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Public health response and medical management of internal contamination in past radiological or nuclear incidents: A narrative review

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Abstract

Following a radiological or nuclear emergency, workers, responders and the public may be internally contaminated with radionuclides. Screening, monitoring and assessing any internal contamination and providing necessary medical treatment, especially when a large number of individuals are involved, is challenging. Experience gained and lessons learned from the management of previous incidents would help to identify gaps in knowledge and capabilities on preparedness for and response to radiation emergencies. In this paper, eight large-scale and five workplace radiological and nuclear incidents are reviewed cross 14 technical areas, under the broader topics of emergency preparedness, emergency response and recovery processes. The review findings suggest that 1) new strategies, algorithms and technologies are explored for rapid screening of large populations; 2) exposure assessment and dose estimation in emergency response and dose reconstruction in recovery process are supported by complementary sources of information, including ‘citizen science’; 3) surge capacity for monitoring and dose assessment is coordinated through national and international laboratory networks; 4) evidence-based guidelines for medical management and follow-up of internal contamination are urgently needed; 5) mechanisms for international and regional access to medical countermeasures are investigated and implemented; 6) long-term health and medical follow up programs are designed and justified; and 7) capabilities and capacity developed for emergency response are sustained through adequate resource allocation, routine non-emergency use of technical skills in regular exercises, training, and continuous improvement.

Keywords

Nuclear accident; Radiological incident; Recovery process; Internal contamination; Public health response; Medical management

1. Introduction

The past century has seen rapid growth of radiological sciences and nuclear technologies and their wide applications in our society. While enjoying the benefits of utilizing them in energy production, radiation medicine and other industries, we also face the risks from radiological and nuclear incidents, either accidental or intended, large-scale or small-size, such as the ^{137}Cs accident in Goiânia, Brazil (IAEA, 1988), the Chernobyl nuclear power plant accident in former USSR (IAEA, 1992), the ^{210}Po poisoning incident in London, UK (Bailey et al., 2008), and more recently the Fukushima nuclear power plant accident in Japan (IAEA, 2015).

Following a radiological or nuclear incident, where workers, responders or the general public are potentially exposed to external radiation and/or internal contamination involving radioactive materials, timely and effective public health response and medical management are important aspects of the overall incident management, affecting both short-term health outcomes and long-term health consequences from the exposures. For decades, government emergency and health agencies, international organizations, scientific communities and industries around the world have been working to develop capabilities and surge capacity in responding to such incidents, but, are we really prepared for the next one?

Experience gained and lessons learned from the management of past incidents allows for better understanding of the capability gaps that need to be filled, in terms of knowledge/ technologies and/or operational implementation (Barquinero et al., 2021; Liutsko et al., 2021). In this paper, public health response to and medical management of internal contamination following 13 radiological or nuclear incidents selected based on the availability of publications and knowledge of the co-authors (Table 1) are reviewed under the auspices of the WHO (World Health Organization) REMPAN (Radiation Emergency Medical Preparedness and Assistance Network, Carr (2010)). Some of the incidents are well known, where large numbers of workers, responders and the public were internally contaminated; others involved only small numbers of individuals but revealed significant challenges in specific technical areas (below).

The selected incidents are reviewed across 14 technical areas that are important for emergency preparedness, emergency response, and the recovery process (Table 2). These technical areas reflect the requirements or recommendations of the International Health Regulations (IHR 2005) on public health response to and medical management of radiation emergencies (WHO, 2016). The incidents are first summarized focusing on public health response and medical management activities relating to internal contamination; they are then evaluated in each relevant technical area taking into account the operational constraints related to each incident at the time of occurrence, and any major capability gaps, technological or operational, are identified and analyzed. Finally, a summary of outcomes, either directly from the reviewed incidents and technical areas or suggested by the authors, to help eliminate any identified capability gaps is presented.

2. Large-scale radiological or nuclear incidents

Large-scale incidents with radioactive contamination of the environment and a large number of individuals are presented in this section, focusing on common aspects of public health, individual monitoring, dose assessment, and medical management in response to internal contamination. Important considerations to take into account in each incident include the radionuclides involved, the exposure pathway (inhalation, ingestion, wound), individual monitoring, dose assessment, and medical management if applicable.

2.1. The Chernobyl accident, USSR

The Chernobyl nuclear power plant accident in USSR occurred on 26 April 1986 during a planned shutdown of the Unit 4 reactor to test the capacity of the turbogenerator to supply power during its rundown for the unit’s internal requirements (IAEA, 1992). A significant amount of radionuclides was released to the environment and contaminated a large area of the former USSR and several other European countries. Radioactive particles deposited within 100 km of the plant mainly contained primary fuel (U, Pu), secondary refractory (Zr, Mo, Ce, Np) and fission (Ru, Ba, Sr) radionuclides. Volatile radionuclides, such as isotopes of Cs, Te and I in the form of condensation particles (most iodine was in gaseous form) contaminated areas up to 2000 km from the plant (Alexakhin et al., 2004; Konstantinov et al., 2016; Anisimov et al, 2018). The highest ^{131}I fallout levels were registered in northern Ukraine, southern Belarus and adjacent areas of European Russia (Izrael, 2002(a);

Alexakhin et al., 2004; Konstantinov et al., 2016; Anisimov et al, 2018). The total activity of ^{137}Cs fallout in the territory of the former USSR was initially estimated to be about 4×10^{16} Bq in (Izrael, 2002(a); Alexakhin et al., 2004), but later reassessment doubled this estimate to about 8×10^{16} Bq (IAEA, 2008).

About 50,000 residents of Pripyat and Yanov were evacuated on April 27, 1986, with 50,000 more residents evacuated from other locations (including the town of Chernobyl) within 30 km of the plant in early May 1986. Sheltering in place was not implemented and supplies of clean food and water were lacking. During the initial response, stable potassium iodine thyroid blocking (ITB) was delayed and then only partially implemented: it was administered to just 70% of the residents of Pripyat (60% on April 26, 1986) (Likhtarev et al., 1994; Ilyin, 1995; Savkin et al., 2001; Linge et al., 2002; Alexakhin et al., 2004; Ilyin et al., 2016; Uyba et al., 2018). Among the power plant staff, thyroid blocking using potassium iodide was implemented but not as a mandatory requirement; administration was dependent on the willingness of the staff members and their immediate supervisor (Kryuchkov et al., 2011).

2.2. The Fukushima Accident, Japan

The Fukushima Daiichi Nuclear Power Plant accident in Fukushima, Japan, was triggered by the Great East-Japan Earthquake and subsequent tsunami on 11 March 2011 (IAEA, 2015). The reactors suffered from complete loss of cooling functions, resulting in core meltdown and the release of a significant amount of radionuclides into the environment (^{131}I, 1.5×10^{17} Bq; ^{137}Cs, 1.5×10^{16} Bq) (Katata et al., 2015).

The affected populations include on-site emergency workers, cleanup workers and the public. Most of these people were residents in the Fukushima Prefecture. No acute radiation syndrome (ARS) was observed in the exposed workers or the public. Six workers received doses (effective dose) exceeding 250 mSv from a combination of external and internal exposures, the tentative emergency exposure dose limit set by the Japanese government (Yasui, 2015). The maximum dose received was around 680 mSv, which was mostly due to internal dose from the intake of ^{131}I (590 mSv) (UNSCEAR, 2014). Radiation doses to the public were much smaller (Kurihara, 2018a). The Fukushima Health Management Survey (FHMS) indicated that 99.4% of the 421,394 residents from Fukushima Prefecture received less than 3 mSv from external exposure within the first four months following the accident (Ishikawa et al., 2015). Internal doses from the intake of ^{134}Cs and ^{137}Cs were minimal, below 1 mSv for almost all residents examined since June 2011, based on whole body counting of about 300,000 people by the Fukushima prefectural government as of September 2016 (Kurihara et al., 2018b). The very low internal doses from ^{134}Cs and ^{137}Cs suggests that the timely restriction on consumption of contaminated food and water has functioned well. Thyroid doses from internal contamination with iodine isotopes, mainly ^{131}I, were estimated by several Japanese experts (Kurihara, 2018a), suggesting that doses would be unlikely to exceed 50 mSv, although assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) indicated that the settlement-averaged thyroid dose could be as high as 83 mSv for children evacuated from one municipality.

Residents living within a 20-km radius of the power plant were asked by the government to evacuate immediately after the accident. The evacuation significantly reduced exposures to the residents; however, it also caused confusion and panic among them. Evacuees were screened for contamination using Geiger-Mueller (GM) survey meters (Kondo et al., 2013). The number of persons screened during 11–21 March 2011 was 72,660, reaching 244,281 by 10 February 2012 (Ogino et al., 2012; Kondo et al., 2013).

As a health follow-up program, the FHMS was launched at the end of June 2011 (Yasumura et al., 2012). It consists of the Basic Survey and the Detailed Surveys, including thyroid ultrasound examinations to detect possible thyroid cancer in children in Fukushima Prefecture. There were about 360,000 children aged between 0 and 18 years as of 11 March 2011. The results of the examinations have been periodically published by Fukushima Prefecture (Fukushima Prefecture, 2018a).

2.3. The Three Mile Island Accident, USA

The Three Mile Island (TMI) accident began in the early morning hours of 28 March 1979 when the unit TMI-2′s main feed water pumps failed. As a result, the reactor safety systems stopped the turbine-generator, and then the reactor itself automatically shut down. Due to improper closing of a relief-valve and erroneous indications on the instrument panel, the operators did not realize that plant was experiencing a loss-of-coolant accident (US NRC, 2018). The overheated reactor core caused a partial meltdown of the TMI-2 reactor. Fortunately, most of the radioactive materials released from the failed reactor core were contained within the reactor and did not escape to the environment, according to "Report of The President's Commission on the Accident at Three Mile Island" (1979). Only about 3.7 $\times 10^{17}$ Bq of noble gases (mainly ^{133}Xe) and 5.5 $\times 10^{14}$ Bq of ^{131}I were released to the atmosphere (UNSCEAR, 1982).

Environmental monitoring began within a few hours of the accident and continued long afterwards. Thousands of environmental samples of air, water, milk, vegetation, soil, and foodstuffs that were collected in 1979 from areas surrounding the TMI nuclear power plant showed very low levels of radioactivity. Careful estimates of radiation doses to the public determined that, on average, people living in surrounding communities received a dose of 15 μSv above background. The maximum dose that an individual located offsite could have received was less than 1 mSv (US NRC, 1979). To date, health studies of the population in the surrounding area and the plant workers have not shown any adverse health impacts are associated with the TMI accident although such impacts cannot be ruled out (Wing et al., 1997). However, the TMI accident led to significant changes in the nuclear industry resulting in upgraded and strengthened plant design and equipment requirements, broader and more robust regulatory oversight, increased involvement of local, state, and federal authorities, enhanced training and staffing requirements, and other improvements.

2.4. The Kyshtym Accident, USSR

The Kyshtym Accident happened on 29 September 1957 at the Mayak Production Association (MPA) (Avramenko et al., 1997; Nikipelov et al., 1989). A nuclear waste storage tank containing high-level waste exploded due to failure of the water-cooling system.

The activity of the waste in the tank was 7.4×10^{17} Bq. About 90% of the total activity settled in the immediate vicinity of the site of the explosion, primarily in the form of coarse particles, the remaining 10% was dispersed by the wind and formed a radioactive trace along the path of the plume. About 67% of this released activity was $^{144}Ce+^{144}Pr$, 25% was $^{95}Zr+^{95}Nb$, and 5.5% was $^{90}Sr+^{90}Y$. The fallout from the radioactive plume lasted 10–11 h and formed the East Urals Radioactive Trace (EURT), which covered a large area north-north-east of the Mayak site.

Several surveys conducted by the MPA staff using automobiles from the date of the accident until the end of 1957, and aircraft in February 1958, provided detailed information on the distribution of the radioactive contamination. The contaminated zone identified, using a criterion of 7.4×10^4 Bq m^{-2} or greater for ^{90}Sr, was a 1,000 km^2. The most significant exposure pathways in the EURT region were ingestion of radionuclides within local foodstuffs (bread, milk and meat, potato and vegetables) and external gamma exposure from gamma-emitting radionuclides deposited in soil.

Three settlements, with a total of 1,100 residents, were located in close proximity to the site of the explosion. They were evacuated and the residents were decontaminated within 7–14 days after the accident; their livestock were slaughtered and buried. From the autumn of 1957, within the EURT region, foodstuff and animal feed products were monitored for contamination and some replacement of contaminated items was initiated to decrease intakes of radionuclides (Akleyev et al., 2017; Bournazyan, 1974).

The EURT cohort, comprised of 21,400 residents from the most contaminated settlements, was identified for a follow-up epidemiological study: the cohort-average doses were 28 mGy for stomach and 78 mGy for red bone marrow (RBM). No cases of chronic radiation syndrome (ChRS), a manifestation of early stage tissue reactions arising from protracted exposure, were diagnosed among the residents of the EURT. A long-term epidemiological study of solid cancer incidence and mortality in this cohort showed a statistically significant linear dose response (Akleyev et al., 2017).

2.5. The Techa River Incident, USSR

The Mayak Production Association (MPA) was the first facility for weapons-grade plutonium production in USSR, becoming operational in December 1948. Early operations led to planned discharges of uranium fission products into the Techa River, starting in January 1949. In addition to this, accidental releases also occurred in the summer–autumn of 1951, due to leaks of high-level waste from storage tanks into cooling and drainage water that then discharged into the river (Alexandrov et al., 2006 and 2007). Studies of river water were carried out once a year: in the summer of 1950, no increased levels of radioactivity were detected, but by the following summer (1951) the total beta-activity in river water was high. When the source of this leak was finally identified in October 1951, planned major releases were then diverted into an isolated body of water, of Lake Karachay, which resulted in a significant decrease in overall discharges into the river. In 1956 the riverbed of the upper Techa was dammed and by-pass canals were constructed, which effectively isolated the most heavily contaminated region from lower parts of the river. Total releases between 1949 and

1956 were 1.15×10^{17} Bq, with a significant contribution from long-lived ^{137}Cs and ^{90}Sr (Degteva et al., 2012).

Radionuclides were transported down the river and deposited in sediment and adjacent floodplain soils (Shagina et al., 2012). There were 41 villages on the banks of the Techa River downstream from the release site. For many villages the Techa River was the main, and sometimes only, water supply for drinking and other uses. The river floodplain was used as cattle pasture and for hay making. Residents of Techa River villages were not informed in reasonable time that contamination in the river posed a danger to their health, as a result, they were subjected to prolonged external and internal radiation exposure.

2.6. The 1954 Castle Bravo Incident, Marshall Islands

From 1946 to 1958 a total of 66 nuclear tests were conducted on or near the Bikini atoll of the Marshall Islands. The largest test, coded Castle Bravo, was a near surface detonation of a 15 Mt thermonuclear device on 1 March 1954. The yield of this detonation was 2–3 times greater than anticipated (Robbins and Adams, 1996), producing a large amount of radioactive fallout. Moreover, unusual meteorological conditions drove the radioactive plume unexpectedly in an eastern direction and led to intense radioactive fallout exposure to the population of the northern atolls of the Marshall Islands and the fishermen on a Japanese vessel “Lucky Dragon No 5” present in the area (Oishi, 2011).

Fallout started on Rongelap atoll (160 km east of the hypocenter) 4–6 h after the detonation and lasted 5–10 h (Robbins and Adams, 1996). The Marshallese on the affected islands were evacuated to the mid-latitude atolls 2–3 days later and decontaminated over there. They were medically observed for two months at the Kwajalein Naval Base before being resettled (Conard et al., 1980).

Acute radiation effects observed among the affected inhabitants, including vomiting, diarrhea and skin burns, were largely due to external radiation exposure of the fallout. The major late effects of radiation exposure among the Rongelap inhabitants were thyroid abnormalities including thyroid failure, nodules and malignant tumors. Organ dose assessments showed that the thyroid absorbed doses were in a range that may cause thyroid failure. Thyroid nodules first appeared nine years after the incident and were particularly frequent in those exposed as children below 10 years of age. In comparison with the un-exposed Marshallese, an excess of thyroid cancers classified as papillary carcinoma were observed among the inhabitants of the exposed islands with the first case diagnosed 11 years after exposure (Robbins and Adams, 1996).

Twenty-three fishermen on the Japanese vessel “Lucky Dragon No 5”, located 130–160 km from the hypocenter, were also exposed to the fallout (Oishi, 2011; Hendriksen et al., 2014). It appears that the food and water consumed at sea were taken from closed containers, substantially reducing potential internal radiation exposures. When they returned home two weeks later, the whole crew was admitted to hospitals in Tokyo with a diagnosis of acute radiation sickness. Long-term medical follow-up of the fishermen was done annually by the National Institute of Radiological Sciences (NIRS) in Chiba, Japan. No thyroid abnormalities have been reported (Conard, 1992).

2.7. The Goiânia ^{137}Cs Accident, Brazil

A teletherapy source containing 5 × 10^{13} Bq ^{137}Cs (in chloride form) was abandoned in an old hospital building in Goiânia, Brazil, which was partially demolished and left without any security. On September 18, 1987 two men got into the building and dismantled the assembly and opened the source without any protection. The source was sold to a junkyard owner who had been fascinated by the "blue brightness" from the source at night. Parts of the source were given to relatives, friends and neighbors as gifts. Remnants of the source, housing and the assembly, were sold for scrap to a second junkyard leading to the further spread of contamination. As the source was in powder form, the contamination spread rapidly. Some of the people who had been exposed were hospitalized with symptoms of acute radiation syndrome (ARS), such as vomiting and diarrhea, but as the cause of their illness was then unknown, they were treated as having a tropical disease or an allergic reaction (IAEA, 1988; Rozenthal et al., 1991). On September 28, one of the patients connected her illness with the source and took part of the source in a bag to the public health department, this led to the discovery of the accident: A physician who suspected the illness could be ARS asked a physicist for help, they confirmed that the material in the bag was radioactive and the dose rate measured at surface was 10 Sv h^{-1}. The physicist evacuated the area and notified the Brazilian National Nuclear Energy Commission (CNEN) immediately (Rozenthal et al., 1991; Brandão-Mello, 1991).

The 11 most serious victims admitted to the hospital were treated by specialists. Seven streets with buildings and houses considered as principal incident foci were isolated and people were evacuated to the city's stadium, the local authorities' designated community reception center, where they were provided with a shower and change of clothes. People who lived in one of the foci or had any contact with the exposed individuals were monitored for potential contamination. Public information sessions and press conferences were organized along with the distribution of 250,000 information pamphlets and a 24/7 telephone advice service (Rozenthal et al., 1991).

A total of 112,000 persons were monitored, of which 129 had internal and/or external contamination. Fifty persons presenting external and slight internal contamination were assigned to the primary (lowest) level of medical management and were subject to close medical surveillance, 20 were assigned to the secondary level and admitted at Goiânia Hospital, due to clinical and hematological abnormalities or radiation injuries, and 14 who presented with severe impairment of the hematopoietic system were designated as tertiary level and transferred to Marcílio Dias Navy Hospital in Rio de Janeiro, which specializes in treating radiation injuries. This tertiary group were further evaluated for any radiation injuries to the skin, bone marrow suppression, their ^{137}Cs body burden and the need to use Prussian Blue decorporation treatment. Four persons died despite the intensive medical care provided. By the end of November 1987, the patients hospitalized in Rio de Janeiro returned to Goiânia Hospital, where decorporation therapy and monitoring continued until it was considered safe to discharge them (Brandão-Mello, 1991; Oliveira et al., 1991 (a)).

Prussian Blue was administered orally to help decorporate ^{137}Cs from 46 patients, with daily dosages ranging from 0.67 to 10 g, which proved to be efficacious. Bioassay data showed that the biological half-life of ^{137}Cs was reduced by 71% for adults, 46% for adolescents and 43% for children. This was found to be independent of dosage administered within the administered range (Melo et al., 1994). In 1987, a center to assist the victims of the ^{137}Cs incident was established in Goiânia. This center has expertise in radiological contamination monitoring, injury diagnosis and treatment, providing health and medical follow-up services.

2.8. The 2006 ^{210}Polonium poisoning Incident, UK

On the 23 November 2006, a former officer of the Russian secret service, Alexander Litvinenko died in London, UK, as a result of poisoning with ^{210}Po, an alpha particle emitter: the estimated intake was around 4×10^9 Bq (Nathwani et al., 2016; Harrison et al., 2017). As the cause of his sickness was only identified just before his death, investigation of any collateral contamination did not start until several weeks after the poisoning event. This revealed ^{210}Po contamination in tens of locations, including hospitals, hotels, offices, restaurants, bars and others associated with transport. Police and health authorities were concerned that other individuals could have been exposed to ^{210}Po through inhalation or ingestion (Croft et al., 2008).

The Health Protection Agency (HPA) in the UK (now part of Public Health England – PHE) was tasked with coordinating and managing public health response measures, including: identifying and securing contaminated areas; preventing further exposures; assessing the health risk for exposed individuals; informing, advising and reassuring people associated with contaminated locations; giving expert technical advice to government and public health services; communicating with the public; and ensuring the remediation and return to use of contaminated areas.

The public health response dealt with thousands of concerned individuals. It was necessary to talk to all of them along with staff and visitors at locations identified during the investigation, followed-up with urine analysis to assess levels of intake of ^{210}Po, where appropriate (Bailey et al., 2008). Approximately 750 individuals were assessed using urine bioassay, of these 139 had levels of ^{210}Po that were above the designated ‘Reporting Level’ (RL) of 30 mBq d^{-1}, showing the possible presence of some ^{210}Po from the incident, with 92, 41 and 6 in the ranges of 30–100, 100–1000 and greater than 1000 mBq d^{-1}, respectively.

Because of the large numbers of samples expected, and the need for rapid reporting of results, a system was developed for rapid assessment of individuals whose urine measurements indicated that their intakes and doses were negligible, while thorough assessments would be made for individuals likely to have higher intakes and doses. Thus, if the measurement was less than the RL, no formal dose assessment was carried out, and the result reported as ‘Below Reporting Level’. If the measurement was above the RL, a standardised dose assessment was carried out assuming 100% intake via inhalation, the most conservative assumption. If the assessment gave a dose less than 1 mSv, it was reported as such. If the assessment gave a dose greater than 1 mSv, a detailed ‘special’ assessment was carried out, where information obtained during the initial risk assessment was used to inform judgements about the potential for exposure from inhalation and/or ingestion.

Individuals, identified from any source, who reported symptoms which could be associated with radiation effects, or were seriously concerned, were reviewed by HPA's Clinical Assessment Team. Of the 186 people assessed, 29 were referred to a special clinic at a London hospital; none were found to be suffering from any acute radiation effects. In the UK, only Mr. Litvinenko received medical treatment as a result of this incident.

Oversea visitors who had stayed in, or visited, one of the hotels or other locations involved in the incident were followed up through international diplomatic, public health and radiation protection channels (Shaw et al, 2010).

3. Workplace radiological or nuclear incidents

Workplace incidents may involve only one or a small number of individuals. In this section, five workplace incidents are presented, where exposure pathways include not only inhalation and ingestion but also wounds and dermal absorption. The experience gained from them in monitoring, dosimetry, decontamination, medical management, and long-term follow up are invaluable.

3.1. The ^{241}Am accident at Hanford, USA

On 30 August 1976, an accident occurred in the Plutonium Finishing Plant on the Hanford Nuclear Reservation in the state of Washington, USA, where a worker was heavily contaminated with ^{241}Am when a resin column containing about100 gram of ^{241}Am and 7 mol L^{-1} nitric acid exploded. He was injured primarily in the face and neck region with a mixture of Am, nitric acid, glass, ion exchange resin, and metal (McMurray, 1983).

After initial decontamination on site, the injured individual was transported to the Hanford Emergency Decontamination Facility (EDF), where besides further external decontamination, the first dose of a decorporation agent, 1 g of Ca-DTPA, was administered intravenously approximately 2 h after the exposure (Breitenstein, 1983). Skin decontamination, wound debridement, as well as occasional surgical removal of embedded fragments from the worker's face, were undertaken in an effort to reduce the body burden of americium, in addition to decorporation using Ca-DTPA administered at two doses per day in the first four days and between Day 16–25. Treatment was switched to Zn-DTPA from Day 5–15 and after Day 26. Treatment with Zn-DTPA continued for over 4 years following the accident (Breitenstein, 1983).

The worker remained isolated in the EDF for approximately 2 weeks after the accident until the threat of airborne americium had been eliminated. Five months after the accident, he returned to live in his home. Over the next decade, he had a variety of health issues. Except for vision issues, most of these were attributed to pre-existing conditions or advancing age. He passed away in 1987. Post-mortem tissue samples were sent to the United States Transuranium and Uranium Registries (USTUR) where a variety of information on his americium exposure, including dose reconstruction, was obtained.

Based on measurements immediately after the accident and post-mortem analysis, it was estimated that of the 1.2×10^{13} Bq of ^{241}Am (100 g) in the reaction vessel at the time of the explosion, up to 1.9×10^{11} Bq was deposited on the injured individual. External decontamination efforts reduced this level to 2.2×10^{8} Bq, mostly located in the face and neck area. Further decontamination and wound debridement reduced this level to approximately 4×10^{7} Bq after about a week. It was estimated that the long-term administration of Ca-DTPA and Zn-DTPA prevented 99% of the internalized ^{241}Am from being deposited in the internal organs (Breitenstein and Palmer, 1989).

3.2. The ^{238}Pu wound accident at Savannah River Site, USA

In June 2010, a glove-box operator at the U.S. Department of Energy's Savannah River Site (SRS), Aiken, South Carolina, sustained a puncture wound while venting canisters containing legacy materials contaminated with ^{238}Pu (Sugarman et al., 2018).

Initial monitoring of the wound site with a zinc-sulfide alpha detector indicated a count rate of 300 dpm. However, it was assumed that radioactive material was deposited on the inner surface of the dermis and soft tissues adjacent to the wound. Therefore, measurements taken from the surface of the skin would not reflect count rates within the wound and in the subcutaneous tissue, including muscle and connective tissue. Subsequent monitoring at the SRS *in vivo* counting facility with a high-purity germanium detector indicated a level of contamination that was orders of magnitude greater than the surface count rates suggested. Urine bioassay was also used for estimation of the contamination.

The wound was gently washed with soapy water and irrigated. The patient received 1.0 g of DTPA-Ca, intravenously, within 1.5 h of exposure. In addition to removal of local soft tissue, the patient was treated with daily DTPA-Zn (1.0 g, intravenously) on days 3–16. For personal reasons, the patient was unavailable for therapy on day 2 and days 17–23. Twice weekly therapy with parenteral DTPA-Zn resumed on day 24 for a total of 71 treatments over 317 days. Therapy was continued based on urinary ^{238}Pu excretion and was discontinued when a plateau in averted dose estimates was achieved. The averted dose (by both physical removal, using punch and excision biopsies, and biochemical removal, using DTPA therapy, of activity from the body) was estimated to be 1.1 Sv, showing the high effectiveness of DTPA in removing ^{238}Pu from the body in this case.

3.3. The ^{239}Pu wound accident at MPA, Russia

On 23 January 2014, at Mayak Production Association (MPA) facility, while carrying out a repair on contaminated equipment, a maintenance worker injured his left palm. He failed to comply with the site requirement to report such incidents and continued with his routine daily work. He continued to work normally until March 18, 2014 when the analysis result from a urine sample, collected on February 11 as part of scheduled routine individual monitoring, indicated that he had incurred a significant internal exposure. He was then removed from routine work and sent for special monitoring on March 19, where actinide contamination of the small wound on his left palm was identified. Based on the measurements using a semiconductor detector, the wound content of ^{239}Pu was estimated to be 1×10^{4} Bq, indicating that excision of the contaminated tissues was necessary. Another daily (24-hour) urine was collected on March 20. Based on the analysis results from this sample and the sample collected on February 11, using the ICRP plutonium biokinetic model (ICRP, 1993) and the NCRP wound model (NCRP, 2007), it was estimated that 1.9×10^3 Bq ^{239}Pu had been transferred from the wound to the blood.

Decorporation therapy using DTPA-Ca started on March 21, with a daily dose of 0.25 g. On the same day, the excision of contaminated tissues was carried out, which resulted in a decrease of ^{239}Pu content in the wound to 5.5×10^2 Bq. Further surgical intervention could have led to tissue damage and loss of motor function in the hand. Subsequent measurements of the residual ^{239}Pu content in the wound confirmed that no further transfer of ^{239}Pu, from the wound to blood, occurred.

The effect of chelation therapy was evaluated on 30 May 2014, using ^{239}Pu measurements in 22 daily urine samples collected between March 20 and May 20. The total amount of the radionuclide excreted during this period of time, as a result of the chelation therapy, was estimated to be 6.5×10^2 Bq, with 5.0×10^2 Bq excreted between March 20 and April 20 and 1.5×10^2 Bq between April 21 and May 20, 2014. The much smaller amount excreted during the second month compared to that excreted in the first month indicated that further therapy would not be justifiable and chelation treatment was terminated on 1 June 2014.

Daily urine samples were collected on September 8, 9, 10 and November 12, 13, 16, 2014. The ^{239}Pu content of these samples was assumed to represent normal excretion (i.e. unaffected by chelation). These results were used to estimate the transfer of ^{239}Pu from the wound to blood and radiation doses: The total transfer up to the end of 2014 was 1.04×10^3 Bq, the dose to bone surface was no more than 580 mSv a year, and the committed effective dose over the next 50 years was no more than 570 mSv.

3.4. The ^{170}Tm incident in Beijing, China

An incident occurred when two workers in a research institute in Beijing, China were grinding 1.11×10^{12} Bq $^{170}Tm_2O_3$ (2.3 g Tm_2O_3 irradiated in a reactor) to a powder in an agate mill bowl. Protective measures, such as using a lead glass shield and wearing lead glass safety spectacles and gauze masks, were taken. During the grinding process, while the workers' head and chest were shielded from the radiation by lead glass, their arms and hands were not and the workers were only wearing medical latex gloves. The grinding process took worker A about 20 min and worker B about 10 min. As no physical discomfort was immediately felt by either worker after this task, they continued their daily non-radioactive work in the laboratory.

More than three months later, during routine workplace monitoring, the radiation health protection department found ^{170}Tm contamination in the laboratory. The two workers were requested to provide 24-hour fecal samples for radiobioassay measurements. Assuming inhalation to be the main intake pathway, intakes and committed effective doses were assessed, the intakes being $(9.2 \pm 1.4) \times 10^5$ Bq and $(1.4 \pm 0.2) \times 10^5$ Bq, and doses being (6.2 ± 0.9) mSv and (0.9 ± 0.1) mSv, respectively for Worker A and Worker B. As the intakes were much lower than the respective annual limit of intake (3×10^6 Bq), medical intervention to accelerate excretion of the inhaled ^{170}Tm was not implemented (Liu et al., 2004).

3.5. The ^{3}H incident in Changchun, China

An incident occurred in Changchun, China, in the 1980 s, when a tritiated water sample with an activity of about 6.5×10^{12} Bq was stored in a container under a cabinet in a non-radiochemistry laboratory. Due to inadequate packaging and improper storage, the tritiated water slowly evaporated over the next 115 days until this issue was discovered. As a result, the whole laboratory building was contaminated. Air samples in the building were collected for radioactivity measurement and laboratory staff were asked to provide urine samples for assessing ^{3}H intakes and resulted radiation doses.

Urine samples from the 345 individuals affected by this incident were collected and analyzed. As the exposure had potentially continued for a period of 100 days or more, the maximum committed effective dose to a laboratory worker that could be inferred from the highest bioassay measurement was estimated to be around 170 mSv, which is 34 times the national annual limit for public exposure, 5 mSv per year at that time (Chen et al., 1990).

4. Technical areas

The WHO International Health Regulations (IHR 2005) Joint External Evaluation (JEE) focuses on the preparedness of a state party in responding to public health events (WHO, 2018). For radiological or nuclear emergencies, it is recommended that capabilities for timely detection and effective response are in place and sustainable. In this review, the capabilities in 14 technical areas are grouped under the topic headings of emergency preparedness, emergency response and recovery processes.

4.1. Emergency preparedness

The goal of emergency preparedness is to ensure that adequate capabilities and capacity are in place which can be mobilized in response to a nuclear or radiological emergency. Such preparedness should be demonstrated through responding to actual emergency incidents or exercises, and is expected to be a sustainable capability that can be mobilized at any time (WHO, 2018).

4.1.1. Legislation, regulations and emergency response plans—Legislation and regulations for radiation and nuclear safety and security should be in place. They provide the fundamental instruments for accident prevention and emergency preparedness. An adequate legal framework is essential for the implementation of response actions. In the early 1950 s, the USSR did not have relevant legislation and regulations for radiation protection of the public in case of radiological or nuclear incidents; otherwise, the release of a large quantity of radionuclides from the MPA to the Techa River could have been prevented.

Regulations should be enforced. In the Goiânia accident, the relevant authorities and individuals designated as being liable for ensuring the safety of the ^{137}Cs radiation source should have had a commitment to maintain the security of the source under a regulatory system (IAEA, 1988). This also applies to the Beijing ^{170}Tm incident, where appropriate personal protective equipment should have been worn by the workers (Liu et al., 2004).

Response plans should set clear roles and responsibilities for the agencies involved in responding to radiological or nuclear emergencies. During the TMI accident, the emergency response plan did not require the utility to notify state or local health authorities in the event of an accident, when nearly all decisions affecting health and safety of the public in surrounding communities actually rested with local and state health and emergency management authorities. In addition, the lack of coordination among federal and state authorities, partly based on incomplete or inaccurate information, contributed to an atmosphere of uncertainty and mistrust (Report of The President's Commission on Accident at Three Mile Island, 1979). In contrast, during the ^{210}Po incident in London, as the UK's emergency response framework specified clear command and control arrangements for a multiagency response, together with the experience gained from many nuclear and counterterrorism exercises, good cross-sector collaboration resulted in an efficient and effective response (Bailey et al., 2008).

Response plans should take various practical considerations into account and be updated after each exercise or real incident. During the Fukushima accident, only a small fraction of the affected populations was subject to timely monitoring as monitoring capacity (thyroid counting, whole-body counting) was limited and the ambient radiation background was significantly elevated by the release of radionuclides (Kurihara et al., 2018b). As a result, in 2012, the Nuclear Regulation Authority (NRA) in Japan issued new guidelines for nuclear emergency preparedness and response, taking the issues identified above into consideration for population monitoring (NRA, 2020).

4.1.2. Incident surveillance and monitoring programs—Robust incident surveillance programs help to prevent radiological or nuclear emergencies from occurring. The root cause of the Kyshtym accident was a failure of the automatic temperature-control system at the MPA waste-storage facility, which stemmed from insufficient cooling-water delivery, resulting in explosive nitrate salt deposits in a storage tank overheating. Had the water-cooling system have been monitored more closely and appropriate remedial action been taken, this accident could have been prevented.

Functioning monitoring programs can help with timely identification of incidents and prevent them from developing into disasters. Accidental releases into the Techa River occurred as a result of failures at the MPA waste-storage facilities in the early 1950 s. Due to the lack of radiation monitoring at the discharge point into the river, the source of the leak was not identified in a timely manner (Alexandrov et al., 2006 and 2007). Similarly, in the ^{3}H contamination incident in Changchun, China, had a workplace monitoring program been in place, contamination of the laboratory environment and personnel would have been recognized much earlier (Chen et al., 1990).

4.1.3. Monitoring and dose assessment capacity—Screening a large, affected population following an incident involving internal exposures is a challenge, as demonstrated by some of the incidents reviewed here, such as the ^{137}Cs accident in Goiânia where over 112,000 individuals were screened for potential external and internal contamination in roughly 3 months following the incident (IAEA, 1988). Such screening helps to identify individuals who require decontamination, further medical attention or more detailed monitoring (for reliable dose assessment) and to address the concerns of the so called ‘worried-well’. Although efforts have been made to increase screening throughput in the past by optimizing the screening process and the management of screening centers (Li et al., 2014; US CDC, 2014), challenges remain when hundreds of thousands of individuals need to be screened in a short period of time: new strategies, algorithms, and technologies could be developed to significantly increase screening throughput.

Development of capabilities and capacity for *in vivo* monitoring (whole body, lung, thyroid, wounds), *in vitro* monitoring (radionuclide bioassay, biomarkers), and dose assessment is an important part of preparedness for responding to a radiological or nuclear emergency where internal contamination of a large population may be involved. Assessing internal contamination intake and associated dose requires reliable information about all of the radionuclides involved, their physicochemical properties, and potential intake scenarios (location, duration, pathways), as well as individual-specific data. Data from environmental monitoring are useful but results from individual monitoring are more reliable, as demonstrated during the response to the Fukushima accident where the behaviour of individuals during the evacuation was found to make their potential exposure difficult to characterize (Kurihara, 2018b). The Fukushima accident also revealed the need to establish practical and robust methods for large population monitoring (whole body, thyroid) in an emergency when other significant challenges (in this case the aftermath of earthquake and tsunami) also exist, to develop capabilities and capacity for early monitoring so internal exposure from short-lived radionuclides, such as ^{131}I can be captured, and to develop robust age-dependent efficiency calibration of *in vivo* detection systems to enable reliable determination of intakes of activity for both adults and children (Kurihara, 2018b).

With capabilities for individual monitoring and dose assessment in place, response can be very effective. When the ^{238}Pu wound incident at the Savanah River Site occurred, the models and procedures in NCRP Report No 156 (NCRP, 2007) were successfully used to manage this case (Sugarman et al., 2018; Toohey et al., 2011). However, gaps in individual monitoring capabilities still remain, for example, a recent international intercomparison exercise revealed the challenges with identification and quantification of mixed radionuclides for *in vitro* monitoring and dose assessment (Li et al., 2017).

For the Mayak ^{239}Pu wound accident, the delay in identifying this accident was not only due to the failure to report it immediately and the lack of any screening system for potential small puncture wounds with actinide contamination, but also the month-long analysis time required for *in vitro* bioassay. Lessons learned from this accident helped MPA to improve its response capability in managing similar incidents, including a method for screening hands for subcutaneous contamination with actinides by measuring X-ray and soft gamma emissions, as well as an improved *in vitro* bioassay procedure with a much shorter turnaround time.

Surge capacity for monitoring large populations and performing dose assessments following a radiological or nuclear emergency has been an important long-standing issue. Both international and national organizations have been developing collaboration mechanisms which can help increase surge capacity (Carr, 2010; IAEA, 2018; Li et al., 2017; Kulka et al., 2017). International and regional agreements and arrangements, including laboratory networks, help to enhance bilateral or multilateral support in responding to an emergency. Accreditation programs, protocol development and standardization, and proficiency test programs are all important components of surge capacity development.

4.1.4. Medical preparedness—Medical preparedness is another important aspect in the preparation for a radiological or nuclear emergency. Medical management plans and response capacity, for use both on-site and in designated healthcare facilities, should be developed, including expertise and management protocols, countermeasures, stockpiles and implementation mechanisms. Functional cooperation among medical, dosimetry and radiological protection groups should be clearly established in procedures and protocols (e.g., criteria and follow-up in case of decorporation therapy; administration of KI thyroid blocking). In addition, international support agreements may be arranged (Carr, 2010; IAEA, 2018).

The effective management of the ^{241}Am accident at Hanford was largely due to the well thought out medical management plan, facilities and countermeasures. Rapid and organized action by the first responders and medical staff significantly reduced the risk of severe health effects to the affected individual. Well-trained responders quickly initiated external decontamination procedures reducing the chance of further internal contamination; timely administration of decorporation agents (Ca-DTPA) and surgical removal of the contaminated wound tissues greatly reduced the radiation dose (Toohey and Kathren, 1995).

Following the Kyshtym accident, in the first few years, medical examinations could not be given to all those exposed because of the large number of people involved, the unexpected development of the incident and the lack of preparedness of medical institutions for a large-scale radiation accident (Akleyev et al., 2017). It was a similar situation with the management of the Techa River incident. The number of Techa residents examined during 1951–1953 was very limited (about 500 persons). In 1953, a specialized hospital in Metlino opened and the number of examinations increased to about 1,000 per year and from 1955, when a specialized dispensary in Chelyabinsk opened, the number of examinations further increased to about 3,500 per year. In the period 1955–1960, when most cases of ChRS were identified, 350–450 people were hospitalized for treatment annually (Akleyev, 2016).

Stockpiles of medical countermeasures, and mechanisms for distribution and sharing them, form another important aspect of medical preparedness. During the ^{137}Cs incident in Goiânia, a total of 46 persons were treated; treatment for some of them lasted for months (Melo et al., 1994). The individual contaminated in the Hanford ^{241}Am accident was treated using DTPA (Ca- or Zn- forms) for years. These two cases demonstrated that adequate stockpiles of therapeutic agents are critical to the successful management of internal contamination incidents. National and international stockpiles, and mechanisms for distribution and sharing them during an emergency, are therefore vitally important and should be developed. Furthermore, evidence-based practical guidelines for medical management of internal contamination are currently lacking, hence, research into the optimization of the use of such medical countermeasures should be encouraged.

4.2. Emergency response

Health protection objectives during the response to a radiological or nuclear emergency include saving lives, avoiding or minimizing short-term severe tissue reactions, reducing long-term stochastic effects, and minimizing psychosocial impacts (IAEA, 2015). Effective response is especially important during the early phase of the emergency when various protective actions need to be taken promptly in order to avoid or reduce radiation exposures. Subsequent efforts can focus on characterizing the radiological situation on-site and off-site to decide upon the best course of action to protect people and the environment (ICRP, 2007). Communication among responders dealing with the emergency needs to be efficient to support good decision making. Proper channels for communication with affected populations should be established and clear, consistent and concise information should be rapidly distributed and further frequent updates given. This may be facilitated by having pre-prepared material and procedures and by employing individuals with specialist knowledge of communicating with the public.

4.2.1. Incident characterization—Early identification of an incident allows timely protective actions, such as evacuation, sheltering, administration of KI for thyroid blocking, and prevention of the spread of contamination. Had the Goiânia accident been identified earlier, wide spread of contamination and significant exposures to some individuals could have been prevented (IAEA, 1988). Similarly, for the London polonium incident, when the victim was admitted in the hospital, the radiation exposure was not identified for a considerable period of time as the instruments in the hospital were not able to detect the alpha radiation from ^{210}Po: early detection could have helped in both managing the victim's medical care and contamination of the environment and other people (IAEA, 2012).

Accurate characterization of the elements of an incident, such as the source term, dispersion and deposition of the released radionuclides, the affected populations and the exposure pathways, is essential in developing effective response plans. During the Castle Bravo incident, due to the lack of knowledge on some aspects of nuclear fusion in hydrogen bombs and the unusual meteorological conditions, the area of significant fallout was far from that predicted (characterized in advance) (Robins and Adams, 1996; Henriksen et al., 2014).

After the Chernobyl accident, in the first a few days, area contamination monitoring was performed by aircraft equipped with radiation detection instrumentation (Izrael, 2002b; Izrael, 2015). Unfortunately, the potential accident scenarios and consequences envisioned in emergency planning had little in common with the actual reality of the Chernobyl disaster, which has now been extensively studied and described in detail (Kryuchkov et al., 2011). The composition of emissions included so-called 'hot particles' (fuel matrix particles), volatile products and inert gases (Alexakhin et al., 2004; Anisimov et al., 2018).

For the Kyshtym accident, following the explosion, the formation of the EURT was quickly characterized and the most significant exposure pathways in the EURT area were identified as ingestion of radionuclides in local produce (grain and grain products, dairy products, and potatoes) and external gamma exposure from radionuclides deposited in soil (Akleyev et al., 2017).

4.2.2. Emergency and risk communication—Effective communication is central to managing public health emergencies, such as nuclear and radiological incidents. Responses to such events need to be timely to save lives, protect public health, reduce mental health impact and mitigate social and economic disruption (WHO, 2018; 2020). In the first 15 h of the Chernobyl emergency, accurate information on the accident and the release of radionuclides was not available, therefore residents of Pripyat and surrounding settlements were not adequately informed about the event. This led to critical delay of the implementation of urgent protective actions, such as stable iodine thyroid blocking and sheltering in place for a whole day on April 26, 1986: residents of Pripyat spent time outdoors as usual and liquidators made their way to the site of the emergency via a route crossing the radioactive fallout path while alternative routes would have avoided the additional exposure (Ilyin et al., 2016).

Communications should be easy to understand, consistent and trustworthy, otherwise, the affected populations may be confused or may lose trust in the response plan and the relevant authorities, which will compromise the effectiveness of the emergency response (WHO, 2017b). During the ^{210}Po incident in London, responders had to deal with thousands of concerned individuals, it was necessary to talk to and assess the risk for each of these individuals along with staff and visitors at locations identified during the investigation. In reporting results to those without any radiation protection expertise, emphasis was placed on giving a clear and simple message. Technical terms and results were avoided; doses assessed as less than 6 mSv were simply described as being ‘of no concern’, with doses ≥ 6 mSv described as being ‘of some concern’ (Rubin et al., 2007).

During Fukushima accident, public distrust of the government and experts was evident; this was primarily due to communication issues (Murakami et al, 2017). As a result, there were environmental measurements organized by non-government organizations to verify the information provided by the government. The Kyshtym accident posed a more serious communication issue: one week after the accident, residents of the three closest settlements (1,100 persons) were required to leave their homes. They were informed that the territory was contaminated with “industrial waste”; they were not told that the waste was radioactive and that radiation exposure is a danger to health (Akleyev et al., 2017).

Real-time exchange of information between response agencies and personnel are important. In the management of the ^{238}Pu wound accident at Savanah River Site, fluid communication between the response personnel contributed to the delivery of timely and appropriate medical care to the affected individual. Real-time communication among health physicists, medical physicists and clinical care providers helped in navigating the uncertainties involved in estimating the level of exposure and associated risk. Effective discussion between the clinical care providers and the affected individual helped in making informed decisions on the treatment plan based on an acceptable risk benefit ratio for decorporation therapy using DTPA (Sugarman et al., 2018).

A mix of communication and engagement strategies may be used simultaneously in community engagement following an emergency. During the ^{137}Cs accident in Goiânia, feelings of panic among the public were related to perceptions of an accident involving radiation. It was noted that some individual's symptoms had actually been caused by these fears. In addition to traditional communication through the media, psychologists were trained to communicate with the public and the responders; a booklet explaining the terms and units related to radiation risks and measurement results was provided to the public (Rozenthal et al., 1991).

4.2.3. Evacuation and sheltering—Sheltering in place (or in designated areas), possibly accompanied with KI thyroid blocking if radioiodine isotopes are involved and the risk/benefit for KI thyroid blocking has been assessed, can be very effective in minimizing exposure and contamination. This is especially important for the early phase of response. During the Chernobyl accident, this measure could have easily been employed if adequate information about the accident and the release of radionuclides had been available in a timely manner (Glygalo and Vorobyov, 2010). Later analysis showed that sheltering in place, if implemented, could have reduced a dose by 5–100 mSv for a person living in Pripyat during 26–27 April 1986 (Linge et al., 2002).

Evacuation is a proven effective public health measure. Soon after the ^{137}Cs accident in Goiânia was discovered, people living or working in the nearest seven blocks were immediately evacuated (Rozenthal et al, 1991). In the Castle Bravo incident, people living in the northern atolls were evacuated and relocated to the middle atolls so large doses were averted (Conard, 1992). Following the Kyshtym accident, residents of the three settlements closest to the accident (1,100 persons) were evacuated as soon as MPA authority was able to arrange temporary accommodation and to estimate compensation payments for the loss of their homes (Akleyev et al., 2017).

However, evacuation can be very disruptive and carries its own risks, so it needs sound justification. It is necessary to carefully evaluate risks and benefits before evacuation is ordered. During the Three Miles Island accident, the population living within 16 km of the plant was initially advised to shelter in place, but on the third day of the accident, following a controlled and intentional release of inert radioactive gas to relieve pressure in one of the vessels, an order was issued by the governor of Pennsylvania to evacuate pregnant women and preschool children within an 8-km radius of the reactor. Although the population of pregnant women and preschool children only amounted to approximately 3,000 to 4,000, this announcement led to evacuation of nearly 200,000 people from the area. The debate among the authorities regarding the need to order an evacuation was exacerbated by the fact that there were no evacuation plans in place that could have accommodated the situation, and the authorities were also fully aware of the potential non-radiological consequences of any mass evacuation (Report of the President's Commission, 1979).

These very same issues are still a matter of some debate, as demonstrated during the aftermath of the Fukushima accident in 2011. Following the Fukushima accident, the Japanese government issued evacuation orders repeatedly over a short period of time without providing enough information on the ongoing situation. The evacuation area was expanded from 3 km initially to 10 km and later 20 km of the power plant, on March 12 due to concerns about deteriorating conditions at the site. As a result of this lack of clarity, a significant number of people had to endure staged evacuation, involving more than one move, to various places inside and outside Fukushima Prefecture. The decision to evacuate would have reduced the residents' exposure; however, as implemented, it also caused confusion and panic among the evacuees and more than 50 hospital patients died during transportation (Tanigawa et al., 2012).

4.2.4. Medical management and administration of medical countermeasures

—Administration of medical countermeasures is often required in response to an emergency where internal contamination is involved. Objectives vary for different types of emergencies and for different phases of an emergency, and so do practical challenges in each emergency (WHO, 2007).

Iodine thyroid blocking (ITB, most of time using KI) has been recommended as a protective action in an emergency where release of radioiodine isotopes is involved or anticipated (WHO, 2017a). Different from other medical countermeasures for internal contamination, ITB is most effective if administered 24 h prior to or 2 h after contamination (WHO, 2017a). Although ITB was not administered to workers or the public during the Three Mile Island accident, debates over its use among agencies led to today's recommendation on its use as an emergency protective medical countermeasure and a stockpiling policy (National Research Council, 2004).

In the Chernobyl accident, stockpiles in Pripyat and the Chernobyl power plant had sufficient KI supply for both workers and the public, but was not administered in a timely and systematic way; in the majority of the 30-km zone, there was no administration at all, and Prypiat was the only place where administration of KI was effective (Prister et al., 2011; Ilyin, 2006). In the southern areas of Belarus, 75% of children only started taking KI tablets from May 2 to May 4; in some locations outside the 30-km zone, KI administration did not start until the second half of May (Alexakhin et al., 2004). Distribution of KI tablets in villages within the 30-km zone was initiated at approximately the same time as evacuation starting 6 days after the accident, which was too late and so had little effect (UNSCEAR, 2000). In rural areas outside the 30-km zone, KI started to be used from the middle of May through August 1986, again too late and without any significant effect on doses to the public (Uyba et al., 2018). It is worthy of note that although ITB is used mainly for lowering thyroid exposure via radioiodine inhalation, it is also effective in reducing thyroid uptake of radioiodine from ingestion of food, milk and drinking water.

Immediate medical action, including decontamination, surgical removal of contaminated wound tissues and administration of medications, were involved in many incidents. In the Hanford ^{241}Am accident, well-trained responders quickly initiated external decontamination procedures reducing the chance of further internal contamination: with surgical removal of the contaminated wound tissues, internal contamination from the wound sites was minimized; and the immediate use of DTPA therapy reduced the patient's body burden of ^{241}Am, preventing significant radiation-induced damage to liver and bone (Breitenstein, 1983).

On-going medical management of internally contaminated individuals, such as decorporation treatment, may last for months or years. Following the ^{137}Cs accident in

Goiânia, a total of 46 people were treated with Prussian Blue; many of them were treated for months (Melo et al., 1994). In the Hanford ^{241}Am accident, treatment with Zn-DTPA continued for over 4 years following the accident (Breitenstein, 1983).

4.2.5. Food and drinking water restrictions—In emergencies where large amounts of radionuclides are released to the environment, timely and effective restrictions on consuming contaminated food and drinking water help reduce internal contamination to affected populations. Clear policy, effective communication, and practical implementation plans, such as logistics to provide replacement food and water and mechanisms for distribution, are most helpful. After the Chernobyl accident, late notification of the public and a delay in the application of urgent countermeasures led to unnecessary intakes of radioactive iodine through the consumption of contaminated foodstuff: consumption of milk contaminated with ^{131}I was the dominant radioiodine intake pathway for the public (Prister and Alexakhin, 2007). The thyroid dose from inhalation intakes for these members of the public was negligible compared with that from ingestion intake from milk (Uyba et al., 2018). The intake of radioiodine through ingestion of local milk and leafy vegetables resulted in more than 4,000 cases (based on reconstructed doses) of thyroid cancer for those individuals whose thyroids were exposed in childhood in the most severely contaminated areas (Balonov, 2006).

However, for the Fukushima accident, internal contamination in the affected population has, according to the results of a large number of individual *in vivo* measurements, been effectively minimized: internal doses are below 1 mSv in terms of committed effective dose for almost all subjects examined since June 2011, suggesting that timely restrictions to prevent the consumption of contaminated food and water have worked well (Kurihara et al., 2018a).

After the Techa River incident was identified, protective measures in the upper Techa River were implemented in August 1951 and in the villages located downstream in 1953–1955: the main measures were a ban on the use of river water for drinking and the construction of wells to provide an alternative drinking-water supply. Other restrictions included the prohibition of fishing and the use of floodplains for cattle grazing and haymaking (Akleyev, 2016).

4.2.6. Population monitoring, decontamination and initial dose assessment—Following a radiological or nuclear emergency, large groups of responders and the public may need to be monitored, decontaminated, and assessed for internal contamination in a very short period of time. Effective organization and management of population screening centers for receiving, monitoring and sorting contaminated individuals, is very important and often faces practical challenges (US CDC, 2014), including:

- Screening for potential external contamination using personal portal monitors or hand-held instruments;
- Performing decontamination and re-screening when necessary;

- Conducting initial assessments for internal contamination using *in vivo* or *in vitro* monitoring techniques;
- Identifying individuals requiring further monitoring, dose assessment, and medical management.

Following the Chernobyl accident, large-scale thyroid monitoring commenced in early May to estimate the radioiodine content in children and adults, by the end of June 1986, about 200,000 people in Belarus, 150,000 people in Ukraine and 45,000 people in Russia had been monitored (Likhtarev et al., 1994; 1996; Stepanenko et al., 1996; Zvonova and Balonov, 1993). The results of those direct thyroid measurements were later used for assessment of doses to the thyroid gland (Uyba et al., 2018). It is worth noting that a limited number of ^{131}I measurements in soil, milk, and leafy vegetables were carried out in contaminated areas soon after the Chernobyl accident. However, they were not used at the time of monitoring for thyroid dose estimation and/or for adjusting protective countermeasures aimed at minimizing exposure to the thyroid (Gavrilin et al, 1999). Dose assessments from intakes of other radionuclides were also performed (Alexakhin et al., 2004; Konstantinov et al, 2016).

Following the Fukushima accident, thyroid screening was initiated on March 24 but the first two campaigns were not successful because background ambient dose-rate was too high (Kurihara et al, 2018b). Within the first month, only a limited number of whole body counters (WBCs) were available. As a result, pregnant women and children evacuated from the areas near the power plant were examined first. The WBCs installed at Fukushima Medical University were not able to operate at that time due to elevated ambient dose rates around the facility (Miyazaki et al., 2012). Therefore, individuals had to travel a long way from their temporary accommodation, inside or outside Fukushima Prefecture, to the WBC facilities of National Institute of Radiological Sciences (NIRS) in Chiba Prefecture or the Japan Atomic Energy Agency (JAEA) in Ibaraki Prefecture. The number of individuals counted at NIRS and JAEA were 174 (from June 27 to July 28, 2011) and 9,927 (from July 11, 2011 to the end of January 2012), respectively.

In the Goiânia ^{137}Cs accident, between September 30 and December 22, a total of 112,000 persons were monitored, of which 120 had external contamination and 129 had internal/ external contamination. For people who had external contamination, urine bioassay was used to screen for any internal contamination. Single ingestion was assumed to be the main intake pathway, and an age-specific biokinetic model was used for intake estimation, bioassay data interpretation and dose calculation (Bertelli and Lipsztein, 1987; IAEA 1988). However, the model had to be adapted to better represent the actual observed bio-kinetics in the children involved in the incident. Intakes could have occurred between 10 and 15 days before the accident was noticed, but the exact time of intake was very difficult to identify, so it was considered to be a single intake on the first day the individual remembered having contact with the open source (a conservative assumption). The fecal to urinary excretion ratio of ^{137}Cs was used to evaluate the effectiveness of Prussian Blue to enhance Cs excretion. From October to December 1988, more than 4,300 samples from 90 persons were analyzed (Lipsztein et al., 1991). In addition, a whole body counter was installed in the Goiânia Hospital. From November 1987 to April 1988 a total of 356 subjects were monitored using the whole body counter, 143 showed internal contamination above the minimum detectable activity, with the highest being $5.92 \pm 0.2 \times 10^7$ Bq (Oliveira et al., 1991(b)).

In the ^{238}Pu wound accident at Savanah River Site, initial monitoring, with a zinc-sulfide alpha detector, of the wound site indicated 300 dpm: However, it was assumed that radioactive material on the shaft of the flag was deposited on the inner surface of the dermis and adjacent soft tissues in the wound, and therefore, skin surface measurements would not reflect subcutaneous dose rates. Subsequent monitoring at the SRS *in vivo* counting facility using a high-purity germanium detector (HPGe) indicated a level of contamination that was orders of magnitude greater than this initial estimate, and confirmed the presence of 13, 17 and 20 keV photons that are characteristic of ^{238}Pu, together with the low-yield 43.5 keV peak (indicating a much higher deposition of ^{238}Pu) and a small 59.5 keV peak, consistent with a trace quantity of ^{241}Am. Dose assessment was performed by coupling the NCRP wound model with the Pu systemic model (NCRP, 2007; Toohey et al., 2011). In this case, rapid recognition of a radiological exposure lead to prompt evaluation, early therapy based on initial dose magnitude estimation, and significant averted radiation dose. Experience gained in this accident would benefit the management of wound contamination cases.

4.2.7. Relocation—Relocation of affected populations may be required in a nuclear or radiological emergency, if justified (IAEA, 2015). Following the Castle Bravo incident, residents from the northern atolls were permanently relocated to the middle and southern atolls (Conard, 1992).

After the Chernobyl accident, a large number of individuals (116,317) were evacuated/ relocated from 187 locations in Belarus, Russia and Ukraine during May to September 1987 (Alexakhin et al., 2004). It has now been recognized that mass relocation of a population is unjustifiable when the majority of their dose had been already acquired (IAEA, 2008), as delayed evacuation only aggravates psychosocial problems (Guskova and Gusev, 2001).

However, following the Techa River and Kyshtym incidents, due to the fact that the floodplain of the Techa River and the EURT area were contaminated with long-lived radionuclides ^{90}Sr and ^{137}Cs, people from these territories needed to be permanently relocated. Between 1952 and 1960, about 8,000 residents of Techa Riverside communities were relocated to areas far from the river. The upper Techa region was included in the buffer zone around the MPA, and, about 48 km^2 of farming land were abandoned (Akleyev, 2016). As a result of the Kyshtym incident, about 10,000 people were relocated from the area with ^{90}Sr deposition greater than 7.4×10^4 Bq m^{-2}, during 1957–1959: The use of 166 km^2 of farming land affected by the EURT was banned and a sanitary protection zone was established in which residency and economic activities were prohibited (Akleyev et al., 2017).

4.3. Recovery process

The recovery process following an emergency can be long and demanding, as was the experience for both the Chernobyl and Fukushima accidents. Long-term environmental monitoring, more detailed dose assessment for affected individuals, as well as health and medical follow up require well planned and justified actions. It is important to recognize long-term recovery needs during the early phase of an emergency and take them into account when scoping overall response efforts, as demonstrated in the ^{210}Po incident in London (Croft et al., 2008).

4.3.1. Long-term environmental monitoring—

After the Chernobyl accident environmental monitoring began almost immediately and has continued for 35 years. Among the consequences of the accident was radioactive contamination of both wild and agricultural ecosystems: the results of environmental contamination monitoring, the impact on people and the biosphere, have been presented in several publications (Alexakhin et al., 2004; Izrael and Bogdevich, 2009; Anisimov et al., 2018).

Following the Fukushima accident, environmental monitoring started without delay. It has been on-going in the past more than 10 years, including monitoring the contaminations in air, soil, fresh water, sea water, forested land, farmland, and food stuffs. The Ministry of the Environment in Japan provided a summary of the monitoring results and health impacts in its booklet published in 2019 (https://www.env.go.jp/en/chemi/rhm/basic-info/1st/introduction.html).

Following the Techa River incident, environmental monitoring has been performed for many years by MPA specialists as well as by several independent laboratories, such as Urals Research Center for Radiation Medicine (URCRM) and Chelyabinsk Regional Center for Sanitary Inspection (CRCSI) (Balonov et al., 2007; Peremyslova et al., 2011; Shutov et al., 2002). The concentration of long-lived radionuclides in river water has stabilized since 1990. The ^{137}Cs concentration in the water became close to that due to global fallout in surface water, while ^{90}Sr concentration was higher due to desorption/resuspension of radionuclides from swampy floodplains heavily contaminated as a result of past accidental releases. River water was completely eliminated from the diet of the local population. The primary route of internal exposure was consumption of local milk and fish contaminated with ^{90}Sr and ^{137}Cs (Balonov et al., 2007). Intake of radionuclides in the 2000 s dropped to 2–4 Bq d^{-1} for ^{90}Sr and 5–10 Bq d^{-1} for ^{137}Cs.

Following the Kyshtym accident, long-term monitoring of local foodstuffs and environmental samples was initiated in 1958, and five settlements located near the evacuation zone (^{90}Sr deposition 2.6–74 kBq m^{-2}) were selected for this purpose. Since the 1960 s, the primary route of internal exposure was consumption of local milk contaminated with ^{90}Sr. By the year 2000, ^{90}Sr concentration in milk decreased by an order of magnitude and ^{90}Sr intakes to around 1 Bq/d (Peremyslova et al., 2001).

4.3.2. Long-term individual monitoring and dose assessment—

Long-term individual monitoring after internal contamination is essential for dose assessment and long-term health risk assessment. For the Chernobyl accident, according to the initial assessment based on direct thyroid measurements, the average thyroid dose from ^{131}I for 650 Pripyat residents (mainly power plant workers) was estimated to be 210 mGy (Khrushch et al., 1988). Estimates of thyroid doses from ^{131}I, derived from direct thyroid measurements, for about 126,000 people from Belarus showed that 331 had doses exceeding 10 Gy, 317 of them were children, with the highest dose being 50 Gy (Shinkarev et al., 2008). More recently, in the joint Ukrainian-American case-control studies of thyroid cancer, thyroid doses were estimated for 607 cleanup workers. The average total thyroid dose (due to all exposure pathways) to those workers was about 199 mGy (Drozdovitch et al., 2020). Organ doses for red bone marrow, lungs and bone from other radionuclides, such as transuranium elements and strontium isotopes, were also assessed for various groups of cleanup workers due to inhalation intake (Khrushch et al., 1988; Popov et al., 1991; Kutkov et al., 1996a; Kutkov, 1998).

For the Fukushima accident, WBC measurements have been well organized during the recovery phase for all local residents and those who were evacuated from Fukushima Prefecture. The results confirmed that internal contamination with $^{134,137}Cs$ has been minimal, with only a very small percentage of people having a high body content of Cs (hundreds of Bq per kg weight) (Fukushima Prefecture, 2018b; Tsubokura et al., 2013), attributed to ingestion of food items that were not inspected (e.g., locally grown vegetables) and tended to be seen in elderly persons in the affected areas (Tsubokura et al., 2014). The $^{134,137}Cs$ body content of these individuals was greatly reduced after they received advice to refrain from consuming potentially contaminated items without inspection.

Following the Castle Bravo incident, there was on-going monitoring of the inhabitants of the most exposed islands of Bikini atoll. It is likely that most intakes occurred by ingestion of radioactive particles deposited on food, eating utensils or on the hands and faces of people. It was determined that 63 fission and activation radionuclides plus $^{239,240}Pu$ were responsible for 98% of the internal dose to any organ, thyroid doses from radioiodine were much higher than doses to other organs or tissues, and internal exposures from long lasting contamination of the environment and chronic intakes was mainly due to the ingestion of seafood and other foodstuff contaminated with a limited number of long-lived radionuclides, such as ^{137}Cs, ^{90}Sr, ^{65}Zn, ^{60}Co and ^{55}Fe. For all population groups the thyroid dose is mainly the result of acute radioiodine intake. Interestingly, considering the composition of the fallout and the likely intake of radionuclides (including 5 iodine isotopes), most of the thyroid dose (estimated to be 80–90%) comes from short-lived iodine and tellurium isotopes (^{132}I, ^{133}I, ^{134}I, ^{135}I and ^{131m}Te, ^{132}Te) and not from ^{131}I (Robbins and Adams, 1996; Simon et al., 2010; Harris et al., 2010).

For the Techa River incident, the reconstruction of internal dose relies strongly on the measurements of ^{90}Sr in Techa River residents, with more than 23,500 tooth-beta counts, in the period 1957 to 1997, and more than 30,000 whole-body counts, in the period 1974 to 2018. These measurement results were used to reconstruct ^{90}Sr and ^{137}Cs intakes (Tolstykh et al., 2011; 2013) and to develop an age and gender specific biokinetic model (Shagina et al., 2015). Absorbed doses in red bone marrow (RBM) significantly exceeded doses in stomach and other extraskeletal tissues due to the incorporation of ^{90}Sr in mineral bone. Individual dose values in the extended Techa River Cohort (TRC) varied over a wide range, with 10% of the TRC members having received doses exceeding 0.1–0.2 Gy to extraskeletal tissues and 0.9 Gy to RBM, and the maximum doses were about 1–2 Gy to extraskeletal tissues, and about 7 Gy to the RBM (Degteva et al., 2019).

4.3.3. Long-term health and medical follow up—Long-term health and medical follow up, including epidemiological studies and periodic medical examinations, have contributed significantly to the effective management of affected populations in some of the reviewed incidents. They also permit the assessment of treatment modalities utilized and provide information on whether they will be of use in future internal contamination incidents. In addition, these studies also generated a wealth of knowledge of radiation effects, especially at low dose and low dose-rate exposures.

Following the Chernobyl accident, substantial effort was devoted to the health and medical follow up of the affected residents and cleanup workers. Among the workers (about 600,000), acute radiation syndrome (ARS) was diagnosed in 134 cases (Guskova et al., 2001; Ilyin, 2001). The main long-term consequences of radiation exposure for this group were radiation-induced skin injuries and cataracts. In the 12-year period after the accident, there were elevated levels of leukemia cases amongst the workers who received high radiation doses. Approximately 6,848 thyroid cancer cases were reported in Belarus, the Russian Federation and Ukraine in children and adolescents between 1991 and 2005, considerably more than would normally be expected. Among the cleanup workers who received doses above 150 mSv, a statistically significant increase (18%) of all solid cancers was observed (Guskova, 2006; Onishchenko, 2011; 2016; UNSCEAR 2011).

To follow up on the health of Fukushima residents, following the accident, the Fukushima Health Measures Survey (FHMS) was launched at the end of June 2011. The FHMS consists of the Basic Survey and the Detailed Survey (Yasumura et al., 2012) and would cost billions of dollars during the 30-year follow up. One of the items on the Detailed Survey is thyroid ultrasound examinations to detect possible thyroid cancer in children as early as possible. The subjects are all Fukushima Prefecture residents aged between 0 and 18 years, as of 11 March 2011, and there are approximately 360,000 in total, the results of these examinations have been published periodically (Fukushima Prefecture, 2018a).

Medical examinations of residents of the Techa River region started in August 1951, including complete blood counts and measurements of radioactivity in excreta (urine and faeces). The number of the Techa residents examined during 1951–1953 was limited to about 500, with 40% of these cases showing physiological changes attributed to their radiation exposure. The number of people examined annually increased to 1000 in 1953 and 3500 in 1955. Approximately 30,000 individuals, exposed due to residency in Techa River villages, between 1949 and 1960, were included in the extended Techa River Cohort (TRC) that has been followed up, for several decades, to assess radiation risks of late stochastic effects. Long-term epidemiological studies of the TRC have established associations between radiation dose and the occurrence of solid cancer and leukemia that appear to be linear in dose response. Estimates of excess relative risks are broadly consistent with those observed in other radiation-exposed cohorts, although this cohort is unique in that it has primarily incurred low-dose-rate environmental exposure (Davis et al., 2015; Krestinina et al., 2013; Schonfeld et al., 2013).

For the Kyshtym accident, from 1957 the population of the EURT have been subject to medical examination and treatment. The EURT cohort, containing 21,400 residents of most contaminated settlements, was established for epidemiological analysis. Increased excess relative risk of solid cancer, both incidence and mortality, has been noted for this cohort over 50 years of follow-up. Individual doses for the cohort members were reconstructed based on their residence history. It should be noted that 1,400 members of this cohort were exposed due to both the EURT and the Techa River. The cohort-average dose values were: 0.028 Gy for stomach and 0.078 Gy for RBM. Long-term epidemiological study of solid cancer incidence and mortality showed a statistically significant linear dose response (Akleyev et al., 2017).

Following the Hanford ^{241}Am accident, on-going medical management consisted of DTPA treatment for over four years and continued health and radiological assessments, with the aim of returning the patient to a normal life (Breitenstein and Palmer, 1989). The long-term use of DTPA, both Ca- and Zn-forms, was shown to be extremely efficacious at enhancing the removal of ^{241}Am from the body. In fact, most of the decontamination and chelation therapies employed in this case are still in use today. The long-term medical and health follow-up of the patient, as well as the generous donation of post-mortem tissues and autopsy results upon his passing, led to a better understanding of americium intake and deposition, as well as the efficacy of DTPA chelation strategies (Breitenstein and Palmer, 1989; Toohey and Kathren, 1995).

5. Review outcomes

The evaluation of relevant incidents involving internal contamination, in the above 14 technical areas, has revealed, directly or indirectly, several gaps that need to be addressed in the future, with major gaps related to rapid screening of large populations, fast and reliable dose estimation, surge capacity for monitoring and dose assessment, evidence-based medical management guidelines, considerations for setting up and sharing medical countermeasure stockpiles, designing health and medical follow up programs, and sustainability of relevant capabilities and capacity developed for emergency response. Note that very often, one outcome may link to multiple technical areas reviewed, and sometimes, it simply presents the call of the authors when current and future developments are considered. The review findings suggest that future research and development efforts need to address the following key areas:

1. New strategies, algorithms and technologies for rapid screening of large populations for potential internal contamination.

Many of the reviewed incidents (e.g. the Fukushima accident, the Goiânia accident, the ^{210}Po incident in London) demonstrated the challenges in screening large populations (adults and children) in a short period of time for potential external/internal contamination with radionuclides. The authors believe such challenges will become even more significant after any future incident, as affected populations will be informed of potential contamination of themselves and their family much faster thanks to the modern communication technology, especially social media. Rapid screening plays a vital role in identifying the most exposed individuals, while providing reassurance and minimizing anxiety among the ‘worried-well’, and helps decision-makers to properly evaluate the situation.

Current strategies and approaches may need to be revisited and revised, and new ones explored to dramatically increase screening throughput.

2. Exposure assessment and dose estimation supported by complementary sources of information, including 'citizen science'.

Public participation in measuring and mapping radioactively contaminated areas and locally produced fruits and vegetables following the Fukushima accident provided an important additional source of information for dose assessment purposes. The availability of information through various media (e.g., internet, weather forecasts, maps, mobile phone based apps etc.) now provides opportunities for engaging affected communities in so-called 'citizen science' activities to map contamination and to estimate exposures in the early emergency phase. 'Citizen science' may also find application in improving the quality of dose reconstruction during the late emergency phase and then the recovery process e.g., by providing data on actual consumption rates for contaminated food and water. In addition, based on the experience of the authors, 'citizen science' may also support building of trust in the authorities and improved communication, thereby reducing the mental health impact of the emergency and of any protective actions.

3. Development and coordination of surge capacity for internal contamination monitoring (both *in vivo* and *in vitro*) and dose assessment through national, regional, and/or international laboratory networks.

Certain reviewed incidents (e.g., the Fukushima accident, the Techa River incident) required performing the monitoring and dose assessments for large populations. These activities need to be conducted in a timely manner however they are time consuming, require special expertise and might exceed the capacity of any individual laboratory. The authors believe that national, regional or global surge capacity can be practically supported through laboratory networks. For example, in Europe the European Radiation Dosimetry Group (EURADOS, Giussani et al., 2019) and the Running the European Network for Biological and Retrospective Physical Dosimetry (RENEB, Kulka et al., 2017) are working on harmonizing and promoting the improvement of *in vivo* and *in vitro* monitoring capacity and providing an operational network for responding to the event of radiological and nuclear emergency situations involving internal exposures. The WHO REMPAN (Carr, 2010) and the IAEA RANET (IAEA, 2018) provide platforms for laboratory networking.

4. Evidence-based guidelines for monitoring and medical management of internal contamination.

Currently used protocols for treating internal contamination with specific pharmaceutic agents, such as chelating therapy with DTPA-Zn/Ca for Pu/Am contamination or Prussian Blue use for Cs contamination, have been used for decades in various modalities. However, the development of these protocols did not follow a systematic, evidence-based approach. Over the years, new clinical evidences have been published and new administrating methods have been developed (e.g. oral administration of DTPA-Zn/Ca; use of nano-carriers for DTPA-Zn/Ca delivery). Systematic review of these developments would help inform evidence-based guidelines.

5. Mechanisms for stockpiling and sharing medical countermeasures between countries.

Many countries have put in place or are aiming at developing national stockpiles of medical countermeasures for radiation emergencies. However, guidance on the formulary and size of such stockpile, as well as protocols for maintaining and operating such stockpiles, are not available. Following the Goiânia accident, 46 persons were treated with Prussian Blue; for some patients, treatment continued for months. In the Hanford ^{241}Am accident, the contaminated individual was treated with DTPA-Zn/Ca for years. These two cases demonstrate that adequate supply of therapeutic agents is critical for successful management of accidents involving internal contamination, especially when many people are involved. In the event of an emergency, should a large number of individuals require decorporation treatment, national stockpiles would become rapidly depleted; new supplies, even if immediately available, would take time to arrive (as evidenced in the early response to Covid-19 pandemic). International arrangements for access and sharing these resources, where possible, would be critical for mitigating such shortages.

6. Designing and justifying health and medical follow up programs.

For many of the reviewed incidents, such as the Chernobyl accident, the Fukushima accident and the Techa River incident, long-term health and medical follow up programs have been planned and implemented. As such programs would require significant resources and many years to implement, e.g. the Fukushima Health Measures Survey (Yasumura et al., 2012), it is suggested that program objectives are well defined and the program designs are justified, taking into account not only the expected health outcomes but also the potential social and economic impacts. Although the Fukushima Health Measures Survey program provides valuable information (Fukushima Prefecture, 2018a), its extensive screening for thyroid cancers in children has been widely viewed as unjustified (Clero et al, 2021).

7. Sustainable capabilities and capacity to manage emergencies involving internal contamination, developed and maintained through adequate resource allocation, training, periodic exercises, and continuous improvement.

Capabilities and capacity developed for emergency response need to be sustained as an emergency may occur at any time. Some capabilities for managing internal contamination, especially laboratory capabilities, are resource-intensive in terms of equipment, supplies, and manpower. National laboratory capacities for monitoring internal contamination which have been invested in and developed over many years appear to be in decline in many countries in recent years, not demonstrated by the reviewed incidents but observed by the authors. However, these capabilities and the capacity need to be sustained. The authors believe that non-emergency use of these capabilities, together with ongoing improvements, regular exercises, training, and laboratory intercomparisons, would help to maintain the required capabilities and capacity.

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Table 1

The 13 selected incidents in this review in Section 1 and Section 2.

	Incident	Radionuclides; main exposure pathways; exposed individuals
1. Large-scale incidents	1.1. The Chernobyl Accident, USSR, 1986	Fuel particles, fission products, activation products; inhalation and ingestion; workers, the public
	1.2. The Fukushima Accident, Japan, 2011	Fission products (mainly ^{131}I, $^{134,137}Cs$); inhalation and ingestion; workers, the public
	1.3. The Three Mile Island Accident, USA, 1979	Fission products (mainly ^{131}I, $^{134,137}Cs$); inhalation and ingestion; workers, the public
	1.4. The Kyshtym Accident, USSR, 1957	$^{144}Ce/^{144}Pr$, $^{95}Zr/^{95}Nb$, $^{90}Sr/^{90}Y$; ingestion; workers, the public
	1.5. The Techa River Incident, USSR, 1949–1956	^{90}Sr, ^{137}Cs; ingestion; the public
	1.6. The 1954 Castle Bravo Incident, Marshall Islands, 1954	Fission products, activation products; inhalation and ingestion; the public
	1.7. The Goiânia ^{137}Cs Accident, Brazil, 1987	^{137}Cs; ingestion; the public
	1.8. The 2006 ^{210}Polonium Poisoning Incident, UK, 2006	^{210}Po; inhalation, ingestion; the public
2. Workplace incidents	2.1. The ^{241}Am Accident at Hanford, USA, 1976	^{241}Am; wound; worker
	2.2. The ^{238}Pu Wound Accident at Savannah River Site, USA, 2010	^{238}Pu; wound; worker
	2.3. The ^{239}Pu Wound Accident at MPA, Russia, 2014	^{239}Pu; wound; worker
	2.4. The ^{170}Tm Incident in Beijing, China	^{170}Tm; inhalation; workers
	2.5. The ^{3}H Incident in Changchun, China	^{3}H; inhalation; workers

Table 2

The 14 technical areas covered by this review in Section 3.

	Technical areas
3.1 Emergency preparedness	3.1.1. Legislation, regulations and emergency response plans
	3.1.2. Incident surveillance and monitoring programs
	3.1.3. Monitoring and dose assessment capacity
	3.1.4. Medical preparedness
3.2 Emergency response	3.2.1. Incident characterization
	3.2.2. Emergency and risk communication
	3.2.3. Evacuation and sheltering
	3.2.4. Medical management and administration of medical countermeasures
	3.2.5. Food and drinking water restrictions
	3.2.6. Population monitoring, decontamination and initial dose assessment
	3.2.7. Relocation
3.3. Recovery process	3.3.1. Long-term environmental monitoring
	3.3.2. Long-term individual monitoring and dose assessment
	3.3.3. Long-term health and medical follow up