±0.16
Urinary bladder	16.7±1.2	13.8±0.8	0.89±0.23	0.28±0.12
Thyroid gland	28.4±4.1	10.1±1.0	1.08±1.03	0.8±0.18

Table 2.2. Average levels of the standardized indicators and dynamics of morbidity with the malignant neoplasms during 1993-2003.

Only approximate and collective (group) dose assessments are available in the literature. Since opinion among dosimetry specialists regarding group doses is divided, there is no single method for dose estimation. Individually registered exposure doses are not available for all individuals included in the specialized record and their verification is not complete. It is also known that data on individual dosimetry in the registration documents were often intentionally lowered (Pitkevich *et al.* 1995). Consequently, the available data on individual and collective exposure doses is not sufficiently reliable for robust scientific analysis.

Since it was not possible to differentiate between subgroups of the cohort on the basis of dose, sub-groups were created based upon the time of arrival in the contaminated zone:

- Liquidators who arrived in the evacuation zone and zone from which inhabitants were later forced to evacuate, between the time of the beginning of the accident and the end of June 1986 (period of the most intense radioactive iodine impact) Group 1;
- Liquidators who arrived in the evacuation zone and zone from which inhabitants were later forced to evacuate, between the beginning of July 1986 and the beginning of January 1988. Group 2;
- Liquidators who arrived in the evacuation zone after the beginning of January 1988. Group 3.

The average age of liquidators at the time of entry into accident zone was 37,2 years for group 1, 34,6 years for group 2 and 33,5 years for group 3.

All three groups of the liquidators worked in areas with high densities of contamination by radionuclides - over 555 kBq/m². The first sub-group was exposed to irradiation by both short-lived and long-lived radionuclides. The second and the third groups were exposed only to the long-lived radionuclides. The third group arrived 18 months after the accident when the majority of land decontamination work and burying of the most radioactive materials had been completed. Consequently, hypothetical exposure doses in the third sub-group are much less than in the first two groups.

Total exposure doses were the highest for those members of the first group who worked directly after the disaster in the most contaminated areas and who were also exposed to irradiation by radioactive iodine. During summer and autumn, hot and dry weather would have increased dust levels and, consequently inhalation exposure to radionuclides.

Analysis of cancer morbidity in these sub-groups has shown high levels of illness in the first and second groups. Total morbidity with tumours at all sites in the first and the second groups is significantly higher than in the reference population. Morbidity with cancer of the stomach, kidney, thyroid and urinary bladder is significantly higher in the first group; lung and kidney cancer is significantly higher in the second group (Table 2.3.).

Tumour site	Morbidity per 100,000			
	Liquidator subgroup 1	Liquidator subgroup 2	Liquidator subgroup 3	Control
All sites	456.1± 10.3	437.8± 10.3	356.5± 34.8	366.4± 5.3
Stomach	50.4± 3.4	42.6± 3.2	42.5± 12.0	42.9± 1.2
Colon	18.7± 2.1	25.5± 2.5	27.5± 9.7	16.1± 0.4
Lungs	57.9± 3.7	67.1± 4.0	60.5± 14.4	53.6± 1.2
Kidney	20.3± 2.2	20.6± 2.2	9.58± 5.7	10.8± 0.4
Urinary bladder	20.6± 2.2	16.6± 2.0	7.61± 5.1	13.8± 0.8
Thyroid gland	40.0± 3.1	25.2± 2.5	9.47± 5.7	10.1± 1.0

Table 2.3. Standardized indicators of morbidity with the malignant neoplasms among liquidators (1993-2003)

It is also apparent from Table 2.3 that morbidity in subgroup 1 differs significantly from that in subgroup 2 only for thyroid cancer. This can be attributed to the fact that the first group suffered the highest exposures to radioactive iodine. Although the incidence of thyroid cancer in the second group of liquidators is significantly lower than in the first group, it still exceeds that in the control group.

The higher level of morbidity in subgroup 2 in comparison to subgroup 3 and the control group may be due to higher irradiation of the thyroid gland from external radiation and by an indirect effect of higher exposure doses in this group (related to land decontamination works and burying of highly radioactive materials) which a number of publications indicate would reduce immune defence capacities.

Thus for the period 1999-2003, it was established that liquidators who worked during 1986 and 1987 were at highest risk of cancer morbidity. Although the liquidators who worked in 1988 in the evacuation and compulsory resettlement zones didn't show different morbidity levels compared to the reference group during this period, the possibility of future additional increase in cancer morbidity among liquidators of this group cannot be excluded.

Dividing the time span of the study and reconsideration of the data, allowed the observation of a significant increase in the relative risk of morbidity with some forms of malignant neoplasms among the whole liquidators cohort from 1997 onwards, as compared to the population of Vitebsk region (Okeanov *et al.* 2004).

While an increase in morbidity was noticed among the liquidators, a reduction was observed among the reference group. Should these trends continue, the differences in morbidity with

lung and stomach cancer will exceed the level of statistical significance in the near future. With this in mind data were re-analyzed taking account of newly obtained statistical indices up to 2003 inclusive (Table 2.4).

Tumour sites	Morbidity index		RR	95% confidence interval	
	Liquidators	Control		Lower boundary	Upper boundary
All sites	464.6	379.3	1.23	1.18	1.27
Stomach	46.9	40.8	1.15	1.02	1.29
Colon	22.2	16.7	1.33	1.11	1.59
Lungs	66.3	52.6	1.26	1.14	1.39
Kidney	19.1	15.4	1.24	1.05	1.47
Urinary bladder	18.7	11.4	1.65	1.37	1.98
Thyroid gland	32.2	12.3	2.62	2.23	3.07

Table 2.4. Relative risk of morbidity with malignant neoplasms among the liquidators averaged over the period 1997-2003.

Russia

Cancer morbidity in the highly contaminated Kaluga and Bryansk regions was higher than across the country as a whole (Ivanov & Tsyb, see Figure 2.2. below). Nine years after the catastrophe, the general oncological morbidity in areas of the Bryansk region that was contaminated with 15 Ci/km² or more was 2.7 times higher than in less contaminated territories of the region (Ushakov *et al.* 1997).

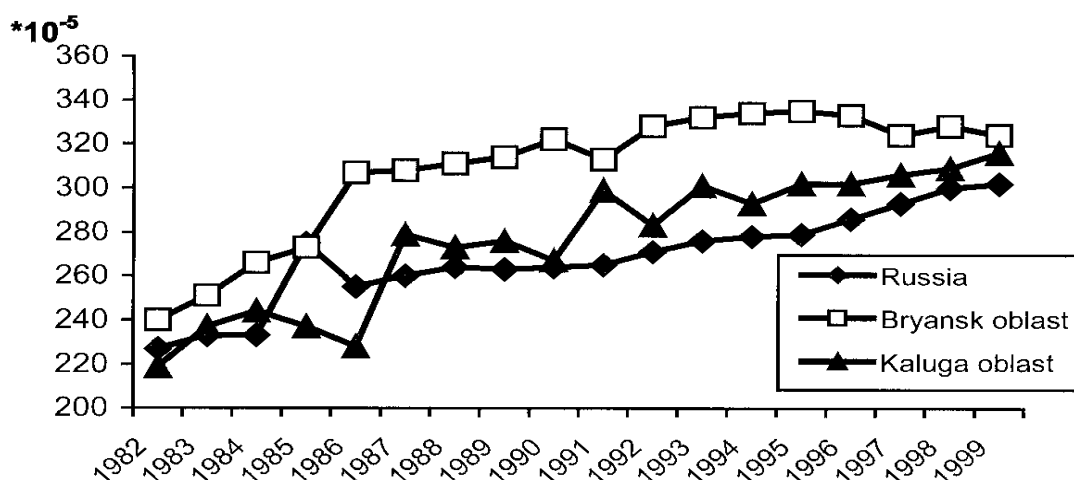


Figure 2.2. Incidence of all solid cancers per 100 000 population in the two radioactively polluted Russian areas, Bryansk and Kaluga, in comparison with Russia as a whole (Ivanov & Tsyb 2002).

Ukraine

Across Ukraine, there was a 12% increase in cancer mortality (Omelyanets *et al.* 2001, Omelyanets & Klementev 2001). In contaminated areas of Zhytomir region morbidity increment of adults with malignant neoplasms increased almost threefold between 1986 and 1994, from 1.34% to 3.91% (Nagornaya 1995).

The increase in cancer in people evacuated from the 30-km zone and in the population of the territories polluted with radiation was higher than for the country in general (Golubchikov *et al.* 2002). In highly contaminated areas, mortality from neoplasms increased by 4-6.2% in men (from 240-250 cases per 100 000 in 1985 to 255-260 cases in 1999) and by 4.2-6.6% in women (from 120-122 cases in 1985 to 125-130 cases in 1999).

Prysyazhnyuk *et al.* (1991, 1993, 1995, 2002, 2004, 2005) analysed data that the Ukrainian cancer registry has collected since its inception in 1987 in order to investigate cancer incidence in three cohorts: Chernobyl catastrophe recovery operation workers (liquidators) who participated in recovery operation works during 1986-1987; evacuees from Pripyat town and the 30 km zone; and the population still living in the heavily contaminated areas listed above, in the 20 years following the Chernobyl radiation release.

The registry collected information on all cases of cancer in the contaminated areas of the Lugyny, Narodichy and Ovruch districts of the Zhytomir region and Borodyanka, Ivankov and Polesskoye districts in the Kiev region. It also accessed data stretching back to 1980 to provide a pre-accident baseline for the residents of the territories that were most heavily contaminated with radionuclides, together with information on all cancer cases in the former Chernobyl district for 1981-1985.

At the time of the accident the total number of this population was 360,700 including 74,400 children aged 0-14 years old (Prysyazhnyuk *et al.* 1995). In 2004 the population of six districts excluding the now deserted Chernobyl district was 211,700 including 34,000 children (The State Committee of Statistics of Ukraine, 2005).

The data from the State registry of Ukraine on Chernobyl victims were used to investigate cancer incidence in liquidators in 1986-1987 and in evacuees. These data were compared with data from the national cancer registry. Medical documents (including emergency notifications of new cancer cases and death certificates) were obtained from all medical institutions where these patients were diagnosed and treated. These documents were then cross-checked to eliminate duplicates and a final database was compiled. This showed that there were 19,836 new cases of cancer registered from 1980 through to 2004. During the period from 1990 to 2004, 6,221 new cancer cases were registered in liquidators and 2,182 in evacuees (Prysyazhnyuk *et al.* 2002a, Prysyazhnyuk *et al.* 2002b, Romanenko *et al.* 2004, Fedorenko *et al.* 2004, Prysyazhnyuk *et al.* 2005).

Annual age-specific and age-standardized incidence rates were calculated directly for the period 1980-2004 and compared with corresponding rates for Kiev & Zhytomir regions (to which the studied districts belong) and to the Ukraine as a whole. The age structure of the population of the USSR in 1979 (according to All-Union census) was used as a standard. The following cohorts were studied: liquidators who participated during 1986-1987 and resident in the Dnepropetrovsk, Donetsk, Harkov, Kiev, Lugansk regions and Kiev city (total 106,844 in 2004); and evacuees from Pripyat and 30 km zone, who resettled all over the Ukraine (56,175 in 2004). The indirect method of standardization was used to analyse cancer incidence in these two groups. Age-specific incidence rates in Ukraine in 1998 were used as a standard.

During 1980-2004 the cancer incidence rate in contaminated territories was somewhat lower than in compared areas. The time trends were similar in all four territories: there was a gradually increasing trend until 1998, after which some decrease of rates was observed in all territories. There was no significant difference between their regression coefficients (Prysyazhnyuk *et al.* 2002b, Prysyazhnyuk *et al.* 2004).

Rates of cancer in liquidators show statistically significant excess in comparison to the national level (Table 2.5).

Time period	Person-years of observation	Actual number of cases	Expected number of cases	SIR (%)	95% confidence interval
Residents of contaminated territories (males + females)					
1990-2004	3 413 232	11 221	13 211	84.9	83.4-86.5
Liquidators 1986-1987 years of participation (males)					
1990-2004	1 228 422	5 396	4 603	117.2	114.1-120.3
Evacuees from Prip'yat and 30 km zone (males + females)					
1990-2004	796 653	2 182	2 599	83.9	80.4-87.5

Table 2.5. Standardized incidence ratios (SIR) for all forms of cancer (Code ICD-9 140-208) in different groups of Ukrainian population affected by the Chernobyl catastrophe

The study of cancer incidence in the main populations affected by the Chernobyl catastrophe (liquidators of 1986-1987; evacuees from Prip'yat and the 30 km zone and the population still living in the territories most heavily contaminated with radionuclides) showed peculiarities of trends in particular types of cancer.

Among Ukrainian liquidators investigated by the State through the Kiev Interdepartmental Expert Commission, digestive system tumours were the most common type of cancer (33.7%), followed by tumours of the respiratory organs (25.3%) and tumours of the urogenital system (13.1%). The fastest increase in oncological pathology was for the urogenital system, for which an almost three-fold increase (from 11.2% to 39.5%) was observed from 1993 to 1996 (Barylyak & Diomina 2003).

The highest level of malignant neoplasms was recorded in liquidators who worked in the mortuary, as drivers, in decontamination and evacuation activities in relation to the 13 different types of tasks considered. All dates of entry to the contaminated zone starting from 26.04.1986 were risk factors for the malignant neoplasm development, and the risk increased with length of stay.

The liquidators investigated by that commission received doses in the range 1-85 cGy. Dose dependence was analysed by spline regression. The data showed a tendency for malignant neoplasms to increase with increasing radiation dose for all age groups. Moreover, by analyzing the data for dose subgroups, it was established that probability of malignant neoplasm developing in those exposed to doses ranging from 1 to 5 cGy was statistically more significant than the probability of malignant neoplasms for the group as a whole. This indicates an increase in the frequency of malignant neoplasms in liquidators who were subjected to low doses of radiation exposure (Klyushin *et al.* 2002). The confidence intervals also decrease with the dose increase, indicating that as radiation exposure increases, variability of malignant neoplasm frequency decreases. This means, that using this methodology it is possible to forecast malignant neoplasms with some precision.

These results were further supported by cytogenetic studies. Lymphocytes harvested from peripheral blood were cultured as recommended by UNSCEAR, WHO and IAEA for surveys of biodosimetry and bioindication of the degree of radiation damage (CART 1989). Amongst liquidators with malignant neoplasms, dose estimation correlated with measures of chromosomal damage. The correlation coefficient for dicentrics was 0.59 and for centric

rings, 0.56. These correlations were stronger for those obtained for non-cancer diseases, and supported the dose estimations used for cancer sufferers. It is possible that these results indicate the production of aberrant lymphocytes by damaged pro-myelocytes of marrow and the suppression of effectiveness of repairing systems in cells of liquidators affected with oncological illnesses.

Small doses of absorbed radiation represent statistically significant factors in the development of malignant neoplasms (Kindzelsky *et al.* 1999, Diomina 2001, Klyushin *et al.* 2001, Diomina *et al.* 2000). This may be related to insufficient intensity of anti-cancer protection of organisms during the effective period of irradiation in the given range of doses. Such processes include elimination of aberrantly changed cells by the immune supervision system over the antigenic constancy of internal media of organism, as well as cellular repair, restoration and compensatory processes.

2.1. Thyroid cancer

During the first months after the catastrophe only a few additional cases of thyroid cancer were predicted. This figure was later revised upwards to a few hundreds but not exceeding a few thousands (Anon 1996).

The Chernobyl catastrophe, however, released enormous quantities of radioactive iodine, which becomes concentrated in the thyroid glands of exposed individuals. The thyroid is one of the most important axes of the endocrine system, so any impact on it will cause severe perturbation of normal bodily functions. Unsurprisingly, there has also been a significant increase in the rates of thyroid cancer observed among the exposed population, with the excess relative risk for thyroid cancer greater than for other forms of cancer.

The cancer of the thyroid gland caused by exposure to Chernobyl radiation appeared to be unusually aggressive, mainly of papillary form, with early and rapid metastasis to form secondary tumours in the lymph glands and lungs (WHO 1996, Ivanov & Tsyb 2002).

The increase in thyroid cancer is illustrated in Figure 2.1.1.

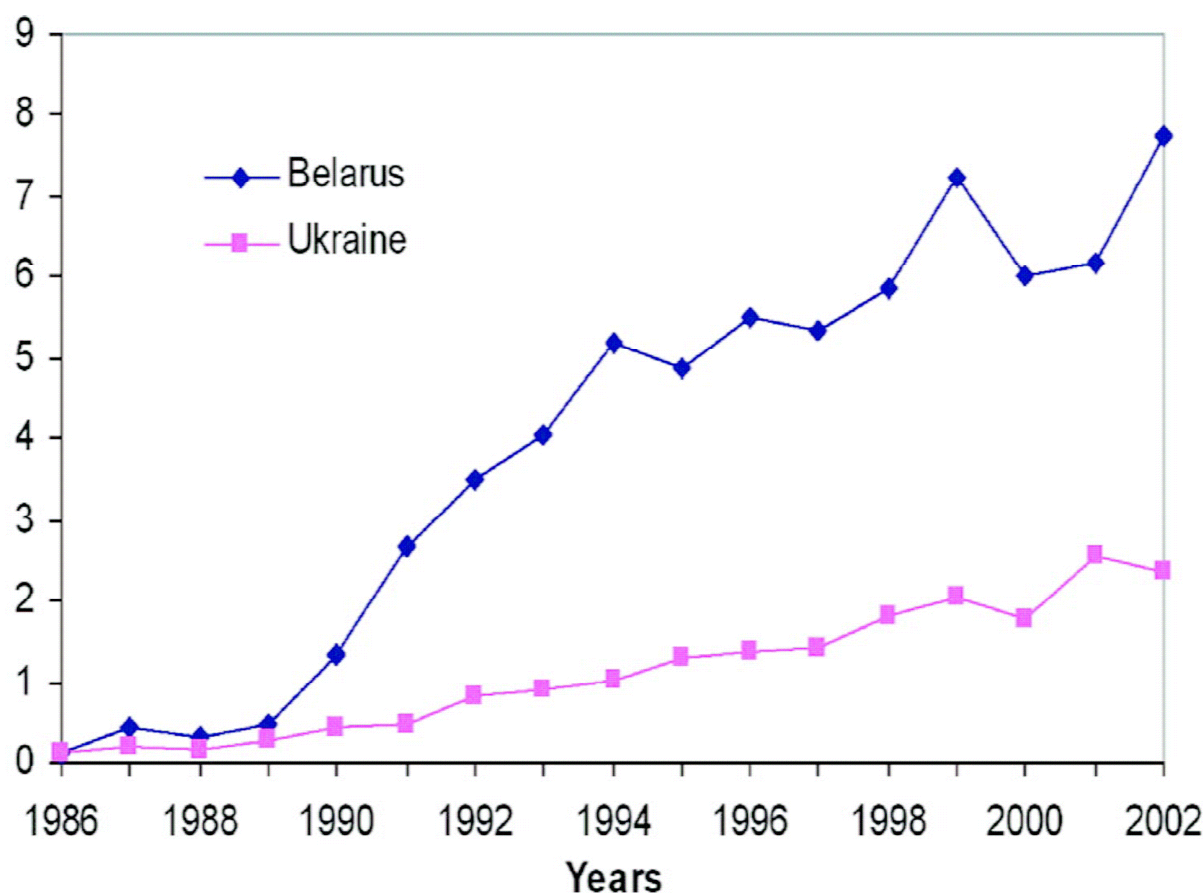


Figure 2.1.1. Annual thyroid cancer incidence rates per 100,000 population for those who were children and adolescents in 1986 (Fairlie and Sumner, 2006)

Belarus

In Belarus, occurrence of thyroid cancer increased 43-fold in children from 1989 to 1994, going from 0.003 to 0.13 cases per 1000 (Lomot' *et al.* 1996). A later study reported that thyroid cancer in children increased 88.5 times, in adolescents 12.9 times and in adults, 4.6 times, as compared to the pre-catastrophe period (Belookaya *et al.* 2002). Cases of children born with thyroid cancer were reported (Busby 1995). Out of one thousand persons surveyed 100 cases of nodules were discovered, 2-3 cases of which were malignant (Krisenko 2002). The excess relative risk (ERR) of these radiation-induced cancers exceeded the risk established for Hiroshima and Nagasaki by over ten times (Malko 2004).

Reports of thyroid cancer incidence in Belarus include:

- 3,748 radiation-induced cases for 1987-1998 according to data from the national register on the six most contaminated areas (Ivanov & Tsyb 2002). This figure is obtained by subtracting the pre-catastrophe background level of 141 cases per year for adults and children from the total of 5,470 reported cases;
- 1,095 cases during 1990-1998 in children who were 0-17 years old at the time of the Chernobyl catastrophe (UNSCEAR 2000);
- 4,401 radiation-induced cases by the end of 2000, including almost 700 in children under 15 years old and 3,709 cases in individuals who were adolescent or adult at the time of diagnosis (Malko 2002);

- “about 6,000” patients, including 1,600 children, were operated on during the period 1987 to 2000 (Drozd 2001);
- “over 8,000” cases by 2001 (Belookaya *et al.* 2002);
- approximately 5,700 radiation-induced cases from January 1, 1987 to December 31, 2002 out of a total of 9,650 cases (Malko 2004 & 2006). This includes around 700 cases in children and adolescents under 15 years old (Malko 2006);
- 1,670 radiation-induced cases out of a total of 8,602 cases in 2002 (Fedorov 2002);
- 1,055 new cases reported in 2002 alone (Postoyalko 2004);
- “about 7,000” radiation-induced cases between 1986 and 2004 (Malko 2006).

Predictions for the future also vary widely but include:

- up to 12,500 cases among of those who were under 18 years of age at the time of the catastrophe (Fedorov 2002);
- 15,000 cases over 50 years (1986-2036) (National Report of Belarus 2003);
- 20,000 cases of radiation-induced thyroid cancer over the lifetime of the victims (Malko 1999);
- 14,000 to 31,400 extra thyroid cancers over 70 years (1986-2056) (Malko 2006);
- up to 50,000 cases in today’s adolescents and young people (Fedorov 2002).

Russia

Russian liquidators suffered three times more thyroid cancer than the national average (Khristanfov & Meskikh 2001). Morbidity with thyroid cancer in the highly contaminated Bryansk region in 1988-1998 was double that of the whole of Russia in 1999 and triple this level in 2004 (Malashenko 2005). In 1986 thyroid cancer morbidity in the regional population was 3.3 per 100,000, but by 2000 it had risen to 13.8 per 100,000. Morbidity in the contaminated areas of the region rose from 5.7 per 100,000 in 1986 to 20.7 per 100,000 in 1999 (Kukishev *et al.* 2001). The frequency of occurrence was higher in the most radiation-contaminated areas of the region (Kukishev *et al.* 2001; Proshin *et al.* 2005). Another, detailed analysis has shown that the actual level of illness may be 3 - 4 times higher (Pilyukova 2004).

In Lipetsk, the number of thyroid cancer cases increased 3.4 times from 1989 to 1995 (Krapivin 1997) with the number of people affected reaching 139 in 1996.

Peak incidence for the entire population (4.4 cases per 100,000) was in 1998, 12 years after the catastrophe (Kukishev *et al.* 2001). Thyroid cancer morbidity within the 0-30 year age group increased 1.5 times from 1991 to 1998 (Ivanov & Tsyb 2002, p. 312, Figure 5.6.). In children, the rate increased from 0.07 cases per 100,000 children in 1991 to 0.19 in 1999, a 2.7-fold increase (Kukishev *et al.* 2001).

Incidence reports include:

- 2,801 radiation-induced cases 1987-2000, based on data taken from the national register on four of the most polluted areas of Russia: 4,173 total cases from which are subtracted the pre-Chernobyl background level before Chernobyl of 98 cases per annum in adults and children (Ivanov & Tsyb 2002);
- 207 cases during 1990-1998 in children 0 to 17 years old at the time of the Chernobyl catastrophe (UNSCEAR 2000);

- 1,591 cases in 1986 - 2000 for Bryansk region compared to 308 cases between 1975 and 1985 (Kukishev *et al.* 2001);
- 2,638 cases in Bryansk region from 1986 to 2005 (Malashenko 2005).

Ukraine

An increase in numbers of thyroid cancers among children and teenagers due to exposure to radioiodine is accepted as fact nowadays (Tronko & Bogdanova 1997). For the Ukraine as a whole, some 24,000 thyroid cancers are expected, of which 2,400 are expected to be fatal (Malko 1999).

Since 1989-1990 an increased incidence of papillary cancer of the thyroid gland has been observed in Ukrainian children and adolescents. To date a total of approximately 4,000 cases had been recorded. Before the catastrophe, occurrence of thyroid cancer among children and adolescents averaged 0.09 cases per 100,000. After 1990, the frequency of occurrence rose to 0.57-0.63 per 100,000. The greatest increase in morbidity was recorded in young people living in the worst contaminated areas of Ukraine (Kiev, Chernigov, Zhytomir, Cherkassy and Rovno regions) (Komissarenko *et al.* 1992, 1993 & 1995). In this area morbidity with thyroid cancer reached 1.32 per 100 000 persons and was 5 times higher than in other regions.

According to the Ukrainian Surgical Clinic of the Endocrinology Institute, over the last 20 years the total number of people suffering from thyroid cancer increased 14 times compared to the pre-catastrophe period (Rybakov *et al.* 2000, Komissarenko *et al.* 2001). The minimum latency period was 3-3.5 years after the catastrophe. The peak of thyroid cancer morbidity among those who were children and teenagers at the time of the incident is predicted to occur in the period from 2001-2006.

Analysis of the age structure of patients with a primary diagnosis of thyroid cancer indicates that the highest disease rates are recorded in children and teenagers (62.5 %) (Vtyurin *et al.* 2001). The majority of the sick (60%) were aged 0-4 years at the time of the Chernobyl accident (Komissarenko *et al.* 2002, Vtyurin *et al.* 2001). However, very few children born after the radioactive release were affected by thyroid cancer, resulting in a gradual rise of the average age of patients as time passed. The prevalence of invasive forms of carcinoma (87.5%) indicates very aggressive tumour development process (Vtyurin *et al.* 2001).

Epidemiological analysis of data from the Ukrainian State Register over the period 1982-2003 established that after 1991, the frequency of thyroid cancer rose significantly for the three different cohorts studied: liquidators of the Chernobyl catastrophe who worked during 1986-1987, the population evacuated from the town of Pripjat and the 30-km exclusion zone, and the population resident in the radioactively contaminated areas (Prysyazhnyuk *et al.* 1995, Prysyazhnyuk *et al.* 2002a&b, Dedov *et al.* 1993, Zubovskij & Tararuhina 1991, Prysyazhnyuk *et al.* 1991, Prysyazhnyuk, 1993).

Incidence reports include:

- 3,914 cases during 1986-1996 including 422 cases in children and 3,492 cases in adolescents and adults (Drobyshevskaya *et al.* 1996);
- 553 cases during 1990-1998 in children who were 0-17 years old at the time of the Chernobyl catastrophe (UNSCEAR 2000);

- 2,371 thyroid cancer operations were conducted between 1986 and 2002 in people who were aged under 18 at the time of the catastrophe (Scheglova 2004);
- 2,674 thyroid cancer operations were conducted on children during the period 1988-2004 (Anon 2005);
- 3,400 thyroid cancer operations were conducted among persons who were children at a time of the accident, 11 of whom subsequently died (National Report of Ukraine 2006).

Analysis of data from the Ukrainian cancer registry (Figure 2.1.2. below) shows a dramatic increase in the incidence of thyroid cancer which is indisputably due to ionizing radiation. In the Ukraine as a whole, this increase was double the expected level in males and three times higher in females. Figure 2.1.3. shows that the level of this pathology increased 5-fold in the city of Kiev and 6-fold in the Kiev region, where a significant part of Pripjat town and 30 km zone population were relocated (Prysyazhnyuk *et al.* 2002b).

Regression coefficients that reflect time trends are: Ukraine 0.12 ± 0.01 (per 10^5 per year); Kiev region 0.41 ± 0.07 ; Kiev city 0.52 ± 0.05 ; Zhytomir region 0.22 ± 0.03 ; contaminated territories 0.41 ± 0.06 . The first thyroid cancer cases in children up to 14 years old living in contaminated territories were registered in 1990 (Prysyazhnyuk *et al.* 1991). Before this year (since 1980) this pathology was not registered in the territory under study.

Figure 2.1.2. Age-standardized average annual thyroid cancer incidence rates in Ukraine in separate time periods (males and females)

Another study was performed in the Chernigov, Kiev and Zhytomir regions during 1990-1999, where radioactive iodine fallouts were recorded (Romanenko *et al.* 2004, Prysyazhnyuk *et al.* 2005). It showed, for the first time, that the incidence of thyroid cancer was dependent on the level of radioiodine fallout. Truncated age-standardized incidence rates in territories with contamination $<100 \text{ kBq/m}^2$ did not exceed 2 cases per 100,000 in males and 5 cases per 100,000 in females. However, in territories with medium and high levels of contamination ($100\text{-}200 \text{ kBq/m}^2$ and $>200 \text{ kBq/m}^2$ respectively), a significant increase in incidence of thyroid cancer was registered. This excess consisted of 4 cases per 100,000 in males and 16 cases per 100,000 in females in 1998-1999. It was shown that radioiodine exposure-induced thyroid cancer tended to increase over time (Romanenko *et al.* 2004, Prysyazhnyuk *et al.* 2005).

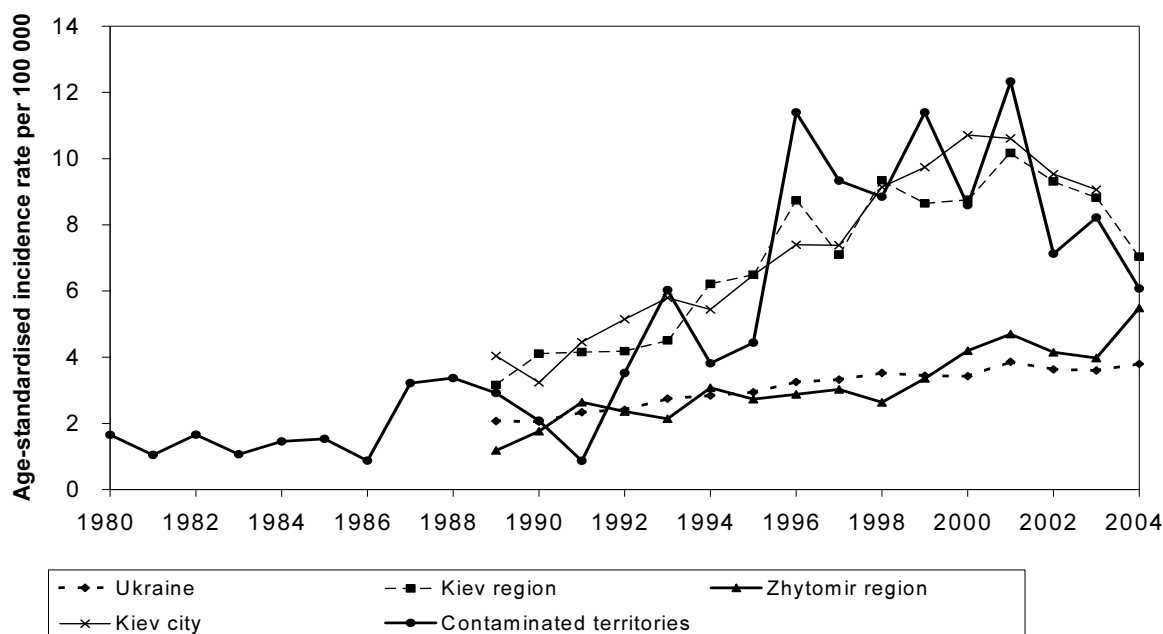


Figure 2.1.3. Thyroid cancer incidence rate in Ukraine, Kiev, Zhytomir regions, Kiev city and the territories most heavily contaminated with radionuclides in 1980-2004. Regression coefficients: Ukraine 0.12 ± 0.01 ; Kiev region – 0.41 ± 0.07 ; Kiev city – 0.52 ± 0.05 ; Zhytomir region – 0.22 ± 0.03 ; contaminated territories – 0.41 ± 0.06 (data from Ukrainian State Register and the local cancer registry)

Comparative analysis of the incidence of thyroid cancer in different sub-groups of the affected population (Table 2.1.1.) suggests that the most significant increase of the national incidence level in 1990-2004 were firstly in liquidators, whose rates were 8.0 times higher than the national average and secondly in evacuees, whose rates were 5.1 times higher. In 1998-2004 they were 9.1 and 6.0 times higher respectively.

Group of observation and time period	Number of person-years of observation	Actual number of cases	Expected number of cases	SIR (%)	95% confidence interval
Residents of contaminated with radionuclides territories (males + females)					
1990-2004	3,413,232	247	151.4	163.1	142.7-183.4
Male liquidators who participated during 1986-1987					
1990-2004	1,228,422	164	20.5	800.7	678.2-923.3
Evacuees from Pripyat and 30 km zone (males + females)					
1990-2004	796,653	174	34.0	511.3	435.3-587.2

Table 2.1.1. Standardized incidence ratios (SIRs) for thyroid cancer (Code ICD-9 193) in different groups of Ukrainian population affected by the Chernobyl catastrophe (data from Ukrainian State Register and the local cancer registry 1990-2004)

A statistically significant excess of thyroid cancer (1.6 times normal) was recorded for the time period 1990-2004 in residents of the territories that were most heavily contaminated with radionuclides (Prysazhnyuk *et al.* 2002b).

In all groups under study significant increase of thyroid cancer incidence was recorded. This may be associated with fallouts of radioactive iodine. The increase was found not only in

children but also in adolescents and adults. Occurrence of extra thyroid cancer cases as an effect of exposure to radioiodine tends to increase in time.

The World Health Organisation (WHO) established that radiation-induced thyroid cancer in the Ukrainian population is not a special clinical entity, but it is the registered medical consequence of the nuclear catastrophe at the Chernobyl NPP, which is determined by aggregate of clinical, epidemiological and morphological factors.

The Surgical Clinic of the Endocrinology and Metabolism Institute of the Academy of Medical Sciences of Ukraine has treated over 3,000 patients suffering from thyroid gland carcinoma, of whom 509 were children or adolescents (Komissarenko *et al.* 2003).

Malignant neoplasms of the thyroid gland observed in child and adolescent patients vary in their characteristics but are generally highly aggressive. Clinically this is expressed in a short latency period, absence of signs of general somatic status change and high organic and lymphatic invasiveness. 46.9% of patients have extrathyroid spread of tumour. Regional metastasis into lymph nodes of neck was noticed in 55.0% of patients. This metastasis forced surgeons to conduct repeated operations to remove residual metastases that appeared shortly after the initial operation. Moreover, 11.6% of patients had distant metastasis into lungs. So far, 6 children treated at this clinic have died of thyroid cancer (Rybakov *et al.* 2000, Komissarenko *et al.* 2002).

Morphological study of tumours showed that over 90% were papillary carcinomas. However, typical papillary carcinomas were noted only in a small number of child or adolescent patients. Solid, follicular and mixed solid-follicular structures of papillary carcinomas were more common. Such carcinomas are classified as a single solid-follicular variant which is characterized by a wide spread through the gland, growth beyond the anatomic capsule of the gland, lymphatic and blood circulatory invasion and frequent invasion of the lymph nodes in the neck.

Given the aggressive nature of the radiation-induced cancers, surgical tactics at the clinic were reviewed to avoid operations aimed at preserving the thyroid (Komissarenko *et al.* 1993, 1995 & 2001). Differentiated and all other forms of thyroid cancer are treated through extrafacial thyroidectomy with a review of regional collectors of lymph backflow and further treatment with radioactive iodine and suppressive therapy with thyroid hormones. Pre-operational cytological and express-histological diagnostics are mandatory.

Execution of primary thyroidectomy led to a decrease in the frequency of localized recurrences of the illness 3.2 times from 2.3 % to 0.7 % as compared to operations aimed at preserving the organ (Komissarenko *et al.* 1995).

Improvements in the operational methods for thyroid cancer treatment decreased specific post-operation complications to 4.3% (persistent laryngeal paresis 3.2%, persistent hypoparathyreosis 1.1%) and reduced the need for repeated operations in relation to recurrences and metastases to 1.8 %. The long-term results of the treatment were also favorable. A survey of 1,253 patients for 5 years after treatment showed a survival rate of 97.3% (Komissarenko *et al.* 2001 & 2002).

Although the new treatments methods offer improved outlook for those diagnosed with thyroid cancer, it is necessary to stress that there remains a high risk of development of papillary thyroid carcinomas among those who, in 1986, were children or adolescents in the

regions of Ukraine hit by the radiation from Chernobyl. They will remain at risk for 40-50 years. Constant surveillance of this group of the population is necessary to increase early diagnosis of the illness and provide the opportunity for conducting the necessary radical surgical treatment and effectively rehabilitating patients.

2.2. Leukaemia

Leukemia is considered to be one of the first expressions of radiation induced illness. According to Sinclair (1996), leukaemia has a latency period of two years and a peak incidence period between six and eight years after exposure. According to Yablokov (2006), due to the poor available statistics secrecy and falsification of medical data originating from the contaminated territories of the former Soviet Union many of the cases diagnosed in the first three years after the incident may not have been formally recorded. Nonetheless the available statistics indicate a serious problem.

Belarus

An excess of acute leukaemia was seen for 1990-1991 among Belarusians working as liquidators between 1986-1987. Beginning in 1992, a significantly increased incidence of all forms of leukaemia was identified in the adult population of Belarus. The greatest increase was observed during 1992-1994 as compared to the pre-Chernobyl period. Some data are presented in Table 2.2.1. From 1996 onwards, incidence of pre-leukaemia conditions tended to increase (Ivanov *et al.* 1997). It has been estimated that the people of Belarus could suffer as many as 2,800 extra cases of leukaemia between 1986 and 2056, with up to 1,880 of these being fatal (Malko 2006).

	1979-1985	1986-1992	1993-1997
Acute leukaemia	2,82±0,10	3,17±0,11*	2,92±0,10
Chronic leukaemia	6,09±0,18	8,14±0,31*	8,11±0,26*
Eritremia	0,61±0,05	0,81±0,05*	0,98±0,05*
Multiple Mieloma	1,45±0,06	1,86±0,06*	2,19±0,14*
Hodgkin' disease	3,13±0,10	3,48±0,12*	3,18±0,06
Non-Hodgkin' Lymphoma	2,85±0,08	4,09±0,16*	4,87±0,15*
Mielodisplastics syndrome	0,03±0,01	0,12±0,05*	0,82±0,16*

* - $P < 0.05$

Table 2.2.1. Leukaemia, lymphoma and other blood diseases (per 100,000 population) morbidity in the population of Belarus 1979 – 1997 (Gapanovich *et al.* 2001).

Russia

Comparison of morbidity before and after the catastrophe (1979-1985 and 1986-1993) for the population of the most severely affected Bryansk region has shown a considerable increase in cases of all leukaemias and in cases of non-Hodgkin's lymphoma (UNSCEAR 2000). There was a noticeable increase in acute lymphatic leukaemia cases in the six most contaminated areas of Bryansk region between 1986 and 1993 (Ivanov & Tsyb 2002). Childhood leukaemia in the Tula region in the post-Chernobyl period significantly exceeded the average Russian ratio, with acute blood cancers in children aged 10-14 being especially prevalent. Morbidity with acute lymphatic leukaemia was higher in the contaminated areas (Ushakov *et al.* 2001). In Lipetsk, cases of leukaemia increased by a factor of 4.5 from 1989 to 1995 (Krapivin 1997, Ivanov & Tsyb 2002, Ivanov *et al.* 2004).

Ukraine

For leukaemia and lymphoma in the population from the contaminated districts of Kiev and Zhytomir there were pronounced annual incidence fluctuations. These annual figures showed an increase for the periods 1987-1991 and 1999-2000 (Figure 2.2.1.).

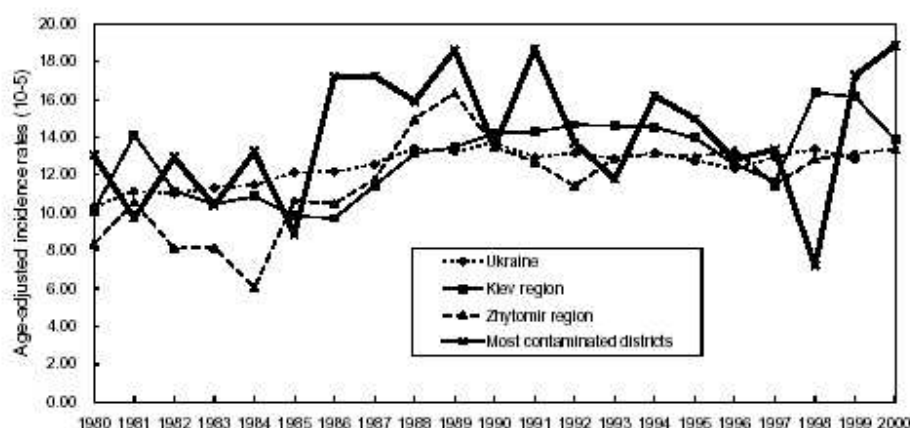


Figure 2.2.1. Incidence rates (male and female) for leukaemia and lymphoma in Ukraine (Prysyazhnyuk *et al.* 2002)

After 1990 a considerable increase in the occurrence of leukaemia and lymphoma was observed in Ukrainian liquidators who worked between 1986 and 1987 (Table 2.2.2. below). There was also an increase in blood cancers among evacuees during 1990-1993, i.e. between 4 and 7 years after the catastrophe. In addition, leukaemia in children in the contaminated areas of Kiev and Zhytomir regions was significantly elevated between 1986 and 1991 (Prysyazhnyuk *et al.* 2002).

Years	Number of person-years of observation	Observed numbers of cases	Expected numbers of cases	SIR
Leukaemia and lymphoma, liquidators (males)				
1990-1997	577 536	183	81.6	224.2
1990-1993	263 084	81	31.8	255.0
1994-1997	314 452	102	49.9	204.6
Leukaemia and lymphoma, evacuees from 30-km zone (males and females)				
1990-1997	408 882	74	59.6	124.2
1990-1993	208 805	43	30.0	143.4
1994-1997	200 077	31	29.6	104.7
Leukaemia, children, contaminated areas of Kiev and Zhytomir districts				
1980-1985	337 076	19	10.88	174.68
1986-1991	209 337	22	6.78	324.35
1992-1997	150 170	7	4.87	143.70
1998-2000	80 656	0	2.59	0.00

Table 2.2.2. Standardized incidence ratios for leukaemia in some Ukrainian populations (Prysazhnyuk *et al.* 2002)

A study of 12 regions of the Ukraine, including 4 regions seriously contaminated by Chernobyl showed an increase in the incidence rate of acute childhood leukaemia in most regions except Kiev city. The incidence rate of acute leukaemia in 10-14 year-olds increased, mainly in the contaminated regions (Moroz 1998, Moroz 2000 & Drozdova 2000, Moroz *et al.* 1999).

A study of children exposed to radiation *in utero* due to the Chernobyl catastrophe in Zhytomir region and of the children from the exposed and the non-exposed population in Poltava region have revealed a significant increase in incidence for all types of leukaemia among exposed children. The rate of acute lymphoblastic leukaemia was more than three times greater in the exposed region (Noshchenko *et al.* 2001).

Analysis of aggregated time periods for leukaemia and lymphoma incidence rates showed higher levels in 1986-1991, 1992-1997, 1998-2000 in comparison with pre-catastrophe period (1980-1985) as shown at Table 2.2.3. When individual subtypes of these diseases were evaluated comparable increase was seen for lymphoid leukaemia in 1986-1991 and (non-significantly) for 1992-1997, 1998-2000. For myeloid leukaemia there was an increase 1986-1991 and 1998-2000. Screening effect could be supposed for the initial increases after catastrophe period. The overall regression coefficients for this entire period do not suggest any significant difference among the different territories.

	Mean annual age-adjusted incidence rate (10 ⁻⁵)			
	1980–1985	1986–1991	1992–1997	1998–2000
Leukaemia and lymphoma	10.12 ± 0.75	15.63 ± 1.06	13.41 ± 1.10	13.82 ± 1.52
Lympho- and reticulosarcoma	1.84 ± 0.33	2.70 ± 0.41	3.70 ± 0.58	3.36 ± 0.90
Hodgkin's disease	1.82 ± 0.34	2.47 ± 0.48	2.10 ± 0.48	1.23 ± 0.50
Multiple myeloma	0.54 ± 0.16	1.03 ± 0.25	0.78 ± 0.22	1.38 ± 0.40
Lymphoid leukaemia	3.08 ± 0.40	4.93 ± 0.59	2.97 ± 0.49	4.11 ± 0.75
Myeloid leukaemia	0.49 ± 0.17	1.99 ± 0.41	1.06 ± 0.30	2.32 ± 0.62
Other leukaemias	2.35 ± 0.36	2.51 ± 0.41	2.81 ± 0.53	1.41 ± 0.53

Table 2.2.3. Leukaemia and lymphoma incidence rates in the population of 5 most contaminated districts in Zhytomir and Kiev regions, Ukraine (Prysyazhnyuk *et al.* 2003)

2.3. Other cancers

Belarus

Between 1987 and 1990, the number of referrals to the Eye Microsurgical Center in Minsk for retinoblastoma (cancer of the retina) doubled (Birich *et al.* 1994). Among 32,000 men evacuated from the 30-km zone, the level of lung cancer morbidity was 4 times higher than the average throughout the country (Marples 1996). In the Gomel region, a noticeable increase in morbidity from intestinal, rectal, breast, urinary bladder, kidney and lung cancer was observed. The incidence of these cancers was correlated with the level of land contamination caused by the Chernobyl catastrophe (Okeanov *et al.* 1996, Goncharova 2000). During 1987-1999, approximately 26,000 cases of radiation-induced malignant neoplasms (including leukaemia) were registered in the country, of which skin cancer accounted for 18.7% of cases, lung cancer 10.5% and stomach cancer 9.5%. Approximately 11,000 people died, 20.3% because of lung cancer and 18.4% from stomach cancer.

Russia

Research into the morbidity and mortality of Russian liquidators, showed that the third most common disease category was malignant neoplasms (6.8%). However, this was the second common cause of death (26.3%). The most widespread cancers were malignant neoplasms of the kidney and urinary bladder, together accounting for 17.6% of all cancers. This was twice as high as the Russian average of 7.5% (Khrisanfov & Meskikh 2001).

The next most frequently reported were malignant tumours in three locations: respiratory organs, stomach and hemoblastosis (9%). Compared to the Russian average, liquidators were diagnosed with malignant tumours in the thyroid gland almost 3 times more frequently, tumours in haematogenic and lymphatic tissues were more than twice as high (Khrisanfov & Meskikh 2001).

Lung cancer was found 1.5 times less frequently than in the rest of Russia and stomach tumours and tumours of the large intestine were also less frequent (Khrisanfov & Meskikh 2001).

The analysis of the distribution of cancer diseases among liquidators who died showed that the largest proportion had lung cancer, followed by stomach cancer. This is in line with data from the rest of Russia. In third place was hemoblastosis, exceeding the general Russian level by more than a factor of two. Among tumours in other parts of the body, most widespread

were brain tumours, tumours in the thyroid gland, kidneys, urinary bladder and larynx (Khrisanfov & Meskikh 2001).

An increase in cancer of the respiratory passages in women has been observed in the most contaminated areas of the Kaluga region (Ivanov *et al.* 1997). Starting from 1995, morbidity from cancer of the stomach, lungs, breast, rectum, colon, thyroid gland, blood-forming and lymphatic tissues in the south-western areas of the region (contaminated above 5 Ci/km²) was higher than average throughout the region (Kukishev *et al.* 2001). In 1997 child morbidity with malignant neoplasms in areas affected by fallout from Chernobyl (Bryansk, Orel, Tula, Lipetsk and Smolensk regions) noticeably exceeded the average value throughout Russia (Ushakov *et al.* 2001). There are indicators that in 1986-1997, incidence of some cancers in the infant population of the Tula region increased as compared to 1979-1985 (Table 2.3.1.).

Cancer	Morbidity index	95% confidence interval
Oral cavity, pharynx	0.08* 0.18**	0.01 – 0.29 0.02 0.07 – 0.37
Thyroid gland	0.00* 0.24**	0.0 – 0.29 1.0 0.12 – 0.46
Adrenal gland	0.08* 0.18**	0.01 – 0.29 0.02 0.07 – 0.37
All cancers	10.3* 11.6**	9.05 – 11.7 10.5 – 12.7

Table 2.3.1. Incidence of cancer in children of Tula region during periods 1979-1985 and 1986-1997 (Ushakov *et al.* 2001). *1979-1985; **1986-1997

During 1990-1994, children in Tula region started becoming ill significantly more often with tumours of the bones, soft tissues and central nervous system (Ushakov *et al.* 2001). In contaminated areas of the region (over 3 Ci/km²) in 1995-1997 a 1.7-fold increase in child morbidity caused by all cancers occurred, with acute leukaemia having risen 2.7 times. There are indicators that child morbidity with malignant neoplasms in reportedly uncontaminated areas of the Tula region in 1995-1997 was substantially lower than in the radiation contaminated areas.

Ukraine

In the most radioactively contaminated territories, the incidence rate of breast cancer was almost stable during 1980-1992 and lower than in the larger comparison areas (Ukraine, Kiev and Zhytomir regions). Then, from 1992-2004, the incidence rate increased in contaminated territories (Prysyazhnyuk *et al.* 2004). Morbidity due to breast cancer in women living in the contaminated territories and among those evacuated increased 1,5 times from 1993 to 1997 (Moskalenko 2003, Prysyazhnyuk *et al.* 2002). Of the affected population subgroups studied, breast cancers exceeded the national level in liquidators. During 1990-2004 the SIR was 190.6% (95% confidence interval 163.6-217%). An analysis of the SIR for two other groups (evacuees and residents of contaminated territories) gave controversial results. According to the local standard, SIR shows statistically significant excess in the actual number of cases compared to the expected number, although if the national standard is used, no excess is visible.

At the same time, the increase in female breast cancer incidence rate in all three groups of victims during the period of observation is obvious. Further monitoring of malignant tumour cases will evaluate whether the “screening effect” has any influence and improve the quality of cancer statistics in Ukraine.

A significant increase in urinary bladder cancer has been detected in the contaminated territories of Ukraine (Romanenko *et al.* 1999). In the period 1987-1994, an increase in the number of children suffering nervous system tumours was observed (Orlov 1995). Male mortality because of prostate cancer increased 1.5-2.2 times in the contaminated territories compared with 1.3 times throughout the entire Ukraine (Omelyanets *et al.* 2001).

Cancer conclusions

Rates of various types of cancer increased significantly in Russia, Belarus and Ukraine after the Chernobyl catastrophe. Impacts were mainly seen in liquidators, children and populations of the contaminated zones.

Significant increases in solid cancers at all sites have been recorded in liquidators from Belarus and Ukraine and in inhabitants of contaminated regions of Russia.

Leukaemia was significantly higher in liquidators in Russia and Ukraine, in adults in Belarus and in children in the contaminated areas of Russia and Ukraine.

Thyroid cancer increased dramatically in all three countries, as expected because of the release of large quantities of radioactive iodine from the Chernobyl catastrophe. Children who were 0-4 years old at the time of exposure were particularly vulnerable to this cancer. One commonly used estimate of collective thyroid dose for the entire populations of three countries is as follows: 5.53×10^5 person-Gy for Belarus, 7.4×10^5 person-Gy for Ukraine and $2 - 3 \times 10^5$ person-Gy for Russia. Using the total collective thyroid dose of 1.6×10^6 person-Gy for three countries and the radiation risk factor for thyroid cancer of $8 \times 10^{-2} \text{ Gy}^{-1}$ (ICRP 1991), about 13,000 thyroid cancer cases are expected in these countries as the consequences by the Chernobyl catastrophe. 10 % of them, i.e. 1,300 cases, will be fatal (Imanaka 2002). This mortality estimate, of course, excludes deaths in other countries. The latency period for radiation-induced cancer of the thyroid gland is not yet established but may be up to 50 years (Komissarenko *et al.* 1995). Consequently, new cases are expected to appear for the next thirty years. Radical surgical techniques can improve the prognosis for thyroid cancer sufferers. Long-term monitoring of at-risk populations will be necessary to allow timely and effective medical intervention. It has been suggested (Cardis *et al.* 1999) that the total number of thyroid cancers among those younger than 5 years of age at the time of the accident could reach between 18,000 – 66,000 cases in Belarus alone.

In addition to the critical groups mentioned above, other populations, such as the evacuees and those living in the vast tracts of land contaminated at lower levels may have been affected as well, but have not been so often researched. Hence relevant data may not always be available. However, morbidity and mortality rate estimates based on collective dose give higher figures than those actually recorded, indicating that many radiation-induced cancers may not have been actually recorded as such.

Data provided by Malko (2006) estimates a figure of 93,080 fatal cancers worldwide, out of a maximum estimate of 270,000 excess cancers worldwide as a result of the Chernobyl catastrophe (see Table 2.3.2.).

Type of cancer	Global cases	% mortality	Global deaths
Thyroid cancer	137 000	10%	13 700
Other solid cancers	123 000	58%	71 340
Leukaemias	12 000	67%	8 040
Total	270 000		93 080

Table 2.3.2. Estimated global mortality from cancer as a result of the Chernobyl catastrophe.

Goffman (1990) made an even more alarming prediction of 475,000 fatal solid cancers, 19,500 leukemia and 475,000 non-fatal solid cancers for aggregated for all the countries of the Northern hemisphere affected by radiation from the Chernobyl accident.

Examples of occurrence of some solid cancers cases as a result of the Chernobyl accident are presented in Table 2.3.3. according to Yablokov (2006).

Location	Region, features	Authority
Retinoblastoma	Increased by a factor of two between 1987 and 1990 in the eye microsurgical centre in Minsk, Belarus	Birich <i>et al.</i> , 1994
Lung	4 times increase observed among a 32,000 evacuees, as compared to the Belarus average	Marples, 1996
Intestines, Colon, Kidneys, Lungs, Mammary glands, Bladder	Increases in the Gomel area (Belarus), correlated with a level of the Chernobyl radioactive pollution	Okeanov, Yakimovich, 1999
Respiratory organs	Increase in the Kaluga area (Russia), correlated with the Chernobyl radioactive pollution	Ivanov <i>et al.</i> , 1997
Bladder	Increase in men from the Chernobyl polluted territories in Ukraine	Romanenko <i>et al.</i> , 1999
	Increase at the liquidators in Belarus	Okeanov <i>et al.</i> , 1996
Nervous system	Increase of 76.9 % from 1986 to 1989	Orlov <i>et al.</i> , 2001
All cancers	Increase (from 1.34 % at 1986 to 3.91 % in 1994 among adults of the polluted territories of Zhytomir area, Ukraine	Nagornaya, 1995
Pancreas	Up to 10-fold increase in the most polluted areas of Ukraine, Belarus and Russia from 1986 to 1994	UNSCEAR, 2000
Breast	Increase by a factor of 1.5 in polluted Ukrainian territories for the period 1993 - 1997	Moscalenko, 2003
All cancers in children	Noticeably elevated (13.1 – 17.1 per 100,000) in the four most polluted Russian areas than the average for Russia (10.5) in the 11 years after the catastrophe	Ushakova, <i>et al.</i> , 2000

	Increase across Belarus for the evacuated children and those living in the polluted regions	Belookaya <i>et al.</i> , 2002
	Exceeded by a factor of 20 times in 1994 in Gomel area (heavy polluted), compared to the less polluted Vitebsk area, Belarus	Bogdanovich, 1997
	Cases recorded in 1995-1996 exceed those recorded for 1968–1987 in Lipetsk city, Russia by a factor of up to 15 times	Krapivin, 1997

Table 2.3.3. Examples of occurrence of some solid cancers cases as a result of the Chernobyl' accident

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3. NON-CANCER ILLNESSES

The tendency of many researchers to focus on the sickness and death resulting from various cancers may have resulted in significant non-cancer health effects and mortality being overlooked to a certain degree. The following section attempts to provide some insight into the various disease syndromes studied in the aftermath of the accident.

As with cancer studies, studies of non-cancer illnesses have tended to focus on critical groups of the population exposed to radiation including liquidators, residents of contaminated zones, evacuees from these contaminated zones and children. Some studies have also been carried out using animal subjects from the contaminated areas, which serve to illustrate the generalised potential health impacts in exposed organisms.

Researchers of Institute of Experimental Pathology, Oncology and Radiobiology (Kiev) conducted studies on rats and mice exposed to radiation in the Chernobyl exclusion zone. Various adverse changes were identified in the respiratory system, peripheral blood vascular system, bone marrow system and reproductive system in these animal populations. In addition damage to metabolic and immune systems were described together with an increase in diseases including cancer. Life expectancy was reduced and early life stage mortality increased (Serkiz *et al.* 1994 & 1997, Yurchenko *et al.* 2001, Serkiz *et al.* 2003, Druzhina *et al.* 2001, Pinchuk *et al.* 1996).

Disturbance to immune system function was observed in both F_0 generations born to unexposed parents and introduced into the exclusion zone and in their continually exposed descendants (Serkiz *et al.* 2003). Moreover, while the immune function of F_1 generation animals at three months of age did not differ from controls, the following generation exhibited symptoms of acute immune dysfunction at the same age.

Taken together, the findings from the animal studies suggest a wide-ranging disruption of body systems with the potential for adverse outcomes with cancerous and non-cancerous diseases. In addition, compromise of the immune system implies possible changes in endocrine function, and in addition suggests an increased possibility of contracting infectious disease (Serkiz *et al.* 2003).

The impacts observed in animals have been paralleled by changes in the health of humans exposed to radiation from the accident, although in many cases the evidence for human impacts has emerged more slowly. The following sections of the report explore the issues related to non-cancer diseases in the human populations exposed to Chernobyl radiation.

3.1 Generalised Non-Cancer Illnesses

(i) Liquidators

A cohort of 68,145 male liquidators who worked between 1986 and 1987 were studied to ascertain the extent of non-cancer mortality and morbidity. They were listed on the State Register of the Ukraine (SRU) of persons affected by the Chernobyl accident and attended annual medical examinations during 1988-2003. The average individual dose of external

total-body irradiation for the cohort was estimated at 0.146 Gy. 11.4% received total-body irradiation doses of less than 0.05 Gy and were designated as the control group in the study. 77.8% of the cohort received doses between 0.05 and 0.249 Gy and 10.8% received doses between 0.25 and 0.7 Gy.

Analysis using the statistical analysis programs SYSTAT, EPICURE and EGRET revealed consistent adverse changes in health status of these liquidators. Over the 17-year period after the Chernobyl accident, the proportion of apparently healthy persons in this cohort decreased by a factor of 9.4 times from 67.6% to 7.2% of the cohort and this health decline was attributable to general somatic diseases. Figure 3.1.1 demonstrates the dynamics of non-tumour morbidity, invalidity and subsequent mortality caused by non-tumour diseases in liquidators working between 1986 and 1987 over the period from 1988 to 2003 (SRU data).

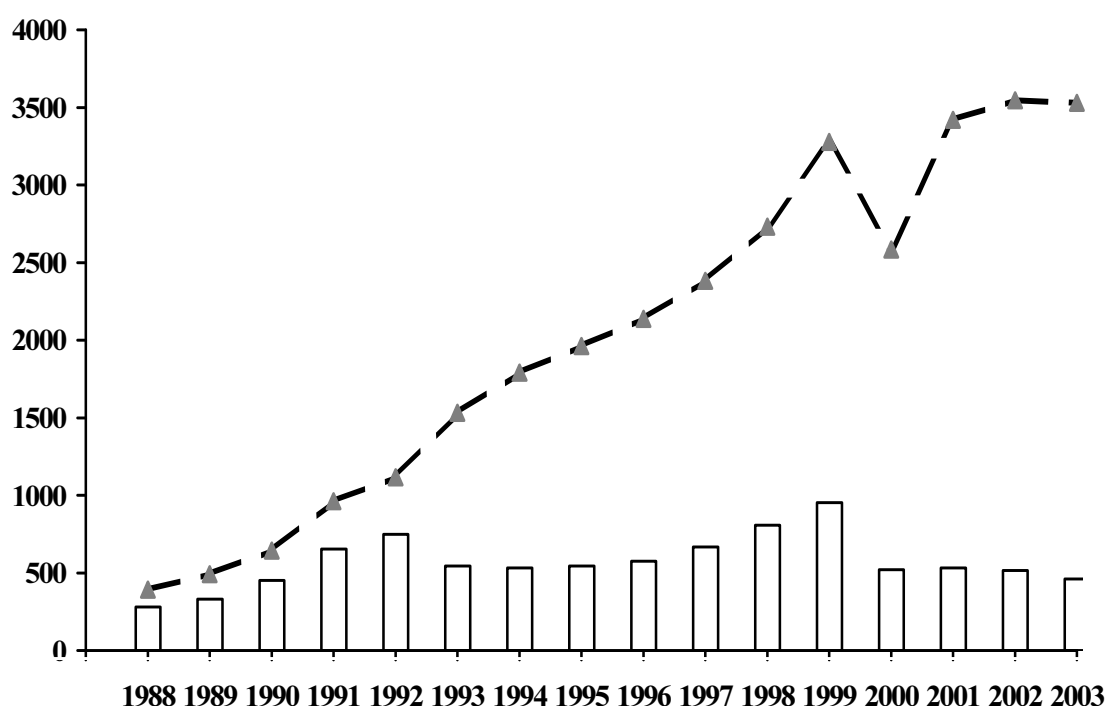


Figure 3.1.1. Dynamics of non-tumour morbidity and prevalence of diseases in 1986-1987 Ukrainian liquidators during 1988-2003 (based on State Register of Ukraine data)

The study showed that during the period from 1988 to 2003 there was a 9.3-fold increase in non-tumour diseases (Tereshchenko *et al.* 2003), mainly attributable to cardiovascular diseases, alimentary system diseases, diseases of the nervous system and sensory organs, and to diseases of the respiratory, skeletal, muscular and endocrine systems. In turn these diseases were the major causes in invalidity and mortality (Tereshchenko *et al.* 2002). A high level of invalidity and incapacity was described in the study population. This increased from 2.7‰ in 1988 to 208.5‰ in 2003 (Figure 3.1.2). Mortality in this group increased between 1988 and 1998, and after a short phase of decline, rose once more to around 10‰ in 2002-2003 (Figure 3.1.3).

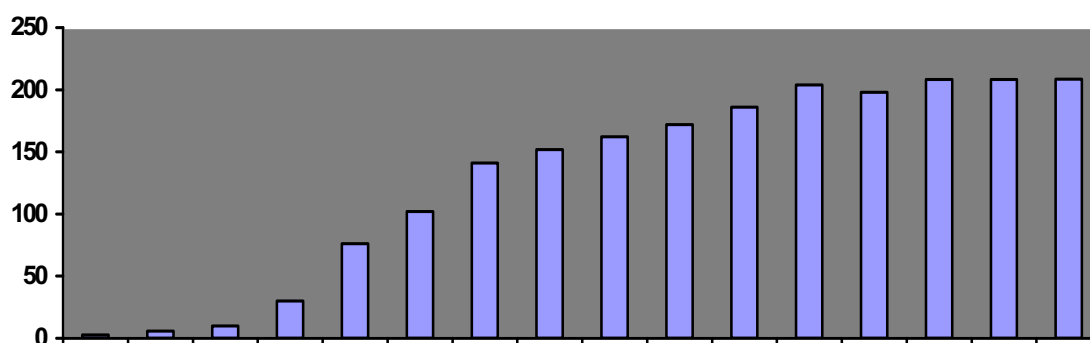


Figure 3.1.2. Dynamics of invalidity/incapacity connected with non-tumour morbidity in Ukrainian liquidators in 1986-1987 during 1988-2003 (based on State Register of Ukraine data)

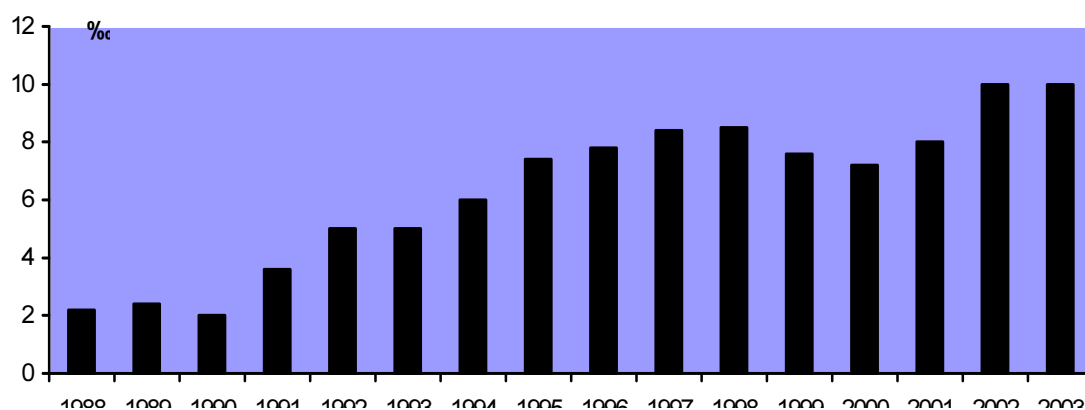


Figure 3.1.3. Dynamics of lethality from non-tumour morbidity in 1986-1987 Ukrainian liquidators during 1988-2003 (based on State Register of Ukraine data)

The level of non-cancer morbidity in the group of liquidators who received the total-body irradiation dose of 0.25-0.7 Gy was significantly higher ($p < 0.05$) than the group of liquidators whose doses fell in the range 0.05-0.249 Gy (Buzunov *et al.* 2004a).

The dose dependence of the morbidity and mortality attributable to diseases other than cancer was investigated with the help of multivariate analysis (multiple logistic regression). The influence of age, external irradiation dose and exposure period were taken into account. The analysis (Buzunov *et al.* 2004b, Tereshchenko *et al.* 2005) demonstrated dose dependent excess risk (ERR- 1/Gy) for: thyroiditis ERR= 0.67 (95% confidence interval 0.18-1.15); hypothyroidism ERR= 0.4 (95% CI 0.21-0.57); cerebrovascular pathology ERR= 1.33 (95% CI 0.58-2.34); diseases of the nervous system and sense organs ERR= 0.57 (95% CI 0.32-0.92) and neurocirculatory dystonia ERR= 1.03 (95% CI 0.30-1.92). These findings are supported by the results of other research (Ivanov *et al.* 1999).

The excess relative risk (ERR) of general mortality for liquidators over 40 years was found to be 0.64 (0.42-0.88). For liquidators under 40 years of age, the ERR for cardiovascular lethality was 1.1 (95% CI 0.83-1.41); for those over 40 years, this figure was determined at 0.64 (95% CI 0.5-0.8).

The Russian Interdepartmental Expert Panel convened under the auspices of the Russian Scientific Radiology Center of the Ministry of Health of the Russian Federation investigated

1,000 medical records of (mostly male) liquidators to ascertain the main diseases causing invalidity or mortality. In cases where it was necessary to clarify the diagnosis, the Council transferred the patients to the best qualified medical facility. Thanks to the completeness of the primary medical documents as well as to high levels of medical training (the Council was composed of leading specialists from various medical fields), the credibility of the diagnoses could be significantly increased (Zubovsky & Smirnov 1999).

In comparison with the indices of general morbidity of the population of Russia for the years 2000-2002 (basic indices of health and health protection for the Russian Federation according to the data of Ministry of Health RF, M. 2003.) morbidity in liquidators exceeds that of average Russian indices by many times (Oradovskaya *et al.* 2001, 2005, Oradovskaya 2004).

A high proportion (64.7%) of liquidators of working age were found to suffer from invalidity or incapacity. In many cases (63%) liquidators were found to be affected by blood circulation system and neurologic and psychiatric diseases. It was notable that ischemic heart disease appeared to develop early, especially among liquidators who were working in 1986. These findings suggest early development of atherosclerotic lesions of coronary and cerebral vessels in people who were exposed to radiation. Over the last few years, the proportion of this group affected by these serious diseases (ischemic heart disease, cerebrovascular stroke and encephalopathy) appears to have increased (Khisanfov & Meskikh 2001).

The most common causes of mortality among liquidators include diseases of the blood circulation system (63%) as well as malignant neoplasm (26.3%). Remarkably few deaths among liquidators, however, have been caused by diseases of the gastrointestinal tract (7%), lung diseases (5%), injuries and poisoning (5%), or tuberculosis (3%) (Khisanfov & Meskikh 2001).

(ii) Children

According to data from the Ministry of Social Protection of the Ukraine, as of the beginning of 2005, the total number of children resident in the contaminated areas who have been born, have lived and will continue to live, under conditions of chronic exposure to low-dose radiation is in excess of half a million.

Ukrainian, Russian and Belarusian researchers continue to publish data on the excess of non-cancer morbidity observed in children residing in the territories contaminated by the Chernobyl accident. General morbidity is above the national level for the general population, as are some specific diseases relating to the endocrine system, the blood and blood-forming tissues and the circulatory system (Baleva *et al.* 2001, Stepanova *et al.* 2001, Tsyb & Ivanov 2001, Cheban 1999). In addition excess morbidity from diseases of the nervous system and sense organs have been identified. Excess levels of some psychiatric disorders (Romanenko *et al.* 2001), diseases of the respiratory and of the digestive system (Avchacheva *et al.* 2001, Korol *et al.* 2001, Metelskaya 2001, Naboka *et al.* 2001), together with diseases of the muscular-skeletal system (Lukianova *et al.* 2003) and of the urogenital system (Romanenko *et al.* 2001), congenital anomalies (Lukianova *et al.* 2003, Stepanova *et al.* 2002), have also been reported in the literature.

“Sick child syndrome” is regarded, anecdotally, as a characteristic of the population of Chernobyl children (Stepanova *et al.* 2003). While past analysis was based only on small samples of clinical patients or on the data of the Public Health Ministry of the Ukraine official

statistical reports, this situation has recently evolved. During the last 5 years, publications based on analysis of the data contained in Ukrainian State National Registers (Tsyb & Ivanov 2001, Ivanov 2002) and the childrens' sub-register of those affected by the Chernobyl accident (Korol *et al.* 2001, Kurbanova 1998) have appeared. In particular, results of cohort studies have been published.

The cohort studies carried out have shown that excess morbidity in children from the contaminated areas the Ukraine, Russia and Belarus vary from 2-7% above controls (Baleva *et al.* 2001) up to 2- 2.5 times more than control populations (Lukianova *et al.* 2003, Romanenko *et al.* 2001). Fully healthy children amounted to 5% of those resident in the 2nd zone (5-15 kBq/m²) against 30% in the control (Lukianova *et al.* 2003).

3.2 Diseases of the respiratory system

One of the distinctive features on the Chernobyl accident was the release into environment of not only fission products, but also nuclear fuel (²³⁸U and enriched ²³⁵U), and radionuclides formed as activation products. The radioactivity entering the atmosphere did so in gaseous, ionic-molecular form, and as a radioactive aerosol - including "hot particles". These latter were formed in two ways: Firstly, as a result of the explosion in the reactor and the heating which occurred subsequently ("solid hot particles") and secondly by wet scavenging of released radionuclides by atmospheric water droplets ("liquid hot particles"). Small particles, up to 5 microns in diameter, are easily drawn into the deeper parts of the lung; those of 20-40 micron diameter are deposited in the upper respiratory pathways (Khrushch *et al.* 1988, Malachanko & Goluenko 1990, Ivanov *et al.* 1990, IAEA 1994). Hence, a varying radiological impact can be anticipated depending upon the nature and size of the particles involved.

Accordingly, during the first ten days following the accident, when emissions to the air were ongoing, irradiation of the bronchopulmonary system occurred as a result of inhalation of airborne radiation. The contribution of different radionuclides to the dose received in the lungs depends upon the chemical form of the radionuclide, its activity and its half-life. During this critical early period, the greatest impacts on the lungs of the exposed population were due to ¹³¹I, ¹⁰⁶Ru and ¹⁴⁴Ce (Chuchalin *et al.* 1998, Tereshchenko *et al.* 2004, Kut'kov 1998, IAEA 1992).

After this time, the release from the reactor and quantities of radioactivity released into the air declined sharply. Atmospheric resuspension of radioactive particles by wind or as a result of industrial activity was considered insignificant. Therefore, further lung irradiation occurred mainly as a result of external irradiation from deposited radioactivity rather than from inhalation (Khrushch *et al.* 1988, Malachanko & Goluenko 1990, Ivanov *et al.* 1990, IAEA 1994). This chronology is important in understanding the emerging patterns of disease among the exposed populations.

Belarus

Among evacuees from the 30-km zone, morbidity of the respiratory system in 1995 was 2,566 cases per 1,000 people compared to 1,660 for the general population (Matsko 1999).

Russia

A more complex long-term study of pulmonary outcomes of the Chernobyl accident was carried out between 1993 and 1998 by the Institute of Pulmonology (Moscow, Russia). The study focused on chronic broncho-pulmonary pathology in liquidators of the power plant accident. (Chuchalin A.G., *et al*, 1993-1998). 440 patients with chronic obstructive pulmonary disease (COPD) were observed using a suite of contemporary clinical and laboratory research methods. This involved peakflow-volumetry, broncho-endoscopy, morphological, immunological and microbiological studies and the use of laser mass-spectrometry (Chuchalin *et al*. 1998).

The study found that radioactive heavy elements could be found in the pulmonary system of the studied liquidators 6-10 years after the accident. Laser mass-spectrometry proved useful in simultaneous studying of the quantitative and qualitative aspects of heavy elements in tissues and in tumors in radiation-exposed subjects. These techniques facilitated an investigation of the distribution of radionuclides in the pulmonary tissues and changes in the elemental composition of tissues in the course of tumor development.

The high prevalence of chronic respiratory problems in liquidators and the prolonged persistence of inhaled radioactive particles in their lungs suggested a concrete link between radioactive exposure and the diseases observed. Under conditions of combined external irradiation and the intake of a mixture of radionuclides the bronchopulmonary system became one of the main "target" - tissues where both stochastic and non stochastic effects were realised in the form of chronic obstructive pulmonary diseases (COPD).

In addition cancer-related molecular abnormalities including K-ras (codon 12) mutation, p16 (INK4A) promoter hypermethylation and microsatellite alterations at seven chromosomal regions in successive biopsies obtained from former Chernobyl cleanup workers in comparison with smokers and nonsmokers without radiation exposure were investigated.

The results indicated that prolonged persistence of inhaled radioactive particles is associated with appearance of allelic loss at 3p12, 3p14.2 (FHIT), 3p21, 3p22-24 (hMLH1) and 9p21 (p16INK4A) in the bronchial epithelium of former Chernobyl clean-up workers. The prevalence of 3p14.2 allelic loss was associated with decreased expression of the FHIT mRNA in their bronchial epithelium in comparison with the control group of smokers. During several years of monitoring, samples of epithelium were collected from the same area of bronchial tree. In epithelium exposed to carcinogens (tobacco smoke and/or radioactivity) the total number of molecular abnormalities was significantly higher as indicated by dysplasia and in morphologically normal foci, which progressed later to dysplasia, than in those samples, which never showed evidence of such progression. These findings indicate that extensive cancer-related molecular abnormalities have occurred sequentially in radiation damaged bronchial epithelium of former Chernobyl clean-up workers (Chuchalin 1997, 1999, 2002, Charpin 1997, Chizhikov 2002).

In another study carried out in Russia, incidence of asphyxia and breathing problems in newborns correlated positively with the level of radioactive pollution experienced in the region (Kulakov *et al*. 2001).

Ukraine

In 1994, 35.6% of morbidity cases among evacuees and among adult and adolescent residents of the contaminated territories were attributed to morbidity of the respiratory organs. The

corresponding figure for children was 61.6% (Grodzinsky 1999). According to the data compiled by the Ukrainian Ministry of Health, adult and teenage victims of the Chernobyl accident showed increases in morbidity of the respiratory system. In the three primary critical groups monitored, pulmonary system diseases in 2000 had grown by 6.5 times (from 3,154 to 20,433 per 100,000) in comparison with 1987 data.

The general morbidity due to pulmonary system diseases amongst the Ukrainian population in 1992 and 2000 respectively was established to be practically the same at 21.3% and 19.6 %; Similarly, morbidity in the population from the contaminated territories remained stable at 17.6 % and 19.8 %; A marked increase, however, took place among the clean-up workers involved in the accident from 18.1 % to 22.7 %, and morbidity among evacuees from such illnesses grew substantially from 20.6 % to 30.1%.

Morbidity attributable to pneumonia increased among all groups of the exposed population between 1992 and 2000, but was most marked among the clean-up workers (from 474 to 835 per 100,000) and among the evacuated persons (from 431 to 765 per 100,000). For the inhabitants of contaminated territories this index increased somewhat less - from 498 to 584 per 100,000, and among the general population of Ukraine a minor increase from 410 to 436 per 100,000 was observed.

Morbidity from bronchial asthma increased both among clean-up workers – (from 47 to 57 per 100,000), and among evacuees (from 45 to 67 per 100,000 respectively between 1992 and 2000. The level of bronchial asthma morbidity, therefore, was higher in these categories of exposed people than among residents of the contaminated territories, (25 and 26 per 100,000 respectively) and among the general population of the Ukraine (23 and 23 per 100,000 respectively).

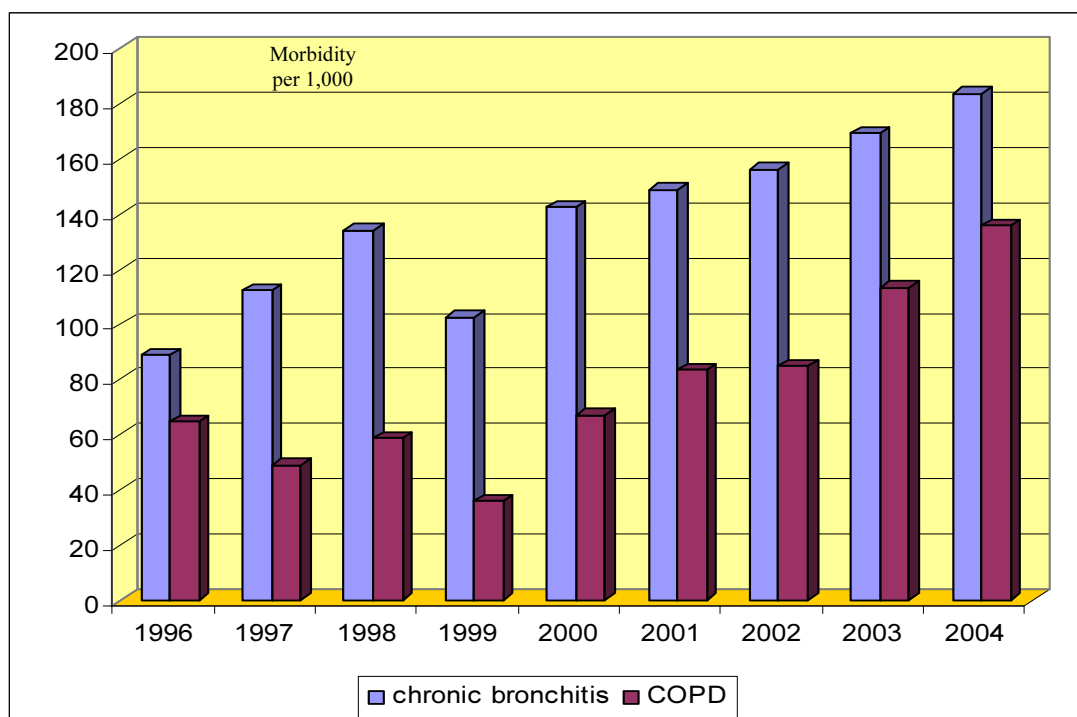
The most noticeable increase in respiratory system morbidity was due to chronic bronchitis and COPD among the clean up workers (from 884-1,005 per 100,000). This decreased, but remained high, among evacuees (718 and 602 per 100,000) but rose slightly for residents of the contaminated territories (330 and 363 per 100,000). The median level for the Ukraine as a whole was recorded at 209 and 236 per 100,000 for the two years in question.

In more recent years (1992-2001) a steady marked growth of pulmonary system morbidity has been recorded among evacuees (from 29.2 % to 47.4 %) and among clean-up workers (from 24.1 % to 42.2 %). This contrasts with the relative stability of this index for the residents of the contaminated territories (from 23.3 % to 26.2 %) and the Ukrainian population as a whole (from 26.0 % to 29.9 %).

Increased morbidity from bronchial asthma was most pronounced among the clean-up workers (from 251 to 639 per 100,000) and the evacuees (from 467 to 790 per 100,000). This contrasted with lesser increases among the residents of contaminated territories (from 348 to 474 per 100,000) and the population of Ukraine as a whole (from 366 to 447 per 100,000).

Increased morbidity from chronic bronchitis and COPD was greatest among the clean-up workers (from 3,723 to 11,328 per 100,000 respectively for the years 1992 and 2001) and amongst evacuees (from 4,668 to 7,431 per 100,000 respectively). For residents of the contaminated territories increases were not so evident over the same time period (3,079 and 4,055 per 100,000). In the general population morbidity increased less and the overall level of morbidity was much lower (2,499 to 2,994 per 100,000) as compared to those populations

exposed to the Chernobyl radiation. Other data suggest that chronic obstructive pulmonary diseases (COPD) and bronchial asthma are among the leading reasons for morbidity, invalidity and excess mortality among liquidators. According to official statistics from the Ukrainian Ministry of Health, morbidity with unspecified chronic bronchitis and emphysema in adolescent and adult victims of the Chernobyl accident grew from 316.4 per 10,000 population in 1990 to 528.5 per 10,000 in 2004, and bronchial asthma grew from 25.7 per 10,000 in 1990 to 55.4 per 10,000 in 2004. Graph 3.2.1. shows the increasing morbidity with time from chronic bronchitis and COPD.



Figur 3.2.1. Results of long-term pulmonary system monitoring of liquidators of the Chernobyl accident at the SCRM outpatient department (Sushko et al 2006)

From 1988 to 2006 the Institute of Clinical Radiology at the Research Center for Radiation Medicine of the Ukraine carried out complex pulmonary investigations on 2,476 male Ukrainian liquidators aged from 21 to 62 (median age 36.7 ± 8.5 years). The pulmonary investigation programme included routine clinical and laboratory methods, respirometry, x-ray examination of the lungs, fibro-bronchoscopy with biopsy of the mucosa and pathomorphological and electron microscopy studies.

Doses of external irradiation, which were documented for 63% of patients, were in the range 5-85 cSv with a mean of 19.7 ± 4.2 cSv. More than 80% of them had taken part in cleanup operations during April to October 1986. Liquidators from the later period (1987-1988) were included in the group only if they participated in decontamination of the power plant, or worked at the sites within the 30-km zone where wastes were buried or contaminated equipment (eg vehicles) were stored. Another 82 people with acute radiation syndrome were also examined. Incorporation of "hot particles" in one of these patients was documented. Radionuclide incorporation into the lungs (mainly ^{137}Cs , ^{60}Co .) was confirmed by whole body counts in 10 liquidators from the general group.

In general, liquidators suffered dry, non-productive coughs during their work periods and directly afterwards. The subsequent development of disease was characterized by progressive development of obstruction and dyspnoea (shortness of breath, difficulty or pain in breathing). Later on, symptoms of chronic obstructive lung disease were observed: cough, sputum and dyspnoea in combination with obstructive mixed ventilation disorders (Tereshchenko *et al.* 2004, Sushko & Shvayko 2003a).

Among the basic forms of nonspecific chronic lung disease in liquidators, chronic obstructive bronchitis (ChOB) dominated, being observed in 79% of patients. A further 13% had chronic non-obstructive bronchitis (ChNB) and 8% suffered from asthma (Figure 3.2.2). Obstructive violations of lung ventilation (59%) were predominant in liquidators suffering from bronchopulmonary pathology. Isolated restrictive violations were noted in 5% of patients. Mixed ventilation disorders were observed in 29% of patients. Ventilation parameters were normal in only 6% of cases, which were diagnosed as chronic non-obstructive bronchitis (Figure 3.2.2.) (Tereshchenko & Sushko (*Eds*) 2004, Sushko & Shvayko 2003a&b, Dzyublik *et al.* 1991, Sushko 2000, Sushko 1998).

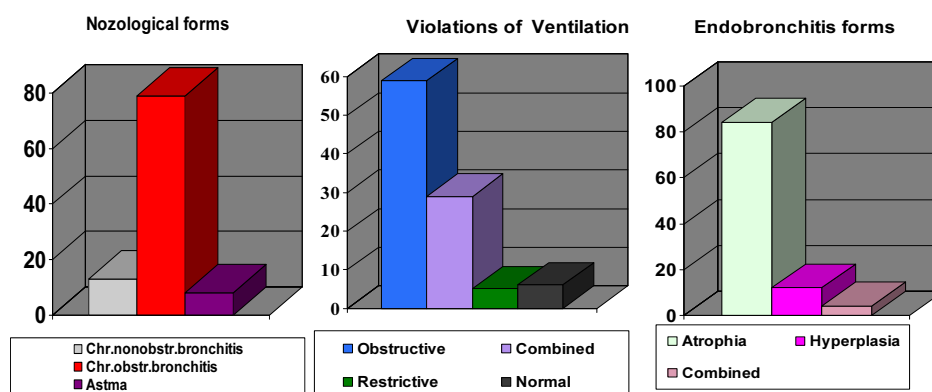


Figure 3.2.2. The main nosological forms, violations of ventilation and types of endobronchitis in male Ukrainian liquidators

Broncho-obstructive syndrome in liquidators has undergone interesting dynamics. In 1988-1991 the most common syndrome was that of isolated obstruction of the small bronchus (52%), followed by the hypotonic dyskinesia of membranous parts of the trachea and the main bronchial tubes (28%) together with , generalized obstruction syndrome (20%). During 1992-1996 the frequency of isolated obstruction syndrome of the small bronchial tubes decreased to 38%, hypotonic dyskinesia of membranous part of a trachea and the main bronchial tubes decreased to 17% and generalized broncho-obstruction syndrome increased to 45% of patients. Currently, generalized bronchial obstruction predominates (52%), followed by isolated obstruction of the small bronchus (31%) and hypotonic dyskinesia of membranous part of the trachea and the main bronchus (17%) (Tereshchenko & Sushko (*Eds.*) 2004, Sushko & Shvayko 2003a&b, Dzyublik *et al.* 1991, Sushko 2000, Sushko 1998, Sushko 2001, Sushko *et al.* 2002).

Endoscopic examination of the tracheobronchial tree in 873 patients revealed a very high prevalence of atrophy of the mucous membrane (84%). This was characterized by thinning of the mucous membrane and impoverishment of the vascularisation. In 12% of patients the opposite changes in bronchofiberscopic pathology were observed: hyperplasia, which

consisted of a thickening, or hypostasis, of the mucous membrane, and a narrowing of segmentary and subsegmentary bronchial tubes. In 4% of patients, both types of changes- atrophic changes in proximal parts and hyperplastic changes in distal parts- were observed (Tereshchenko & Sushko (*Eds.*). 2004, Sushko & Shvayko 2002, Shvayko & Sushko 2001).

In 80% of patients, catarrhal-sclerotic changes of the bronchial mucosae were accompanied by deformation of the tracheobronchial tree. This type of change was characterized by fine light pink longitudinal connective scars on the mucous membrane, mainly at the openings of segmentary and subsegmentary bronchial tubes in the lower lobes. The prevalence of catarrhal-sclerotic changes correlates with the atrophied form of endobronchitis. Isolated sclerotic changes of bronchial mucosae were reported in 16% of patients and catarrhal changes in 4% (Tereshchenko & Sushko (*Eds.*) 2004, Sushko & Shvayko 2002, Shvayko & Sushko 2001).

Stage 0 inflammation was recorded in 34% of patients, stage 1 in 63% and stage 2 in 3%, based on Lemoine's categorisation (Lemoine 1956). This demonstrates a low degree of activity in the productive inflammatory process in the overwhelming majority of cases and is linked to the prevailing forms and types of pathological changes in tracheobronchial mucosa in those liquidators who suffer from chronic obstructive pulmonary disease (COPD).

Results of bronchofibroscopic studies of the tracheobronchial tree mucosae in liquidators suffering from COPD have shown that the primary variant of chronic bronchitis is chronic diffusive stage 1 inflammation /atrophied endobronchitis with catarrhal-sclerotic changes (Tereshchenko & Sushko (*Eds.*). 2004, Sushko & Shvayko 2002, Shvayko & Sushko 2001).

The clinical pathomorphology of COPD in patients is characterised by: transformation of regeneration processes, microvessel damage, fibrillogenesis disorders and modification of inflammatory processes. The changes identified are summarised in the table below. Because plano-cellular metaplasia and cellular atypia are precancerous conditions, liquidators who worked in 1986-87 require ongoing pulmo-oncological vigilance.

Transformation of inflammation process kinetics	1. Hyporeactivity (low level of neutrophilic granulocytes and macrophage lamina propria of bronchus mucous membrane) 2. Prevalence of productive component inflammation over exudation
Characteristics of microcirculation pathology of bronchial mucous membrane	1. Distinct pathology of endothelial cells 2. Erythrocyte adhesion to endothelial cells 3. Conformationally-functional reconstruction of microvessels 4. Sclerosis of microcirculation vessels components
Intensification of involutonal process in bronchus mucous membrane	1. Widespread planocellular metaplasia of superficial epithelium of bronchial mucous membrane 2. Multilayer basal membrane of capillaries 3. Lipid inclusions in cytoplasm of endothelium cells 4. Lipid dystrophy of muscular cells 5. Inclusion of lipofuscin in lamina propria of bronchus mucous membrane 6. Widespread occurrence of hyalinosi and fibrosis
Characteristic changes of bronchial mucous membrane	1. Acceleration of cell population renewal 2. Widespread occurrence of planocellular metaplasia of superficial epithelium of bronchial mucous membrane

	3. Distinct basal cell hyperplasia in superficial epithelium of bronchus 4. Presence of epithelium cells with modified phenotype in bronchial mucous membrane 5. Depopulation of adipocytes of superficial epithelium of bronchus
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Table 3.2.1. Characteristics of pathomorphology of COPD in liquidators

Under the airborne exposure conditions with a combined influence of external irradiation and a mixture of radionuclides in varying physico-chemical forms, the pulmonary system was one of the main “target” tissues of exposure, resulting in elevated incidence of COPD during the first 3-5 years after the accident at Chernobyl in the group of liquidators. Analysis of the dosimetric, clinical and epidemiological data confirms that the group at primary risk is clean-up workers employed during the 1986-1987 period.

3.3. Diseases of the digestive system and other organs

The increase in child morbidity due to digestive system diseases was higher in contaminated territories as compared to uncontaminated territories, where acidic geology promoted Cs-137 migration from soil to plants (Naboka 2003, Shestopalov *et al.* 2004). This increase of digestive system diseases was driven largely by an increase in chronic gastritis (Avchacheva *et al.* 2001) gastroduodenitis, ulcer of the stomach and duodenum, liver and gall-bladder disease together with biliary tract and pancreatic disease (Korol *et al.* 2001).

An increased intensity of caries of both primary and permanent teeth (85-92%) (Lutska *et al.* 2001, Khomenko *et al.* 2001) was also observed in the subject population. Atrophy of stomach tissues was found 5 times more often and intestinal metaplasia 2 times more often respectively in the residents of contaminated areas as compared to the control group (Avchacheva *et al.* 2001). Children exposed to thyroid doses above 2Gy suffered twice as many diseases of the digestive system as those who were less heavily exposed (Kurbanova 1998).

Belarus

During the period between 1991-1996 prevalence of peptic ulcers among the population of Belarus increased by 9.6% (Kondratenko 1998). In 1995, morbidity from diseases of the digestive system among evacuees and the inhabitants of the contaminated territories (3,298 cases per 100,000) was 1.8 times higher than for the general Belarus population (1,817 per 100,000) (Matsko 1999).

Russia

Diseases of the gastrointestinal tract ranked fourth (6.4%) within the whole range of diseases reported in liquidators. Stomach ulcers made up the highest proportion, accounting for 53.9% of diseases of the digestive organs.

10.6% of all deaths of liquidators were reported as caused by diseases of the digestive organs. These diseases rank third in the hierarchy of reported diseases, after cardiovascular diseases and cancer. Liver diseases also increased in 2004 compared to 1991-1997. Until 1997, liver pathology reported was basically chronic hepatitis (5%),

but after 1998 a considerable proportion consisted of the more more serious disease liver cirrhosis (Zubovsky & Smirnov 1999, Khrisanfov & Meskikh 2001).

Increased dental caries has been reported in children and adolescents residing in radioactively contaminated regions. Children born after the catastrophe exhibit more frequent dental pathology while a markedly increased frequency of combined malformations of the teeth and jaws have been observed in children irradiated before birth (Sevbitov 2005). These malformations are positively correlated with level of radioactive contamination. In children permanently residing in contaminated territories such malformations are 1.5-2.2 times as frequent. The overall pattern of dental anomalies is illustrated in Table 3.3.1. for two contaminated regions of Russia

	Up to 5 Ci/km ²	5-15 Ci/km ²	15-45 Ci/km ²	Children born
Teeth anomalies	3.7	2.4	2.8	Before 1986 (n=48)
	4.2	4.6	6.3	After 1986 (n=82)
Teeth row anomalies	0.6	0.4	0.6	Before 1986 (n=8)
	0.6	0.6	1.7	After 1986 (n=15)
Occlusion	2.6	2.4	2.2	Before 1986 (n=39)
	4.4	5.2	6.3	After 1986 (n=86)
Age norm	5.3	5.7	3.1	Before 1986 (n=77)
	2.6	2.0	0.6	After 1986 (n=28)

5 Ci/km² - Don, the Tula area (183 persons); 5 - 15 Ci/km² - Uzlovaya, Tula area (183 persons); 15 - 45 Ci/km² - Novozybkov, Bryansk area (178 persons).

Table 3.3.1 Frequency of dental anomalies (in %) among children in the territories with differing levels of radioactive pollution (Tula and Bryansk areas, Russia), (Sevbitov et al. 1999)

Ukraine

Widespread incidence of peptic ulcers, chronic cholecystitis (inflammation of the gallbladder), cholelithiasis (gallstones) and pancreatic pathology has been reported in all areas of the Ukraine with high levels of Chernobyl contamination (Yakimenko 1995, Komarenko *et al.* 1995). Digestive system problems among adult evacuees from Prypyat' city and the 30-km zone were more common than in the rest of the population (Prysyazhnyuk *et al.* 2002).

In 1994 morbidity with diseases of the digestive system represented 6.4% of reported illnesses in adult and adolescent victims of radiation exposure. The index of digestive system morbidity among people living in strict radiation control zones in 1996 was 281 compared with 210 for the whole Ukrainian population (Grodzinsky 1999).

During 1988-1999 a doubling of digestive system morbidity was observed in the population still living in contaminated areas (Prysyazhnyuk *et al.* 2002). As ever, children were severely impacted. Prevalence of digestive system disease was 4.66 per 10,000 children in 1988 and 10.1 in 1999. A clear tendency towards increasing digestive organ pathology was reported

(Prysyazhnyuk *et al.* 2002, Korol *et al.* 1999, Romanenko *et al.* 2001), with digestive system disorders being the most common cause of ill-health in children living in the contaminated territories (Romanenko *et al.* 2001). Children irradiated *in utero* developed gastro-intestinal tract pathology at a rate of 18.9% compared to 8.9% in the control group, a statistically significant difference (Stepanova 1999).

3.4. Illnesses of the blood circulation and lymphatic systems

The radioactive pollution from Chernobyl has been associated with not only malignant, but also non-malignant illnesses of the blood-forming organs and circulatory system.

Haemorrhagic conditions were 4.0 times more common than before the accident, and congenital jaundice occurred 2.9 times more frequently in newborns whose mothers came from the following radiation-contaminated territories: in the Ukraine, Polesky district of the Kiev region (20-60 Ci/km²); in Belarus, Chechersky district of Gomel region (5-70 Ci/km²) and; in Russia, Mtsensky and Volkhovsky districts of Orel region (1-5 and 10-15 Ci/km² respectively) (Kulakov *et al.* 2001).

An increase in diseases of the circulatory system due to vascular dystonia and hypotonia was seen in children (Serduchenko *et al.* 2001) and an increase of serum cholesterol level and other symptoms of early atherosclerosis were found in 55.2% of children 2-15 years age with an individual radiation dose of 0.1-1.5 mSv/year (Azarenok 2001). Children who received thyroid doses above 2 Gy suffered 2.6 times more circulatory diseases and blood disorders than less exposed children (Kurbanova 1998). The excess relative risk per 1 Gy (ERR/Gy) for cerebrovascular diseases was found to be 1.17 (95% CI 0.45-1.88) (Ivanov *et al.* 2000). The risk of significant cerebrovascular diseases due to external radiation (ERR for 100 mGy/day) was calculated to be 2.17 (95% CI 0.6-3.69) (Ivanov *et al.* 2005).

Belarus

Ten years after the accident, diseases of the blood circulation system had increased 5.5 times as compared to the period before Chernobyl accident and a greater increase was noted in the contaminated areas (Manak *et al.* 1996).

In 1995, morbidity of blood and blood-forming tissues for evacuees was 3.8 times higher than for the general population of Belarus (279 and 74 cases per 100,000 respectively) (Matsko 1999). For inhabitants of the contaminated territories and evacuees, morbidity with illnesses of blood and blood-forming tissue and cardiovascular system diseases in 1995 were 2.4 and 3 times higher than generally for Belarus (175 and 74 per 100,000; 4860 and 1,630 per 100,000 respectively) (Matsko 1999).

During the 10 years after the accident, the number of individuals registered as being sick, whose primary disease was in the circulatory system, increased 3.5-fold in Gomel region and 2.5-fold in Mogilev region (Nesterenko 1996). As compared to 1985, the occurrence of leukopenia (an abnormally low number of white blood cells) and anemia in some districts of Mogilev region increased 7-fold during the first three years after the accident (Gofman, 1994b). Although some of these anemia cases are no doubt related to alimentary deficiencies, a significant proportion could be related to radiation impact on the marrow that develops leucocytes and erythrocytes. The increase of iron deficiency anemia in Belarus appears to be

correlated to the level of radioactive contamination (Dzikovitch *et al.* 1996, Nesterenko 1996). Lead pollution, however may have been a confounding factor in this study.

Abnormal arterial blood pressure - both high and low - is more frequently detected in adults and children living in the contaminated territories (Nedvetckaya & Lyalikov 1994, Sykorensky & Bagel' 1992, Gontcharik 1992). Increased systolic arterial pressure has been reported in those exposed to radiation (Zabolotny *et al.* 2001). Belarusian girls and young women who lived for 10-15 years in areas with levels of ^{137}Cs ranging from 1 to 5 Ci/km² had disturbed blood supply to the legs as measured the vasomotor reactions of large veins of the lower limbs (Khomitch & Lisenko 2002, Savanevsky & Gamshey 2003). Those living in the contaminated regions of Belarus suffered more frequent disturbances of cardiac rhythm compared to those in non-contaminated territories (Arinchina & Milkamanovich 1992). In Mogilev region, increased arterial blood pressure was reported more frequently in adults in areas where the contamination level exceeded 30 Ci/km² (Podpalov 1994).

Russia

Diseases of the blood and the blood-forming system are a factor in the elevated morbidity of children from territories affected by Chernobyl fallout in Russia (Kulakov *et al.* 2001). The number of persons with lymphocytes having adaptive reactions decreased in radioactively polluted areas whereas the number of persons with increased lymphocytic radio-sensitivity increased (Burlakova *et al.* 1998). Changes in the quantitative composition and functional activity of lymphocytes were reported in pregnant women in contaminated parts of the Kursk region; a considerable increase in immune complexes was measured in blood serum (Alymov *et al.* 2004). Significantly higher absolute and relative numbers of lymphocytes and basophils were recorded in adults living in areas where soil caesium contamination was in the range 15-40 Ci/km² (Miksha & Danilov 1997).

The leading cause of morbidity and mortality in Russian liquidators was disease of the circulatory system (63%). The most common were ischemic heart diseases (72%). It is worth noting that ischemic heart disease developed early, especially among liquidators who were on service in 1986. This may be explained by the early development of atherosclerotic lesions of coronary and cerebral vessels in people who were exposed to radiation. The second most common disease of the cardiovascular system observed was idiopathic hypertension (38%), and in third place was autonomic dysfunction (12.9%) (Khryanfov & Meskikh 2001).

With a comparative epidemiological study of liquidators (males) in the age range of 35 to 64 years it is for the first time established that liquidators in the distant period 13-17 years after the Chernobyl accident have a different structure of risk factors with respect to the development of cardiovascular diseases. The most profound disturbance is that of the vegetative regulation according to the hyper-sympathetic type during the night period and a reduction in the bronchial capacity over the small bronchi. A new syndrome, specific to liquidators (the syndrome of night hypeosympathictonia) has been identified. It is prognostically unfavorable for the development of cardiovascular diseases (Sherashov 2005).

Ukraine

Amongst those living in contaminated territories in the Ukraine during 1988-1999, morbidity due to blood and blood circulation diseases increased by a factor of 10.8-15.4 (Prysyazhnyuk *et al.* 2002). The morbidity level related to the blood, circulatory and hematopoietic systems for adults evacuated from Prypyat city and the 30-km zone was higher for than for the general population (Prysyazhnyuk *et al.* 2002). Early atherosclerosis and coronary heart disease developed in evacuees from 30-km zone and those living in areas polluted with radionuclides (Prokopenko 2003).

57.8% of children irradiated *in utero* developed diseases of the cardiovascular system (including autonomic dysfunction) (compared with 31.8% in the control group, $p < 0.05$) (Prysyazhnyuk *et al.* 2002). In 1996, indices of morbidity for adults and adolescents living in territories under strict radiation control were 30.2 for diseases of hematopoietic system and 430 for diseases of blood circulation system compared with 126 and 294 respectively for the general Ukrainian population. Blood circulation illnesses in adults and adolescents in the contaminated territories in 1994 comprised 8% of the reported illnesses (Grodzinsky 1999).

3.5. Illnesses of the Musculo – Skeletal and Cutaneous Systems

Disease	Region, specific features	Reference
Anaemia	7-fold increase in Mogilev region. This was correlated to contamination level	Gofman 1994b, Dzikovich <i>et al.</i> 1996, Nesterenko 1996
Morbidity with the blood circulation system illnesses	Level of primary morbidity increased 3.5 times in Gomel region from 1986 and 2.5 times in Mogilev region	Nesterenko, 1996
	3-6 times higher in the contaminated areas as compared to average in Bryansk region	Komogortseva 2001
Arterial hypertension	More frequent in territories of Mogilev region polluted with radiation exceeding 30 Ci/km ²	Podpalov 1994
Disturbances in cardiac rhythm revealed on electrocardiogram	More frequent and stable disturbances in case of ischemic disease on the polluted territory	Arinchina & Milkamanovich 1992
	Correlated to content of incorporated caesium-137	Bandazhevsky 1999
Disturbance of autonomic regulation of the heart activity	On Belarus contaminated territories	Nedvechkaya & Lialykov 1994, Sykorensky & Bagel' 1992, Goncharik 1992
Lymphocyte macrocytosis	6-7 times more frequent in Belarus contaminated territories	Bandazhevsky 1999

Table 3.5.1. Summary of findings of studies of the relationship between the Chernobyl-derived radioactive pollution and circulatory system morbidity in Ukraine, Belarus and Russia

The limited availability of data on the impact of Chernobyl radiation on the musculo-skeletal system and skin integument is not due to the absence of such impact but to the fact that these systems were regarded as less critically sensitive to radiation. Consequently they were less well studied. Some reported skeletal symptoms such as pains in the chest bone and vertebral column are known to accompany some forms of leukemia. Liquidators often complained about pains in the joints and bones, which may be related to osteoporosis.

Nonetheless, some problems involving the skeletal system have been identified. On the basis of a dynamic survey of pregnant women, maternity patients, newborn infants and children in radiation-contaminated territories of Ukraine (Polesky district in Kiev region; 20-60 Ci/km²), Belarus (Chechersky district of Gomel region; 5-70 Ci/km²) and Russia (Mtsensky and Volkhovsky districts of Orel region; 1-5 and 10-15 Ci/km²) it has been shown that newborns increasingly suffer from developmental abnormalities of the musculo-skeletal system (Kulakov *et al.* 2001).

Belarus

Morbidity due to disease of the musculo-skeletal system and connective tissue in evacuees and inhabitants of the contaminated territories was 1.4 times higher than for the entire population in 1995 (6,166 and 1,124 cases per 100,000 respectively) (Matsko 1999).

Ukraine

The morbidity level for diseases of the musculo-skeletal system in adult evacuees from Prypyat city and the 30-km zone was higher than for other population sub-groups (Prysyazhnyuk *et al.* 2002). During 1988-1999, double the disease of the musculo-skeletal systems was observed for the population still living in the contaminated territories. A greater than 4-fold increase in morbidity due to skin and subcutaneous diseases was reported for these groups during 1988-1999 (Prysyazhnyuk *et al.* 2002). In 1996 the index of morbidity with diseases of the musculo-skeletal system in people living in zones of strict radiation control was 333 whereas for the whole Ukrainian population it was 307 (Grodzinsky 1999). Foetal skeletal investigations also showed impacts (see section 3.11.).

3.6. Imbalances of hormone/endocrine status

Studies of exposure to Chernobyl radiation have generated an extensive literature on endocrine system impacts. In part this is due to the thyroid gland being a primary target organ of radiological impacts of emitted iodine isotopes.

3.6.1. Thyroid gland illnesses

The thyroid gland is the main target organ for radioactive iodine (Ilin *et al.* 1989, Dedov *et al.* 1993). The thyroid concentrates 30-40% of the total amount of iodine radioisotopes entering the organism in adults, and 40-70% in children; the concentration of iodine in the thyroid far exceeds its average concentration in the body as a whole (Ilin *et al.* 1989, Dedov *et al.* 1993). Increased iodine uptake has also been demonstrated in the hypophysis (pituitary gland), where the average iodine concentration is 5-12 times higher than that in the body as a whole (Zubovskij & Tararuhina 1991). The maximum concentration of radioactive iodine in thyroid tissue will follow 13-15 hours after exposure takes place.

In the case of thyroid irradiation, children are the highest-risk group. Under conditions of equal radiation exposure the effective radiation dose to the thyroid gland is inversely proportional to age. Children who received thyroid doses above 2Gy suffered 6 times more endocrine disorders than those who received lower doses (Kurbanova 1998).

Thyroid dysfunction, which will progress with time, will have considerable impact on metabolism. It is also possible that thyroid pathology and dysfunction of endocrine regulation connected to it could influence the development of pubertal pathology (abnormalities of physical and sexual development) and of reproductive function. Thyroid pathology, such as chronic thyroiditis, leading to hypothyroidism is a catalyst of premature ageing processes among the affected population. This premature ageing and other effects of thyroid dysfunction may lead, ultimately, to increased mortality in the population.

Hypothyroidism is a common consequence of thyroid gland disturbance and has been reported in areas contaminated by releases from Chernobyl (Dedov & Dedov 1996). Structural and functional disorders of the thyroid gland negatively impact functioning of the parathyroid gland since, topographically, the thyroid and parathyroid glands are tightly linked. Reduction in parathyroid function is the most common complication of operation for surgical treatment of thyroid cancer. Approximately 16% of all operations for removal of the thyroid gland lead to parathyroid inefficiency (Demedchik *et al.* 1994).

Belarus

Morbidity with hypothyroidism in the Gomel region increased 7-fold from 1985 to 1993, whereas morbidity with autoimmune thyroiditis increased more than 600 times from 1988 to 1993. In 1993, more than 40% of children surveyed in the Gomel region had enlarged thyroid glands (Astachova *et al.* 1995, Biryukova & Tulupova 1994). Significantly higher levels of thyroid gland morbidity and of diabetes were detected among 1,026,046 maternity patients from parts of Belarus with contamination over 1 Ci/km² (Busuet *et al.* 2002).

Russia

An increase in endocrine diseases in Russian children occurred as a result of an increase in thyroid diseases, with a high prevalence of nontoxic nodular goitre (Baleva *et al.* 2001) diffuse goitre (Ivanov *et al.* 2005) and thyroid autoimmune disorders (Baleva *et al.* 2001). In males, diffuse goitre was significantly dependent on radiation dose ($p=0.03$) with an estimated odds ratio 1.36 per 1 Gy (Ivanov *et al.* 2005).

Ukraine

Damage to the thyroid gland was observed in 35.7% of 3 019 adolescents from Vinnitsa and Zhytomyr regions who were 6-8 years old at the time of the accident (Fedyk 2002). Primary functional reaction of the thyroid gland was observed in 1986-1987, followed by chronic autoimmune thyroiditis (1990-1992) and clinical manifestation of disease in 1992-1993 (Stepanova 1999). Among these children, 32.6% developed pathology of the thyroid gland compared with 15.4% in the control group ($p<0.05$) (Stepanova 1999).

According to Ukrainian legislation (Verhovna Rada of Ukraine 2001) and the conclusions of the National Committee for Radiation Protection of the Ukraine of April 25, 1997, the thyroid gland is considered to be over-irradiated in children under the age of 7 at any radiation dose

above 5 centiGy, in children over 7 years and adolescents at above 10 centiGy and for adults when the dose exceeds 30 centiGy. In relation to this standard data from certificated thyroid dose measurements in the population in different contaminated regions are quite dramatic. For example, in Narodichsky district of the Zhytomyr region in the Ukraine, which was one of the most contaminated regions, thyroid radiation doses were in the range of 100-2,000 centiGy for children and 10-200 centiGy for adults (Ukrainian Ministry of Health 1994).

In the majority of officially “clean” regions of Ukraine and the city of Kiev, radiation doses for thyroid gland exceeded the permissible dose. For instance, among children from 151 settlements of Ternopol region, the radiation doses for thyroid were over 10 centiGy.

Children from Kiev also received thyroid radiation doses in excess of the permissible dose. These children were officially classified as “sufferers” from the accident due to the excessive irradiation of their thyroid (Ukrainian Ministry of Health 1996).

The National Centre for Radiation Medicine of the Academy of the Medical Sciences of Ukraine, Research Centre “Endopolymed” and the Association of Chernobyl Doctors conducted research on health effects during the post-accident years (Cheban 1999 & 2002). More than 25 thousand people were examined and classified:

- children of different ages, including those who were irradiated *in utero*;
- adults who were evacuated from the exclusion zone;
- those who continue to live in the contaminated territories of Ukraine, Belarus and Russia;
- liquidators of the Chernobyl accident including those who worked long term (no less than 5 years) or still work in the 30-km exclusion zone;
- unauthorized persons living in 30-km exclusion zone (“self-settlers”).

This research was conducted in the context of complex state and international programs to mitigate the impacts of the Chernobyl accident and for the social protection of the population. Chronologically, this research can be divided into three periods:

- early thyroid effects: October 1986 - May 1987;
- medium-term thyroid status during 1987-1989;
- long-term effects 1990-2005.

The first clinical forms of effects of thyroid irradiation (namely, chronic thyroiditis leading to hypothyroidism) became clearly apparent after 1992-1993. The results of clinical observations were confirmed by official epidemiological statistics. Changes in the thyroid system of sufferers were typical of non-stochastic radiation effects, with effects depending upon the length of exposure, dose and type of thyroid irradiation.

Those at highest risk of the development of chronic thyroiditis and hypothyroidism were those with the most complicated combined character of thyroid irradiation such as combination of internal ^{131}I and short-lived iodine radioisotopes irradiation with external gamma-irradiation. This group included former inhabitants of the area within a 30-km radius surrounding the Chernobyl power plant, Chernobyl clean-up workers of the “iodine period” up to end of July 1986, particularly women.

It is essential to introduce long-term systems of screening, diagnostics and monitoring for sufferers at the national level, to ensure timely detection, treatment and rehabilitation of persons at risk and those with developed thyroid pathology.

3.6.2. Other endocrine problems

During the early years after the Chernobyl accident an increase in secretion of cortisol, insulin, adrenocorticotrophic hormone and corticotropin was reported in the population of the entire contaminated area (Tronko *et al.* 1995), which in turn resulted in hypertensive disease, progressive atherosclerosis, diabetes and obesity. Normalization of hormone secretion was not observed until more than 5-6 years after subjects left areas with increased radiation levels.

Belarus

Morbidity due to endocrine system disease, nutritional disorders, metabolic and immune disorders in evacuees from the exclusion zone as well as in the population of the contaminated territories was more than twice as high as in the general Belarus population. In 1995, cases per 100,000 were 2,317 (evacuees) and 1,272 (population of contaminated zone) compared to the national average of 583 (Matsko 1999).

Concentration of T4 and TSG hormones increased in maternity patients from Gomel and Vitebsk regions whereas the concentration of T3 hormone decreased (Dudynskaya & Surina 2001). A tripling of the occurrence of endocrine illnesses in the contaminated territories occurred during the six years after the accident (Shilko *et al.* 1993).

There is also evidence of statistically significant increases in Type 1 *diabetes mellitus* in the highly polluted Gomel area of Belarus. Table 3.6.1 presents data about the incidence rate for Type 1 *diabetes mellitus* in Belarus.

Area	1980-1986	1987 – 2002
Low polluted territories (Minsk area)	2.25 ± 0.44	3.32 ± 0.49
Heavily polluted territories (Gomel area)	3.23 ± 0.33	7.86 ± 0.56*

* P < 0.05

Table 3.6.1. Incidence rate of Type 1 diabetes in children and adolescents in Belarus, 1980 – 2002 (Zalutskaya *et al.*, 2004)

Russia

Disturbances in the balance of estradiol, progesterone, luteinizing hormone and testosterone were observed 5-6 years after the accident in the population of territories hit by the Chernobyl release (Gorptchenko *et al.* 1995). Occurrence of endocrine system diseases in children living in Chernobyl contaminated parts of the Tula region had increased five-fold by 2002 as compared to the pre-accident period (Sokolov 2003). Morbidity in the adult population living in the highly contaminated south-west territories of Bryansk region exceeds the regional average 2.6 times (Sergeeva *et al.* 2005). Hyperprolactinemia, an increase in the pituitary hormone prolactin, was recorded in 17.7% of surveyed women of childbearing age living in radiation-contaminated Russian territories; imbalance in this hormone can greatly disrupt menstruation and cause infertility (Strukov 2003).

Ukraine

An increased level of autoimmune endocrine illness - autoimmune thyroiditis, thyrotoxicosis and diabetes – was first observed in 1992 in the Ukrainian contaminated territories and persists currently (Tronko *et al.* 1995). The morbidity level due to pathology of the endocrine system for adult evacuees from Prypyat city and the 30-km zone was found to be higher than in the rest of the population (Prysyazhnyuk *et al.* 2002). Concentration of the adrenal gland hormone cortisol appeared to be increased in pregnant women associated with an increased level of incorporated strontium: $1,793.1 \pm 232.43$ nmol/l as compared to the control level of 995.9 ± 69.88 nmol/l (Duda & Kharkevich 1996).

The main risk of health damage in children living in the contaminated territories was correlated with endocrine system pathology (Romanenko *et al.* 2001). Widespread endocrine related infertility has been observed in females irradiated *in utero* (Prysyazhnyuk *et al.* 2002). The index of morbidity for endocrine disease in people living in territories under strict radiation control was in 1.4 times that observed in the whole Ukrainian population in 1996 (54.2 compared with 37.8) (Grodzinsky 1999).

3.7. Disturbances / abnormalities of immunity

Allergies and autoimmune conditions may develop as a result of immune system disturbances. Changes in quantity and sub-polarization of blood lymphocytes take place under the influence of even small amounts of ionizing radiation. This leads to immune deficiency and the potential spread of pathologic conditions dependant upon immune system function, including infectious disease (Lenskaya *et al.* 1999). Internal exposure to radiation results in gradual development of autoimmune reactions, whereas external exposure causes a more rapid response (Lisiany & Ljubich 2001).

Belarus

Changes of cellular and humoral immunity were discovered in healthy adults living in territories contaminated with radionuclides in Belarus (Soloshenko 2002, Kyrylchek 2000). Significant changes in humoral immunity were discovered in the puerperal period in 156 maternity patients in the Gomel and Mogilev regions: the levels of serum immunoglobulin A, M and G in women from the contaminated areas (^{137}Cs over 5 Ci/km^2) was increased and the immunologic value of breast milk was lowered (Iskritsky 1995). Decreases in quantities of immunoglobulin agents of classes A, M, G and of secreted immunoglobulin A (sA) at the beginning of lactation was discovered in another survey of maternity patients in the contaminated territories (Zubovich *et al.* 1998). A significant decrease in the levels of T-lymphocytes and B-lymphocytes as well as a decrease in phagocyte activity of heterophilic leukocytes was discovered in adults from the contaminated areas (Bandazhevsky 1999).

An increase of autoimmune thyroiditis (Hashimoto goiter) correlated with absorbed radiation dose to the thyroid gland was discovered in contaminated parts of Belarus. In 1993 more than 40 % of the surveyed children in the Gomel area of Belarus exhibited pathology of the thyroid gland. According to expert estimates, in Belarus alone, some 1.5 million people are at risk of pathological changes taking place in the thyroid gland (Goffmann 1994a, Lipnick 2004).

A study of the immune system status of 4,000 men exposed to small doses of radiation (Bortkevich *et al.* 1996) showed that chronic radiation exposure leads to loss of the immune system ability to resist development of infectious and non-infectious diseases. Surveys of cellular and humoral immunity in the Gomel region showed that immune changes developing in children chronically exposed to radiation depend on the radionuclides involved: different effects were found with exposure to equivalent levels of strontium, caesium and other radionuclides (Evets *et al.* 1993).

Russia

Studies of the population of the contaminated territories in Russia revealed suppressed immune function. Decreased immunity was manifest in reductions in the numbers of leukocytes, activity of T-lymphocytes and of killer cells as well as in increased numbers of cases of thrombocytopenia and various forms of anemia. By 2002, the frequency of immune and metabolic effects in children from parts of the Tula region contaminated with Chernobyl fallout increased 5-fold compared to the pre-Chernobyl level. However, non-radiation-related morbidity remained at the same level in both “clean” and impacted areas (Sokolov 2003). It was believed that the noticeable increase of allergic dermatitis and eczema cases discovered in female employees of hothouse farms in “clean” areas of the Bryansk region reflected a decrease in immune competence (Dubovaya 2005).

A significant decrease in relative and absolute numbers of T-cells (CD+), a rise in immunoregulatory index, T-helpers (CD4+) and T-suppressors (CD8+) and a decrease in relative number of leukocytes were reported in children and adults from polluted parts of the Bryansk region. Imbalance in the immune system of children at the time of birth was correlated with *in utero* dose of radiation. In the radioactively polluted zones, there was a statistically significant correlation between the dose a child received before birth and the immune-regulatory index (ratio of T4-helpers and T8-suppressors) (Kulakov *et al.* 2001).

Ten years after the Chernobyl catastrophe, a high rate of the symptoms of a disorderly function of the immune system was already being discovered. Nineteen to twenty years after the catastrophe at the CNPP, 87-100% of liquidators going through a specialised investigation show clinical symptoms of immune deficit, the average indices being 89.4%. In accordance with observations of liquidators from three regions of Russia, they show a manifestation of high rates of occurrence of chronic somatic diseases. The presence of the more widespread chronic diseases has been observed in 85-98% of those investigated. 80-84% have revealed the presence of three or more chronic diseases.

Ukraine

7-8 years after the accident, the number of leukocytes in the peripheral blood in evacuees from the 30-km zone was found to be lowered (Baeva & Sokolenko 1998). The most unfavorable changes were observed in children with high *in utero* doses of thyroid irradiation (over 200 cGy). Among children irradiated *in utero*, 43.5% developed immune deficiency compared with 28.0% in the control group ($p < 0.05$) (Stepanova 1999). Exposure of the central organs of foetal immunogenesis (thymus and red bone marrow) to radiation resulted in

substantial dose-dependent disruption of the children's immune system (Stepanova 1999; Stepanova *et al.* 1998, Stepanova *et al.* 2001, Vdovenko 1999 & 2005).

3.8. Infection and invasions

An increase in the number and seriousness of intestinal toxicoses, gastroenteritis, dysbacteriosis, sepsis, viral hepatitis and respiratory viruses in regions polluted with emissions from Chernobyl (Batyan & Kozharskaya 1993, Kapytonova & Kryvitskaya 1994, Nesterenko *et al.* 1993, Busuet *et al.* 2002) has been reported.

Congenital infections occurred 2.9 times more often than before the accident in newborns whose mothers came from radiation-contaminated parts of the Polesky district of the Kiev region (up to 20-60 Ci/km²), the Chechersky district of the Gomel region (5-70 Ci/km²), Mtsensky and Volkhovsky districts of the Orel region (1-5 Ci/km² and 10-15 Ci/km²) (Kulakov *et al.* 2001).

Belarus

Herpes virus infections causing *in utero* and infantile mortality were reported in the worst contaminated areas of the Gomel region (Matveev *et al.* 1995). Increased invasiveness of *Trichocephalus trichiurus* (trichocephaliasis) in Gomel and Mogilev regions correlated with density of the radioactive contamination (Stepanov 1993). Increased prevalence and severity of tuberculosis was reported in the contaminated areas (Belookaya 1993) though the national increase in tuberculosis morbidity was insignificant. Morbidity with tuberculosis increased particularly rapidly after 1991 in contaminated areas of the Gomel region. By 1993 the rate was 50.4 cases per 10,000, rising to 60.5 cases per 100,000 in 1994. Drug-resistant and hard to cure forms of tuberculosis also appeared (Borchevsky *et al.* 1996).

Increased cryptosporidia infection was discovered in the Mogilev and Gomel regions (4.1% against 2.8% in the reference group) (Lavdovskaya *et al.* 1996). In 1993-1997, greater frequency of virus infections due to hepatitis B and C as well as greater spread of hepatitis viruses D and G were discovered among 2,814 adults and adolescents who suffered from the Chernobyl radiation in the Vitebsk region. This could lead to increased mortality from cirrhosis and primary liver cancer in the future (Zhavoronkova *et al.* 1998). Morbidity with viral hepatitis in highly contaminated parts of the Gomel and Mogilev regions more than 6-7 years after the accident was double the average level in Belarus (Matveev 1993). Activation of cytomegalovirus infection in pregnant women was also discovered in highly contaminated areas (Matveev 1993) and activation of herpes viruses was discovered in all contaminated territories (Voropaev *et al.* 1996).

Russia

An increase in cryptosporidia infections was found in the Bryansk region (8% compared to 4.1% in the reference group). Children in contaminated areas were more frequently affected with pneumocystosis (56.3% against 30% in the reference group) (Lavdovskaya *et al.* 1996). Morbidity with microsporia, caused by fungal infection with *Microsporum sp.* and commonly called "ringworm", occurred statistically significantly more often and developed in a more severe form in radiation-contaminated parts of the Bryansk region (Rudnitsky *et al.* 2003; see table 3.8.1. below).

Years	Two “contaminated” districts	“Clean” district
1998	56.3	32.8
1999	58.0	45.6
2000	68.2	52.9
2001	78.5	34.6
2002	64.8	23.7

Table 3.8.1. Number of microsporia infections per 100,000 inhabitants in three parts of Bryansk region, 1998- 2002 (Rudnitsky *et al.* 2003)

3.9. Chromosomal aberrations and other genetic characters

Radiation can induce two types of chromosome aberrations: unstable ones which include dicentrics, centric rings and acentric fragments; and stable ones such as reciprocal and other types of translocations. The number of dicentric and ring chromosomes, which are the main indicators of radiation mutagenesis at the chromosomal level, and stable ones which are often associated with chemical mutagenesis, increased simultaneously after the accident in exposed populations (Pilinskaya *et al.* 1994, Lazutka 1995). The unstable chromosomal aberrations, which decrease with time after cessation of radiation exposure, were confirmed as the consequences of overexposure to radiation (Shevchenko & Snigireva 1996).

The frequency of chromosomal aberrations in areas of the Ukraine, Belarus and Russia that were contaminated by Chernobyl fallout is noticeably higher than the global figure (Lazjuk *et al.* 1999a&b, Pilinskaya *et al.* 1994, Sevankaev *et al.* 1995, Stepanova & Vanyurikhina 1993, Vorobtsova *et al.* 1995, Mikhalevich 1999). Some of the relevant data are summarised in table 3.9.1. below.

Region and date of analysis	Number of people studied	Number of cells analyzed	Aberrant cells	Chromosomal aberratns	Multi-aberrant cells	References
Ukraine, before 1986	n/a	n/a	1.43±0.16	1.47±0.19	n/a	Pilinskaya <i>et al.</i> 1991
Gomel' region, Belarus, 1986 - 1987*	56	12 152	6.40 ± 0.7	n/a	n/a	Mikhailevich 1999
30-km zone, 1998-1999	33	11 789	5.02±1.95	5.32±2.10	0.017±0.066	Bezdrobna <i>et al.</i> 2002
Ukraine Kiev region, 1998-1999	31	12 273	3.20±0.84	3.51±0.97	0.009±0.25	Bezdrobna <i>et al.</i> 2002
The world, 2000	n/a	n/a	2.13±0.08	2.21±0.14	n/a	Bochkov <i>et al.</i> 2001

Table 3.9.1. Comparative frequency (mean% ± SD) of aberrant cells and chromosomal aberrations per 100 lymphocytes in Ukraine, Belarus and the world

Increase in chromosomal aberrations	In territories with contamination over 3 Ci/km ²	Bochkov 1993
	In self-settlers in the exclusion zone of Ukraine	Bezdrobna <i>et al.</i> 2001
	Increase in number of chromosomal diseases determined by structural aberrations of chromosomes resulting from <i>de novo</i> mutations	Lazjuk <i>et al.</i> 2001
	Increase in aberrations as radioactive pollution rises in Ivano-Frankovskaya region, Ukraine	Sluchik <i>et al.</i> 2001
Unstable chromosome exchanges	In self-settlers in the exclusion zone of Ukraine	Bezdrobna <i>et al.</i> 2001
Increase in number of abnormal chromosomes	In women from the contaminated parts of Mogilev region; with children from the contaminated areas of Brest region	Lazyuk <i>et al.</i> 1994
Decrease in frequency of mitoses	Contaminated areas of Bryansk region	Pelevina <i>et al.</i> 1996
Increase in number of mutations of the satellite DNA	Mutation frequency is correlated to the area contamination level	Dubrova & Plumb 2002

Table 3.9.2. Summary data on disorders of the genetic apparatus

Belarus

The number of chromosomal aberrations in somatic cells was elevated in those living permanently in contaminated parts of Belarus (Nesterenko 1996, Goncharova 2000). The frequency of dicentrics and circular chromosomes in women from the contaminated areas of the Mogilev region were significantly higher than in the reference group (Lazyuk *et al.* 1994). Chromosomal aberrations in children increased from $5.2 \pm 0.5\%$ in 1987 to $8.7 \pm 0.6\%$ in 1988 ($p < 0.001$). A significant increase in multi-aberrant cells (with 2-4 aberrations) from $16.4 \pm 3.3\%$ in 1987 to $27.0 \pm 3.4\%$ in 1988 ($p < 0.01$) was observed in children. The frequency of multi-aberrant cells (3-4 aberrations) increased with time in children living in the heavily radiation-contaminated areas of Khoyniki and Bragin districts (Mikhalevich 1999).

Russia

The frequency of chromosomal aberrations increased 2-4 times in inhabitants of territories with contamination levels over 3 Ci/km^2 (Bochkov 1993). The mitotic index (number of mitoses per 1,000 blood cells) in inhabitants of two polluted parts of Bryansk region (Klintsovsky and Vishkovsky districts) was significantly lower than the reference group (Pelevina *et al.* 1996).

Ukraine

From 1987 onwards, scientists from the cytogenetic lab of the Research Centre for Radiation Medicine of Ukrainian Academy of Science monitored the following groups of people: those who had recovered from acute radiation sickness, liquidators (mainly of 1986-1987), Chernobyl power plant personnel (including sarcophagus workers), self-settlers from the 30-km zone, and children and adults from the regions of obligatory and voluntary evacuation.

The data obtained demonstrate a dose-dependent rise in the frequency of somatic chromosome aberrations (Pilinskaya *et al.* 1999 & 2001), which was in good agreement with the results of other authors (Bochkov 1993, Lloyd & Sevankaev 1996, Maznik 1999, Sevankaev 2000, UNSCEAR 2001, Diomina 2003, Suskov *et al.* 2005, Maznyk 2005).

At the age of 10-12 years, children exposed to an antenatal red bone marrow radiation dose of 10.0-376.0 mSv had a higher, dose-dependent, frequency of chromosomal aberrations (Stepanova *et al.* 2001, Stepanova *et al.* 2002b). A residual cytogenetic effect remained in 37.5% of 15-17 year olds.

Prolonged exposure to even low doses of ionizing radiation could be "doubling" on cytogenetic criteria and induce specific chromosome damages in indicator cells (human peripheral blood lymphocytes) and can also cause the death or functional disturbance of somatic and germinal cells. This can lead to stochastic and, possibly, some nonstochastic effects with a mutation component, especially multifactorial pathologies. Subsequent detailed studies (Pedan & Pilinskaya 2004, Pilinskaya *et al.* 2005, Shemetun & Pilinskaya 2005) investigated radioinduced "dysgenomic effects" (adaptive responses and chromosome instability, whether delayed, hidden or transmissible; and the "bystander effect") as well as comparing the primary structure chromosome damage with identified harmful health effects due to human irradiation.

Examination of the same persons before and after the Chernobyl accident revealed a 6-fold increase in frequency of radiation-induced dicentric and ring chromosomes (Matsko 1999). The frequency of stable aberrations of chromosomes in lymphocytes of the peripheral blood increased significantly in the population of the contaminated territories (where ^{137}Cs content of soil was 110-860 kBq/m²), and among young people evacuated from the 30-km zone (Maznik & Vinnikov 2002, Maznik *et al.* 2003). The level of mutations gradually decreased during the subsequent 14 years of the survey (Maznik 2004). However, more than 12-15 years after the accident the frequencies of aberrant cells and chromosomal aberrations in the inhabitants of the zone remained significantly higher than in the residents of Kiev region.

In the 30-km exclusion zone, the frequency of both chromosome type (one-hit and two-hit aberrations) and chromatid type aberrations increased in lymphocytes (Table 3.9.3.). The elevated frequency of single-hit acentrics in the presence of two-hit dicentrics and centric rings is characteristic for continuous exposure to low dose rates of low-LET radiation.

	Chromatid type aberrations			Chromosome type aberrations						
						dicentrics + centric rings				
	breaks	exchanges	total	fragments	interstitial deletions	with fragment	without fragment	total	abnormal monocentric	total
30 km zone						0.22 ± 0.05	0.10 ± 0.03	0.33 ±0.06	0.23 ± 0.05	2.16 ±0.24
Kiev area	2.31 ±0.1 2*	0.02 ±0.0 1	2.33 ±0.1 2*	0.89 ± 0.12	0.04 ± 0.02	0.08 ± 0.03*	0.05 ± 0.02*	0.13 ±0.03*	0.12 ± 0.03*	1.18 ± 0.13*

* - significant differences

Table 3.9.3. Frequency ($M \pm SEM$, per 100 cells) of various types of chromosomal aberrations with the evacuees from the exclusion zone and the residents in Kiev area (Bezdrobna *et al.* 2002)

The frequency of non-stable chromosomal aberrations in children from Narodichi village (soil contamination approx. 15 Ci/km²) remained at a relatively constant level for more than 10 years whereas the frequency of stable chromosomal damages increased (Pilinskaya *et al.* 2003a).

It is possible that the frequency of chromosome aberrations reflects the general characteristics of chromosomes of the entire organism. Chromosome mutations in somatic cells are indices of high risk of morbidity with different illnesses. This is evidenced by correlations between levels of chromosome aberrations and number of pathologic conditions (Kutko *et al.* 1996).

Though chromosome disturbances apparent in lymphocytes were not directly related to development of hereditary diseases or to their transfer to the next generations, such disturbances reflect profound disturbances of genetic and ontogenetic processes. The frequency of dicentric and ring chromosomes in women examined after the accident and with their newborn children was practically equal (Matsko 1999).

3.10. Illnesses of the urogenital and reproductive system

Accumulation of radionuclides in a woman's body leads to increased production of the male hormone testosterone, which causes expression of male attributes (reviewed by Bandazhevsky 1999). Conversely, impotence became more common in men of 25-30 living in the radiation-polluted regions (Khvorostenko 1999).

Studies of pregnant women, newborn infants and children in radiation contaminated parts of the Ukraine (Polesky district in Kiev region - 20-60 Ci/km²), Belarus (Chechersky district of Gomel region - 5-70 Ci/km²) and Russia (Mtsensky and Volkhovsky districts of Orel region: 1-5 and 10-15 Ci/km²) have shown that children from the polluted territories suffer from retardation of sexual development. Among congenital malformations, the number of disturbances in genital organ development is increasing most rapidly. Mothers suffer from the later occurrence and disturbances of periods and more frequent gynecological problems, anemia during and after pregnancy, anomalies in the commencement of labor and untimely breaking of waters (Kulakov *et al.* 2001).

Belarus

There is increase of number of children with sexual development abnormalities in the territories with increased level of radioactive contamination (Sharapov, 2001). Acceleration of sexual development was observed in puberty-aged girls (13-14 years old) who had been exposed to radiation in their past (Leonova, 2001). In territories polluted with strontium and plutonium, slower sexual development has been observed both in boys (for 2 years) and in girls (for 1 year), while in territories polluted primarily with caesium, increases in the rates of sexual development have been found (Paramonova & Nedvetskaya, 1993). By 2000, the level of sexual development abnormalities was 5 times higher in girls born after the Accident in the heavily contaminated territories of Belarus and 3 times higher in boys compared with their contemporaries from "conventionally clean" regions (Nesterenko *et al.*, 1993).

Analysis of health status of 1,026,046 maternity patients from territories with pollution levels exceeding 1 Ci/km² has revealed a significantly higher level of urogenital system morbidity (Busuet *et al.* 2002). During 1991-2001 gynecological morbidity of fertile age females increased across the country and the number of pregnancy and birth complications also increased (Belookaya *et al.* 2002). Number of unfavorable outcomes of pregnancy and medical abortions increased in the contaminated regions (Golovko & Izhevsky 1996). Disturbances of menstrual activity were observed in the majority of females of childbearing age in the radiation-contaminated areas (Nesterenko *et al.* 1993). Increases in frequency of infertility and impotency were also reported in the contaminated areas. In the contaminated regions, primary consultations because of infertility were 5.5 times higher in 1991 as compared to 1986. The following have been identified as causes of infertility: pathology of the seminal fluid (increased 6.6 times), polycystic ovary syndrome (increased 2 times) and endocrine problems (increased 3 times). Impotence in young men (25-30 years) correlated to the level of radiation contamination of the land (Shilko *et al.* 1993).

Russia

Structural changes in seminiferous tubules of testicles and disturbance in spermatogenesis were reported in 75.6% of surveyed men in Kaluga region (Pissarenko 2003).

In areas of increased radiation level, a considerable increase in kidney infections, chronic pyelonephritis and stones in the kidneys and ureters were observed in adolescents (Karpenko *et al.* 2003). Pregnancy pathology increased after the accident, while genito-urinary diseases in 1994 composed 6.1% of the morbidity structure of adults and adolescents of the Ukrainian Chernobyl victims (Grodzinsky 1999). In prostate adenoma patients from the contaminated territories, 53% had mutagenic inactivation of tumour-suppression genes. In 96% of cases, pre-cancer changes in urinary bladder were also reported (Prysyazhnyuk *et al.* 2002, Romanenko *et al.* 1999). These symptoms may be connected with the impact of low-level radiation, which leads to genetic instability with possible development of invasive cancer of the urinary bladder. During 1988-1999, morbidity of the urogenital system more than doubled in the population still living in the contaminated territories (Prysyazhnyuk *et al.* 2002).

In areas affected by Chernobyl fallout, cases of inflammation of the female genital organs increased considerably and occurrence of ovarian cysts and uterine fibroids doubled 5-6 years after the accident. The frequency of menstrual disturbances increased three-fold as compared to the pre-accident period. During the first years after the accident, women tended to experience heavy periods, but after 5 - 6 years, light and infrequent periods were predominant (Gorptchenko *et al.* 1995). More than 8-10 years after the accident, the threat of interrupted pregnancy became more frequent in evacuees from the 30 km zone and those living in the contaminated territories and pre-eclampsia and premature births were increasingly observed (Golubchikov *et al.* 2002; Kyra *et al.* 2003).

The reproductive health of female evacuees and liquidators, as well as women living in regions subjected to the highest radioactive contamination, has been studied in some detail. The control group included the women living in regions conventionally considered clean (Yagotin in the Kiev area and the town of Poltava). Average indices of three years before the accident were also taken into account. The database comprised over 20,000 pregnant women and their newborns (Lukyanova 2003, Dashkevich & Janyuta 1997, Dashkevich *et al.* 1992).

There was a 3-fold growth in inflammatory disease of the internal reproductive organs, disturbances of the menstrual cycle and benign ovarian tumours (Lukyanova 2003, Ivanyuta & Dubchak 2000). The analysis of data regarding 1,017 radiation-exposed girls and teenagers showed a delay on the onset of puberty in 11% and various disturbances of menstrual function in 14% (Lukyanova 2003, Dashkevich *et al.* 1992, Dashkevich *et al.* 2001).

Incorporation of caesium-137 in the placenta has also been reported. Histological study of placentas revealed acute disturbances in blood circulation, intensified proliferative activity of syncytiotrophoblast and the presence of poorly differentiated and underdeveloped forms of fibroblasts in terminal villi of the stroma (Lukyanova 2003, Zadorozhnaya *et al.* 1993). Disturbances in blood circulation and dystrophic and involutive changes in the placenta are dose-related (Lukyanova 2003, Lukyanova *et al.* 2005).

A correlation between the level of radionuclides in the placenta and inhibited growth of the foetus was established. Incorporation of radionuclides into placentas of women living in the contaminated areas was 4.9 Bq/kg, which resulted in reduced birth-weight in babies, against a background of placental hypoplasia, non-uniformity of its thickness, presence of infarcts, cysts and deposits of calcium salts in the placenta. In recent years, elevated content of alpha-

radionuclides were found in the osteal systems of stillborn children whose mothers lived in radiation control regions (Lukyanova 2003, Zadorozhnaya *et al.* 1993).

The analysis of gestational complications has shown that in the radiation risk group, 54.1% of pregnant women had complications of pregnancy (pre-eclampsia, anaemia, foetoplacental failure), while in the control group, complications occurred in only 10.3%. According to ultrasonic inspection, the risk of inhibited foetal development was observed in 35% of radiation risk group women, which was 3 times higher than in the general population (Lukyanova 2003, Dashkevich & Janyuta 1997, Sergienko 1997, Sergienko 1998).

Childbirth complications occurred in 78.2% of the radiation risk group, 2.2 times higher than in the control group. Of particular concern was a steady growth in uterine haemorrhaging. Studies of the concentrations of foetoplacental complex hormones revealed alterations that would have contributed to the development of hemorrhagic complications, as well as considerable perturbations of the haemostasis system (Lukyanova 2003, Dashkevich & Janyuta 1997, Sergienko 1997).

The number of childbirths in the controlled territory decreased by 35-40% (Dashkevich & Janyuta 1997). The impacts on the reproductive health of women in the Ukraine during the post-emergency period resulted in negative consequences for the fertile and thus contributed to deterioration of a whole demographic situation, with only 62% of the mortality compensated by birth rate (Lukyanova 2003, Dashkevich & Janyuta 1997).

3.11. Congenital malformations and diseases in infants and children

As discussed in the last section, the placenta accumulates radionuclides. These penetrate the foetus and cause foetal dysplasia, structural and functional abnormalities in different organs and systems, including the skeletal system.

Both pregnancy complications and morpho-functional changes in the placenta can cause neonatal pathology. Various deviations in the health of newborns were 3 times more common than in children of mothers from the control group. Frequently observed problems included disturbance of early neonatal adaptation processes (neurological disorders, edematous, icteric and hemorrhagic syndromes, disturbances in respiratory development, greater loss of body mass and slowness in its restoration). Among diseases of the newborn, asphyxia and respiratory disorders appear to predominate, attributable to the frequent obstetric complications suffered by the mothers during pregnancy (Lukyanova 2003, Dashkevich & Janyuta 1997, Dashkevich *et al.* 1992, Epstein *et al.* 2004, Sergienko 1998).

Endometrial hypoxia and asphyxia during birth were met 5.3 times more frequently than before the accident; non-infectious respiratory disorders were 9 times more frequent in newborns whose mothers came from radiation polluted territories in Polesky district of Kiev region (up to 20-60 Ci/km²), Chechersky district of Gomel region (5-70 Ci/km²), Mtsensky and Volkhovsky districts of Orel region (1-5 Ci/km² and 10-15 Ci/km²) (Kulakov *et al.* 2001).

Non-infectious respiratory disorders were 9 times more frequent in newborns whose mothers came from radiation polluted territories in Polesky district of Kiev region (up to 20-60 Ci/km²), Chechersky district of Gomel region (5-70 Ci/km²), Mtsensky and Volkhovsky districts of Orel region (1-5 Ci/km² and 10-15 Ci/km²) (Kulakov *et al.* 2001). Endometrial

hypoxia and asphyxia during birth were more than 5 times more common than before the accident.

A higher proportion of *in utero* irradiated children developed pathology of the respiratory system: 26.0% compared to 13.7% in the control group ($p < 0.05$) (reviewed by Prysyzhnyuk *et al.* 2002).

A dynamic survey of pregnant women, maternity patients, newborn infants and children on radiation contaminated territories in Ukraine (Polesky district in Kiev region; 20-60 Ci/km²), Belarus (Chechersky district of Gomel region; 5-70 Ci/km²) and Russia (Mtsensky and Volkhovsky districts of Orel region; 1-5 and 10-15 Ci/km²) indicated an increase in the number of development deficiencies related to the digestive apparatus of newborns (Kulakov *et al.* 2001).

Another study concerned a group of 1114 Ukrainian children exposed *in utero*. Group I was composed of the children born to women who were already pregnant at the time of the accident and who were evacuated from city of Prip'yat; Group II also comprised children born to women who were pregnant at time of the accident, but who continued to live in contamination zones II-III. Group III, the controls, were children born to women living in "clean" territories.

Foetal exposure to radiation resulted in lower level of health of children at all stages of postnatal development (Stepanova *et al.* 1997, Stepanova 1997, Stepanova *et al.* 2002a, Stepanova *et al.* 2003). Chronic somatic pathology occurred more often in children with a foetal thyroid exposure over 0.36Gy. Above 1.0Gy it was recorded in almost all children.

Disturbance of physical development in children exposed to ionizing radiation up until the 16th week of foetal development (an average dose of 0.31Gy) was observed more often than in the control, whereas after 16th week (an average dose of 0.85Gy), frequent pathological deviations were identified during puberty.

Radiation exposure of the central organs of foetal immune system development (thymus and red bone marrow) resulted in substantial dose-dependent disruption of the children's immune system (Stepanova *et al.* 1998, Stepanova *et al.* 2001, Vdovenko 1999 & 2005).

Exposure of the foetus to medico-biological risk factors in a combination with radiation contributed to higher frequency of small anomalies of development. The average occurrence rate among children exposed to antenatal radiation was 5.52 ± 0.22 , whereas in the control it was only 2.95 ± 0.18 ($p < 0.001$). A correlation ($r = 0.61$) existed between the number of small anomalies in a child's development and exposure dose during foetal development.

At the age of 10-12 years, children exposed to an antenatal red bone marrow radiation dose of 10.0-376.0 mSv had a higher, dose-dependent frequency of chromosomal aberrations (Stepanova *et al.* 2001, Stepanova *et al.* 2002b). A residual cytogenetic effect remained in 37.5% of 15-17 year olds.

Children born to parents exposed to radiation also had a low level of health, suffering higher morbidity rates than the Ukraine as a whole. During the last 5 years these varied from 1134.9 to 1367.2‰ compared with 960.0-1200.3‰ across the Ukraine). Only 9.2% were described as "practically healthy". Of 13,136 children born to liquidators of the 1986-1987 period,

1,190 were registered as having congenital development anomalies (9.6‰). The highest frequency was recorded in children born in the first post-accident years (Stepanova *et al.* 1999, Stepanova *et al.* 2004).

With the aim of evaluating possible genetic effects in the first generation of those exposed to radiation immediately after the accident, the members of families of Ukrainian liquidators of the 1986-1987 period were examined. The majority of children whose fathers were liquidators exhibited numerous small anomalies of development. The frequency of chromosomal aberrations (Stepanova *et al.* 2004, Shestopalov *et al.* 2004) and mutations in micro-satellite-associated fractions of DNA was higher than in their older brothers and sisters who had been born before the accident (Weinberg *et al.* 2001).

Higher levels of mutations in micro-satellite fractions of DNA have been noted in the first generation of the parents exposed to radiation (Dubrova 1992, Dubrova *et al.* 1998a&b). All the above gives reason to classify children and teenagers exposed to antenatal radiation before birth into the group of mutation risk.

Ukrainian researchers collaborating with Bristol University determined average uptake of radioactivity in organs of deceased newborns as shown in the Table 3.11.1.below (Lukyanova 2003, Lukyanova *et al.* 2005). Even these low doses can be significant for the continually growing and developing foetus.

Organ	Contamination (Bq/kg)
Ribs	1.01±0.24
Spinal column interior	0.67±0.02
Developing teeth	0.4±0.02
Liver	0.39±0.05
Tubular bones	0.32±0.02
Spleen	0.205±0.03
Thymus	0.14±0.015

Table 3.11.1. Average uptake of radioactivity in organs of deceased newborns

Morphological examination of the bone tissue revealed localised changes in blood circulation (dystrophic changes in the arteriolar walls), reduction in the number of osteoblasts, dystrophic changes of osteoblasts and osteoclasts which were of smaller size and settled irregularly in 20% of cases. The apparent imbalance in the ratio of osteoblasts to osteoclasts could trigger destructive processes in the developing bone tissue (Lukyanova 2003, Lukyanova *et al.* 2005).

As the highest levels of radionuclide incorporation were found in the foetal bone tissue and developing teeth, it was decided to study the status of the skeletal system in more detail. The study showed some children born after the Chernobyl accident suffered qualitative change of the skeletal system structure from an early age. These changes were of mixed character with a prevalence of osteofibromatosis, osteopenia and osteoporosis.

A trend of developing systemic dysplastic processes was found in children that were born after the Chernobyl accident, in chondral tissue (significant level of dysmesenchymoses, skeleton dysmorphism), bone tissue (dysplastic osteofibromatosis, systemic hypoplasia of dental enamel) and connective tissue (significant levels of microangiopathy, fibrosis of

arterioles and venules of liver, spleen, retina and mitral valve prolapse). These changes can indicate mesenchymal dysplasia, and gender and group ambiguity of results in connective, chondral and bone tissues can indicate to heterogenic radiosensitivity of examined children (Arabskaya 2001).

In the majority of children of this cohort, microcirculation disturbance and development of hypoxia were found, which initiate dystrophic processes in the bone tissue (including microangiopathies, activation of lipid peroxidation, changes of structural and functional properties of cell membranes and erythrocyte ultrastructure, decrease in osmotic resistance and endurance of erythrocytes and lowering of their content of 2,3-diphosphoglycerate).

The research disclosed modulation of development of the skeletal system, including changes in structural and functional properties of osteoblasts, activation of remodeling processes in bone tissue and abnormality of formative phase of its mineralization combined with destruction of the osseous bone tissue.

It was also disclosed that, in children examined, foetal teeth incorporated alpha-radionuclides irregularly and that this influenced changes of the timing of dentition. Specifically, it led to earlier second dentition followed by impairment of the condition of the periodontal tissue and early development of dental caries. This represents premature biological ageing of these tissues with the changes of processes of osteogenesis beginning as early as during the period of intrauterine development.

It has been shown that 13.2% of children in this cohort lagged their contemporaries from “supposedly clean” regions by biological age, whereas 46.9% showed signs of more advanced aging than their contemporaries, which can indicate to activation of processes of early ageing in children that were born after the Chernobyl accident (Lukyanova *et al.* 2005, Arabskaya 2001, Antipkin & Arabskaya 2003, Arabskaya *et al.* 2005).

It was demonstrated that exposure to radiation leads to the activation of bone tissue remodeling processes. These processes cannot be related to so-called radiation “hormesis”, as they have negative influence upon the quality of newly formed bone tissue and attainment of peak bone mass in children born after the Chernobyl accident (Lukyanova *et al.* 2005, Arabskaya 2001).

Based upon the obtained data in this cohort of children, research was conducted into the health status and status of the skeletal system in the “first generation”, i.e. offspring of women who were acutely exposed to radiation in their childhood and adolescence during the Chernobyl accident.

Indices of antenatal and intranatal period determine the child’s future health status in many respects. It was established that women who received thyroid gland irradiation in their childhood experienced pregnancy complications more frequently than women of the same age but from “supposedly clean” regions, and the complications were more likely to occur during pregnancy with female foetuses.

Irradiation in childhood negatively influenced reproductive health and resulted in very low pregnancy rate (25.8%). Variability depends on radiation dose (decreasing from 41% in those who received lesser doses to 12.5% in those who received large radiation doses in childhood).

This indicates the extreme radiation sensitivity of the female reproductive system in childhood and adolescence (Tolkach 2002).

The high radiation sensitivity of the bone system is indicated not only by the significant frequency of developmental problems with the skeletal and dental system, but also the 3-fold increase in the rate of development of osteoporosis in examined women, which was clinically manifested as bone fractures before pregnancy in 11.1% of women (4.2% in control group). A significant rate of nonspecific manifestations of hypocalcaemia during pregnancy - sural cramps, ossalgia, and dental caries in 74.2% (compared to 12.5% in controls) - were also recorded (Arabskaya *et al.* 2002, Antipkin *et al.* 2003).

These results indicate that, in this cohort of women, foetal development occurred under complicated conditions deriving from both maternal reproductive dysfunction and profound changes of mineral homeostasis. The rate of birth of children with congenital anomalies was significantly higher in this cohort of women compared to female residents of "supposedly clean" territories. Primary and secondary hypogalactia (lack of breast milk) occurred in one third (33.8%) of women compared with 12.5% in the control group.

The first generation of children born to mothers irradiated in their childhood and adolescence was physiologically immature at birth. Children were more frequently unwell during their first year of life, with early development of chronic problems. The proportion of healthy children was very low.

In the first generation of offspring, early onset of dental caries had greater prevalence than in children from "supposedly clean" territories. In the first generation of irradiated mothers' offspring, the skeletal system pathology was the 3rd most common effect in children (behind pathology of digestive organs and pathology of lungs) and was detected twice as often as in their contemporaries from "supposedly clean" regions. Ossalgia and fractures were 5 times more frequent (Arabskaya *et al.* 2003, Arabskaya *et al.* 2004).

Even when body development in this cohort proceeds normally, it more frequently lags behind that of children of residents of officially "clean" regions.

It has been established that, in the first generation of children born to mothers irradiated in their childhood, early development of adaptive changes in the skeletal system is followed by quantitative changes of bone tissue structure, the character of which depends on the dose and kind of radiation that their mothers were exposed to in childhood, as well as on mothers' age at the period of irradiation. Higher radiation doses were linked to early osteofibrosis and osteoporosis development in offspring, especially in girls. Lower doses caused osteopenia and osteomalacia. Irradiation of mothers when young, irrespective of dose, resulted in osteofibrosis in the early childhood of offspring. Irradiation of mothers during puberty also promoted early development of scoliosis in offspring. Early histoarchitectonic changes of bone tissue were followed by not only changes of bone physical properties but also by disturbance of mineral homeostasis and changes of structural and functional properties of bone-forming cells (Tolkach 2002, Arabskaya *et al.* 2002, 2003 & 2004, Antipkin *et al.* 2003).

These bone system changes and structural changes of bone tissue in this cohort of children can be interpreted as possible clinical and biological effects of ionizing radiation, as it was established that the nature of qualitative changes of skeletal system in offspring depended on

the doses of radiation their mothers were exposed to in childhood. The research gives reason to believe that biological effects of irradiation of mothers in childhood are similar to those in the first generation of their offspring, although further investigations are required.

Increases in frequency of children with congenital malformations, such as cleft lip and palate, duplication of kidneys and ureters, polydactyly, malformations of nervous and circulatory system development, atresia of esophagus and anus, web-foot, anencephalia, spina bifida and underdevelopment of limbs, were observed in all contaminated territories during the first several years after the accident (Goncharova, 2000, Ibragimova, 2003; Dubrova *et al.*, 1996).

Belarus

Table 3.11.2, summarizes the evidence for increased prevalence of congenital malformations in children born 1-3 years after the accident in two of the most contaminated regions of Belarus: Gomel and Mogilyov regions. Tables 3.11.3. and 3.11.4. then go on to summarise the relationship between contamination level and malformation frequency for Belarus as a whole.

District	1982—1985	1987—1989
Gomel region		
Brginsky	4.09 ± 1.41	9.01±3.02
Buda-Koshelevsky	4.69 ± 1.21	9.33±2.03*
Vetkovsky	2.75 ± 1.04	9.86±2.72
Dobrushsky	7.62 ± 1.96	12.58±2.55
Elsky	3.26 ± 1.35	6.41±2.42
Kormyansky	3.17 ± 1.20	5.90±2.08
Lelchitsky	3.28 ± 1.16	6.55±1.98
Loevsky	1.56 ± 1.10	3.71±2.14
Hoiniksky	4.37 ± 1.16	10.24±2.55*
Chechersky	0.97 ± 0.69	6.62±2.33*
Mogilyov region		
Byhovsky	4.00±1.07	6.45±1.61
Klimovichsky	4.77±1.44	3.20±1.43
Kostyukovichsky	3.00±1.22	11.95±2.88**
Krasnopol'sky	3.33±1.49	7.58±2.85
Slavgorodsky	2.48±1.24	7.61±2.68
Cherikovsky	4.08±1.66	3.59±1.79

Total	3.87±0.32	7.19±0.55***
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* $P > 0.05$ (*), ** $P > 0.01$; *** $> P 0.001$

Table 3.11.2. The frequency of births of children with congenital malformations (per 1000 deliveries) in Gomel and Mogilyov regions of Belarus before and after the Chernobyl accident (Nesterenko 1996)

Contamination, Ci/km ²	1982 –1985	1987 – 1992
under 1	4.72 (4,17 – 5,62)	5.85 (5.25 – 6.76)*
1-5	4.61 (3.96 - 5.74)	6.01(4.62 – 7.98)**
Over 15	3.87 (3.06 – 4.76)	7.09(4.88– 8.61)**

* $P > 0.05$, ** $P > 0.01$

Table 3.11.3 Prevalence of congenital malformations (per 1000 live births) under the different levels of radio contamination of Belarusian territories (Lazjuk et al. 1996, Goncharova 2000)

	≥15 Ci/km ² , 17 districts		<1 Ci/km ² , 30 districts	
	1982-1985	1987 - 1995	1982-1985	19987 – 1995
Anencephaly	0.28	0.44	0.35	0.49
Spina bifida	0.58	0.89	0.64	0.94*
Cleft lip and/or palate	0.63	0.94	0.50	0.95*
Polydactyly	0.10	1.02*	0.26	0.52*
Limb reduction defects	0.15	0.49*	0.20	0.20
Down's syndrome	0.91	0.84	0.63	0.92*
Multiple malformations	1.04	2.30*	1.18	1.61*
Total	3.87	7.07*	3.90	5.84*

* $P > 0.05$

Table 3.11.4. Occurrence of congenital malformations (per 1000 born alive) in the territories with a different level of the Chernobyl radioactive pollution, Belarus (Lazjuk et al. 1999)

Russia

An increase in prevalence of congenital malformations has been observed in the most contaminated region of Russia, i.e. Bryansk region (Ljaginskaja & Osypov 1995, Ljaginskaja et al. 1996), as well as in contaminated districts of Tula region (Khvorostenko 1999).

3.12. Premature Ageing

Although individuals can vary in their reaction, ionizing radiation can be regarded as a special “exogenous” form of ageing and promotes non-tumour somatic pathology (Kovalenko 1988). Prospective epidemiological studies of atomic bomb survivors revealed that ionizing radiation significantly increased the non-cancer mortality. The biological mechanisms involved are unknown (Bazyka *et al.* 2004).

The relative age of people living in radiation contaminated areas of Ukraine increased: their biological age exceeded calendar age by 7-9 years (Mezhzherin 1996). Average difference between biological and calendar age calculated upon ageing markers in 306 liquidators ranged from 5 to 11 years (Polukhov *et al.* 1995 cited by Ushakov *et al.* 1997).

There is also evidence of associated premature mortality. The average age of death from myocardial infarction (heart attack) in men and women who lived or used to live on territories with pollution levels exceeding 555 kBq/m² caesium-137 is 8 years less than the average across Belarus (Antypova & Babichevskaya 2001).

Illnesses of the blood circulation system, typical for elderly people, such as arteriosclerosis and hypertension etc are developing among the observed liquidators 10-15 years earlier than is normal. An increase, among liquidators, of the spread of diseases typical among the elderly indicates their premature ageing. Absence of practically healthy people among the observed group is also an indication of premature ageing. A high spread of diseases of the gastrointestinal tract, the hepatobiliary system and the bones and joints is also observed (95 %) (Oradovskaya *et al.* 2001&2005, Oradovskaya 2004).

3.13. Diseases of the sense organs

In contaminated areas around Chernobyl, morphological and functional disorders of visual apparatus, cataracts, destruction of the vitreous body and refraction anomalies were encountered with greater frequency than in neighboring, cleaner regions (Bandazhevsky 1999).

A survey of pregnant women, maternity patients, newborn infants and children in radiation contaminated territories in Ukraine (Polesky district in Kiev region - 20-60 Ci/km²), Belarus (Chechersky district of Gomel region - 5-70 Ci/km²) and Russia (Mtsensky and Volkhovsky districts of Orel region - 1-5 and 10-15 Ci/km²) showed an increase in the number of sensory organ development deficiencies, including congenital cataracts, in newborn infants (Kulakov *et al.* 2001).

Clouding of the lens, an early symptom of cataracts, was found in 24.6% of exposed and 2.9% of control children (Avchacheva *et al.* 2001). The children who were exposed before 5 years of age have more problems with accommodation of eyes and showed the highest excess above the control for all groups of diseases. For example, a 6.5 times increase in the incidence of diseases of the digestive system was recorded in affected children examined during 1987-1999 (sub-register RCRM “Children” data) (Serduchenko *et al.* 2001, Korol *et al.* 2001).

Ocular effects in patients since the Chernobyl accident have been classified as either specific irradiation injuries, attributable solely to radiation exposure, or ophthalmopathology that is

observed under normal conditions, but for which radiation exposure is an important additional risk factor.

The first group includes radiation cataracts, radiation chorioretinopathy (including “chestnut” and “diffraction grating” syndromes, which are rare and found only in individuals irradiated under special conditions). “Chestnut syndrome” is a form of radiation angiochorioretinopathy, which derives its common name from the chestnut-leaf-shaped malformations, which appear in the retina. “Diffraction grating syndrome”, in which spots of exudate were scattered on the central part of the retina, was observed in an individual irradiated in special conditions, within direct sight of the exposed core of the 4th reactor (Fedirko 1997).

Radiation cataracts can be caused by high dose exposure, but also by doses less than 1 Gy. Mathematical modeling data indicate radiation cataract is a stochastic effect of radioactive exposure. The absolute risk of radiation cataract is adequately described by non-threshold model, based on a whole-body external radiation dose and the exposure time. The relative risk per 1 Gy is 3.45 (1.34-5.55) (Fedirko 2000, 2002).

The second group of pathologies, namely diseases which appear under normal conditions, but which are more widespread in radiation affected population, is more significant. Radiation exposure caused by participation in emergency work at Chernobyl promoted premature occurrence of involutinal and dystrophic changes of the eye and development of ocular vessel pathology, and leads to significant dose-dependent increase in chorioretinal degeneration, such as age-dependent macular degeneration (AMD) and involutinal cataracts. Central chorioretinal deg with clinical symptoms of AMD was the most frequent form of retinal pathology in the later period (136.5 ± 10.7 per 1,000 persons in 1993 and 585.7 ± 23.8 per 1,000 persons in 2004). Involutinal cataract is the most widespread form of crystalline lens pathology. Its prevalence during the period of monitoring increased from 294.3 ± 32.0 per thousand exposed individuals in 1993 to 766.7 ± 35.9 per 1,000 in 2004 (Fedirko 1997 & 1999a, Buzunov & Fedirko 1999, Fedirko 2005).

According to mathematical modeling data, risk factors for involutinal cataracts and central chorioretinal degeneration in liquidators are age, time after exposure and the absorbed dose of external irradiation. Relative risk of AMD was 1.727 (1.498; 2.727) per year of calendar age, 6.453 (3.115; 13.37) per $1 \sqrt{(d * t)}$, where d is the dose in Gy and t - time under risk in years (Fedirko 2002).

Moreover, there was a high prevalence of dose dependent vitreous destruction, chronic conjunctivitis and benign neoplasms of the skin of the eyelid (Fedirko 1997 & 1999b, Buzunov & Fedirko 1999). Irradiated individuals also suffered a decrease in ocular accommodation ability - of 0.78 dioptries per 1 Gy (Sergienko & Fedirko 2002).

Radiation exposure promotes premature ageing of the eye. Combination of long-term monitoring of eyes of irradiated populations and mathematical modeling of absolute risks of ocular disease has shown that retinal angiopathy increases with radiation dose in a predictable fashion. Statistically significant increase of involutinal cataracts risk can be expected by the fifth year after exposure and AMD by six years after exposure.

It is recommended that eye disease among inhabitants of radiation-contaminated areas be monitored on a regular basis. It is also extremely important to collect data on eye conditions among descendants of irradiated people.

Belarus

In 1996, cataracts among Belarusian evacuees from 30-km zone were more than three times higher than that for the population as a whole (44.3 compared to 14.7 cases per 1,000) (Matsko 1999).

Cataracts are more frequent in parts of Belarus with radioactive pollution exceeding 15 Ci/km² (Paramey *et al.* 1993, Goncharova 2000).

Year	Average incidence in Belarus	Population of zone 1-15 Ci/km ²	Population of zone exceeding 16-40 Ci/km ²	Evacuees from zone with > 40 Ci/km ²
1993	136.2	189.6	225.8	354.9
1994	146.1	196.0	365.9	425.0

Table 3.13.1. Occurrence (cases per 10 000 population) of cataract morbidity in various groups of Belarus population in 1993-1994 (Goncharova, 2000)

The number of opacities in both eyes are greater in more highly contaminated territories (Tables 3.13.2. and Figure 3.13.1.) and correlates with level of ¹³⁷Cs in Belarusian children (Arinchin & Ospennikova, 1999).

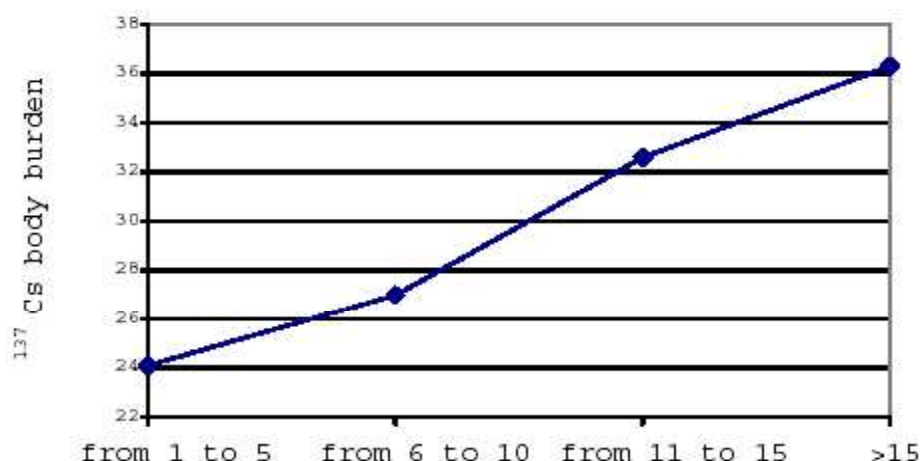


Figure 3.13.1. Relationship between the number of lens opacities and the level of ¹³⁷Cs activity in the body of the Belarusian children (Arinchin & Ospennikova 1999)

Region under study, contamination level and number of children in study	Percentage of children with a given number of opacities in both lenses		
	1-5 opacities	6-10 opacities	>10 opacities
Brest area, 137-377kBq/m ² (n=77)	57.5%	17.9%	6.7%
Vitebsk area 3.7 kBq/m ² (n=56)	60.9%	7.6%	1.1%

Table 3.13.2. Multiple opacities (%) in both lenses of Belarusian children, 1992 (Arinchin & Ospennikova, 1999)

More than half the inhabitants (54.6%) of Ukrainian regions polluted with radionuclides suffer varying degrees of hearing disorders (Zabolotny *et al.* 2001).

3.14. Neurological disorders

The psychoneurological consequences of the Chernobyl accident deserve special attention since neurons form a highly differentiated and non-proliferative tissue. Experimental evidence that some areas of the central nervous system are particularly sensitive to the radiation damage has existed for many years (review: Loganovsky 1999). Considering that, so far full neuronal repair has not been observed (Zachary 2005, Taupin 2006), there is a probability of development of organic brain damage conditions long after the radiation exposure occurred (Glazunov *et al.* 1973, Nyagu 1995). Twenty years after the Chernobyl catastrophe, many new research data have accumulated showing that even comparatively low levels of ionizing radiation can lead to stochastic as well as to certain specific changes of the central and peripheral nervous systems such as radiation-induced encephalopathy (Martsynkevych 1998, Zhavoronkova *et al.* 1998).

Postradiation encephalopathy of various degrees has been observed in all patients surviving acute radiation syndrome. This condition is etiologically heterogeneous. The major factor influencing the probability of its development (over 48% according to results of the analysis of variance) was the absorbed radiation dose (Nyagu 1999, Nyagu & Loganovsky 1998). Based on this, cognitive dysfunction could be categorized as directly related to the dose of ionizing radiation. Similar dose-dependent results were found in the epidemiological surveys conducted in Russia (Birykov *et al.* 2001). Other factors included patient's age, presence of cerebrovascular pathology as a co-morbidity, and psychological stress.

For patients with symptoms of acute radiation exposure, the maximum relative risk (RR) of disruption of brain functional organization has been estimated to be 5. Among liquidators of the Chernobyl accident who worked there in 1986-87, the relative risk was 3.65 (reaching 4 for those working for extended periods in the restricted zones). For comparison, patients with chronic cerebral pathology have RR of 3, and for those with posttraumatic stress disorder the relative risk was 2. Working in the 30-km restricted zone for 10 years also increased chances of deterioration of mental health by 3.4-6.2 times compared to unexposed population (Nyagu 1999, Nyagu & Loganovsky 1998).

In Russian liquidators, neurological diseases were the second most common group of diseases, accounting for 18% of all morbidity. The most widespread disease in this group is encephalopathy of various origins (34%). The frequency with which this disease occurred grew significantly from the period 1991-1998 (25%) to 2001 (34%). Serious effects, such as severe disturbances of the cerebral blood flow, also became more widespread (10% in 1998 and 17% in 2001) (Khrisanfov & Meskikh 2001, Zubovsky & Smirnov 1999, Meskikh 2001, Zubovsky 2006).

During the post-Chernobyl period, non-oncological morbidity among liquidators was found to directly correlate with the radiation dose they received. This includes mental, endocrine, digestive system diseases, cardiovascular and urogenital diseases. At the initial stage, development of autonomous dysfunction was observed (Zozulia & Polishchuk 1995).

Autonomous dysfunction among those who had received doses of $\geq 0,3$ Sv, was the first stage of development of a neuropsychiatric pathology. Approximately 3-5 years after the onset of autonomous dysfunction, it transformed in many survivors into postradiation encephalopathy. The combined exo- and somatogenic encephalopathy developed in the majority of liquidators over a period of years. Moreover, children with high dose (>0.3 Gy) thyroid gland exposure also frequently displayed autonomous dysfunction. Due to autonomous dysfunction, neurological morbidity among the irradiated population has grown significantly (Nyagu 1991, 1993, 1994, 1995, Nyagu & Zazimko 1995, Nyagu *et al.* 1996). Other research found that children who were exposed to thyroid radiation doses above 2 Gy suffered 1.9 times as many mental disorders and 1.6 times as many nervous system disorders as controls (Kurbanova 1998).

According to a longitudinal survey of pregnant women, maternity patients, newborns and children in radiation-contaminated territories of Ukraine (Polesye district of Kiev region, 740-2,200 kBq/m² (20-60 Ci/km²)), Belarus (Chechersk district of Gomel region, 185-2,590 kBq/m² (5-70 Ci/km²)) and Russia (Mtsensk and Volkhov districts of Orel region, 37-185 kBq/m² (1-5 Ci/km²) and 370-555 kBq/m² (10-15 Ci/km²), respectively), the number of congenital abnormalities of the nervous system development in newborns increased. The incidence of perinatal encephalopathy after 1986 was observed in these areas at levels 2-3 times higher than before the accident (Kulakov *et al.* 2001). In Ukraine, prevalence of neurological diseases grew during the 10-year period by more than 80%, from 2,369 per 10,000 children in 1988 to 4,350 per 10,000 children in 1999 (Prysyazhnyuk *et al.* 2002).

Neuropsychological research on the mechanisms of radiation-caused damage to the nervous system showed the presence of cognitive dysfunction involving cortico-subcortical networks and deep brain structures, together with many other changes. These findings are confirmed by a number of experimental and clinical observations (Voloshin *et al.* 1993, Zhavoronkova *et al.* 1993, Nyagu 1993, Nyagu *et al.* 1996, Gourmelon *et al.* 2001).

Neurological and psychiatric disorders among adults were also considerably higher in radiation-contaminated territories (in Belarus, 31.2% against 18.0%). Decreased short-term memory and deterioration of attention activity was observed among high school students aged 16-17 in contaminated territories. The degree of these conditions correlated directly with the levels of radioactive contamination. Comparison of morbidity among rural machine operators (n=340) of Narovlya district of Gomel region in Belarus (heavy contamination) with that of a similar group (n=202) from Minsk suburbs with low radioactive contamination revealed a 6-fold higher (27.1% compared to 4.5%) prevalence of cerebrovascular pathologies in those residing in heavily polluted territories (Ushakov *et al.* 1997). A similar finding was reported by Lukomsky *et al.* (1993): neurological morbidity among 1708 surveyed adults in Kostyukovich district of Mogilev region (contamination density with ¹³⁷Cs over 1,110 kBq/m² (30 Ci/km²)) was noticeably higher than that of 9170 persons from slightly contaminated districts of Vitebsk region.

During the first five years after the Chernobyl catastrophe, marked increases were observed in the incidence of neurological diseases and vasomotor dyscrasia in Ukraine, with a significant increase in vasomotor dyscrasia between 1989 and 1990 and in neurological disease between 1990 and 1991 (Table 3.14.1.).

Year	1987	1988	1989	1990	1991	1992
Neurological diseases	2641	2423	3559	5634	15041	14021
Vasomotor dyscrasia	1277	434	315	3719	3914	3124

Table 3.14.1. Neurological morbidity (per 100 000 of adult population) on Ukrainian territories contaminated after the Chernobyl catastrophe in 1987 – 1992 (Nyagu 1995)

In 1988-1999, disorders of the neurological system and sensory organs in people living in the contaminated territories of Ukraine increased by 3.8-5.0 times (Prysyazhnyuk *et al.* 2002). Among the adult evacuees from Pripyat city and the 30-km zone, the morbidity levels were much higher than the average Ukrainian levels for these disorders (Prysyazhnyuk *et al.* 2002). Morbidity with neurological diseases among adult and adolescent population (including the evacuees) in contaminated territories of Ukraine in 1994 constituted 10.1% of total morbidity, and among children, 6.2% (Grodzinsky 1999).

Overall, based on the findings presented in this chapter, the Chernobyl-related neurological disorders may have affected hundreds of thousands of adults and children in Belarus, Russia, and Ukraine (Table 3.14.2).

Endpoint	Region, population group, effect	Reference
Decrease of performance in mathematics and languages	Children exposed <i>in utero</i> in Norway	Ushakov & Karpov 1997
Neurological and sensory organs morbidity	Among employees of enterprises of the Russian Nuclear Power Ministry, twice higher than in the population of surrounding areas	Yablokov 2000
Cerebrovascular pathology	Six times more frequent in the group of rural machine operators from a contaminated region of Belarus	Ushakov <i>et al.</i> 1997
General neurological morbidity, decreased short-term memory, deterioration of the attention activity	Increased in the contaminated regions of Belarus	Lukomsky <i>et al.</i> 1993

Table 3.14.2. Examples of possible link between the radiation pollution and the neuropsychiatric diseases (Yablokov 2001)

The high incidence of such a diversity of neurological disorders among patients affected by the Chernobyl accident suggests that these diseases may have multiple causes. To fully appreciate them, one needs to consider "the accident factor" – a complex condition in which a person experiencing a global nuclear ecological accident is exposed to ionizing radiation in combination with other ecological hazards (in particular - lead, surfactants and other toxic chemicals applied broadly in post-Chernobyl emergency activities), and to high psychological "catastrophe" stress (high risk level associated with carrying out the emergency activities, evacuation, resettlement, etc.), as well as the necessity of overcoming the social crisis (Nyagu *et al.* 1995, Aleksandrovskij *et al.* 1989, Ilin 1994, Guskova & Buldakov 1996, Rumyantseva *et al.* 1995).

3.15. Mental, Psychological and CNS disorders

The mental health impact of Chernobyl constitutes probably the most widely experienced scientific, public health and social problem. The UN Chernobyl Forum Expert Group “Health” (EGH)(World Health Organisation 2005) has outlined four related areas of concern: stress-related symptoms; effects on the developing brain; organic brain disorders in highly exposed clean-up workers, and suicide. It is currently recognised that the CNS is sensitive to radiation exposure, and degree of its dysfunction can be quantified by electrophysiological, biochemical and/or behavioural parameters. Abnormalities in CNS functions detected by any of these methods may occur even at a low dose of whole body radiation (Gourmelon *et al.* 2005).

Exposure of children in utero: radiation doses, methods of their calculation, and correlation with changes in the postnatal development

Considerable progress has been made in the last decades in understanding the effects of ionizing radiation on the developing brain. Epidemiological studies of individuals who survived the atomic bombing of Hiroshima and Nagasaki and were exposed *in utero* confirmed vulnerability of the developing fetal brain to radiation injury. Severe mental retardation, decrease of intelligence quotient (IQ) and/or worsening of school performance, as well as occurrence of microcephalia and seizures, especially upon the exposure at 8–15 and 16–25 weeks after fertilization, were among the most frequently observed effects (Otake & Schull 1984, Otake & Schull 1998, ICRP Publication 49 1986, Schull & Otake 1999).

Analysis of the dosimetry data indicated that the threshold for the development of mental retardation after intrauterine irradiation at gestation terms of 8–15 weeks is 0.06–0.31 Gy. If exposure occurred at 16–25 weeks of gestation, the threshold level increased to a dose of 0.28–0.87 Gy (Otake *et al.* 1996). The question of the increased lifetime prevalence of schizophrenia in survivors prenatally exposed to atomic bomb radiation is still open to discussion (Imamura *et al.* 1999).

However, direct application of the Japanese data to the Chernobyl situation is hardly possible because Chernobyl accident produced significantly lower overall fetal doses, but a much higher impact on the fetal thyroid due to incorporation of radioactive iodine released from the burning reactor.

In other words, the radiobiological situations in Japan and in Chernobyl were qualitatively and quantitatively different. Thus, adequate predictive models for the next 10-20 years can only be developed for the Chernobyl accident after detailed evaluation of its own impacts over the past 20 years.

Preliminary analysis of the results obtained in the three affected countries - Belarus, Russia, and Ukraine - has shown a tendency towards development of mild mental retardation and some behavioral disorders in the prenatally exposed children, and prevalence of borderline nervous and psychological disorders in their parents (Nyagu *et al.* 1996, Nyagu *et al.* 1998, Kozlova *et al.* 1999, Nyagu *et al.* 2002, Souchkevitch & Tsyb 1996).

Children exposed *in utero* at 16–25 weeks of gestation were found to be at particularly high risk of a range of conditions, including:

- increased incidence of mental disorders and personality disorders due to brain injury or dysfunction - F06, F07;
- disorders of psychological development - F80–F89;
- paroxysmal states (headache syndromes - G44, migraine - G43, epileptiform syndromes - G40);
- somatoform autonomous dysfunction - F45.3; and
- behavioural and emotional disorders of childhood - F90–F99 (Napreyenko & Loganovskaja 2004, Loganovskaja 2005).

In Belarus, exposed children manifested a relative increase of psychological impairment and a lower IQ compared to children in the control groups, but these trends did not seem to be associated with their fetal thyroid exposure doses (Igumnov 1999, Kolominsky *et al.* 1999).

Another study from Belarus reported that thyroid radiation doses exceeding 0.5 Sv for various children groups, from those exposed *in utero* up to those at 1.5 years, caused an overall reduction of intelligence (Bazyltchik *et al.* 2001). Igumnov & Drozdovitch (2000) also found a reduction of the IQ in children exposed *in utero* to higher doses. Other studies of prenatally irradiated children demonstrated a possible correlation between radiation and psychosocial developmental factors (Gayduk *et al.* 1994, Ermolina *et al.* 1996, Nyagu *et al.* 2002). Increased prevalence of specific developmental, speech-language and emotional disorders, as well as a lower mean IQ and more cases of borderline IQ results in prenatally exposed children in Belarus were attributed to social and psychological factors (Gayduk *et al.* 1994). In contrast, a later study demonstrated that children irradiated *in utero* had the highest indices of mental morbidity and were more likely to display borderline intelligence and mental retardation that were linked to prenatal irradiation (Ermolina *et al.* 1996).

Potential links between radiation exposure and levels of thyroid-stimulating hormone (TSH) seems to be of special interest (Nyagu *et al.* 1993, Nyagu *et al.* 1998) (See also chapter 3.4.13). TSH levels tend to increase once fetal thyroid exposure dose reaches a threshold of 0.3 Sv. Radiation-induced malfunction of the thyroid-pituitary system was suggested as an important biological mechanism underlying development of mental disorders in prenatally irradiated children (Nyagu *et al.* 1996a,b, Nyagu 1998). It was hypothesized that the left hemisphere of the brain (limbic-reticular structures) is more vulnerable to prenatal irradiation than the right one (Loganovskaja & Loganovsky 1999).

The following findings were observed in prenatally exposed group of children:

- IQ performance/verbal discrepancies with verbal decrements;
- a higher frequency of low-voltage and epileptiform EEG patterns and left hemisphere lateralised dysfunction;
- an increase ($p < 0.001$) of δ - and β -power and a decrease ($p < 0.001$) of α - and θ -power; and
- an increased incidence of paroxysmal and organic mental disorders, somatoform autonomic dysfunction, disorders of psychological development, and behavioral and emotional disorders.

Cerebral dysfunction of exposed children was etiologically heterogeneous (Nyagu *et al.* 2002a).

Using the model described in ICRP Publication 88, a strong correlation was discovered between foetal gestational age and the thyroid exposure *in utero*. In simple terms, the later the intrauterine period of development at the time of exposure, the higher the foetal thyroid dose (Nyagu *et al.* 2004).

On account of the contradictory results of the mental health assessments of the *in utero* exposed children and the etiology of the observed neuropsychiatric disorders in the literature, a thorough study of the potential radiation effects on the mental health of the *in utero* exposed children was performed within the framework of Project 3 (Health Effects of the Chernobyl Accident) of the French-German Initiative for Chernobyl. A cohort of 154 children born between April 26th, 1986 and February 26th, 1987 to mothers who had been evacuated from Pripyat to Kiev, and 143 classmates from Kiev, were examined using the Wechsler Intelligence Scale for Children (WISC), the Achenbach test and the Rutter A(2) test. Mothers were tested for their verbal abilities (WAIS), depression, anxiety and somatization (SDS, PTSD, GHQ 28). Individual dose reconstruction of the children was carried out considering internal and external exposure. ICRP Publication-88 was applied for calculation of effective foetal, brain and thyroid internal doses for children of both groups. Of 52 children from Pripyat (33.8%) who had been exposed *in utero* to equivalent thyroid doses >1 Sv, 20 (13.2%) had been exposed *in utero* to foetal doses >100 mSv. The prenatally exposed children show significantly more mental disorders and diseases of the nervous system. Exposed children showed lower full-scale IQ due to lower verbal IQ and therefore an increased frequency of performance/verbal intelligence discrepancies. When IQ discrepancies of the prenatally irradiated children exceeded 25 points, there appeared to be a correlation with the fetal dose. The exposed and control mothers did not show differences in verbal abilities, but conditions such as depression, PTSD, somatoform disorders, anxiety/insomnia, and social dysfunctions were all more common in exposed than in control mothers from Kiev (Nyagu *et al.* 2004a,b,c).

The radioneuroembriological effect — intelligence disharmony due to verbal IQ deterioration — has been revealed at the radiation accident on the nuclear reactor (at 8–15 and later weeks of gestation, fetal >20 mSv and thyroid doses in utero >300 mSv. Spectral θ -power decrease (particularly, in the left fronto-temporal area), β -activity increase together with its lateralization towards the dominant hemisphere, disorders of normal interhemispheric asymmetry of visual evoked potentials, the vertex-potential can be considered as the neurophysiological markers of prenatal exposure. The most critical period of cerebrogenesis at the radiation accident on the nuclear reactor, resulted radioactive iodine release into the environment, are the later terms of gestation (16–25 weeks) than that at uniform external exposure (Loganovskaja & Nechayev 2004, Loganovskaja 2004 & 2005).

A follow-up study is currently underway, funded by the US National Institutes of Health (NIH), to examine the health and mental health of a cohort of 18-19 year olds, who were exposed at the age range from *in utero* development up to 15 months old when the accident occurred, and were at the age of 11 years at the time of their first assessment.

Mental health of prenatally exposed children

The current concept about prenatal brain exposure effects stipulates that 1 Sv of foetal exposure at 8–15 weeks of gestation reduces IQ score of a child by 30 points. Correspondingly, it can be assumed that every 100 mSv of prenatal irradiation may be expected to decrease IQ score by no more than 3 points. The excess of severe mental

retardation is 0.4 per 1 Sv at 8–15 weeks and, to a lesser extent, at 16–25 weeks of gestation (European Commission Radiation Protection 100, 1998). Thus, the evidence-based radioneuroembriologic effects in humans range from dose-related intelligence reduction up to mental retardation, microcephalia and seizures.

Intelligence of exposed children from Pripjat evaluated through a standard IQ test significantly differed from that of the control group from Kiev (Table 3.15.1.), including:

- Increased incidence of low IQ (IQ<90), especially in the verbal IQ portion;
- 2 times increase in incidence of average IQ (scores of 91–110) and more than 3 times decrease in incidence of high IQ (scores of 121–140);
- Increased frequency of IQ score discrepancies: about 14% of the exposed and 4.5% of the control children had IQ discrepancies of >25 points from expected, indicating a disharmoniously developed intelligence.

Index	Exposed group (Prypyat, n=108)	Control group (Kiev, n=73)	t	P
Full scale IQ				
M±SD	112.9±13.3	118.6±10.8	–3	<0.003
Median	112	120		
Min-Max	76–151	96–137		
Verbal IQ				
M±SD	106.7±13.2	115.8±13.2	–4.5	<0.001
Median	108	116		
Min-Max	70–143	85–138		
Performance IQ				
M±SD	117.2±15.2	118.7±9.6	–0.7	>0.05
Median	119	121		
Min-Max	74–153	97–140		
IQ discrepancies pIQ–vIQ				
M±SD	10.4±14.7	2.9±12.5	3.6	<0.001
Median	10	3		
Min-Max	–29–(+54)	–22–(+33)		
Paired t-test	7.4	1.9		
P	<0.001	>0.05		

Table 3.15.1. IQ scores of children without moderate to very severe confounding factors

The children of the control group demonstrated a similar distribution of verbal and performance IQ scores (Figure 3.15.1.). However, the distribution of the IQ values of the exposed children (verbal and performance IQ) showed distinctive differences. Verbal and performance IQ curves plotted separately revealed that the exposed children had a lower verbal IQ throughout the whole cohort: the distribution started at lower levels and never reached the distribution level of the control children (Figure 3.15.2.).

There was no clear relationship between intelligence and the periods of cerebrogenesis as of April 26 1986 in children with or without moderate to very severe confounding factors.

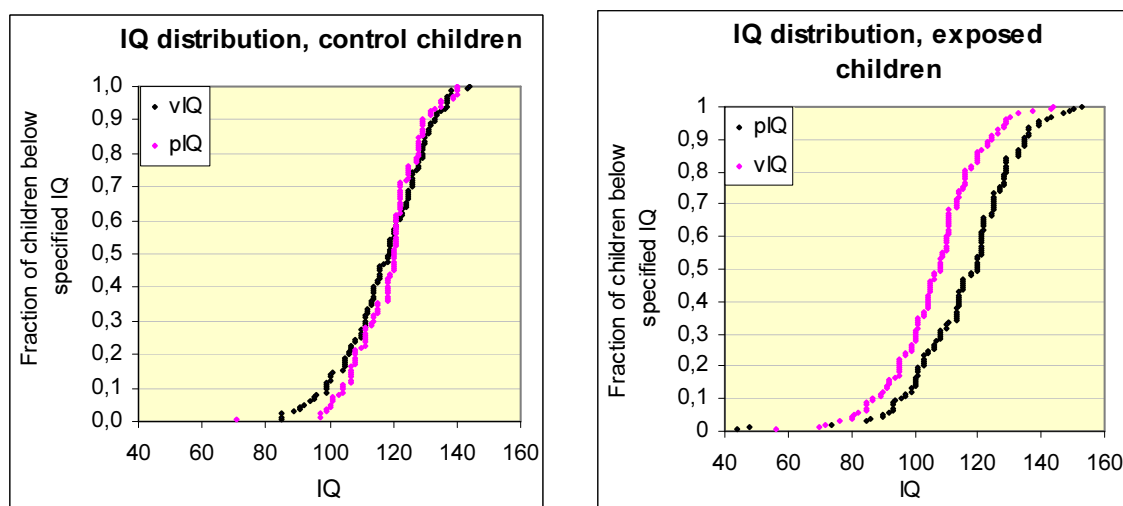


Figure 3.15.1. Fraction of control and exposed children below specific verbal and performance IQ.

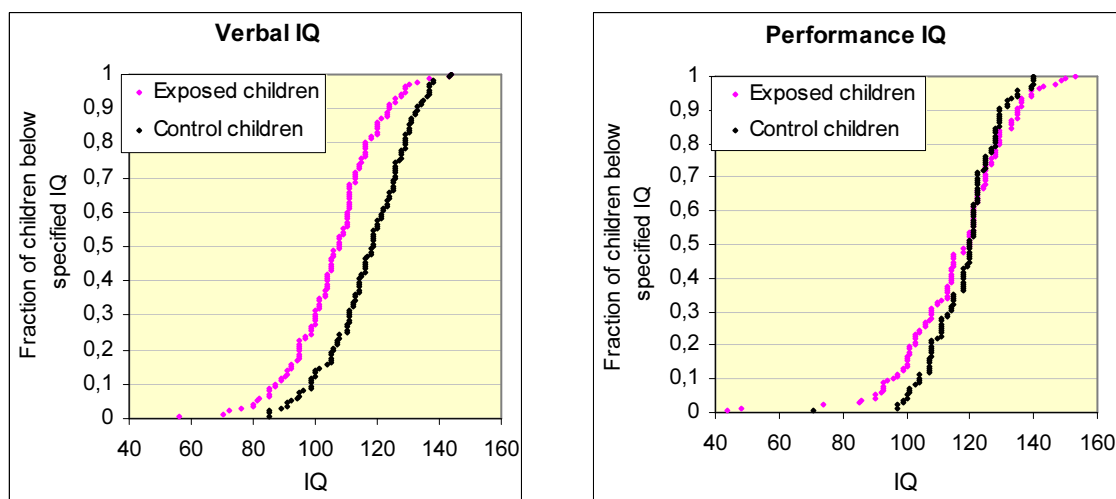


Figure 3.15.2. Fraction of control and exposed children below specific IQ differentiated by verbal and performance IQ scores

In addition to lower IQ scores, prenatally exposed children experienced higher incidence of neuro-psychiatric disorders than the control children. Among those without moderate to very severe confounding factors, children irradiated *in utero* had even more neuro-psychiatric disorders compared to the control children (Table 3.15.2.).

Disease or disorder	Exposed children (n=121)	Control children (n=77)	χ^2	p
Diseases of the Nervous System				
Neurologically healthy	73 (60.3%)	66 (85.7%)	14.5	<0.001
Unconfident indication of epilepsy (G40)	9 (7.4%)	1 (1.3%)	3.7	<0.05
Migraine (G43)	3 (2.5%)	0	1.9	>0.05

Other headache syndromes (G44)	31 (25.6%)	10 (13%)	4.6	<0.05
Sleep disorders (G47)	4 (3.3%)	0	2.6	>0.05
Other disorders of autonomous nervous system (G90)	3 (2.5%)	0	1.9	>0.05
Neurological comorbidity	2 (1.6%)	0	1.3	>0.05
Mental and Behavioral Disorders				
Mentally healthy	19 (15.7%)	45 (58.4%)	39.3	<0.001
Organic mental disorders (F06 & F07)	20 (16.5%)	3 (3.9%)	7.3	<0.01
Neurotic, stress-related and somatoform disorders (F40–F48)	56 (46.3%)	20 (26%)	8.2	<0.01
Non-organic sleep disorders (F51)	6 (4.9%)	3 (3.9%)	0.12	>0.05
Mental retardation (F70)	1 (0.8%)	0	0.64	>0.05
Disorders of psychological development (F80–F89)	9 (7.4%)	0	6	<0.05
Childhood behavioral and emotional disorders (F90–F98)	31 (25.6%)	9 (11.7%)	5.7	<0.05
Mental comorbidity	21 (17.2%)	3 (3.9%)	8	<0.01

Table 3.15.2. Diseases of the Nervous System (G) and Mental and Behavioural Disorders (F) according to the ICD-10 in children without moderate to very severe confounding factors

There were no differences in verbal IQ results between mothers of the two groups. Thus, the deterioration of the verbal IQ of the exposed children cannot be explained by the influence of the verbal IQ scores of their mothers.

Irradiation in infancy and childhood

Similar observations may be applicable to other areas of healthcare dealing with relatively low radiation exposure levels. It has become increasingly clear that CNS radiotherapy in infancy and childhood may have serious long-term effects on cognition and endocrine function. As the treatment of childhood cancer has improved, long-term survival has become more common (Anderson, 2003). Currently, it is still assumed that the lowest dose on the brain which may be associated with late deterministic effects of childhood irradiation is 18 Gy, resulting in disorders of cognitive function, histopathological changes and neuroendocrine effects (UNSCEAR 1993).

It must be recognised, however, that delayed radiation brain damage has been reported among a cohort of 20,000 Israeli children 20 years after childhood scalp irradiation (X-ray irradiation for ringworm (*Tinea capitis*) management), in which they received an average dose to the brain of only 1.3 Gy (Yaar *et al.* 1980 & 1982, Ron *et al.* 1982).

More recently, effects of low doses of ionizing radiation (>100 mGy) in infancy (radiotherapy of cutaneous haemangioma) on cognitive function in adulthood have been reported in a cohort study in Sweden (Hall *et al.* 2004).

Thus, radiation exposure in infancy and childhood is associated with dose-dependant cognitive decline in adulthood. The reported radiation dose thresholds for delayed brain damage may be as low as 0.1–1.3 Gy to the brain in infancy and childhood. Further research is warranted for reassessment of the risk-benefit ratio of long-term consequences of cranial radiotherapy in infancy and childhood. Intellectual development can be adversely affected when the infant brain is exposed to ionising radiation at doses in the region of 100 mGy. For comparison, computed tomography of the skull produces approximately 120 mGy (Hall *et al.* 2004).

Mental and CNS disorders of adults

There is a gap in knowledge concerning evidence-based estimates of radiation effects on mental health. Opinions concerning neuro-psychiatric effects of low dose (<1 Sv) exposure are contradictory.

According to information presented in the Report of the UN Chernobyl Forum EGH, increased levels of depressive, anxiety (including post-traumatic stress symptoms), and medically unexplained physical symptoms have been found in Chernobyl-exposed populations compared to controls (Viinamaki *et al.* 1995, Havenaar *et al.* 1997a, Bromet *et al.* 2000). Exposed populations exhibited symptoms of anxiety twice as frequently as unexposed populations. People experiencing the Chernobyl disaster were 3-4 times more likely to report multiple unexplained physical symptoms and subjective poor health (Havenaar *et al.* 1997b, Allen & Rumyantseva 1995, Bromet *et al.* 2002).

Mental health consequences for the general population were mostly subclinical and did not reach the level satisfying criteria for a psychiatric disorder (Havenaar *et al.* 1997b). An epidemiological study in the Gomel region (Belarus) observed that 64.8% of the population sample (n=1617) had a GHQ-12 score above the threshold of 2 (presence of psychological distress). DSM-III-R psychiatric disorders were found in 35.8% of population (n=265), with especially high rates for affective (16.5%) and anxiety disorders (12.6%). A higher prevalence of mental health problems was observed among people evacuated from the Chernobyl exclusion zone (66.9%, Odds Ratio (OR) 3.78), and in mothers with children under 18 years of age (53.5%, OR 2.84). All mental problems in the examined population were attributed to stress (Havenaar 1996, Havenaar *et al.* 1995, 1996). However, these subclinical symptoms had important consequences for health behavior, specifically medical care utilization and adherence to safety advisories (Havenaar *et al.* 1997a, Allen & Rumyantseva, 1995). To some extent, these symptoms were driven by the belief that their health was adversely affected by the disaster, and by the fact that they were diagnosed by a physician with a “Chernobyl-related health problem” (Bromet *et al.* 2002, Havenaar *et al.* 2003). Notwithstanding this possible cause, the symptoms experienced are no less distressing for the individual.

Disorders among liquidators

The clean-up workers (“liquidators”) of the Chernobyl accident are under the highest risk of neuro-psychiatric disorders due to their greatest exposure to both the radiation and the other factors of the disaster aftermath.

Personnel of the Chernobyl exclusion zone who have been working since 1986 were the highest risk group for neuropsychiatric disorders (93—100% of population affected). Organic,

including symptomatic, mental disorders (F00—F09) were predominant. Work and life in the Chernobyl exclusion zone since 1986 for ten or more years were associated with probability of mental health deterioration 3.4-6.2 times higher in comparison with general population, and 2-3.9 times higher in comparison with survivors of military conflicts or natural disasters. Mental health deterioration in the Chernobyl personnel was related to (a) their exposure dose and (b) duration of work in the Chernobyl exclusion zone, pointing to a potentially cumulative effect (Loganovsky 1999). In a considerable proportion of the personnel, especially those who continued their work in the 1990s, pathology met the criteria of Chronic Fatigue Syndrome (CFS), leading to suggestions that CFS may be developing under the combined impacts of low or very low doses and psychological stress (Loganovsky *et al.* 1999, Loganovsky 2000b).

In terms of specific categories of effect, organic (ICD-10: F03, F06, F07), somatoform (F45), schizotypal (F21), affective (dysthymia) (F34.1) and enduring personal changes after catastrophic experience (F62.0) were all observed in liquidators. Post-traumatic stress disorder (PTSD), psychosomatic, organic, and schizoid abnormal developments of personality were documented according to local psychiatric classification, ICD-10, and DSM-IV criteria (Loganovsky 2002).

A total of 26 of 100 randomly selected liquidators with fatigue met the CFS diagnostic criteria. Their absorbed doses were estimated to be <0.3 Sv.

CFS may therefore be one of the most widespread consequences of the radioecological disaster, resulting from an interaction of several hazardous environmental factors (Loganovsky 2000b, 2003). Moreover, although CFS prevalence significantly ($p<0.001$) decreased (from 65.5% in 1990–1995 to 10.5% in 1996–2001), prevalence of Metabolic Syndrome X (MSX) significantly ($p<0.001$) increased in the same period (from 15 to 48.2%). CFS and MSX are considered to be the first stages of other neuropsychiatric and/or physical pathology development, and CFS can transform into MSX (Kovalenko & Loganovsky 2001). Thus, CFS in these patients can be viewed as a sign of forthcoming neurodegeneration, cognitive impairment, and neuropsychiatric disorders (Volovik *et al.* 2005).

In Ukraine, a cross-sectional study of representative cohort of liquidators (the Franco-German Chernobyl Initiative sub-project 3.8.1 'The database on psychological disorders in the Ukrainian liquidators of the Chernobyl accident') was conducted using a standardized structured psychiatric interview questionnaire — the Composite International Diagnostic Interview (CIDI). Preliminary results showed an almost two-fold increase in the prevalence of all mental disorders (36%) in liquidators compared with the Ukrainian general population (20.5%), and a dramatic increase in depression prevalence in liquidators (24.5%) compared to the general population of Ukraine (9.1%) (Demyttenaere *et al.* 2004, Romanenko *et al.* 2004). Analysis of these results continues. Anxiety (panic disorder) was also increased in liquidators (12.6% vs 7.1%). At the same time, alcohol dependence among liquidators was not much higher than that of the total population, 8.6% vs 6.4% (Romanenko *et al.* 2004), ruling out a major contribution from this factor.

Radiation risks of non-cancer effects in Chernobyl liquidators have been calculated during the last five years (Biryukov *et al.* 2001, Buzunov *et al.* 2001, 2003). For some non-cancer diseases among liquidators, estimates of excess relative radiation risk (ERR) were derived for the first time for the following conditions: mental disorders with ERR 1/Gy=0.4 (95% CI, 0.17; 0.64); neurologic and sensory disorders with ERR 1/Gy=0.35 (0.19; 0.52); endocrine

disorders with ERR 1/Gy=0.58 (0.3; 0.87). In mental disorders, higher radiation risks were calculated for neurotic disorders: ERR = 0.82 (0.32; 1.32) (Biryukov *et al.* 2001). The highest excess relative risk per 1 Gy was found for cerebrovascular diseases, at 1.17 (0.45; 1.88) (Ivanov *et al.* 2000). Recently, the significant cerebrovascular diseases risk from averaged dose rate was defined for external doses >150 mGy (ERR for 100 mGy/day = 2.17, with 95% CI = (0.64; 3.69) (Ivanov *et al.* 2005).

Mental health assessment of liquidators has significant limitations. For a start, researchers mostly deal with mental disorders registered in the national healthcare system, not with the data obtained from well-designed psychiatric studies with standardized diagnostic procedures. Together with the ongoing changes of the psychiatric system in the post-Soviet countries, this may lead to dramatic underestimation of mental disorders.

For example, according to the official Public Health Ministry of Ukraine data, the prevalence of all mental disorders (registered) in the Ukrainian population was 2.27% in 1990, 2.27% in 1995 and 2.43% in 2000. However, according to the results of the World Health Organization (WHO)-sponsored World Mental Health (WMH) Survey Initiative, where the WMH version of the WHO Composite International Diagnostic Interview (WMH-CIDI) was used, the prevalence of any WMH-CIDI/DSM-IV disorder in Ukraine was 20.5% (95% CI, 17.7–23.3%) (Demyttenaere *et al.* 2004). Based on this discrepancy, it is possible to estimate that the national Ukrainian psychiatric system may underestimate the frequency of mental disorders by ~10 times. The WMH-CIDI/DSM-IV disorders included so-called psychological disorders (anxiety, depression, somatization, alcohol abuse, etc.) only, and did not take into account severe mental disorders such as psychoses, organic mental disorders, and mental retardation.

According to data from the Russian Medical-Dosimetric Register, the incidence of psychiatric disease takes the 5th place among liquidators (Ivanov, Tsyb 1999) However, according to data from the Expert Councils which investigate the connection between illness and exposure to Chernobyl-derived radiation, the portion of psychiatric disorders is even higher (Khrisanov, Meskih 2001, 2004).

More than 2,000 liquidators from various Russian regions have been observed over many years. Over 40% have been found to be suffering from organic cerebral diseases of vascular or mixed origin. These cerebral diseases result from long lasting cerebral ischemia. This occurs as a result of disruption of central regulatory functions and from possible damage to the endothelium of small blood vessels (Rumyantseva *et al.* 1998, Rumyantseva & Chinkina 1998, Soldatkin 2002).

Threshold doses of radiation exposure for various mental conditions

Some deterministic radiation effects in the central nervous system (CNS) can be caused not only by cell (neuron) damage, but by interactions with functions of other tissues as well. Such ‘functional deterministic effects’, in particular, include changes of electroencephalogram (EEG) and retinogram, and vascular reactions. These effects can have significant clinical consequences, particularly for the nervous system (ICRP Publication 60, 1991). In spite of the fact that the mature CNS is commonly considered to be resistant to radiation exposure, there is a growing body of evidence in support of radiosensitivity of the brain (Nyagu & Loganovsky 1998).

Morphological injuries of the CNS could develop following local brain exposure of 10–50 Gy. The brain tolerable dose was assumed to be 55–65 Gy, and the tolerable fractional dose - 2 Gy (Guskova & Shakirova 1989, Gutin *et al.* 1991, Mettler & Upton 1995). Brain necrosis was observed after local brain exposure at doses of ≥ 70 Gy, and development of radiogenic dementia was considered to be possible. Primary CNS damage following total body irradiation was considered to be possible at exposure doses of >100 Gy, causing the cerebral form of Acute Radiation Sickness (ARS). Secondary radiation CNS damage may occur at doses of 50–100 Gy (the toxemic form of ARS) (Guskova & Bisogolov 1971). The threshold of radiation-induced neuroanatomic changes was assumed to be at the level of 2–4 Gy of whole body irradiation (Guskova & Shakirova 1989).

Exposure to a dose of >250 mGy was a significant risk factor for neuropsychiatric and vascular disorders. Thyroid exposure to 300 mGy and more was a significant risk factor for vascular and cerebrovascular disorders. When thyroid exposure exceeded 2 Gy, this created a significant risk for development of mental, vascular and cerebrovascular diseases, and disorders of peripheral nervous system. Confounding non-radiation risk factors for neuropsychiatric (cerebrovascular) pathology included industrial hazards, stress, smoking, hereditary factors and lifestyle (Buzunov *et al.* 2001, Buzunov 2003).

In the early experimental studies *in vitro* and *in vivo* conducted 40–45 years ago, morphological changes of neurons were observed at doses as low as 0.25–1 Gy of total irradiation (Alexandrovskaia 1959, Shabadash 1964). A dose of 0.5 Gy has long been accepted as a threshold of radiation injury of the CNS with the primary neuronal damages (Lebedinsky & Nakhilnitskaja 1960). Persistent changes in the brain bioelectrical activity occurred at thresholds of 0.3 - 1 Gy and increased directly proportionally to the dose absorbed (Trocherie *et al.* 1984).

These and other data suggest that alterations in CNS functioning could occur after exposure to relatively low doses of radiation (Mickley 1987). Exposure to ionizing radiation significantly modified the neurotransmission in a dose-dependant manner (Kimeldorf & Hunt 1965), resulting in multiple biochemical events in the brain and behavioral effects (Hunt 1987). In addition to direct effects, ionizing radiation can modify CNS functions and behavior indirectly through the CNS reactivity to the radiation damage of other systems (Kimeldorf & Hunt 1965, Mickley 1987). Slowly progressive CNS radiation sickness was observed following a single exposure to total irradiation of 1–6 Gy (Moscalev 1991). Similarly, the UNSCEAR Report (1982) described a slowly progressive degeneration of brain cortex that developed after an exposure to 1–6 Gy (Vasulescu *et al.* 1973).

The EEG-patterns and topographical distribution of spontaneous and evoked brain bioelectrical activity in overexposed liquidators, especially in long-term workers of the Chernobyl zone, significantly deviated from the same tests results in the control and comparison groups (Nyagu *et al.* 1992, 1999, Noshchenko & Loganovskii 1994, Loganovsky 2000). There were many consistent reports about characteristic neurophysiological (Danilov and Pozdeev 1994, Zhavoronkova *et al.* 1994, 1995a,b, 1998, Vyatleva *et al.* 1997), neuropsychological (Khomskaia 1995, Zhavoronkova *et al.* 1996, 2000), and neuroimaging (Zhavoronkova *et al.* 1994, Kharchenko *et al.* 1995, Kholodova *et al.* 1996, Voloshina 1997) abnormalities in liquidators, supporting clinical data about radiation-caused organic brain damage (Chuprikov *et al.* 1992, Krasnov *et al.* 1993, Romodanov & Vynnyts'kyj 1993, Napreyenko & Loganovsky 1995, 1997, 1999, 2001a,b, Nyagu & Loganovsky 1998, Revenok 1998, 1999, Zozulya *et al.* 1998, Morozov & Kryzhanovskaja 1998, Lysyanyj

1998). Changes in brain asymmetry and interhemispheric interaction can be produced not only by a dysfunction of subcortical limbic-reticular and mediobasal brain structures, but also by damage to the white matter, including the corpus callosum (Zhavoronkova *et al.* 2000). The EEG findings suggested subcortical disorders at different levels (diencephalic or brainstem) and functional failure of the right or left hemispheres long after radiation exposure has ceased (Zhavoronkova *et al.* 2003).

Increased rates of neuropsychiatric disorders and somatic pathology were observed in liquidators of 1986-1987, especially in those who have worked for 3-5 years within the Chernobyl exclusion zone. Prevalence of neuropsychiatric disorders among Chernobyl clean-up personnel of 1986-1987 who received doses >250 mSv was 80.5%, while their colleagues irradiated with doses <250 mSv had an almost four times lower prevalence rate of 21.4% ($p<0.001$) (Bebeshko *et al.* 2001, Nyagu *et al.* 2003). Chernobyl personnel working since 1986 constituted the highest risk group for development of neuropsychiatric disorders, among which organic (including symptomatic) mental disorders (F00—F09) dominated (Loganovsky 1999).

Chernobyl exposure significantly affected various cognitive endpoints. A 4-year longitudinal study of the cognitive effects of the Chernobyl nuclear accident was conducted in 1995-1998. The controls were healthy Ukrainians residing several hundred kilometres away from Chernobyl. The exposed groups included liquidators, forestry and agricultural workers living within 150 km of Chernobyl. Accuracy and efficiency of cognitive performance were assessed using ANAMUKR, a specialized subset of the Automated Neuropsychological Assessment Metrics (ANAM) battery of tests. Analyses of variance, followed by appropriate paired comparisons, indicated that, for the majority of measures, the 4-year averaged levels of performance of the exposed groups (especially the liquidators) were significantly lower than those of the controls. Longitudinal analyses of performance revealed significant declines in accuracy and efficiency, as well as psychomotor slowing, for all exposed groups over the 4-year period. These findings strongly indicate impairment of brain function resulting from both acute and chronic exposure to ionizing radiation (Gamache *et al.* 2005).

The EEG-patterns of liquidators differed significantly from those of the control groups (Loganovsky & Yuryev, 2001). Among Chernobyl accident survivors who had a confirmed ARS diagnoses and were irradiated at the dose of 1–5 Sv, neurophysiological markers of ionizing radiation were discovered (Loganovsky & Yuryev 2004). The relationship between neurophysiological effects and radiation dose was detected only at the doses >0.3 Sv suggested as the threshold for these effects (Loganovsky 2000–2002). Above this dose, a ‘dose–effect’ relationship was observed between dose and characteristic morphometric neuroimaging features of organic brain damage (Bomko 2004). In some cases, organic brain damage has been verified by clinical neuropsychiatric, neurophysiological, neuropsychological, and neuroimaging methods (Loganovsky *et al.* 2003 & 2005b). The cerebral bases of deteriorations in higher mental activity resulting from such disorders following a limited period of irradiation are pathology of the frontal and temporal cortex of the dominant hemisphere and of middle structures with their cortical-subcortical connections (Loganovsky 2002, Loganovsky & Bomko 2004 & 2005).

Neuropsychiatric and neuropsychophysiological follow-up studies confirmed that ARS patients who survived after the Chernobyl disaster showed progressive structural-functional brain damage, including post-radiation encephalopathy (post-radiation organic brain syndrome) along with other symptomatological mental disorders (Nyagu & Loganovsky

1998). To date, post-radiation organic brain syndrome has been reported in 62% of patients who had a confirmed ARS. The apathetic type of organic personality disorder (F07.0) was typical for ARS after-effects. It had a progressive clinical course and correlated with the severity of ARS and the dose of exposure. The apathetic type of organic personality disorder was typical for moderate to severe ARS consequences (Loganovsky 2002). Organic brain damage in the remote period of ARS was verified by clinical neuropsychiatric, neurophysiological, neuropsychological, and neuroimaging methods (Loganovsky *et al.* 2003).

In the Adult Health Study in Hiroshima, no significant association was found between exposure to atomic bomb and vascular dementia or Alzheimer's disease detected 25 to 30 years later. Instead, risk factors for dementia were patient's age, higher systolic blood pressure, history of stroke, hypertension, head trauma, lower milk intake and lower education (Yamada *et al.* 1999, 2003). However, the same Adult Health Study discovered a statistically significant effect of ionizing radiation on the longitudinal trends of both the systolic and the diastolic blood pressure, the major contributor to development of dementia. This phenomenon is compatible with the degenerative effect of ionizing radiation on blood vessels (Sasaki *et al.* 2002). The recent analyses confirmed earlier findings of a correlation between non-cancer mortality and atomic bomb radiation dose. In particular, increasing trends were observed for cardiovascular diseases (Shimizu *et al.* 1999). This can be viewed as direct evidence of radiation effects in doses equal to or more than 0.5 Sv for cardiovascular (including stroke), digestive, and respiratory diseases (Preston *et al.* 2003).

Epidemiological studies of the atomic bomb survivors have reported dose-related increases in mortality from diseases other than cancer. Increased cardiovascular mortality and morbidity was associated with radiation dose (Kusunoki *et al.* 1999). The non-cancer effects in the atomic-bomb survivors were observed at doses of ~0.5 Sv (half the dose level considered as a threshold in earlier studies), which should stimulate interest to deterministic effects and non-cancer morbidity and mortality following the Chernobyl accident (Shimizu *et al.* 1999, Fry 2001, Preston *et al.* 2003, Yamada *et al.* 2004). However, the current epidemiological data do not provide clear evidence of a risk of cardiovascular diseases at the dose range of ionizing radiation of 0-4 Sv. Further research is needed to characterize the possible risk (McGale & Darby 2005).

Ionizing radiation and schizophrenia

In Japan, atomic bomb exposure is known to have affected mental health of many survivors, and the care of their mental health was considered to be of high importance (Honda *et al.* 2002). The prevalence of anxiety symptoms and somatization symptoms was still elevated in atomic bomb survivors some 17-20 years after the bombings had occurred, indicating the long-term nature of the psychiatric effects (Yamada & Izumi 2002). However, these studies were related to neurotic symptoms only — anxiety and somatization. At the same time, the cross-reference of The Life Span Study database and the schizophrenia register in the Department of Neuropsychiatry, University School of Medicine, Nagasaki, revealed that the prevalence of schizophrenia in A-bomb survivors was very high, at 6% (Nakane & Ohta 1986).

Current estimates of lifetime prevalence of schizophrenia in general population groups vary from 0.9 to 6.4 with an estimated mean prevalence of 1.4–4.6 per 1,000 (Jablensky 2000). In the WHO-sponsored 10-country study (Jablensky *et al.* 1992), the incidence rate of schizophrenia in Honolulu (USA) was 1.6 and in India, 4.2 per 10,000 population (McGrath

et al. 2004). The incidence of schizophrenia in India was the highest worldwide, and could not be explained by an inadequate psychiatric care alone (Tsirkin 1987). India has areas of high natural radiation background due to monazite sands in Kerala, Madras, and Ganges delta, which result in high average absorbed dose rate in air of $1,800 \text{ nGy}\cdot\text{h}^{-1}$ (UNSCEAR 2000). The coastal belt of the Trivandrum and Quilon districts of Kerala has a very high natural radioactivity, over 15 mSv per year (Rajendran *et al.* 1992). Worldwide annual exposures to natural radiation sources would generally be expected to be in the range 1–10 mSv, with 2.4 mSv being the present estimate of the central value (UNSCEAR 2000).

Since 1990 a significant increase in schizophrenia incidence was reported among the Chernobyl exclusion zone personnel compared to the general population (5.4 per 10,000 in the EZ versus 1.1 per 10,000 in the Ukraine in 1990) (Loganovsky & Loganovskaja 2000).

According to the neural diathesis-stressor hypothesis, development of genetically predisposed schizophrenia can be stimulated by certain environmental stressors. This event is considered as a model of the ionizing radiation effects. There are compatible reports on increases in schizophrenia spectrum disorders following exposure to ionizing radiation from a range of sources, including atomic bombs, nuclear weapons testing, the Chernobyl accident, environmental contamination by radioactive waste, radiotherapy, and in areas with naturally high background radioactivities (Loganovsky *et al.* 2004a, 2005a). The results of experimental radioneurobiological studies support the hypothesis of schizophrenia as a neurodegenerative disease (Korr *et al.* 2001, Gelowitz *et al.* 2002, Schindler *et al.* 2002). Exposure to ionizing radiation causes brain damage, with cortical-limbic system dysfunction and impairment of informative processes at the molecular level, that can trigger schizophrenia in predisposed individuals or cause schizophrenia-like disorders (Loganovsky *et al.* 2004a, 2005a).

Suicides

Suicides were the leading cause of death among liquidators living in Estonia after the Chernobyl accident (Rahu *et al.* 1997). Age-adjusted mortality from suicide was also increased among the Chernobyl clean-up workers compared to the general population in Lithuania (Kesminiene *et al.* 1997). These findings have to be replicated in studies of clean-up workers from other countries using standardized methodology for suicides to ensure compatible output.

In summary, the complex of stressful events unleashed by the accident, including the self-fulfilling consequences of the official label ‘Chernobyl victim’ given to the affected population, the multiple stressor events that occurred in the former Soviet Union before and after Chernobyl, and the culture-specific ways of expressing distress, make medical (including psychological) findings difficult to interpret precisely. At the same time, a growing pool of information on cerebral/CNS effects of low-dose radiation has been obtained in recent years. This includes:

- non-cancer effects in the atomic bomb survivors at doses of 0.5 Sv (Shimuzu *et al.* 1999, Preston *et al.* 2003);
- epidemiological evidence of dose-related cognitive decline following radiotherapy in childhood with possible threshold for delayed radiation brain damage at brain

exposure doses as low as 0.1–1.3 Gy (Yaar *et al.* 1980, 1982, Ron *et al.* 1982, Hall *et al.* 2004);

- cognitive and emotional-behavioral disorders (WHO 1996, Nyagu *et al.* 1998, 2002a, Kolominsky *et al.* 1999, Loganovskaja & Loganovsky 1999, Igumnov & Drozdovitch 2000);
- neurophysiological abnormalities in prenatally exposed children (Nyagu *et al.* 1996a,b, 1998, 2002a, Loganovskaja & Loganovsky, 1999);
- post-radiation organic brain syndrome in ARS patients (Nyagu *et al.* 2002b, Loganovsky 2002) and characteristic neurophysiological, neuropsychological, and neuroimaging abnormalities in liquidators, supporting clinical neuropsychiatric data about organic brain damage following exposure to doses of >0.3 Sv manifesting in the left fronto-temporal limbic dysfunction and schizophreniform syndrome (Loganovsky 2000a & 2002, Loganovsky & Loganovskaja 2000);
- Chronic Fatigue Syndrome (CFS) at exposure to low and very low radiation doses combined with psychological stress (Loganovsky *et al.* 1999, Loganovsky 2000b);
- indications of schizophrenia and related disorders (Nakane & Ohta 1986, Imamura *et al.* 1999, Loganovsky & Loganovskaja 2000, Loganovsky *et al.* 2004 & 2005)

These effects associated with exposure to low-level ionising radiation require further investigation, including research on their biological mechanisms at various levels, from molecular to whole organism.

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4. HEALTH PROBLEMS IN OTHER COUNTRIES THAN UKRAINE, RUSSIA AND BELARUS

Although the greatest environmental contamination and human health impacts of the Chernobyl accident were felt by Ukraine, Belarus and Russia, other countries were by no means free from contamination. A major part (estimates vary from 53 to 67 %; Fairlie & Sumner, 2006) of all Chernobyl caesium-137 fell out outside Belarus, Ukraine and Russia, principally in other European countries Table 4.1. below summarises maximal ^{137}Cs concentrations recorded in other countries. This includes the lingering global contamination baseline of 2-4 kBq/m² arising from atmospheric nuclear weapons tests, which were mostly carried out in 1961 and 1962 (UNSCEAR 2000).

Country (region)	Maximum concentration (kBq/m ²)	Reference
Greece	35-65	Simopoulos 1989, Kritidis <i>et al.</i> 1990
Austria, Sweden, Finland, Norway, Slovenia, Poland, Romania, Hungary, Switzerland, Czech Republic & Greece	40-185	De Cort 2001
UK (Scotland, Wales, NW & SW England), Italy, Estonia, Slovak Republic, Eire, Germany & France	10-40	De Cort 2001
Latvia, Denmark, Netherlands, Belgium & Lithuania	2-10	De Cort 2001
Spain & Portugal	<2	De Cort 2001
France (Alpes de Provence)	~45	CRIIRAD & Paris 2002
France (Corsica)	>20	CRIIRAD & Paris 2002
Israel (centre of country)	115 Bq/kg	Neeman & Steiner (2001)
Israel (Golan heights)	38.0 Bq/kg	Neeman & Steiner (2001)

Table 4.1. Maximum concentrations of ^{137}Cs in soil across Europe and the Middle East

National legislation in Ukraine, Russia and Belarus sets an official definition of “contaminated” at 1Ci/m² or 37kBq/m². Using this definition, many of the countries in Table 4.1 above contain contaminated land and Table 4.2 below shows that several European countries contain significant tracts of land that are above this limit.

Country	Area contaminated 37-185 kBq/m ^{2*}
Sweden	12,000 km ²
Finland	11,500 km ²
Austria	8,600 km ²
Norway	5,200 km ²
Bulgaria	4,800 km ²
Switzerland	1,300 km ²
Greece	1,200 km ²
Slovenia	300 km ²

Italy	300 km ²
Republic of Moldova	60 km ²
Total	45,260 km ²

Table 4.2. Amount of land in European countries meeting the definition of “contaminated” used by Ukraine, Russia and Belarus (UNSCEAR 2000)

According to De Cort *et al.* (1998), more than 40 % of Europe was polluted with Chernobyl fall out with levels more than 4,000 Bq/m² (4 kBq/m²).

Health effects ranging from chromosomal aberrations to congenital malformations and thyroid cancer were recorded in countries from Norway through to Turkey. Others that may have been affected have not been investigated.

Chromosomal aberrations were recorded to the west of Chernobyl, in Austria and Germany, and to the north, in Norway (Table 4.3.). Among the affected populations were the Saame people, nomads whose lives revolve around their reindeer.

Region	Sample	Date	Method	Mean elevation	Reference
Salzburg, Austria	17 adults	1987	Dics + cring	Approx. 4-fold	Pohl-Rüling <i>et al.</i> 1991
Germany, southern regions	29 children + adults	1987-1991	Dics + cring	Approx 2.6-fold	Stephan, Oestreicher 1993
Norway, selected regions	44 reindeer Saames 12 sheep farmers	1991	Dics + cring	10-fold	Brogger <i>et al.</i> 1996

Table 4.3. Chromosome aberrations in lymphocytes of persons living in West European regions contaminated by Chernobyl releases; dics dicentric chromosomes, cring centric rings (Schmitz-Feuerhake 2006)

Across Western Europe and Scandinavia, numerous studies identified *in utero* exposure to Chernobyl radiation as a cause of increased spontaneous abortions, low birth weight and reduced infant survival (Table 4.4.).

Country	Effects	References
Europe: Greece, Hungary, Poland, Sweden	Stillbirths	Scherb <i>et al.</i> 1999b, 2000b, 2003
Poland	Infant mortality	Korblein 2003a
Norway	Spontaneous abortions	Ulstein <i>et al.</i> 1990
Hungary	Low birth weight	Czeisel 1988
Finland	Premature births among malformed children	Harjulehto <i>et al.</i> 1989
Finland	Reduced birth rate Stillbirths	Harjulehto <i>et al.</i> 1991 Scherb, Weigelt 2003
Germany Total (FRG + GDR)	Perinatal deaths	Korblein, Kuchenhoff 1997; Scherb <i>et al.</i> 2000a, 2003
Southern Germany	Early neonatal deaths	Lüning <i>et al.</i> 1989
Bavaria	Perinatal deaths, stillbirths	Grosche <i>et al.</i> 1997; Scherb <i>et</i>

		<i>al.</i> 1999a, 2000a, 2003
Bavaria	Reduced birth rate	Korblein 2003a

*Table 4.4. Observed increase of stillbirths, infant deaths, spontaneous abortions, and low birth weight after in utero exposure by the Chernobyl accident. *) Perinatal deaths summarize stillbirths and deaths in the first 7 days from birth **) Reduced birth rate is considered as a measure for spontaneous abortions (Schmitz-Feuerhake 2006)*

To the west and southwards, from Germany through Croatia to Bulgaria and Turkey, increased congenital malformations were recorded in children who were exposed before birth (see Table 4.5.). Scherb & Weigelt (2002) found significant elevations in incidence of stillbirth and deformities, including deformities of the heart, in Bavaria. They estimated that, between October 1986 and December 1991, Chernobyl could have been responsible for between 1 000 and 3 000 congenital malformations in the region; and that further follow-up research should be carried out. A later study by the same authors (Scherb & Weigelt 2003) used data from Bavaria, the former GDR, West Berlin, Denmark, Hungary, Iceland, Latvia, Norway, Poland & Sweden to support a relative risk estimate for stillbirths of 1.0061 per kBq/m² or 1.3 mSv/a (p=0.000026). Significant increases in congenital malformations recorded in Moldova have been attributed to the combined effects of pollution from pesticides and Chernobyl; however, more research is needed to ascertain the contribution each makes to these diseases (Grigory *et al.* 2003).

Country/Region	Effects	References
Turkey	Anencephaly, spina bifida	Akar <i>et al.</i> 1988/89; Caglayan <i>et al.</i> 1990; Güvenc <i>et al.</i> 1993; Mocan <i>et al.</i> 1990
Bulgaria, Pleven region	Malformations of heart and central nervous system, multiple malformations	Moumdjiev <i>et al.</i> 1992
Croatia	Malformations by autopsy of stillborns and cases of early death	Kruslin <i>et al.</i> 1998
Germany		
Former German Democratic Republic, Central registry	Cleft lip and/or palate	Zieglowski & Hemprich 1999
Germany: Bavaria	Cleft lip and/or palate Congenital malformations	Scherb & Weigelt 2004 Korblein 2003a, 2004; Scherb & Weigelt 2003
Germany: Annual Health Report of West Berlin 1987	Malformations in stillborns	Strahlentelex 1989
Germany: City of Jena (Registry of congenital malformations)	Isolated malformations	Lotz <i>et al.</i> 1996

Table 4.5. Observed increase of congenital malformations after in utero exposure by the Chernobyl accident outside Belarus, Ukraine and Russia (Schmitz-Feuerhake 2006)

Down's syndrome typically occurs in around 1 in 1,000 births, but was elevated in Western Europe (Figure 4.1.) and Scandinavia (Table 4.6.). A statistically significant increase in frequency was apparent in January 1987, corresponding to children conceived during the period of maximal Chernobyl fallout (Sperling *et al.*, 1994b).

Region	Results	References
Sweden	“Slight” excess in most exposed areas (30 %)	Ericson, Kallen 1994
Scotland, Lothian region (0.74 million inhabitants)	Excess peak in 1987 (2-fold significant)	Ramsay <i>et al.</i> 1991
South Germany	Most children conceived close to time of accident	Sperling <i>et al.</i> 1991
Berlin West	Sharp increase after 9 months	Sperling <i>et al.</i> 1991, 1994a&b

Table 4.6. Increase of Down’s syndrome after in utero exposure by the Chernobyl accident (adapted from Schmitz-Feuerhake 2006).

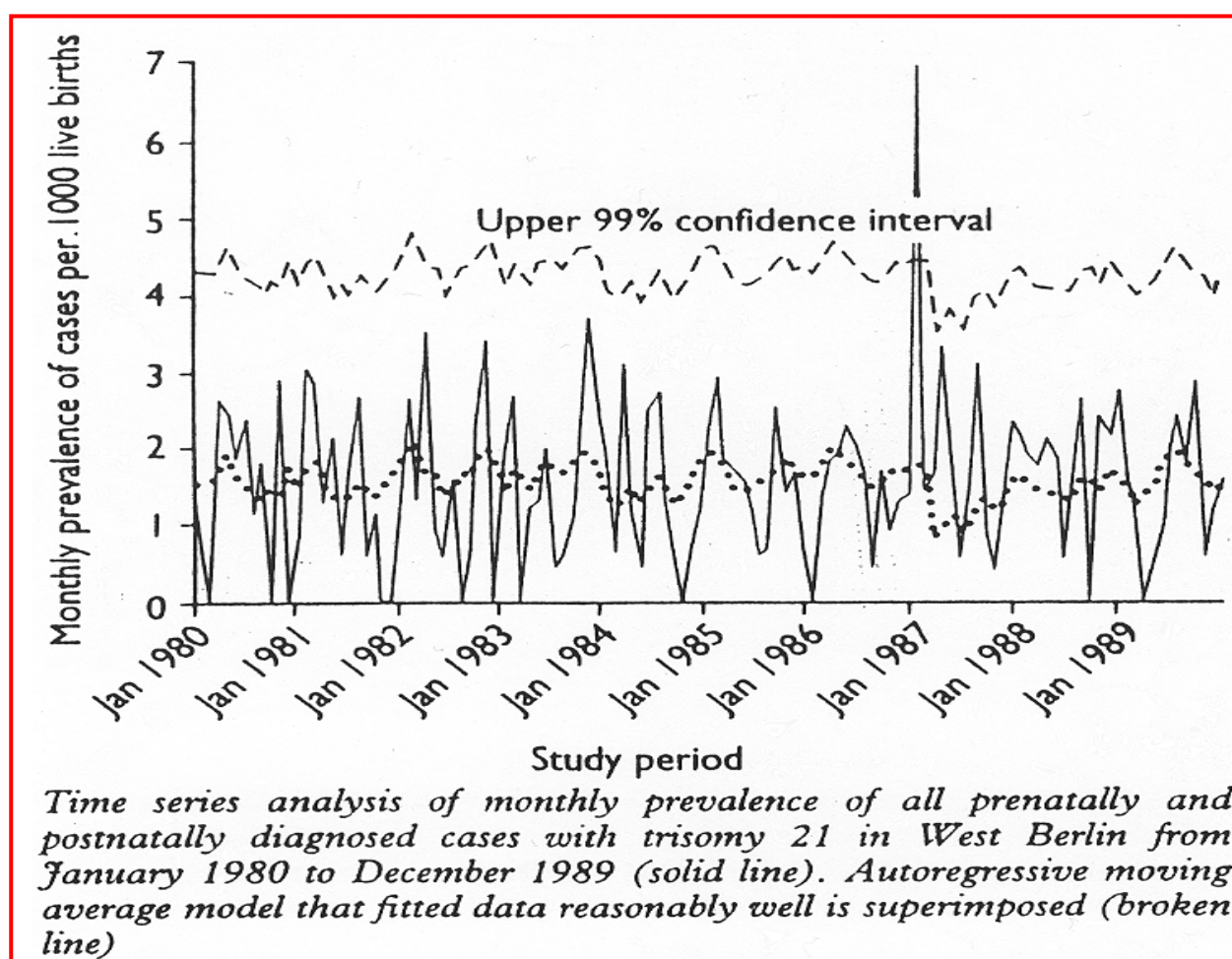


Fig.4.1. Frequency of newborns with Down’s syndrome in West Berlin, 1980 – 1989.

Asthma was also observed in *in utero* exposed children who subsequently emigrated from exposed areas to Israel (Table 4.7).

Region	Results	References
Immigrants to Israel from contaminated areas	Asthma	Kordysh <i>et al.</i> 1995

Table 4.7. Observed health defects in children after in utero exposure by the Chernobyl accident except malformations and Down’s syndrome (Schmitz-Feuerhake 2006)

In Sweden, a cohort study of over a million people in the most heavily contaminated areas of the country showed a slight increase in deaths from all cancers using data from 1986-1996. According to the authors of the report, an estimate of 300 cancers has been predicted based on total received dose (Tondel *et al.* 2004).

Research into the contamination and health effects of Chernobyl in Austria are summarised by Bundesministerium für Umwelt (1995) and Mraz (1988).

The average level of ^{137}Cs contamination in Austria was 23.4 kBq/m². The contaminated air from Chernobyl came to Austria in two waves: first via Turkey and Romania to the south-east of Austria and the second from east, to the regions north of the Alps. The geographical distribution correlated significantly with rainfall during the last days of April and the first days of May 1986 resulting in actual contamination ranging from almost nil (no rain) to 200 kBq/m² (heavy thunderstorms).

In the eastern part of Austria in the weeks after the accident, vegetables such as spinach and salad vegetables were not allowed to be sold to the public. Milk, especially milk from the alpine regions, was contaminated for more than a year.

In regions without precipitation, especially the eastern part of Austria, ^{131}I concentrations in air were high during the one or two days during which the radioactive cloud passed over. Doctors in this regions reported that the number of people with thyroid diseases increased from 1990 onwards.

An analysis of existing data for thyroid cancer made by the Austrian Institute for Applied Ecology in 1998 indicated that in regions where the gamma-radiation dose was high in the first days after the accident, the incidence rate of thyroid cancer in 1995 was higher than in other regions of Austria.

In the years 1997 and 1998, some Austrian media reported an increase of thyroid cancer, leukaemia and non-Hodgkins lymphoma. However, despite the fact that Austrian Statistics provide much health-related data that could be used to investigate correlations with exposure of the population to Chernobyl-derived radiation, the Federal Health Ministry of Austria did not investigate incidence rates of thyroid cancer or leukaemia with reference to the Chernobyl impact in Austria.

Children born in eastern Romania between July 1, 1986 and December 31, 1987 were significantly more likely to suffer childhood leukaemia than those born either before or after this period (Davidescu *et al.* 2004).

About 3,000 liquidators came from Armenia; eighty children of these men were studied and found to be in generally poor health, suffering conditions including secondary pyelonephritis, gastrointestinal problems, tonsillitis, hyperthermic convulsions and epilepsy. Only 15 children (27,3%) were described as “healthy in practice” (Hovhannisyan & Asryan 2003).

The Czech Republic received fallout resulting in maximal contamination levels of 185 kBq/m², though some locations were lower than detection limit. Average concentrations across most of the country were 5.3kBq/m², except for West Bohemia, which was less contaminated at 2.3-2.8 kBq/m². A study of thyroid cancer covering 247 million person-years

found that between 1976 and 1990, thyroid cancer was rising at a rate of 2% per year. However, from 1990 onwards there was a significant excess rise in thyroid cancer incidence on top of this 2%. This did not appear to be related to age, but women were much more likely to be affected than men. The additional increase in females suffering from thyroid cancer after 1990 was 2.9% per annum; for men the figure was 1.8% (Murbeth *et al.* 2004). Since areas adjacent to the Czech Republic, i.e. Bavaria in southern Germany and parts of the former GDR experienced similar contamination profiles (Murbeth *et al.* 2004), it is reasonable to assume they may also have experienced similar increases in thyroid cancer incidence.

Thyroid cancer was significantly elevated in northern England (rate ratio 2.2, 95% CI 1.3-3.6, with a particularly high in Cumbria, the area which received the most fallout from the accident (12.19%, 95% CI 1.5-101.20) (Cotterill *et al.* 2001). The incidence in Cumbria before Chernobyl was lower than normal and long-term research was recommended to clarify the situation (Cotterill *et al.* 2001, Stiller 2001).

In Greece, several nuclear physics laboratories performed contamination research immediately after the Chernobyl accident. The main focus of this work was the analysis for radioactive contamination of thousands of soil samples, particularly for deposited ^{137}Cs .

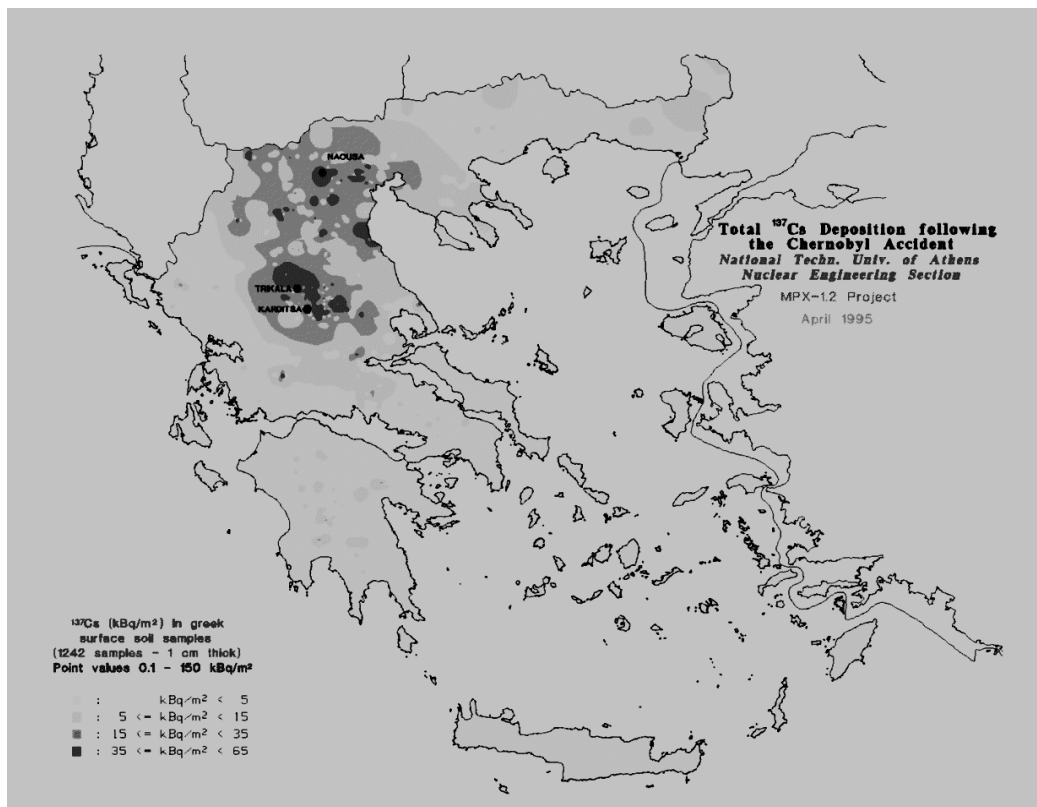


Figure 4.2. Caesium-137 contamination levels in surface soil in Greece (Simopoulos 1989)

Among others, two main laboratories exhibited their studies in a comprehensive way by presenting a geographical distribution of surface deposited caesium-137 (Simopoulos 1989, Kritidis *et al.* 1990). The highest levels ($35\text{--}65\text{ kBq/m}^2$) occurred around Thessaloniki in the north and in the central region of Thessalia. However, despite this evidence of significant contamination and anecdotal reports of health effects in Greece, there has been a lack of research at the national level, which needs to be addressed in the future.

Conclusions

On the basis of the above information, it is reasonable to conclude that the Chernobyl accident has caused, and will continue to cause, a significant amount of morbidity and mortality across Europe, from Scandinavia, through Western Europe, south to where Turkey straddles the border between Europe and Asia, and beyond. In many countries of the Northern Hemisphere, dose data are missing. Because of the short-lived nature of some of the critical radio-isotopes, particularly ^{131}I , it will be impossible to back-calculate the exposure to which the populations were exposed. Nevertheless, well-organised and well-funded retrospective and prospective studies should be carried out to clarify, as far as possible, the extent of morbidity and mortality resulting from the Chernobyl accident.

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