occupational exposure assessed by the operator of the nuclear power plant, first-year organ doses were also estimated for emergency workers (exposure assessment).

- The lifetime risks of cancer was estimated for all solid cancers combined, and also for individual cancer sites most closely associated with radiation exposure and with a known dependence of the magnitude of risk on age-at-exposure (leukaemia, thyroid cancer and female breast cancer). The lifetime risks were estimated for both sexes and three different ages at exposure (1 year [infant], 10 years [child], and 20 years [adult]). Calculations of the cumulative risks for the 15 years following the accident were also performed. Health risks for male emergency workers were estimated for three different ages (20 years, 40 years, and 60 years) (risk characterization).

Findings

In view of the estimated exposure levels, an increased risk of cancer is the potential health effect of greatest relevance. The relationship between radiation exposure and lifetime risk of cancer is complex and varies depending on several factors, mainly radiation dose, age at time of exposure, sex and cancer site. These factors can influence the uncertainty in projecting radiation risks, in particular when assessing risks at low doses.

Outside the geographical areas most affected by radiation, even in locations within Fukushima prefecture, the predicted risks remain low and no observable increases in cancer above natural variation in baseline rates are anticipated.

Some health effects of radiation, termed deterministic effects, are known to occur only after certain radiation dose levels are exceeded. The radiation doses in Fukushima prefecture were well below such levels and therefore such effects are not expected to occur in the general population.

The estimated dose levels in Fukushima prefecture were also too low to affect fetal development or outcome of pregnancy and no increases, as a result of antenatal radiation exposure, in spontaneous abortion, miscarriage, perinatal mortality, congenital defects or cognitive impairment are anticipated.

In the two most affected locations of Fukushima prefecture, the preliminary estimated radiation effective doses for the first year ranged from 12 to 25 mSv. In the highest dose location, the estimated additional lifetime risks for the development of leukaemia, breast cancer, thyroid cancer and all solid cancers over baseline rates are likely to represent an upper bound of the risk as methodological options were consciously chosen to avoid underestimation of risks. For leukaemia, the lifetime risks are predicted to increase by up to around 7% over baseline cancer rates in males exposed as infants; for breast cancer, the estimated lifetime risks increase by up to around 6% over baseline rates in females exposed as infants; for all solid cancers, the estimated lifetime risks increase by up to around 4% over baseline rates in females exposed as infants; and for thyroid cancer, the estimated lifetime risk increases by up to around 70% over baseline rates in females exposed as infants. These percentages represent estimated relative increases over the baseline rates and are not estimated absolute risks for developing such cancers. It is important to note that due to the low baseline rates of thyroid cancer, even a large relative increase represents a small absolute increase in risks. For example, the baseline lifetime risk of thyroid cancer for females is just three-quarters of one percent and the additional lifetime risk estimated in this assessment for a female infant exposed in the most affected location is one-half of one percent. These estimated increases presented above apply only to the most affected location of Fukushima prefecture. For the people in the second most affected location, the estimated additional lifetime cancer risks over baseline rates are approximately one-half of those in the highest dose location. The estimated risks are lower for people exposed as children and adults compared to infants.

In the next most exposed group of locations in Fukushima prefecture, where preliminary estimated radiation effective doses were 3–5 mSv, the increased lifetime estimates for cancer risks over baseline rates were approximately one-quarter to one-third of those for the people in the most affected geographical location.

Among Fukushima Daiichi nuclear power plant emergency workers, the lifetime risks for leukaemia, thyroid cancer and all solid cancers are estimated to be increased over baseline rates, based upon plausible radiation exposure scenarios. These scenarios and their corresponding estimated risks are detailed in the body of this report. A few emergency workers who inhaled significant quantities of radioactive iodine may develop non-cancer thyroid disorders.

Conclusions

This health risk assessment is based on the current state of scientific knowledge. The assessment models used were derived from previous radiation events and experience, which do not exactly match the pattern of exposure seen in Fukushima; thus, adjustments were required. The dose estimates and assumptions used in this assessment were deliberately chosen to minimize the possibility of underestimating eventual health risks. The values presented in the report should be regarded as inferences of the magnitude of the health risks, rather than as precise predictions. Moreover, it is also important to note that the exposure data upon which this report is based are preliminary and include only data that were available as of September 2011. Because scientific understanding of radiation effects, particularly at low doses, may increase in the future, it is possible that further investigation may change our understanding of the risks of this radiation accident.

This health risk assessment concludes that no discernible increase in health risks from the Fukushima event is expected outside Japan. With respect to Japan, this assessment estimates that the lifetime risk for some cancers may be somewhat elevated above baseline rates in certain age and sex groups that were in the areas most affected.

These estimates provide valuable information for setting priorities in the coming years for population health monitoring, as has already begun with the Fukushima Health Management Survey.

On the basis of these findings, the continued monitoring of food and the environment remains important. When additional dose estimations become available from studies undertaken by UNSCEAR and others, such data can be used to further refine these risk estimates.

Preface

The World Health Organization (WHO) conducts a programme on radiation and health that aims to promote safe and appropriate use of radiation to protect patients, workers and the general public in planned, existing and emergency exposure situations. WHO's involvement in radiation and health began within a decade of its founding, and the International Commission on Radiological Protection has been in official relations with WHO since 1956. In 1972 the World Health Assembly requested the WHO Director-General to cooperate with the International Atomic Energy Agency (IAEA), the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and other international organizations in evaluating the world situation regarding the medical use of ionizing radiation and the effects of radiation on populations.

Global public health security is one of the key priorities of WHO's agenda. The World Health Assembly requested the Director-General in 2005 to enhance WHO's capacity to implement health-related emergency preparedness plans and to prepare for disasters and crises through timely and reliable assessments. The nature of WHO's work on emergencies – whether resulting from natural, intentional or accidental events – requires a high level of coordination with a variety of partners within the United Nations system, as well as with external partners. One of the lessons from the 1986 Chernobyl nuclear accident was the need to strengthen international cooperation in radiation emergencies. The Joint Radiation Emergency Management Plan of the International Organizations, last published in 2010, establishes the mechanisms for implementing a coordinated response and describes the roles of each party. Within this joint plan, WHO is responsible for the coordination of public health risk assessment and response.

The decentralized structure of WHO – with its headquarters in Geneva, Switzerland, six regional offices and 147 country offices – provides optimal conditions for interacting with the Organization's 194 Member States. After the 11 March 2011 Great East Japan Earthquake and Tsunami, Tokyo Electric Power Company's (TEPCO) Fukushima Daiichi nuclear power plant was severely damaged and a substantial amount of radioactive material was released into the environment. The potential risks of human exposure to radiation resulting from this accident received priority attention around the world. As the United Nations directing and coordinating authority on international public health issues, WHO was directly engaged in assessing and communicating public health risks.

Assessment of the health risks arising from this accident requires knowledge of the radiation doses delivered to populations within Japan and beyond. WHO undertook an initial assessment of radiation doses received by populations inside and outside Japan as a consequence of the Fukushima Daiichi accident, which was published in May 2012.

This report summarizes the results of a health risk assessment conducted by a group of independent experts convened by WHO. UNSCEAR, the International Labour Organization and the Government of Japan participated as observers. It represents the first international effort to estimate radiation risks from this accident at the global level.

The health risk assessment, which is based upon currently available preliminary data, gives an indication of the health implications of this accident. Such information can support the identification of needs and priorities for public health actions. This report is primarily intended for use by policy makers and health professionals in WHO Member States, as well as by international organizations.

1. Introduction

On 11 March 2011 Japan suffered a magnitude 9 earthquake, the largest ever recorded in the country. The 2011 Great East Japan Earthquake created a series of large tsunami waves that struck the east coast of Japan, causing widespread damage to infrastructure, including to several nuclear power plants (NPPs). In most cases these power plants were successfully shut down. However, at the Fukushima Daiichi NPP the earthquake and tsunamis knocked out the power supply to the facility, and consequently the means to control and cool the reactors. In the days that followed, reactor meltdown, venting and hydrogen gas explosions released radionuclides into the environment.

Public health actions to manage and reduce the negative consequences of this event were taken by authorities in Japan and by other national authorities around the world. In Japan, a 3-km evacuation zone was put in place around the site, which was then quickly increased to a 20-km evacuation zone, with a sheltering zone between 20 and 30 km. As the availability of environmental monitoring data increased, other protective actions were implemented to reduce doses in the longer term, including the relocation of people in some areas (designated as "deliberate evacuation areas"). Stable iodine for thyroid blocking was distributed but it is thought that only a small number of persons in specific locations actually consumed stable iodine, because consumption (as opposed to distribution) was not officially recommended in most places (*1*). Provisional regulatory limits for the radioactive content of food were promptly established, and food monitoring was conducted at the local level on the basis of testing guidelines prepared by the Government of Japan. This monitoring meant that food samples were tested before being supplied to the market in the early harvest season and those samples found to contain higher concentrations of radionuclides than the provisional regulatory limits were subjected to appropriate measures. Furthermore, in case the contamination was spread over an area, distribution restrictions were implemented for foods from that area. Similarly, monitoring of tap water was conducted by both the central and local governments and by the water supply utilities, with special emphasis on Fukushima and neighbouring prefectures.

Around the world, the primary concern of governments was to protect their citizens residing in or visiting the most affected regions of Japan in the days and weeks after the nuclear accident, but there was also consideration of whether any steps were needed within their own countries, such as restrictions on food imports from Japan.

1.1 Motivation

Since the onset of the nuclear accident, the health risk of human exposure to radiation has received priority attention around the world. In its role as the United Nations directing and coordinating authority on international public health issues, WHO was directly engaged in assessing and communicating public health risks from all three components of the disaster, i.e. the earthquake, tsunami and nuclear accident. In line with its defined role in radiation emergency response among international organizations, WHO is responsible for public health risk assessment and response (*2*).

Soon after the accident, WHO developed a formal health risk assessment (HRA) to estimate the risks to human health from radiation exposure due to the Fukushima Daiichi NPP accident. The HRA requires dose estimates; therefore, WHO conducted a preliminary global dose estimation for the general public, which was published in May 2012 (*3*). Based on conservative assumptions, first–year effective doses were estimated to be below 10 mSv in most of Japan with a few exceptions, and well below 0.01 mSv in the rest of the world.

1.2 Purpose and audience

This HRA is based on preliminary dose estimates and is intended to give an indication of the radiation-related health implications of the Fukushima Daiichi nuclear accident. Such information can support the identification of needs and priorities for public health actions. The target audience includes policy makers and health professionals as well as relevant international organizations.

It should be noted that this report discusses health risks rather than health effects (see Box 1). It is not intended to provide estimates of the disease burden in the population or to calculate possible excess disease cases due to the radiation exposure resulting from this accident.

1.3 Scope

The scope of the HRA includes the general population in Fukushima prefecture, the rest of Japan and around the world, and the Fukushima Daiichi NPP emergency workers, i.e. employees of the Tokyo Electric Power Company (TEPCO) and contractors exposed during the emergency phase. It does not include first responders (e.g. police, fire fighters, and Japan self-defence forces) because the information about their radiation doses was not available to the HRA Expert Group within the timeframe of its work.

The general population groups are defined by geographic location, age and sex. Four distinct geographical areas are identified based on preliminary estimated doses. The geographical coverage includes the whole world, with greater spatial detail in the estimated risks presented for Japan, and in particular for the Fukushima prefecture. Age groups considered are 1-year-old infants, 10-year-old children and 20-year-old adults.

Box 1. Health effects versus health risks

Health effects are changes in the health status of an individual or population, identifiable either by diagnostic or epidemiological methods.

Health risks express the likelihood or probability of a health effect to occur under defined circumstances and exposure to a certain hazard, e.g. radiation. Risks are estimated using available data and mathematical models.

Health risks from exposure *in utero* are considered in the risk characterization but are not quantitatively assessed.

For the emergency workers, the assessment considers male workers in age groups of 20-, 40- and 60-year–olds. The exposure assessment is based on dosimetric reports from the Japanese government and TEPCO.

This report examines a number of cancer and non-cancer health endpoints, on the basis of the estimated doses. The assessment considers separately specific cancer sites regarded as being more radiosensitive and with potentially higher risks at younger ages-at-exposure (*4*) – i.e. leukaemia (*5*), thyroid cancer (*6*) and breast cancer (*7*) – plus all solid cancers combined. It also covers non-cancer health effects, such as thyroid diseases, cardiovascular diseases and lens opacities.

This assessment focuses on radiation-related health risks. The psychological impact, recognized as the largest public health issue after the 1986 Chernobyl nuclear accident, is considered and discussed. However, it is not quantitatively assessed as the evaluation of social and psychosocial hazards and their risks to health requires different approaches, such as a Health Impact Assessment[1].

1.4 Overview of the process

This report is focused on the first of the three components of a risk analysis process, which are risk assessment, risk management and risk communication (see Figure 1) (*8*). Risk assessment predicts the likelihood of occurrence of adverse events based on scientific evidence. It does not attempt to indicate the level of risk that can be considered acceptable, or the appropriate level of public health protection. These considerations are within the scope of risk management. The third component, risk communication, is also an essential part of this process.

The HRA process is typically described as consisting of four basic steps: hazard identification, dose-response assessment (or more general hazard characterization), exposure assessment and risk characterization. These steps are defined below.

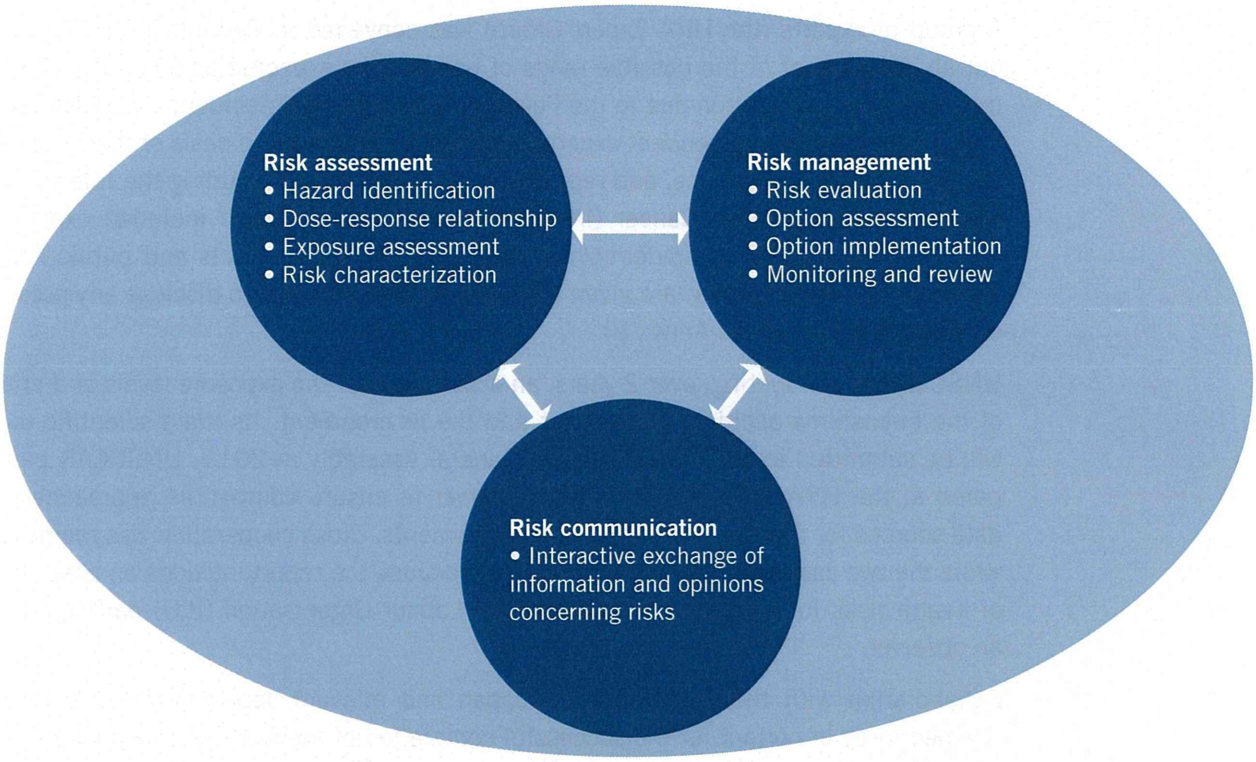
Hazard identification: This first step in a risk assessment is the identification of the type and nature of adverse effects that an agent can cause in a population, based on studies in humans and laboratory animals. In the context of this report, hazard identification is the process used to identify the specific radiation sources (i.e. radionuclides) and the type of harm they could cause.

Dose-response relationship: This second step examines the relationship between exposure to a particular agent and any adverse health effects in humans as a result of this exposure. The relationship is usually based on existing evidence from epidemiological studies that describe the endpoints for adverse human health effects at relevant exposures and the dose-response relationships for the different endpoints. In the context of this report, the endpoints considered include cancer as well as non-cancer risks.

Exposure assessment: This step gathers information about how much of a particular substance different groups have been exposed to, how the exposure took place (i.e. through

1. A Health Impact Assessment (HIA) is a means of assessing the health impacts in diverse economic sectors using quantitative, qualitative and participatory techniques (for more information, see http://www.who.int/hia/en/).

Figure 1. Risk analysis



Adapted from "Principles and methods for the risk assessment of chemicals in food". Environmental Health Criteria, No. 240. Geneva, World Health Organization, 2009.

which exposure pathways) and for how long the exposure occurred. In the context of this report, doses for the general population (*3*) as well as emergency workers are considered.

Risk characterization: This last step of the risk assessment process integrates the information collected in the previous steps to estimate qualitatively or quantitatively the risk of adverse health effects (i.e. cancer and non-cancer risks) under defined exposure conditions. In the context of this report, the risk characterization includes the quantitative estimation of specific cancer risks. Risk characterization takes into consideration the influence of several parameters, such as sex, age at the time of exposure, and attained age. Non-cancer risks are qualitatively assessed.

The report is organized in sections as shown in Figure 2.

Figure 2. Organization of this report

Introduction	Chapter 1	What is the motivation, purpose, scope and process for this health risk assessment?
Hazard identification	Chapter 2	What is the agent and what health problems are potentially caused by the agent?
Dose-response relationship	Chapter 3	What are the health problems at different exposure levels?
Exposure assessment	Chapter 4	What exposures are likely to occur, and what is the resulting dose to humans?
Risk characterization	Chapter 5/6	What is the estimated human health risk from the exposure? What are the uncertainties?
Public health considerations	Chapter 7	What are the public health implications and policy options?
Summary and conclusions	Chapter 8	What are the key findings?

1.5 Procedures

A group of experts (the HRA Expert Group) was convened in December 2011 to carry out an assessment of the possible range of health risks expected as a result of the human exposure to radiation due to the Fukushima Daiichi NPP accident. The HRA Expert Group consisted of independent experts, selected by WHO on the basis of their scientific competence and experience, and representatives from WHO, including the International Agency for Research on Cancer (IARC). The HRA Expert Group included experts on radiation risk modelling, epidemiology, dosimetry, radiation effects and public health. The experts, whose profiles are given in Annex A, were required to disclose any potential conflicts of interest (see Annex B).

UNSCEAR is conducting, over 2 years, an assessment of the exposure levels and effects of the Fukushima accident on humans and the environment. Its main scientific report will be submitted to the United Nations General Assembly in 2013. UNSCEAR participated in the HRA Expert Group as an observer to ensure compatible approaches and data sources for the two United Nations assessments. Close cooperation was maintained while the two assessments were in progress. Because the report includes an assessment of health risks for workers, the International Labour Organization (ILO) participated as an observer.

Collaboration with the Government of Japan and relevant Japanese institutions was deemed to be important for the successful completion of the work as they provided data for HRA. These representatives were observers at the meetings.

The HRA Expert Group met on two occasions in Geneva (December 2011 and March 2012) and communicated electronically. The HRA Expert Group agreed on the most appropriate dose-response models for estimating the health risks, considering different age groups and adverse health effects, and taking into account possible effect modifiers and other population characteristics.

The HRA Expert Group used, where possible, the existing evidence and the most widely accepted knowledge on the nature and probability of the effects that was available. Evidence-based decision making and expert consensus by unanimous agreement was achieved whenever possible. In a few cases decision making was based on majority agreement, with consideration of dissenting opinions and their rationale. For the general population, the HRA Expert Group considered the dose estimates provided by an international expert panel (the Dose Expert Panel), established by WHO in June 2011 (*3*). For the Fukushima Daiichi NPP workers, dose estimates were provided by the Government of Japan and by TEPCO.

2. Hazard identification

This chapter discusses the main radionuclides released during the Fukushima Daiichi NPP accident. It then describes current knowledge on health hazards from ionizing radiation as identified by key research findings, including those on cancer and non-cancer diseases. The relationship between these diseases and the dose is discussed in Chapter 3.

2.1 Identification of the source term

The amount and type of radionuclides released during a nuclear accident is called the source term. An early estimate of the source term was used in the preliminary dose estimation of the Fukushima accident published by WHO (*3*). The amount of radionuclides released during the accident and deposited around Japan was evaluated using both environmental monitoring data and computer simulation based on atmospheric dispersion modelling of radioactive materials (*9,10*). The basis for the estimation of the source term includes operational records, observed parameters and the chronology of events at the site.

Actual environmental measurements showed variability in the radionuclide composition for different locations in Japan. In the WHO preliminary dose assessment, the relative isotopic composition of the radioactive deposits on the ground was assessed in Japan on the basis of soil contamination. Two assumed radionuclide compositions were used (see Table 1).

Table 1. Assumed relative isotopic composition of the radioactive deposits on the ground (on 15 March 2011) from (*3*). The two approaches are based on publicly available data.

Radionuclide	Approach A[a]	Approach B[b,c]
^{131}I	7.8	11.7
^{132}I	7.6	–
^{132}Te[d]	7.6	8.0
^{134}Cs	0.92	0.94
^{136}Cs	0.16	0.2
^{137}Cs	1	1
^{140}Ba	–	0.1
^{110m}Ag	–	0.01
^{129m}Te	–	1.5

a. *Readings of soil monitoring around Fukushima NPP.* Ministry of Education, Culture, Sports, Science and Technology (http://radioactivity.mext.go.jp/en/ accessed 13 May 2012).

b. *Synthèse des informations disponibles sur la contamination radioactive de l'environnement terrestre japonais provoquée par l'accident de Fukushima Daiichi.* Paris, Institut de Radioprotection et de Sûreté Nucléaire, 13 juillet 2011.

c. *Interim report on radiation survey in Iitate village area conducted on March 28th and 29th.* 4 April 2011 (http://www.rri.kyoto-u.ac.jp/NSRG/seminar/No110/Iitate-interim-report110404.pdf, accessed 13 February 2013).

d. ^{132}Te (Tellurium-132) is important the first few days after a nuclear accident. It has a half-life of 3.2 days and decays to ^{132}I (iodine-132), which has a half-life of 2.3 hours.