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REVIEW

The Fukushima accident and travel medicine — Analysis and recommendations

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Summary The accident at the nuclear site in Fukushima has fostered a fear of the consequences of radioactive contamination among many, especially regarding travel to Japan and the import of Japanese goods. We give a general overview of the assessment of the effects of ionizing radiation and a summary of the consequences of the Japanese accident. We report the results of the measurement of radionuclide intake among travelers returning from Japan, carried out at the whole-body counter of the Institute for Work Design of North Rhine-Westphalia (LIA.NRW) in Düsseldorf.

Introduction

Japan as a travel destination has been viewed with reservations after the devastation caused on the Japanese east coast following the 2011 Tōhoku earthquake and the resulting tsunami. Especially the accident at the nuclear site of Fukushima Daiichi is a cause of concern for many travelers. We regularly receive inquiries from German employers and employees, travelers and companies about the safety of people traveling to and from Japan and about the safety of goods imported from Japan. Many company physicians, general practitioners or practitioners of travel medicine worldwide are confronted with this issue since Japan is currently the third-largest economy by gross domestic product[1] and accounts for a large percentage of the worldwide trade in goods and services.[2]

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We attempt to give some basic information on radiation protection for readers without a deep knowledge in the field, with a special focus on the issues surrounding the nuclear plant accident in Japan which is useful especially for employees sent on an assignment in the country or expatriates. We will also report on measurements of radionuclide intake performed at the whole-body counter of the LIA.NRW (Landesinstitut für Arbeitsgestaltung Nordrhein-Westfalen, Institute for Work Design of North Rhine-Westphalia) in Düsseldorf on a large number of travelers returning from Japan.

The health impact of ionizing radiation

The harmful impact of high doses of ionizing radiation on the human body is well known.[3] The International Commission on Radiological Protection (ICRP) reviews and evaluates the research in this area and issues regular recommendations for radiological protection (e.g. dose limits). These recommendations often form the basis upon which national legislation is established, e.g. the German Radiation Protection Ordinance (Strahlenschutzverordnung).[4] The most recent recommendation of the ICRP is the report 103[5] of the Commission from 2007.

Before considering these recommendations, it should be noted that human beings are exposed during their whole life to unavoidable doses of ionizing radiation from terrestrial and cosmic sources. The numerical value of this dose is subject to large regional fluctuations. The worldwide average value is about 2.4 mSv per year.[6] The environmental exposure varies with geographic location, nutrition and lifestyle. The typical dose in most regions of the earth lies between 1 mSv and 10 mSv per year.[6] In some very high background radiation areas, the annual doses can reach up to 100 mSv.

Deterministic (non-stochastic) effects of ionizing radiation (damage to the tissue) can only occur with doses well above 100 mSv.[5] The value of 100 mSv represent an approximate threshold value for tissue damage[5] which increases proportionally to the dose. Symptoms of acute radiation syndrome only start to appear for doses of about 1000 mSv, which can lead to death if the dose is increased further.

The German legal[4] and the ICRP-recommended[5] dose limits for occupational exposure to ionizing radiation lies well below the threshold value for deterministic effects, at 20 mSv per year. The purpose is to minimize the risk of potential stochastic effects of the radiation exposure. Stochastic effects are randomly occurring disease patterns (cancer, cardiovascular diseases, lens opacities) whose probability can be enhanced by exposure to ionizing radiation. It appears scientifically plausible, with noted exceptions, that also below 100 mSv the incidence of stochastic effects will be proportional to the dose.[5] The validity of this so-called linear no-threshold (LNT) model for stochastic effects, which is used for the purposes of radiation protection, is the subject of current research in radiobiology.[7,8] Based on current knowledge, the detriment-adjusted nominal risk coefficient is about 0.42% per 100 mSv for adult persons according to the ICRP.[5]

Assessment of the radiological consequences of the Fukushima accident

A tsunami generated by a magnitude 9 earthquake flooded the nuclear site of Fukushima Daiichi on the northeast coast of Honshū on March 11, 2011. The reactors had been automatically shut down after the earthquake, but the flooding by seawater and the breakdown of the external power supply resulted in the loss of the reactors' cooling systems. This caused overheating, hydrogen explosions after following emergency ventings of the reactor core and probably a partial meltdown of the fuel in three of the reactors at the site. Large amounts of radioactive material were released into the environment, first to the atmosphere and later to the sea by the release of cooling water. A detailed description, analysis and review of the causes and effects of the accident can be obtained from the GRS (Gesellschaft für Anlagen- und Reaktorsicherheit),[9] the IRSN (Institut de Radioprotection et de Sûreté Nucléaire)[10] or the IAEA (International Atomic Energy Agency).[11–13]

To protect the civilian population, the Japanese authorities established an evacuation zone 20 km around the site, in line with ICRP recommendations. After environmental measurements, further steps were taken to minimize the dose of the general population. People were relocated in some areas, and provisional limits for the radionuclide contents of food were established. The local authorities were responsible for the monitoring, based on guidelines established by the Japanese government. Trade restrictions were imposed for food originating from contaminated areas based on measurements. Drinking water was closely monitored by local and national agencies as well as the utilities, with special emphasis on Fukushima and the neighboring prefectures. All these actions and precautions were extensively reported by the Japanese government and the IAEA.[11–13]

An extensive investigation of the radiological consequences of the accident and a preliminary dose estimate has been recently released by the World Health Organization (WHO).[14] Based on available environmental data about the activity and radionuclides deposited on the ground and found in food, data on the environmental dose rate, dosimetry calculations and comparison with whole-body measurements, the expert panel of the WHO determined dose bands for the immediate vicinity of the nuclear site, for the Fukushima prefecture, the rest of Japan and the world population. Under very conservative assumptions, the WHO established a dose band of 10–50 mSv in the first year after the accident for persons in two regions with high exposure near to the nuclear site. In these regions, the overwhelming contribution to the total effective dose results from external exposure. The dose band lies between 1 mSv and 10 mSv for the rest of the Fukushima prefecture. In most other regions of Japan, the effective dose resulting from the accident lies between 0.1 mSv and 1 mSv,[14] a range which is below the ICRP dose limit[5] of 1 mSv for planned exposures to the general population and which would be considered acceptable worldwide. For the rest of the world, the WHO calculated a negligible dose of below 0.01 mSv, in most cases even far below this value. Further and more detailed reports of the WHO and UNSCEAR are expected to be released in 2013.

Release of radionuclides and the contamination of food and water

Dosimetric importance of released isotopes

The energy produced in a nuclear reactor stems from the fission of the uranium isotope ^{235}U. The fission, next to the release of neutrons, photons and energy, leads to the creation of two lighter nuclei. These lighter fission products accumulate during the use of the reactor fuel and form potentially harmful sources of radiation if they happen to be released from the containment. The atomic masses of the fission products mainly concentrate around the regions of mass 95 and mass 135 (see Fig. 1). The overwhelming part of the isotopes produced decay very rapidly (within a few hours at most), while some have half-lives that range into days or even years. These constitute (if they emit radiation of sufficient energy) the isotopes of main dosimetric importance for the general public since they can be dispersed over large distances before they decay. The volatility of the elements produced also plays a role since the much heavier activation and fusion products (trans-uranium elements with mass range around 240) as well as some of the transition metals stemming from fission do not disperse in gaseous form. The isotopes of dosimetric relevance are summarized in Table 1.

The environmental measurements in Japan indicate that only very limited amounts of strontium isotopes were released in the accident. The results of the ^{90}Sr analysis reported by the Ministry of Education, Culture, Sports, Science and Technology (MEXT)[16,17] show that ^{90}Sr has no radiological relevance in comparison to the radiation exposure expected from $^{134,137}Cs$.

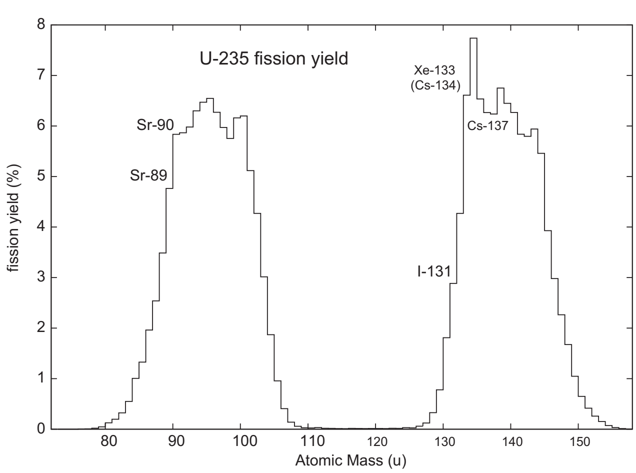

Figure 1 Fission yields by mass number (chain yield) of the fission of ^{235}U by thermal neutrons, as performed in a nuclear reactor (data from [15]). Most of the fission products decay very quickly and have no relevance in dosimetry. Other decay chains may reach longer-lived isotopes which, however, emit only very low-energy radiation (such as ^{93}Zr, ^{129}I or ^{135}Cs) or are not volatile (^{95}Zr, ^{95}Nb). The main chains of relevance for dosimetry are indicated with their end product (^{134}Cs is not a fission product but results from the neutron activation of ^{133}Cs, the stable end product of the $A = 133$ chain).

While ^{131}I had a high significance in the first weeks after the event, today only the cesium isotopes ^{134}Cs and ^{137}Cs are still of concern. They constitute the overwhelming part of the external exposure from surface contamination and of the committed dose from ingestion of food. To estimate this contribution better, the dose factor for the respective isotopes is given in Table 1. The dose factors, which are used to convert an activity intake into a dose, depend on the intake path (here ingestion is considered rather than inhalation), the absorption in the gastrointestinal tract, the age at intake and the total time period considered. For the cesium isotopes, the dose factors for the 30-year committed dose are $1.9 \cdot 10^{-8}$ Sv/Bq and $1.3 \cdot 10^{-8}$ Sv/Bq (see Table 1) for an adult of the general public as given by the ICRP.[18–20] This means that in the absence of additional artificial external exposure (which can be assumed for all prefectures except Fukushima), the recommended dose limit of 1 mSv for adults of the general public would only be reached after ingestion of more than 52 kBq of ^{134}Cs or 77 kBq of ^{137}Cs (or a proportional combination of both) through food.

The provisional limits set by the Japanese government after the accident were 500 Bq/kg for the sum of ^{134}Cs and ^{137}Cs activities for most foodstuffs. Since April 1st, 2012, this limit was lowered to 100 Bq/kg[21] for general foods, 10 Bq/kg for drinking water, and 50 Bq/kg for milk and infant foods. The European Union has followed the Japanese limits for the import of foodstuffs from Japan.[22–24] The food in Japan was, and still is, extensively tested, and the results of the analysis can be found on the website of the Ministry of Health, Labor and Welfare (MHLW, www.mhlw.go.jp).[25] The measurements mainly cover milk and milk products, meat and eggs, fishery products, vegetables and fruit, cereals (including rice) and drinking water. Food exceeding the activity concentration limits is discarded - it is banned from marketing by the government and not recommended for consumption.

The sampling of the foodstuffs is not representative as it focuses on foods of particular public interest or with presumably high activity concentrations. Nevertheless, the data is sufficient for a clear picture of the contamination of foodstuffs in Japan. Fukushima is clearly the prefecture which is mainly affected, with the prefectures Gunma, Tochigi, Ibaraki and Chiba being affected to a lesser extent. The uptake of cesium in crops and livestock differs strongly from species to species and cannot be generalized to groups of foodstuff. The Japanese government has thus released very specific recommendations for the consumption of certain foodstuffs from the prefectures concerned, as well as bans on the marketing of specific food products from these prefectures, which can also be obtained from the website of the MHLW.[25]

In February 2012, the Ministry of Health, Labor and Welfare released new standard limits for radionuclides in foods,[21] along with an estimate of the effective dose from radionuclides in food based on the monitoring data. The new limits were introduced in order to ensure that the effective dose from ingestion cannot exceed 1 mSv per year, taking into account the intake and dose factor for each age category. The dose of 1 mSv would be achieved if 50% of all marketed foods and 100% of drinking water, milk and infant foods were contaminated with $^{134,137}Cs$ at the

Table 1 Main isotopes of dosimetric relevance after releases from a nuclear power plant. The ingestion half-life (time after which only half of the ingested activity is still retained in the human body, after accounting for decay, breathing and excretion) is usually well below the half-life from physical decay. The committed dose factor gives the conversion of a unit intake to the total effective committed dose after a certain time interval. The values given are those for an adult member of the general public as given by ICRP-67,[18] ICRP-68[19] and ICRP-72.[20]

Isotope	Half-life	Committed dose factor [Sv/Bq] (ingestion)			Body part with highest eff. dose
		1 Year period	30 Year period	Up to age 70	
^{89}Sr	50.53 d	$2.6 \cdot 10^{-9}$	$2.6 \cdot 10^{-9}$	$2.6 \cdot 10^{-9}$	Colon
^{90}Sr	28.78 y	$6.6 \cdot 10^{-9}$	$2.7 \cdot 10^{-8}$	$2.8 \cdot 10^{-8}$	Bone surface
^{131}I	8.02 d	$2.2 \cdot 10^{-8}$	$2.2 \cdot 10^{-8}$	$2.2 \cdot 10^{-8}$	Thyroid
^{134}Cs	2.06 y	$1.8 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$	$1.9 \cdot 10^{-8}$	Evenly distributed
^{137}Cs	30.07 y	$1.2 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	$1.3 \cdot 10^{-8}$	Evenly distributed

maximum level permitted by the new standard limits. Based on the monitoring data, the median ingestion dose is estimated at 0.043 mSv/y, and the 90-percentile at 0.074 mSv/y by the MHLW,[21] which is negligible compared to the annual dose from the ingestion of natural radionuclides in food (mainly ^{40}K) of about 0.2 mSv/y for Japan (2008).[21] The internal exposure from ingested radionuclides is thus not a source of concern, neither for the local population nor for travelers and tourists.

Geographic spread of the contamination

Since significant internal exposures can be ruled out, careful attention should be paid to possible external exposure resulting from the fallout of $^{134,137}Cs$. Since there was apparently no breach of the containment of the reactors 1 and 3 at the site, the release from these units was limited to the volatile fission products released when the pressure vessels had to be vented to prevent a breach of the containment. These ventings lead to a build-up of hydrogen in the refueling bay above the reactor vessel which caused the explosions that made headlines worldwide. Unit 4 was not operational at the time of the natural disaster, so only the spent fuel pond was at risk in this building. Unit 2 at the site shows only minimal external damage, but is the cause of most of the surface contamination in the region. While the venting of units 1 and 3 occurred at times where the wind was blowing to the east and the cloud dispersed over the pacific, the release during March 15 (most probably from unit two) was deposited on land to the northwest of the plant. There are several maps (for example in the IRSN[10] and WHO[14] reports or the Japanese reports to the IAEA [12,13]) detailing the surface contamination in the area around the plant. The ambient dose rates from the SPEEDI monitoring system[26] or the surface deposition of cesium isotopes (in Bq/m^2) are available from MEXT.[27]

All these maps show that only the areas in Fukushima prefecture immediately surrounding the plant (evacuation area) and the fallout-contaminated area to the northwest of the plant (deliberate evacuation area including the towns of Iitate and Katsurao), and to a much lesser extent the areas immediately outside the evacuation area (evacuation prepared area), are of concern regarding external exposure to ionizing radiation. Inside Fukushima prefecture, there may be local spots where a higher exposure can occur. Since the dose is determined by exposure time and the area is largely covered with forests, this is not expected to lead to any significant external doses to travelers and tourists.

The wind blowing to the east has lead to a geographically limited soil contamination. According to first estimates, only about 10% of the released activity was deposited on land. Since the total released activity was about one order of magnitude lower than the Chernobyl accident, it can be estimated that the land contamination from the Fukushima accident represents about 1% of the contamination from Chernobyl. For the inhabitants of Fukushima prefecture, this still represents an emergency situation (in the sense of ICRP-103[5]) as external doses of up to 20 mSv per year are possible in the first year (dose band of 1 mSv—10 mSv in the first year according to the preliminary WHO estimate[14]). However, the rest of Japan was not affected by noteworthy surface contamination and a stay in the country will not lead to a higher external exposure as long as the contaminated areas in Fukushima prefecture are avoided.

Whole-body counter measurements at the LIA.NRW in Düsseldorf

The radiation protection services department of the Institute for Work Design of North Rhine-Westphalia (LIA.NRW) in Düsseldorf is an approved laboratory for incorporation monitoring (ALIM) within the German framework of physical radiation protection control. During routine operation, the incorporation monitoring laboratory applies the monitoring methods for the assessment of the committed dose in the case of internal radiation exposure, by in-vivo and in-vitro methods. The in-vivo monitoring is carried out with a whole-body counter (WBC) which is capable of determining the whole-body activity of gamma-emitting radionuclides, as well as organ doses to the thyroid. The dose resulting from the intake of alpha- or beta-emitters can be assessed in-vitro through the analysis of bioassays (urine samples). The laboratory for incorporation monitoring of the LIA.NRW carries out several hundred measurements each year to determine the committed dose in the framework of radiation protection control.

After the Fukushima accident and the resulting concerns among many travelers and tourists returning to Germany from Japan, the Ministry of Labor, Integration and Social Affairs of North Rhine-Westphalia offered to all travelers and tourists returning from Japan the possibility to undergo a whole-body measurement at the LIA.NRW free of charge. More than a hundred people took advantage of this service until the end of 2011.

An overview of the results of our measurements is given in Fig. 2. It should be noted that the measured individuals had been staying in different parts of Japan and for different time frames. We do not mean to imply that our data constitutes a significant or representative sample, but we are nevertheless of the opinion that the results roughly represent the exposure of the average tourist or traveler in Japan during the time after the Fukushima accident.

In the days after the event, the short-lived isotopes ^{131}I ($T_{1/2} = 8$ d) and ^{132}Te ($T_{1/2} = 3.2$ d) as well as the daughter nucleus ^{132}I ($T_{1/2} = 2.3$ h) were measured in radiologically insignificant quantities. Often the measured values were below the detection limit (but still above the decision threshold) or just above. The highest measured whole-body activity of ^{131}I of around 600 Bq (measured one week after the accident) would constitute a committed dose of 0.08 mSv under the very extreme assumption of a single acute inhalation directly after the earthquake on March 11. The very rapid decay of the iodine and tellurium isotopes meant that three weeks after the accident the presence of these isotopes could not be detected anymore. For current travelers and tourists, these short-lived isotopes are no source of concern anymore, as only trace amounts would still remain in the environment today.

The cesium isotopes ^{134}Cs and ^{137}Cs could be measured in very low concentrations one week after the accident. Mostly, the values were below the detection limit (but still above the decision threshold) or only slightly above. Some higher values could be measured later (more than 100 days after the accident), but still in insignificant amounts from the standpoint of radiation protection. Assuming an inhalation 90 days before the measurement (the standard procedure for routine cesium monitoring according to German law), the highest committed dose would amount to

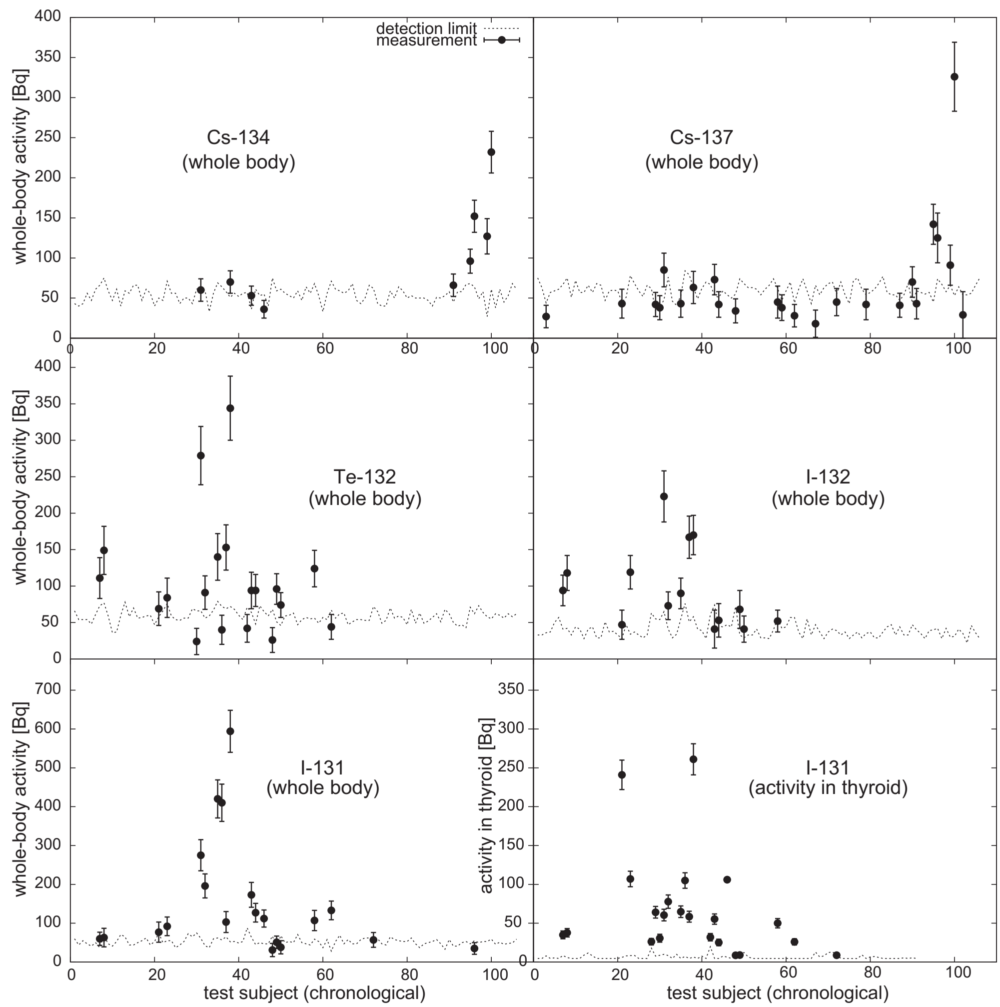

Figure 2 Results of the whole-body measurements of radionuclide intake performed at the radiation protection services department of LIA.NRW in Düsseldorf. The measured whole-body activities of the radionuclides ^{131,132}I, ^{132}Te and ^{134,137}Cs are given as a function of test subject number in chronological order. For ^{131}I the thyroid activity was determined as well. The measurements mainly cover the first weeks after the accident when there was large demand for testing among travelers. The dotted line represents the detection limit of the measurement. All values above the decision threshold are given with 1σ-errorbars.

0.009 mSv in the case of ^{137}Cs and 0.01 mSv in the case of ^{134}Cs. Both these values constitute negligible doses. To put these values into perspective, the average dose received from cosmic radiation during a roundtrip flight Frankfurt-Tokyo amounts to about 0.2 mSv (a dose all returning travelers and tourists are exposed to on average).

Our measurements are in line with the findings of the WHO.[14] 77% of all monitored subjects exhibited no measurable intake of gamma-emitters. The 23% where a value could be detected only had minimal whole-body activities of the relevant isotopes (see Fig. 2). The measured values all result in insignificant committed doses that amount to values between a hundredth and a tenth of the ICRP dose limit from planned exposure of 1 mSv for the general population.

Conclusions and review for practitioners

The 2011 Tōhoku earthquake, the resulting tsunami and the accident at the Fukushima nuclear site have widespread implications in many areas. We have tried to highlight the main points regarding the radiation protection implications for travelers and tourists, for which objective data and scientific evaluations exist and that can be of use for medical travel advice.

Japan is a stable and highly developed country that until now has not given cause to safety concerns among travelers. However, more than one year after the natural disasters of May 2011, many travelers still regularly inquire about possible health hazards resulting from an elevated exposure to ionizing radiation. Even if, as we explained, a strong reduction of the exposure in the vicinity of the plant has already occurred for physical reasons and the rest of the country never experienced substantial exposures, the distrust level among those seeking advice remains high.

In general, it is often asked whether travel to Japan is medically acceptable. We want to stress that the exposure to ionizing radiation for travelers and tourists in Japan will not be higher than the world average if one does not venture into the restricted areas around the Fukushima nuclear site, or at least does not stay in these areas for an extended period of time. Travel can be undertaken to all freely accessible areas, and there is no need to limit travel duration.

One main area of concern is the local food. Here it should be emphasized that, just as for foodstuffs imported from Japan, and for the reasons explained above, the local food does not give rise to health concerns. The local food is subject to regular sample checks in line with an elaborate safety concept based on measurements. The limits for cesium contamination are set in a way that even if 50% of all food consumed and all of the drinking water, milk and infant foods were contaminated at the maximum permissible level (an extremely unlikely scenario), it would result in a committed dose lower than 1 mSv (the ICRP-recommended limit value for exposure of the general population) for all age groups.[21] The whole-body measurements we carried out among travelers returning from Japan confirm the view that there should not be any concern for a significant ingestion of radioactive isotopes from local food.

Goods imported from Japan have initially been subject to scrutiny. Meanwhile, regular checks and measurements have shown that there is no reason for concern regarding imported goods. Still, some travelers are asking whether they should use radiation measurement devices in Japan to perform self-checks of contamination. We strongly discourage the use of such devices. On the one hand, the quality and measurement precision of readily available and affordable devices is mostly insufficient. On the other hand, the handling, measurement and interpretation of results requires experience and should be left to experts. Furthermore, the unavoidable detection of fluctuating background radiation can lead to misinterpretations and misplaced worries where no real threat is posed.

In summary, there are no indications against travel to Japan from a radiological point of view. The external exposure as well as the internal exposure from ingestion of radionuclides will, on average, not be higher than the world average. The total radiation exposure for people living in Japan will remain within the range of natural exposure in Japan. The total radiation exposure in Japan will be lower than the natural radiation exposure for a large part of the European population. Only the restricted areas and evacuation zones around the Fukushima nuclear site should be avoided, but they are not freely accessible anyway. Higher than average exposure is possible when staying in Fukushima prefecture. The consumption of purchased Japanese food is possible without restrictions as the food is subject to monitoring in line with international standards, and the current data strongly indicates that the ingestion pathway is of minor importance.

Conflict of interest statement

None.

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