Overview

The Chernobyl Accident and its Consequences

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Abstract

The accident at the Chernobyl nuclear power plant was the worst industrial accident of the last century that involved radiation. The unprecedented release of multiple different radioisotopes led to radioactive contamination of large areas surrounding the accident site. The exposure of the residents of these areas was varied and therefore the consequences for health and radioecology could not be reliably estimated quickly. Even though some studies have now been ongoing for 25 years and have provided a better understanding of the situation, these are yet neither complete nor comprehensive enough to determine the long-term risk. A true assessment can only be provided after following the observed population for their natural lifespan. Here we review the technical aspects of the accident and provide relevant information on radioactive releases that resulted in exposure of this large population to radiation. A number of different groups of people were exposed to radiation: workers involved in the initial clean-up response, and members of the general population who were either evacuated from the settlements in the Chernobyl nuclear power plant vicinity shortly after the accident, or continued to live in the affected territories of Belarus, Russia and Ukraine. Through domestic efforts and extensive international co-operation, essential information on radiation dose and health status for this population has been collected. This has permitted the identification of high-risk groups and the use of more specialised means of collecting information, diagnosis, treatment and follow-up. Because radiation-associated thyroid cancer is one of the major health consequences of the Chernobyl accident, a particular emphasis is placed on this malignancy. The initial epidemiological studies are reviewed, as are the most significant studies and/or aid programmes in the three affected countries.

Key words: Chernobyl; radioactive contamination; radiation risk of thyroid cancer; radiation thyroid dose; thyroid cancer

Statement of Search Strategies Used and Sources of Information

We searched our own peer-reviewed data and personal files as well as PubMed for English-language articles, references of relevant articles and textbooks published during the period from the Chernobyl accident, 1986, including those that appeared in the former Soviet Union official sources, through to October 2010, using the search terms 'Chernobyl and thyroid', 'thyroid cancer', 'radiation-induced thyroid cancer', 'liquidators and Chernobyl', 'radiation risk', and 'radiation dose and 131I and Chernobyl'. We also searched websites of international organisations including the World Health Organization (WHO), United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), International Atomic Energy Agency (IAEA), United Nations International Children's Emergency Fund (UNICEF), United Nations Development Program (UNDP) and International Agency for Research on Cancer (IARC). In addition, we used Russian or country-specific language sources, such as published articles, proceedings of the official scientific conventions, textbooks and websites of the government-owned institutions in Belarus, Russia and Ukraine.

Introduction

The accident at the Chernobyl nuclear power plant (CNPP) that occurred 25 years ago on 26 April 1986 was the worst industrial accident involving radiation in the 20th century. Before this, the only experience of radiation...
exposure to a large population was the atomic bombings of Hiroshima and Nagasaki in 1945. The nature of the radiation exposure after Chernobyl was very different from that in Japan: protracted versus acute single dose, mostly internal versus external irradiation, involvement of different spectra of isotopes, irregular and patchy radioactive contamination of the environment, and radiation exposure of a population of millions of people of all ages. That is why many consequences, both related to health and society, could not be anticipated from what had been learnt from the radiation exposure to the Japanese population in 1945.

Here we review some technical aspects of the accident and provide information on the radioactive releases that caused contamination of large areas in the former Soviet Union countries, Belarus, Russia and Ukraine, particularly those in the immediate vicinity of the accident site. We also describe the major groups of the population affected by the accident and consider the information available on the radiation dose received by this population. In a separate subsection we highlight epidemiological and medical studies of millions of people of all ages. That is why many consequences, both related to health and society, could not be anticipated from what had been learnt from the radiation exposure to the Japanese population in 1945. There were seven deaths during the first night of the accident: two staff members and five firemen involved in firefighting actions. Among 237 firemen and CNPP employees examined within several days for acute radiation sickness, manifestations of varying degrees of severity were found in 134 individuals. Despite the intensive therapy provided, including 13 bone marrow transplantations, 28 patients died within 4 months of the accident from various causes of death. Myelosuppression was the major cause of death, but 19 more deaths were registered up to 2004, and in these cases bone marrow failure was unlikely to be the underlying cause [4].

The estimated release of radioactivity from the destroyed reactor reached a total of about 13 EBq (1 EBq = 10^18 Bq) [1,5,6]. The main radionuclides released are listed in Table 1. 131I and 137Cs are the most significant for dose received by the exposed population. Radioactive emissions from the CNPP were characterised by a wide spectrum of physicochemical forms and composition: gaseous, steam aerosol, aerosol mixtures, fuel particles, mineral particles with entrapped radionuclides, aggregates of different mineral particles and organic compounds. The composition varied from monoelement noble gases and atomic iodine or ruthenium, to multielement compounds and aggregates, fuel components, etc.

### Accident and Radioactive Releases from the Chernobyl Nuclear Power Plant

The CNPP is located in the north of Ukraine, close to the junction of the borders of three states, Ukraine, Belarus and Russia. The accident at Reactor Number 4 took place shortly after midnight on 26 April 1986. A number of accounts of the accident, some giving a minute by minute sequence, have been published. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [1], the course of events could be summarised as follows. Due to some reactor design flaws and human error during experimental operations immediately preceding the accident, overheating of the fuel rods and fragmentation in the active zone led to the rapid transfer of excessive heat to the coolant water and induced a shock wave breaking the primary coolant system pipeline joints. The leaking water instantaneously turned to steam. This first explosion caused displacement of the reactor core during which the remaining cooling water was driven out of the system. Without coolant, part of the nuclear fuel vapourised as a result of the increased temperature and this eventually resulted in a large explosion that destroyed the reactor and the building surrounding it, dispersing reactor debris and radioactive materials to the CNPP, the immediate vicinity and more widely into the environment. The initial fires that occurred after the major explosion were brought under control by the end of the night of the accident. However, fuel materials remaining at the meltdown site grew hot, ignited combustible products formed in the disrupted core milieu and caused an explosive fire. Tremendous efforts were made to extinguish it, including dumping of various fission- and fire-control materials from helicopters, but the radioactive releases continued for about another 10 days [2,3].

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Half-life</th>
<th>Activity released (PBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noble gases</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85Kr</td>
<td>10.72 years</td>
<td>33</td>
</tr>
<tr>
<td>133Xe</td>
<td>5.25 days</td>
<td>~6500</td>
</tr>
<tr>
<td>Volatile elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>129mTe</td>
<td>33.6 days</td>
<td>240</td>
</tr>
<tr>
<td>132Te</td>
<td>3.26 days</td>
<td>~1150</td>
</tr>
<tr>
<td>131I</td>
<td>8.04 days</td>
<td>~1760</td>
</tr>
<tr>
<td>133I</td>
<td>20.8 h</td>
<td>~2500</td>
</tr>
<tr>
<td>134Cs</td>
<td>2.06 years</td>
<td>47</td>
</tr>
<tr>
<td>136Cs</td>
<td>13.1 days</td>
<td>36</td>
</tr>
<tr>
<td>137Cs</td>
<td>30.0 years</td>
<td>~85</td>
</tr>
<tr>
<td>Elements with intermediate volatility</td>
<td></td>
<td></td>
</tr>
<tr>
<td>89Sr</td>
<td>50.5 days</td>
<td>~115</td>
</tr>
<tr>
<td>90Sr</td>
<td>29.12 years</td>
<td>~10</td>
</tr>
<tr>
<td>103Ru</td>
<td>39.3 days</td>
<td>&gt;168</td>
</tr>
<tr>
<td>106Ru</td>
<td>368 days</td>
<td>&gt;73</td>
</tr>
<tr>
<td>140Ba</td>
<td>12.7 days</td>
<td>240</td>
</tr>
<tr>
<td>Refractory elements (including fuel particles)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>92Zr</td>
<td>64.0 days</td>
<td>84</td>
</tr>
<tr>
<td>99Mo</td>
<td>27.5 days</td>
<td>&gt;72</td>
</tr>
<tr>
<td>141Ce</td>
<td>32.5 days</td>
<td>84</td>
</tr>
<tr>
<td>144Ce</td>
<td>284 days</td>
<td>~50</td>
</tr>
<tr>
<td>239Np</td>
<td>2.35 days</td>
<td>400</td>
</tr>
<tr>
<td>238Pu</td>
<td>87.74 years</td>
<td>0.015</td>
</tr>
<tr>
<td>239Pu</td>
<td>24 065 years</td>
<td>0.013</td>
</tr>
<tr>
<td>240Pu</td>
<td>6537 years</td>
<td>0.018</td>
</tr>
<tr>
<td>241Pu</td>
<td>14.4 years</td>
<td>~2.6</td>
</tr>
<tr>
<td>242Pu</td>
<td>376 000 years</td>
<td>0.00004</td>
</tr>
<tr>
<td>242Cm</td>
<td>18.1 years</td>
<td>~0.4</td>
</tr>
</tbody>
</table>

Data are inferred from [2,8,16,19].

* Decay corrected to 26 April 1986.
graphite, silicates and others, each with different radionuclide proportions [5].

Over 90% of ${}^{90}$Sr, $^{141,144}$Ce and isotopes of Pu and $^{241}$Am were released in the form of fuel particles measuring 10 $\mu$M and less [5]. Seventy-five per cent of $^{137}$Cs contamination within the exclusion zone (the 30 km zone around the CNPP) could also be attributed to this physical form. At longer distances, contamination of the territories in European countries was due to steam aerosol and gaseous mixtures, and to the particles of submicron size, containing $^{103,106}$Ru, $^{131,133,135}$I, $^{132,134,137}$Cs and radioactive noble gases. The same isotopes were also detected in Pacific and Atlantic Oceans, and even in the Americas and Asia, emphasising the global scale of the accident. After the completion of a sarcophagus around the destroyed reactor and building in November 1986, active emissions into the environment were no longer observed [1,2].

Radioactive Contamination of Territories

The dynamic meteorological conditions, including the wind, cloudiness, temperature, humidity and precipitations, together with varying physicochemical characteristics of the radioactive materials released at different times after the reactor destruction, defined the heterogeneous pattern of the ground contamination [7–9]. Figure 1 shows reconstructed plume traces over part of Europe.

Further monitoring of the territories permitted a contamination pattern to be established based on average $^{137}$Cs deposition densities (this isotope is easy to measure, has a long half-life and is radiologically significant), as shown in Figure 2 for the territories around Chernobyl and in Figure 3 for the whole of Europe. The highest density of contamination was observed in the vicinity of the CNPP. However, the levels exceeding the expected background could be detected as far as up to 3000 km from the accident site.

The territories of Belarus, Russia and Ukraine were most heavily affected by the accident, as detailed in Table 2. From the total $^{137}$Cs activity of about 64 TBq (1.7 MCi) deposited in Europe in 1986, Belarus received 23%, Russia 30% and Ukraine 18%, resulting in radioactive contamination of about 3% of the European part of the former Soviet Union [10]. There were also contaminated areas in Austria, Finland, Germany, Norway, Romania and Sweden (Figure 3).

The radioactive isotopes of iodine ($^{131,133,135}$I), which are short-lived radionuclides belonging to the group of light volatile substances, played a key role in the contamination of the environment. It is worth mentioning, however, that only $^{131}$I has a high radiological significance. Among other isotopes, only $^{133,135}$I increased the general exposure dose, especially for the thyroid, but due to their short half-lives their effect was restricted to the areas within the immediate vicinity of the CNPP.

Because of the rapid decay of $^{131}$I, collection of a large number of samples for detailed analysis was difficult [11]. However, the results of model calculations based on the limited number of measurements and determinations of $^{131}$I to different radionuclides ratios, especially $^{137}$Cs (which varied 5–60-fold in different measurements), allowed reconstruction of contamination density maps [1,5,12]. The most contaminated areas were: in Belarus the three regions in the east and southeast: Brest, Gomel and Mogilev; in Russia the four southwestern regions: Bryansk, Kaluga, Tula and Orel; and in Ukraine the six northern regions:
Cherkassy, Chernigov, Kyiv, Rovno, Volyn and Zhitomir (see Figure 1). The refined $^{131}$I contamination maps are expected to be published by UNSCEAR in 2011. This will enable a more accurate estimation of thyroid dose, which is essential for radiation epidemiology and public health assessment of the health consequences of the accident.

Most radionuclides released by the accident have already decayed. Attention over the next few decades will probably be centred on $^{137}$Cs and $^{90}$Sr; the latter being more important in the areas closest to the CNPP [5].

Groups Radiologically Affected by the Accident

There are three major groups of individuals for whom estimation of radiation health effects after Chernobyl is particularly important. These are the workers involved in the actions during the accident or in the mitigation of the aftermath, those individuals who lived close to the CNPP site and were evacuated after the accident, and those who continued to reside in the contaminated areas further from the CNPP. All were exposed to radiation at different times after the accident, under different circumstances and to different spectra and amounts of radioactive elements. Thus, accumulated effective doses are quite different among the groups and furthermore there are large uncertainties in dose estimates.

Liquidators

The first category is further subdivided into those who were at the CNPP during the first day of the accident and took part in emergency measures, and those who were engaged in recovery operations from 1986 to 1990. In the literature the second group is often referred to as ‘liquidators’, the term officially introduced by the former Soviet Union. There were about 600 emergency workers at the CNPP until 26 May, and about 600 000 liquidators, including both civilians and servicemen, until 1990. Estimated external doses in the 134 emergency workers with symptoms of acute radiation sickness ranged between 0.8 and 16 Gy, being markedly higher than internal doses, calculated to be between 0.021 and 4.1 Gy for the thyroid in the 23 firemen who died of bone marrow failure [13]. It was suggested that the lower thyroid doses might have been brought about due to the stable iodine pills taken by emergency workers. Among the liquidators, the average effective doses ranged from 15 to 170 mSv, with individual variations from $<10$ to $>500$ mSv in 1986–1987 [1]. Internal exposures to the thyroid may have ranged from $<0.15$ to 3 Gy, with an average of 0.21 Gy in those who took part in the activities in and around the CNPP during the first few months after the accident [14]; the short-lived radioiodine isotopes decayed rapidly after that.

Evacuated Residents

There was a mass evacuation of residents of the settlements nearest to the CNPP, depending on the radiological situation and their distance from the power plant [15–18]. On 27 April, about 50 000 people were evacuated from the town of Pripyat located 3 km from the CNPP. This is where most employees at the CNPP and their families resided.
Fig. 3. Ground deposition of $^{137}$Cs in Europe after the Chernobyl accident [9].

Table 2
European countries contaminated by Chernobyl fallout in 1986

<table>
<thead>
<tr>
<th>Area with $^{137}$Cs deposition density range (per km²)</th>
<th>37–185 kBq/m²</th>
<th>185–555 kBq/m²</th>
<th>555–1480 kBq/m²</th>
<th>&gt;1480 kBq/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russian Federation</td>
<td>49 800</td>
<td>5700</td>
<td>2100</td>
<td>300</td>
</tr>
<tr>
<td>Belarus</td>
<td>29 900</td>
<td>10 200</td>
<td>4200</td>
<td>2200</td>
</tr>
<tr>
<td>Ukraine</td>
<td>37 200</td>
<td>3200</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>Sweden</td>
<td>12 000</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Finland</td>
<td>11 500</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Austria</td>
<td>8600</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Norway</td>
<td>5200</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>4800</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Switzerland</td>
<td>1300</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Greece</td>
<td>1200</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Slovenia</td>
<td>300</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Italy</td>
<td>300</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Republic of Moldova</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Based on [1,9].
before the accident. During the 10 days after the accident, to 7 May 1986, a similar number of people who lived inside the 30 km zone surrounding the CNPP were evacuated from areas in Ukraine and Belarus. Active evacuations continued until September 1986 and involved a total of about 116 000 people, mostly from areas in Ukraine and Belarus. Estimates of external effective doses reconstructed for about 30 000 residents of the 30 km zone indicate the dose range to have been from 0.1 to 380 mSv, with an average of 17 mSv [19]. Mean thyroid doses from $^{131}$I, based on about 5000 direct measurements and about 10 000 questionnaires collected from Ukrainian evacuees, were 0.11–3.9 Gy in children, 0.066–0.39 Gy in adolescents and 0.066–0.40 Gy in adults [20,21]. In Belarusian evacuees, the estimates were 1–4.3, 1 and 0.68 Gy, respectively [22]. These investigations showed an important in verse correlation between thyroid dose and age at exposure.

**General Population**

Reconstructed maps of soil contamination with $^{137}$Cs (Figure 2) taken together with demographic data for Belarus, Russia and Ukraine, indicate that the population of contaminated territories (i.e. with $^{137}$Cs levels exceeding 37 kBq/m$^2$) was above 5 million at the time of the accident, comprising around 1 million children (<15 years old) and about 200 000 adolescents. Because the number of residents of contaminated territories was substantially greater than in the two categories of clean-up workers described above, and also because the residents included individuals of all ages who might have been exposed to diverse radiological conditions at different geographical locations, dose estimates in them are more complicated and are intrinsically associated with large uncertainties. This is of particular note in the differences observed in the estimates of average collective and individual doses. Models of accumulated dose from external sources are based on soil $^{137}$Cs contamination levels and are normalised to isotope deposition density. Estimates of external dose range from 11 to 24 μSv/kBq/m$^2$ in 1986 for contaminated territories of the three countries; the doses were higher in rural and lower in urban areas [1]. Study of external doses in one contaminated settlement in Russia in 1987 found individual doses to be within a 2–13 mGy range, with a mean of 5 mGy [23]. Internal doses for the thyroid rely on direct thyroid measurements (several 100 000 were taken cumulatively after the accident), individual questionnaires and computer modelling. Estimates indicate that the doses varied in a wide range from <0.05 mGy to >2 Gy in Belarusian, Russian and Ukrainian individuals of all age groups with averages of <0.3–0.7 Gy in children and individual doses up to 10 Gy [24–30]. Thyroid doses exceeding 2 Gy were observed almost exclusively in younger children aged less than 4 years [30] and they were usually higher in the residents of rural areas than in urban areas with a similar contamination level [29]. It is worth noting that organised administration of prophylactic or thyroid-blocking doses of stable iodine was not common. According to some surveys, from 1 to about 25% of the residents of contaminated territories reported taking potassium iodide pills shortly after the accident, but the recall rate was low [29,31]. In part this was due to poor preparedness for large-scale accidents such as one that happened at the CNPP, and in part to inappropriate information from the authorities. An official announcement in the mass media appeared only on 28 April, i.e. 2 days after the reactor was destroyed. The delay was caused initially by insufficient understanding of the scale of the accident, as well as apprehension of possible massive panic within the exposed population. It might be expected that if clear instructions on essential safety measures had been delivered swiftly and timely (e.g. taking potassium iodide pills, not consuming fresh milk and vegetables grown in the open plots, not going outside, etc.), health consequences, at least for the residents of contaminated territories, would be less dramatic. A cost–benefit analysis carried out in Belarus for 2566 thyroid cancers in children and adolescents diagnosed and treated during 1990–2005 showed that if potassium iodide prophylaxis had been provided, budget expenditures would have decreased by $400 000 per 100 000 of population [32]. It is also of note that after the Chernobyl accident, several laws regulating the dissemination and handling of ecological information were brought in within the former Soviet Union countries. In Russia, for instance, information on emergencies and ecological, meteorological, demographic and sanitary-epidemiologic data of importance for safe industrial operations and for individual and public safety has been decreed to be open and non-restricted [33].

**Major Medical and Epidemiological Studies of the Chernobyl Accident**

The scale of the accident and the number of people affected by it were unprecedented; therefore, initially, it was very difficult to predict possible health consequences. In 2002, Nagataki [34], evaluating the state of knowledge about Chernobyl, designated the major post-accident periods as follows: 1986–1989 information difficult to obtain; 1990–1991 exchanges with other countries initiated; 1992 case reports: childhood thyroid cancer; 1992–1994 period of ascertainment; 1995 ascertainment and search for causes; 1996–present investigations carried out that will continue into the future.

The first health screenings in the most contaminated areas around Chernobyl were started shortly after the accident, mostly organised through local medical authorities. Only from 1990, after the request from the Government of the former Soviet Union in October 1989, were international efforts initiated that still persist today.

The first important collaboration was the International Chernobyl Project co-ordinated by the International Atomic Energy Agency (IAEA). During 1990–1991, 200 experts from 25 countries examined the health status of the population, including haematological, cardiovascular and thyroid disease, radiogenic cataract, cancer prevalence, fetal abnormalities and mental health for possible radiological consequences. The study involved a total of 825 000 people from 2225 settlements in the three affected states [3]. One
of the purposes was also to evaluate the mitigation measures undertaken and to develop health-related advice for the population residing in contaminated areas. The major findings of this project generally confirmed the previously established surface contamination levels; the whole body lifetime doses were estimated not to exceed 160 mSv and were several times lower than initial estimates of about 350 mSv. Actual thyroid doses were difficult to confirm. Stress and anxiety in the population were significant, but apparently not radiation related; no increase in leukaemia or solid cancers was observed at that time and thyroid dose estimates in children were suggestive of the possible increase in thyroid cancer incidence in the future. The extent of population evacuation that had occurred, and the foodstuff restrictions that had been put in place, seemed to be sometimes excessive.

In February 1990, the Government of the former Soviet Union appealed to the Sasakawa Memorial Health Foundation (SMHF) of Japan to provide assistance, specifically to the population of the contaminated territories. SMHF, in collaboration with the Japan Shipbuilding Industry Foundation (now the Nippon Foundation), created a 5 year programme initially entitled the Chernobyl Sasakawa Health and Medical Cooperation Project. According to the report of experts who evaluated the situation in the areas close to Chernobyl, the major concerns were fear and anxiety among the residents, poor dissemination of information and insufficient understanding of health problems in the population. Therefore, the provision of a direct health examination, particularly in children, was identified as the highest priority task [35]. In May 1991, the health examination of children began in five centres established in Gomel and Mogilev (Belarus), Kiev and Zhitomir (Ukraine) and Bryansk (Russia) with a special focus on direct thyroid dose measurement, thyroid examination and blood tests (also including hormone and antibody measurements) according to an agreed, unified protocol. To implement the project, SMHF donated to each centre five mobile units equipped with whole body counters, ultrasound machines and blood analysers, 10 buses for patient transportation, as well as other medical and diagnostic equipment, computers, supplies and medicines. In total, 158 995 children aged 0–10 years at the time of the accident had been examined by April 1996. The project also supported training in Japan and on-site, visits of experts to the community, and focused on the Gomel region of Belarus. A comparative study of thyroid diseases in children born before and after the accident was designed to involve 21 601 persons screened between February 1998 and December 2000 using the approaches established during the first project [39]. In total, 32 thyroid cancers (equating to 0.15% of the children screened) were diagnosed, of which 31 were in the group of 9720 children born before the accident, one in a child born between 27 April and 31 December 1986 (i.e. possibly exposed in utero), whereas no thyroid cancers were detected in the group of 9472 children born after the accident. The estimated odds ratios of the frequency of thyroid cancer in the group born before the accident compared with the in utero exposed group were 11 and 121 compared with those born after the accident. The conclusion regarding the likelihood of a causal link between direct external or internal exposure to short-lived radionuclides including $^{131}$I and $^{137}$Cs was drawn.

The extended SMHF project provided a good opportunity for collaboration with the Belarus/Russia/European Union/International Agency for Research on Cancer epidemiological case–control study (reviewed in another paper by Hatch and Cardis in this special issue of Clinical Oncology) aimed to evaluate the risk of thyroid cancer after exposure to $^{131}$I, and to identify any risk-modifying factors. In a united effort, all individuals aged less than 15 years at the time of the accident from the Gomel and Mogilev regions of Belarus and from the Bryansk, Kaluga, Tula and Orel regions of Russia (a total of 276 at the end of study) and at least four closely matched population-based controls (1300 persons) were analysed. Individual thyroid doses were reconstructed and used to estimate the dose–response relationship. It was found to be significant and linear up to 1.5–2 Gy [40]. The odds ratio for thyroid cancer varied from 5.5 to 8.4 for a dose of 1 Gy according to different risk models; this was generally comparable with risk estimates for external exposures [41]. Importantly, a strong modifying effect of iodine deficiency was observed: the relative risk for developing cancer was 3.2 in iodine-deficient areas, whereas a dietary supplementation with potassium iodide reduced the risk about three-fold (relative risk of 0.34). This study was the largest population-based investigation in young people living in the Chernobyl area; it provided strong definitive evidence of causal association between the risk for thyroid cancer and internal exposure to radiiodine at a young age. The major route of $^{131}$I ingestion by residents was its incorporation into the food chains of pastured cattle, mostly cows, and the consumption of fresh milk as well as from vegetables and fruits grown in open soil. Incorporation of $^{137}$Cs may have contributed to dose formation. This is why both $^{131}$I in the thyroid and in milk, and $^{137}$Cs in soil, food and in the body are considered for dose reconstruction [42].

The World Health Organization (WHO) also played an active role in studying and managing the health
consequences of Chernobyl. One of the largest projects was the International Project on the Health Effects of the Chernobyl Accident (IPHECA) launched in May 1991 and completed in 1996, with international budgetary support primarily from the Government of Japan and with a contribution from the Czech Republic, Slovakia, Switzerland and Finland [43]. IPHECA included a number of pilot projects: brain damage in utero, an epidemiological registry, haematology, medical and psychological rehabilitation of Chernobyl liquidators, oral health, radiation dose reconstruction and the effects on the thyroid. In collaboration with the SMHF project, over 210 000 children were examined. The findings were in line with the earlier SMHF projects: by the end of 1994, 565 children (333 in Belarus, 24 in the Russian Federation, 208 in Ukraine) who lived in contaminated regions were diagnosed for thyroid cancer, but no significant increase in the incidence of leukaemia or other blood disorders was observed [44].

In February 1999, the WHO and SMHF started the Chernobyl Telemedicine Project, whose aim was to improve early diagnosis, treatment, and follow-up of patients with thyroid cancer, primarily in the Gomel region of Belarus. A satellite-based telematic system was established that allowed an exchange of thyroid ultrasound and cytology images, and of related information on the patients, between the Thyroid Oncology Center in Minsk, the Research Center for Radiation Medicine in Gomel and Nagasaki University School of Medicine with synchronised databases [45–48]. By September 2000, information on 330 cases was entered into the database and reviewed independently, thus improving diagnosis.

Another important project was the establishment of the Chernobyl Tissue Bank in October 1998 based on funding from the European Commission, WHO, SMHF and the US National Cancer Institutes and approved by the Governments of Belarus, Russia and Ukraine [49]. This is also reviewed in this special issue in a paper by Thomas et al.

Even at present, when major causes of health consequences of the CNPP accident, at least with regard to thyroid cancer, are clarified, international activities continue. One of them is the Chernobyl Thyroid Diseases Study Group of Belarus, Ukraine and the USA [50]. The study follows a cohort of 25 161 individuals (11 918 in Belarus and 13 243 in Ukraine) born between 26 April 1968 and 26 April 26 1986, with direct thyroid measurements available shortly after the accident to improve individual dose estimates and to collect health-related information based on bi-annual (or annual) screenings. The project was started in December 1996 in Belarus and in April 1998 in Ukraine.

During the first screening in 1998–2000, 45 thyroid cancers were detected in Ukraine [51]. An approximately linear dose–response relationship was found with an excess relative risk estimate of 5.25 per 1 Gy. The older age tended to associate with a decreased risk of thyroid cancer. The fraction of cancers attributed to radiation was estimated to be 75% (95% confidence interval 50–93%).

Reconstruction of thyroid doses in Belarus is now ongoing for a new evaluation of the risk of radiation-associated thyroid cancer [52]. In Ukraine, there are extensive risk analyses of thyroid cancer and of other thyroid diseases among individuals exposed in utero to $^{131}$I from Chernobyl fallout [53] as well as of that of non-cancer thyroid neoplasms [54] and autoimmune thyroiditis [55]. The results of this large-scale project are expected to further refine conclusions of the earlier, concurrent and ongoing studies.

In April 2009, a new Chernobyl programme was launched by four United Nations agencies, IAEA, UNDP, UNICEF and WHO, with financial support from the United Nations Trust Fund for Human Security. The objectives, primarily set in Belarus, are translation-oriented, i.e. to develop effective practical advice for the residents of contaminated territories based on the results of investigations around Chernobyl obtained so far.

**Discussion**

Here we present an overview of the major aspects of the accident at the CNPP, the initial response to the accident, both locally and with the involvement of international bodies, and its radiological and health consequences, with a particular focus on thyroid cancer.

As a result of the large release of radioactivity, large groups of the population received radiation doses. These included clean-up workers and the general population that was either evacuated from the settlements in the vicinity of the CNPP shortly after the accident or continued to live in the territories of Belarus, Russia and Ukraine, which were contaminated by fallout. Health consequences were initially difficult to forecast. Apart from the effects of acute exposure to ionising radiation in firemen, information about the contamination levels of the affected territories, spectrum of pollutant radionuclides and doses accumulated by the residents were hard to come by. That is why, after the initial years of domestic effort, large-scale international collaborations were initiated, involving many governmental and non-governmental organisations from a number of countries and from the worldwide community. Through co-operative investigations, the health status and dosimetric data were obtained to provide grounds for assessing the consequences. First reports about the increase in thyroid cancer incidence in children and adolescents in Belarus and Ukraine [56,57] were met cautiously by the experts because of doubts in the accuracy of diagnosis, too short a period of latency (which would be expected to be about 10 years, as seen from the A-bombings of Hiroshima and Nagasaki) and insufficient evidence of a link between Chernobyl radiation and cancer outbreak. With time, however, essential proof was found and the efforts of both health authorities in the three most affected countries and of the international parties could be better focused on the high-risk groups and using more specialised means. These still continue today.

A number of lessons have been learnt from the accident at the CNPP, for example, that a disaster in one country may affect others, that appropriate handling of vital information about the accident, and better preparedness for accidents that involve radioactive releases may result in less adverse consequences; that international collaboration even on
delicate issues could be established and it can be effective. In the medical arena, a wealth of experience has been accumulated, including the recognition that there may be a relatively short period of latency for thyroid cancer after internal exposure to radioiodine, coupled with advances in the diagnosis and treatment of young patients with thyroid cancer.

Although issues of non-thyroid cancer, somatic diseases and mental consequences remained beyond of the scope of this review, these should not be forgotten too. The psychological effects of the accident are reviewed in this special issue in a paper by Bromet et al.

In conclusion, although the major health effects of the Chernobyl accident have become clearer over the past 25 years, we are still far from understanding all the consequences. Studies are still required to investigate whether the clinical course and the long-term effects of treatment of radiation-induced diseases are the same as or different from the same disorders of sporadic aetiology. Investigations similar to that of the life span study of Japanese A-bomb survivors and focused follow-up of patients diagnosed and treated after Chernobyl and in high-risk groups may provide essential answers to improve the quality of life of those exposed to fallout from the accident, as well as to optimise radiation safety and public health systems worldwide.

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