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Title	From Hiroshima and Nagasaki to Fukushima 2: Health effects of radiation and other health problems in the aftermath of nuclear accidents, with an emphasis on Fukushima
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1 The Atomic Bomb at 70 Years -Nuclear disaster and health- 2: Impact of nuclear
2 accidents on health and society – a review of health effects of radiation and other
3 problems arising in the aftermath of nuclear accidents with special emphasis on the
4 Fukushima accident

5

6 **Abstract**

7

8 Currently, 437 nuclear power plants are in operation around the world to meet
9 increasing energy demands. Unfortunately, major nuclear accidents have occurred over
10 the last 6 decades, i.e. the Kyshtym (1957, Russia), Windscale Piles (1957, England),
11 Three Mile Island (1979, USA), Chernobyl (1986, Russia) and Fukushima accidents in
12 2011. The impacts of nuclear disasters on individuals and societies are diverse and
13 enduring. The accumulated evidence about the radiation health effects on atomic bomb
14 survivors and other radiation-exposed victims has formed the basis for national
15 regulations concerning radiation protection. Past experiences has indicated, however,
16 that common issues were not necessarily physical health problems directly attributable
17 to radiation exposure; they were associated with psychological and social aspects in the
18 affected populations. Evacuation and long-term displacement also created severe
19 health-care problems in those who are most vulnerable, such as hospitalized patients
20 and elderly people. An open and joint learning process is essential to prepare and
21 minimize the impact of future nuclear accidents.

22 (159 words)

23

24 **Key words**

25 nuclear disaster, health effects, radiation exposure, evacuation, psychological impacts

26

27 **Key messages**

28

- 29 · Currently, 437 nuclear power plants (NPPs) are in operation around the world; half
30 are located in areas more densely populated than the area of the Fukushima
31 Daiichi NPP, suggesting a severe nuclear accident would affect a large number of
32 people.
- 33 · Although major nuclear accidents are uncommon, there have been five in the past
34 six decades, resulting in not only severe health effects attributable to radiation
35 exposure but also other serious health issues.
- 36 · In addition to the severe health effects of radiation exposure (i.e., acute radiation
37 syndrome and an increased incidence of cancer), a critical issue following the
38 Chernobyl accident was adverse effects on mental health, which has also been
39 observed following the Fukushima accident.
- 40 · The Fukushima accident revealed severe health risks of unplanned evacuation and
41 relocation for vulnerable population such as hospitalised patients and elderly
42 people requiring nursing care, as well as a failure to respond to emergency medical
43 needs at the NPP. Furthermore, displacement of a large number of people has
44 created a wide range of public health care and social issues.
- 45 · Health care professionals should balance the protection from radiation with other
46 health risks when addressing problems arising in a nuclear disaster.

47

48

49 **Search strategy and selection criteria section**

50

51 We conducted a systematic review of the published literature and documents in PubMed,
52 Medline, CiNii, and Google Scholar with search terms “Kyshtym accident”, “Windscale
53 Piles accident”, “Chernobyl accident”, “Three Mile Island accident” or “Fukushima
54 accident”, and “radiation disaster”, “nuclear accident, evacuation” or “evacuation of
55 hospital, disaster” together with “Fukushima”. We also examined the reports of the
56 United Nations Scientific Committee on the Effects of Atomic Radiation for the
57 Chernobyl and Fukushima accidents and those published by the United States and
58 Japanese government on the Three Mile Island and Fukushima accidents, including
59 references cited in these reports. For the empirical data, we could not identify
60 peer-reviewed articles or reports on the latest results from the Fukushima Health
61 Management survey and thus decided to review those on its official web site. With
62 regard to the impact on mental health, we searched PubMed, Medline, CiNii, Google
63 Scholar and reviewed published studies in addition to employing the above-mentioned
64 methods, with search terms “mental health” and “nuclear disaster”, and “stigma”,
65 “PTSD” or “psychiatric disorder” together with “nuclear disaster” or “atomic bombing”.
66 We also reviewed non-peer reviewed literature including the media using the terms
67 such as “radiation stigma” and “Fukushima” for other socio-behavioural issues. We also
68 assessed the regulations and legislations on radiological protection using the
69 International Commission on Radiological Protection and official documents published
70 by the United State and Japanese governments.

71

72 **Introduction**

73

74 Since the atomic bombings of Hiroshima and Nagasaki—one of the most tragic events in
75 the human history, accumulated evidence on the radiation effects on atomic-bomb
76 survivors and other radiation-exposed victims has formed the basis for national and
77 international regulations on radiation protection.¹ The peaceful use of nuclear energy
78 has been pursued since December 1953 when US President Eisenhower delivered
79 “Atoms for Peace” speech,² and many nuclear power plants (NPPs) have been built
80 around the world to meet increasing energy demands. Unfortunately, though, severe
81 nuclear accidents occurred,³ resulting in negative health effects directly attributable to
82 radiation as well as various indirect health and social impacts.⁴⁻⁶ Currently, 437 NPPs
83 are in operation around the world, and more will be constructed as developing countries
84 are seeking for efficient and stable energy sources.⁷ A severe accident at one of these
85 plants would affect a large number of people.⁸

86

87 This paper describes previous major nuclear accidents, with a special emphasis on the
88 Fukushima accident in 2011. We assess not only medical but also psychological and
89 societal issues related to major nuclear accidents. We then summarise the lessons
90 learned and major policy implications. We conclude the paper by discussing better
91 preparedness with the aim to minimise the health effects of radiation and to cope with
92 other critical health-care and social needs after such accidents.

93

94 **Past major nuclear accidents**

95 Over the last 7 decades, more than 440 major radiation accidents occurred worldwide.
96 Majority of them were related to radiation devices and radioisotopes with limited
97 consequences.⁹ Although uncommon, 20 criticalities including the Fukushima accident
98 occurred, resulting in significant influences on people and environment. In the
99 meantime, the International Nuclear and Radiological Event Scale (INES) was
100 developed as a worldwide tool to understand the significance of nuclear and radiological
101 events.³ Until the Fukushima accident, four major nuclear accidents had been rated as
102 INES level 5 or greater. They include; Kyshtym (1957, Russia), Windscale Piles (1957,
103 England), Three Mile Island (1979, USA), and Chernobyl (1986, Russia) as described
104 below (Table).

105

106 *The Kyshtym accident*

107 Soon after the Second World War, liquid radioactive wastes dumped from the nuclear

108 facilities, the Mayak Nuclear Materials Production Complex (PA “Mayak”) in the
109 southern Urals, Russia and, caused serious contamination of the Techa River and the
110 vicinity of the nuclear compound.¹⁰ On September 29, 1957, a serious accident occurred
111 at the PA “Mayak” called Kyshtym accident. Failure in the cooling system used for the
112 concrete tanks containing highly active nitrate-acetate wastes caused a chemical
113 explosion, resulting in a huge release of chemicals and radioactive fission products into
114 the atmosphere and disposition of these materials onto the surrounding area. An area of
115 105km length and 8·9km width was contaminated with Sr-90. More than 10,000 people
116 were eventually evacuated.¹¹ This accident was rated as level 6 on the INES scale
117 (Significant release of radioactive material).³

118

119 *Windscale Piles accident*

120 On October 10, 1957, a fire broke out in the Windscale Piles, a nuclear reactor designed
121 to produce plutonium at Windscale Works, Sellafield, in the UK, and irradiated
122 uranium oxide particles were released.^{11,12} Although no citizens were evacuated, a milk
123 distribution was banned in an area stretching from 10 km north of Windscale Works to
124 20 km to the south. This was the first severe accident of a nuclear facility which led to a
125 large discharge of radionuclides including I-131 and was rated as INES level 5 (limited
126 release of radioactive material).¹²

127

128 *Three Mile Island accident*

129 The Three Mile Island (TMI) accident was the first major NPP accident to advise the
130 evacuation of residents. On March 28, 1979, troubles in the cooling systems of the
131 TMI-2 reactor resulted in the release of large amounts of vaporized coolant into the
132 atmosphere.¹³ Pregnant women and preschool children living within a 5-mile (8-km)
133 radius of the plant were advised to evacuate. Two days later, a plan was made to expand
134 the evacuation zone to a 10-mile and then a 20-mile (32-km) radius; the population
135 subject to evacuation increased from 27,000 within a 5-mile radius to 700,000 within a
136 20-mile radius.¹⁴ In the preliminary evacuation plan, evacuation was believed necessary
137 only for a 5-mile radius of the TMI,¹⁴ where there were just three nursing facilities and
138 no hospitals. Within the 20-mile radius of the TMI, there were 14 hospitals and 62
139 nursing facilities.¹⁴ Fortunately, the reactor was brought under control, and hospital
140 evacuation was avoided. Although the health effects of radiation exposure to residents
141 were negligible, the TMI accident, which was also rated INES level 5 (Severe damage to
142 reactor core), highlighted such challenges as evacuating hospitals and nursing homes in
143 the event of nuclear accidents.^{14,15}

144

145 *Chernobyl accident*

146 The Chernobyl accident in 1986 was the worst nuclear accident in history and was the
147 first accident to be rated INES Level 7 (Major release of radioactive material). Among
148 600 workers involved with the emergency response, 134 workers developed acute
149 radiation syndrome (ARS), resulting in 28 deaths.⁴ In all, 220,000 residents were
150 evacuated. One of the most significant public health effects of radiation was an
151 increased incidence of thyroid cancer in pediatric residents. Ingestion of contaminated
152 dairy products was the main route for absorbing radioactive iodine.⁴ Increased cancer
153 incidence due to low-dose exposure has not been established.⁴ The Chernobyl accident,
154 however, revealed other serious issues not directly attributable to radiation health
155 effects: i.e. long-term psychosocial effects.⁵

156

157 *The Fukushima Daiichi NPP accident*

158 Japan previously operated 54 NPPs along its coasts.¹⁶ The occurrence of a compound
159 disaster, in which an earthquake, tsunami, or other natural phenomenon would cause
160 such a critical event as an NPP accident, was perhaps inevitable in such a seismically
161 active country. The 6.8-magnitude Chuetsu offshore earthquake in 2007 caused a
162 leakage of contaminated water from the spent-fuel pool of the Kashiwazaki-Kariwa NPP.
163 The event did not develop into a critical accident, but it was a precursor to the disaster
164 at the Fukushima Daiichi NPP.¹⁷

165 On March 11, 2011, a 9-magnitude earthquake occurred off the east coast of Japan,
166 generating massive tsunamis, which severely damaged coastal areas and claimed
167 18,470 lives (15891 deaths, 2579 missing as of May 8, 2015).¹⁸ The Fukushima Daiichi
168 NPP was the only NPP to lose its core cooling capacity entirely after the disaster, which
169 caused severe damage to the nuclear cores and led to an INES Level 7-rated accident.
170 Consequently, substantial amounts of radioactive material escaped into the
171 environment.^{19,20}

172

173 **Japan's response to the Fukushima Dai-Ichi accident**

174 While all-out efforts were being made to cool the nuclear fuels, the government
175 progressively issued emergency evacuation orders between March 11 and 13 to
176 residents living within a radius of 3, 10, and 20 km of the NPP (Figure 1). Most of
177 residents living within the 20-km radius had been evacuated by March 15, when the
178 strongest radioactive plume was released.²¹

179 Hydrogen explosions occurred at Reactor No. 1 on March 12 and Reactor No. 3 on March

180 14 injuring 16 emergency workers. It was difficult for the injured to access medical
181 services since local emergency medical institutions had either closed or were barely
182 operating.²² (Panel 1)

183

184 **Radiation exposure to emergency and recovery workers**

185 In response to the accident, several thousand workers—mostly contractors—performed
186 on-site emergency operations.¹⁹ According to a 2013 TEPCO report, under 1% of all such
187 workers were found to have been exposed to a radiation dose (effective dose, combined
188 external and internal sources) of 100 mSv or higher; the average dose was 11.9 mSv
189 (Figure 2)(Panel 2). Among 173 workers whose exposure dose exceeded 100 mSv, 86%
190 were skilled TEPCO workers. The dose rates of six emergency workers exceeded 250
191 mSv; however no worker received a radiation exposure dose beyond 1000 mSv.²⁶ Notably,
192 most of the injuries or illnesses were not related to radiation exposure (Panel 3). The
193 maximum exposure dose among JSDF personnel and firefighters involved in the
194 emergency operation was 81.2 mSv.²⁸

195

196 Thus, no acute effects of radiation exposure such as ARS have been observed following
197 the Fukushima accident. In this sense, protection of emergency workers from radiation
198 may have been achieved. However, for those with radiation exposure greater than 100
199 mSv, a small increase incidence of cancer attributable to radiation exposure may be
200 expected.^{6,29,30}

201

202 **Radiation exposure to Fukushima Prefecture residents**

203 In a nuclear accident, exposure to radioactive materials takes several pathways:
204 external exposure from radionuclides deposited on the ground (groundshine) or in the
205 radioactive cloud (cloudshine), and internal exposure from inhalation of radionuclides
206 or by ingesting food or water.³⁰

207

208 *Early radiation exposure*

209 According to reports released in August 2014, estimated external effective doses for
210 between March 11 and July 11, 2011 were no more than 2 mSv in 94% of the
211 respondents (mean dose, 0.8 mSv).^{31,32} The maximum external exposure was 25 mSv,
212 and most doses occurred soon after the accident.³³ However, exposure to radioactive
213 iodine is a major concern, particularly among paediatric residents.⁴ In Fukushima, tap
214 water, food, and raw milk were tested soon after the accident, and distribution
215 restrictions were implemented for food, including dairy products.^{19,34} Unlike with the

216 Chernobyl accident, incorporation of radioactive iodine in Fukushima is believed to
217 have been mainly via inhalation.^{6,35} The maximum dose rate of exposure occurred after
218 the massive radioactive plume was released on March 15.²⁰ Based on System for
219 Prediction of Environmental Emergency Dose Information (SPEEDI) data, the
220 maximum average thyroid dose in the most affected district was estimated to be
221 approximately 80 mGy for 1-year-old infants—the age-group most vulnerable to
222 radioactive iodine.⁶

223

224 Direct measurement of internal radiation doses was, however, possible only for a limited
225 number of evacuees owing to the difficult circumstances after the accident. According to
226 a report using thyroid monitors for 62 evacuees from the 30-km zone, maximum and
227 median thyroid equivalent doses in adults of 33 and 3.6 mSv, respectively, and 23 and
228 4.2 mSv in children.³⁶ Another study employing a whole-body counter determined that
229 detectable iodine activity was found in 25% of 196 evacuees and medical support
230 members who remained in the 20- to 30-km indoor-sheltering zone. Their maximum
231 thyroid equivalent dose and median dose were 18.5 and 0.67 mSv, respectively.^{35,37} In
232 the World Health Organization (WHO) preliminary estimation, exposure dose in the
233 first year was extrapolated from measurements as of mid-September 2011.³⁰ Due to the
234 Dose Expert Panel's timeframe, updated data of dose estimation were not incorporated.
235 Therefore in the WHO's assessment, the dose estimates and assumptions were
236 deliberately made so as to minimize underestimation of potential health risks, i.e., err
237 on the side of caution. The report showed that the greatest risk was found among
238 paediatric females exposed in the most heavily exposed areas in Fukushima Prefecture.
239 The excess absolute risk for these people was estimated to be small, but, they had a
240 comparatively high relative increase in lifetime risk due to the low baseline risk
241 estimated for this area.³⁸ The WHO's Health Risk Assessment (HRA) report
242 recommended continuing monitoring children's health due to these risks.

243

244 The United Nations Scientific Committee on the Effects of Atomic Radiation
245 (UNSCEAR) 2013 report relied principally on data and literatures available before the
246 end of September 2012.⁶ This report, may have overestimated actual exposures due to
247 the limited available information at this time. The assessment of radio contamination of
248 the thyroid through direct methods found doses 3-5 times lower than those estimated by
249 the Committee.⁶ Based on these potential over-estimates, the UNSCEAR report
250 identified the potential increased risk of thyroid cancer among pediatric residents of the
251 districts with the highest estimated average radiation exposure and recommended close

252 monitoring and follow-up of affected children.

253

254 Stable iodine tablets are one recommended radiation protection measures.³⁹ In the early
255 stages following the accident, there was confusion as to whether residents needed the
256 tablets.¹⁹ However, estimations of thyroid tissue equivalent doses suggest no need for
257 the stable iodine tablets.¹⁹ High iodine intake through daily seaweed ingestion in the
258 Japanese diet may suppress the incorporation of radioactive iodine by the thyroid
259 gland.⁴⁰ Nonetheless, public concern over the initial thyroid exposures has led to the
260 implementation of a screening program for all children in Fukushima, while there is
261 ongoing debate in the Japanese medical community about the ethical aspects of this
262 program, as well as its implications for overdetection and overtreatment of thyroid
263 abnormalities.⁴¹

264

265 *Radiation exposure after acute phase*

266 In Fukushima, municipalities have monitored the radiation dose from external
267 exposure using a simple measurement device, such as a glass badge. Based on the
268 results of a glass badge test conducted from September to November 2011 in
269 Fukushima,^{33,42} the first year dose was calculated to be around 2.1 mSv in the northern
270 part of Fukushima Prefecture.

271

272 In the WHO's preliminary dose estimation, a lifetime cumulative dose of twice the first
273 year dose was assumed based on a reference first year dose for all organs/tissues.^{30,38}
274 The doses estimated for subsequent years in Fukushima City were generally consistent
275 with this assumption. For example, in the case of Fukushima City, the mean annual
276 dose estimated from the glass badge measurement decreased from 0.56 mSv in 2012 to
277 0.44 and 0.32 mSv in 2013 and 2014, respectively.⁴² Thus, the lifetime dose beyond the
278 first year in Fukushima City may be around 2 mSv, consistent with the assumptions of
279 the WHO's preliminary dose estimation.

280

281 Radioactive cesium intake by ingesting food is the primary concern among residents
282 living in radiation-affected areas.⁴³ Whole-body counter assessments of internal
283 radiation levels in residents of Minamisoma City, close to the Fukushima Daiichi NPP,
284 found levels of internal exposure that were too high to be due only to initial exposure,⁴⁴
285 and a subsequent study of risk factors for internal contamination found an association
286 with food type and attention to food preparation.⁴⁵ Radioactive cesium has been
287 detected in mushrooms, wild vegetables, such meat as boar and birds in fields where the

288 ambient dose was relatively high.⁴⁶ Radioactive cesium has also been detected in some
289 types of preserved food, such as dried persimmons. It has been detected in marine
290 products from river mouths in areas with relatively high ambient doses and in fish from
291 coastal waters near the Fukushima Daiichi NPP.⁴⁶ Residents in areas closest to the
292 nuclear power plant can be exposed to very high levels of internal contamination even
293 after a year since the accident through the consumption of these foods,⁴⁷ and
294 interventions to educate these residents and change food consumption practices can
295 lead to rapid declines in internal contamination, indicating the importance of food—and
296 especially wild foods—as a contamination pathway. Also, a simple radioactivity
297 inspection is conducted prior to cooking food for school lunches in many regions.^{48,49} In
298 Fukushima, the radioactive cesium detection level of fast track screening is usually 5–10
299 Bq/kg, and actual levels in tested foods were far lower.^{50–52} An assessment by the
300 Ministry of Health, Labour, and Welfare in spring 2012 reported low additional internal
301 exposure due to radioactive cesium intake at 0.0022 mSv / year in Fukushima.⁵³

302

303 **Non-radiation-related events in Fukushima**

304 The major impacts of a severe nuclear accident are not limited to the health effects of
305 radiation. Significant non-radiation related health disorders and psychological
306 disturbances were observed among the affected population following the Chernobyl
307 accident.⁵ The Fukushima accident underscored the importance of non-radiation-related
308 issues, such as evacuation and long-term displacement of vulnerable people, and mental,
309 psychological, and social factors.

310

311 *Evacuation of hospitals and nursing-care facilities*

312 Approximately 2,200 inpatients and elderly people at nursing-care facilities were
313 rapidly evacuated before March 14, 2011. During or soon after evacuation, however,
314 more than 50 inpatients and elderly people at nursing-facilities died¹⁹ from causes such
315 as hypothermia, deterioration of underlying medical problems, and dehydration. The
316 lack of medical support before, during, and after the evacuation was a major reason for
317 the loss of life during the evacuation, and emphasizes the danger of unprepared
318 evacuation for vulnerable populations.⁵⁴

319

320 *Effect of relocation, displacement, and changes in living environment*

321 By May 2011, approximately 170,000 residents had been evacuated (voluntarily for
322 about 20,000).¹⁹ The evacuation and relocation had various negative effects, particularly
323 on the elder requiring nursing care and hospitalized patients.^{55–57} After the accident, the

324 mortality rate among evacuated elderly people requiring nursing care increased about
325 3-fold in the first 3 months after evacuation and remained about 1.5-fold higher
326 afterward compared with before the accident.^{54,58,59} Women accounted for 70% of the
327 deaths: many of them were over 75 years old, and the main cause was pneumonia.
328 Repeated relocation and the frequent changes in living environment posed significant
329 adverse effects on the elderly people's health.⁵⁹ Their deaths were caused indirectly by
330 the earthquake and tsunamis and were therefore certified by the local government as
331 disaster-related deaths (DRDs).⁶⁰ The DRDs in Fukushima accounted for 56% (1793 of
332 3,194 in total) of all DRDs in the entire Tohoku region.⁶¹ Changes in the living
333 environment also influenced those not evacuated. Families and communities became
334 separated owing to differences in perceptions of radiation risk⁶²; friction occurred
335 between evacuees and residents of the evacuation destinations; mental and physical
336 changes in the residents through the impact on their lifestyle and overall spirits were
337 observed.⁶³⁻⁶⁷

338

339 *Mental health problems and poor health perceptions after NPP accidents*

340 Understandably Fukushima residents feared the invisible radiation exposure, even
341 though external and internal doses were very low compared with the Chernobyl
342 accident.^{65,68} After the Chernobyl accident, similar problems were reported, and the
343 media disseminated misleading information on increased thyroid cancer among
344 citizens.⁶⁹ The psychological impact on adults was most strongly associated with their
345 risk perception.⁷⁰ The Chernobyl Forum held in 2006 reported that the studies of adults
346 from the areas contaminated with radioactivity found a two-fold increase in
347 posttraumatic stress disorder (PTSD), and other mood and anxiety disorders and
348 significantly poorer subjective ratings of health.⁷⁰ Based on these findings, the Forum
349 concluded that adverse effects on mental health were the most serious public health
350 issue after the accident. Likewise, the significant impact of the Fukushima accident on
351 mental health was found in a survey about mental health and lifestyle conducted among
352 residents of evacuation zones.⁷¹ The survey identified the great difficulties of evacuee
353 families, who were separated and obliged to move to unfamiliar areas after the
354 accident—similar to those observed among Chernobyl evacuees.^{68,72,73} The Fukushima
355 mental health survey employed the Kessler six-item psychological distress scale (K6) to
356 assess psychological distress (scores >20 denote significant, and 13-19 mild to moderate
357 problems). The proportion of adult respondents with K6 ≥13 was 14.6% in 2011 and
358 11.9% in 2012,⁷¹ much higher than the usual state of approximately 3%.⁷⁴ Although only

359 a minority of people responded to the questionnaire, these results suggest that problems
360 in mental health persist among adult Fukushima evacuees.

361

362 Chernobyl evacuees who were children at the time of the accident perceived its
363 consequences more seriously than their unaffected colleagues; however, their
364 perceptions were not linked to such mental conditions as depression,⁷⁵ suggesting
365 resilience among Chernobyl's young generation.⁷⁶ The mental health and lifestyle
366 survey through the Fukushima Health Management Survey investigated the mental
367 health of child evacuees using the Strengths and Difficulties Questionnaire (SDQ). The
368 proportion of SDQ ≥16 in 4- to 6-year-old children and elementary school children (aged
369 6–12 years) was 24.4% and 22.0%, respectively, in 2011. That was twice the normal,⁷⁷
370 indicating the presence of severe psychological difficulties among child evacuees.
371 However, the proportion of SDQ ≥16 diminished to 16.6% and 15.8%, respectively, in 4-
372 to 6-year-old children and elementary school children in 2012,⁷¹ indicating that
373 resilience among the child evacuees to that observed after the Chernobyl accident.

374

375 The Fukushima mental health survey also investigated traumatic factors in the
376 evacuees by employing a PTSD checklist (PCL).⁷¹ The proportions of PCL ≥44 among
377 adults were 21.6% in 2011 and 18.3% in 2012, similar to that for rescue and cleanup
378 workers (PCL ≥50, 20.1%), and greater than that for residents (PCL ≥44, 16%) in lower
379 Manhattan after the World Trade Center September 11 attacks.^{78,79} These results
380 indicated the magnitude of traumatic factors in the psychiatric influences among adult
381 evacuees in the Fukushima accident.

382

383 *Psychological consequences for disaster workers*

384 Workers involved in the clean-up process after Chernobyl (often termed liquidators or
385 cleanup workers) suffered various mental and physical morbidities.^{70,80} Following the
386 Fukushima accident, TEPCO workers came under public criticism. Those workers were
387 stigmatized and discriminated against.⁸¹ In a study conducted 2–3 months after the
388 disaster, TEPCO workers who had suffered discrimination or slurs were two to three
389 times more likely to have adverse psychological consequences than those without such
390 exposure.⁸² A follow-up study showed both immediate and long-lasting psychological
391 effects of discrimination.⁸³ These investigations indicate that when workers are rejected
392 from the society they are trying to save, such experiences may lead to ongoing health
393 consequences; longitudinal studies are warranted.

394

395 *Discordance in families and communities*

396 In addition to the psychiatric problems described above, complex psycho-social issues
397 arose in Fukushima including discordance in families and in society. Displacement, fear
398 of radioactive exposure, compensation, employment, and other personal reasons
399 produced rifts among residents and in communities. Three types of discordance may
400 adversely affect families or communities in this way.⁸⁴ First, different perceptions of the
401 radiation risk result in discordance among family members. Parents with young
402 children are especially susceptible to conflicts: mothers may prefer to move to other
403 regions for their children's sake, whereas fathers may be reluctant to do so.⁸⁵ Second,
404 interfamilial conflicts in the community result from disparities in governmental
405 restrictions and compensations. Third, frustrations arise between evacuees and
406 residents of communities accepting large numbers of evacuees (e.g., Iwaki). With time,
407 the relationship between evacuees and recipient community members gradually
408 deteriorates because of the undefined period of the evacuees' stay, population increase,
409 and rise in land prices. Discordance may become a difficult issue among Fukushima
410 evacuees and reduce the resilience that the communities once had.

411

412 *Stigma and self-stigma*

413 Stigma is another issue among the evacuees and may arise through ignorance about
414 radiation. For example, young women in Fukushima are afraid that some people may
415 view them negatively owing to assumptions regarding the effects of radiation on future
416 pregnancy or genetic inheritance.⁸⁶ Through such misconceptions, evacuees often try to
417 conceal the fact that they formerly lived in Fukushima.⁸⁵ A similar phenomenon was
418 reported among atomic bomb survivors,⁸⁷ who often hesitate to talk about their life
419 history and their experiences of the bombing. This is a type of self-stigma, which is
420 induced and reinforced by public stigma. One study has demonstrated that self-stigma
421 causes three different emotional reactions among stigmatized people: righteous anger;
422 loss of self-esteem; and indifference.^{82,88} In Fukushima, self-stigma appears to have
423 caused various emotional reactions leading to distress.⁸⁵ Since the psychological effects
424 of self-stigma cannot be ignored, it is necessary to develop countermeasures for public
425 stigma to prevent affected people from further stigmatizing themselves.

426

427 *Lifestyle-related problems*

428 The Fukushima accident forced many evacuees to change various lifestyle aspects, such
429 as diet, physical exercise, and other personal habits. The proportions of evacuees
430 following government direction having less regular physical exercise (less than

431 once/week), drinking excessively (over 44·g ethanol/day), suffering mental problems,
432 and experiencing sleeping difficulties were 51%, 10%, 20%, and 70%,^{71,89} respectively.
433 Those proportions were higher than in other areas of Japan.⁷⁴ These changes in
434 health-related behaviours have raised concerns over the future risk of cardiovascular
435 diseases among evacuees. According to a longitudinal analysis of the Fukushima Health
436 Management Survey,⁹⁰ an increased proportion of overweight individuals (body-mass
437 index > 25 kg/m²) was significantly higher in evacuees than non-evacuees (31.5% to
438 38.8% after the accident in evacuees, whereas 28.2% to 30.5% in non-evacuees).^{90,91}
439 After the accident, increased prevalence was observed in hypertension (53.9% to 60.1%),
440 diabetes mellitus (10.2% to 12.2%), and dyslipidemia (44.3% to 53.4%) among the
441 evacuees, but not the non-evacuees.^{90,91} Based on these results, the local government
442 has promoted health awareness among evacuated residents.⁹²

443

444 **Lessons learned from the Fukushima and past severe nuclear accidents**

445 After a nuclear accident, uncertainty over the extent and gravity of the accident results
446 in confusing and contradictory information being issued by various sources, including
447 administrative authorities, operators of the plant, the media, and scientists.^{13,14,19,24,93}
448 Restriction of information on the accident may further accelerate public anxiety, leading
449 to proliferation of inaccurate information and public distrust.^{94,95} In such a disordered
450 situation, health care professionals are often asked to explain the risks to the
451 community.⁹⁶ Information about the accident, including what is clear and what is not,
452 needs to be disclosed by authorities and operators in a timely and organised fashion.
453 Scientific messages based on accumulated evidence from atomic bombings and past
454 nuclear accidents and provided by health care professionals should be used to enhance
455 the public's understanding of the impacts of the accident on the public's health.

456

457 The consequences of nuclear accidents vary substantially, ranging from short- to
458 long-term health effects and from direct health to social and psychological effects. In the
459 acute phase of an accident, the serious health effects due to uncontrolled exposure and
460 multi-casualty accidents that require abundant medical resources are major
461 concerns.^{4,22} Inadequate protection of the public from radiation exposure may lead to an
462 increased incidence of cancer later in life.⁴ Meanwhile, we should be aware of potential
463 adverse health risks accompanying the protective measures themselves; i.e., increased
464 health risks associated with an unplanned evacuation or the relocation of vulnerable
465 populations such as hospitalised patients and the elderly in nursing care
466 facilities,^{54,58,59,64} and poor medical responses to life-threatening trauma or illnesses

467 within an evacuation zone around the nuclear facility.^{22,27} Following the acute phase,
468 displacing hundreds of thousands of people creates a wide range of public healthcare
469 and social issues that strike at the weakest link of the healthcare and societal
470 system.⁸⁹⁻⁹² Among these, major psychological consequences are most commonly
471 observed after a nuclear accident.⁶⁹⁻⁷³

472

473 The evacuation for a large population and vulnerable people needs to be carefully
474 planned.⁶⁴ Surrogate emergency systems that support local medical responses should be
475 deployed promptly after an accident. Mental and psychological care as well as
476 behavioural and social support for displaced people need to be put in place with
477 coordinated approaches by the government, municipalities, academic organizations and
478 volunteer groups. Finally, general public health services are prerequisite to counteract
479 long-term adverse health effects after a severe nuclear accident.⁹⁶ For all of these
480 countermeasures, health care professionals should balance the protection from
481 radiation with other health risks, and make efforts to mitigate the psychological effects
482 that are most strongly associated with the risk perceptions of radiation.⁷⁰ These
483 challenging tasks constitute the agenda of future research.

484 (4349 word)

485

486 **Contributors**

487 KT, AO, KK, KS, SY and RC set the conceptual framework of the report. AH, KT, AO,
488 HY, MM, JS, TO, TT, MA, TI and NH contributed to drafting. KS, KT, AH and AO did a
489 systematic review and contributed to the critical revision. All authors contributed to the
490 discussion and have seen and approved the final version of the report.

491

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505

506 ***Panel 1: Tokai-Mura criticality accident and development of radiation emergency***
507 ***medical hospitals in Japan***

508

509 In September 1999, a criticality accident at the JCO uranium-conversion plant in
510 Tokai-Mura, Japan occurred when workers inappropriately poured enriched uranyl
511 nitrate solution into a precipitation vessel, triggering fission reactions (Tokai-Mura
512 criticality accident).²³ The local government advised residents to evacuate from the area
513 within a 350 m radius of the plant. It took 19 hours to terminate the criticality. Three
514 workers were exposed to a massive dose of neutron and gamma ray radiation and
515 developed ARS, resulting in two deaths from an estimated exposure exceeding 6 Gy
516 equivalent. Besides these 3 workers, 169 JCO employees, 260 emergency personnel and
517 234 residents were exposed to radiation with maximum estimated doses of 48, 9.4 and
518 21mSv, respectively. Although there were human casualties, no major release of
519 radioactive materials was observed and therefore this accident was graded as INES
520 level 4, i.e., an accident with local consequences. The Tokai-Mura criticality accident
521 highlighted the importance of integrated critical care for patients exposed to high dose
522 radiation. In addition, risk communication was indicated as one of the key issues in
523 public relation after a nuclear accident.²⁴

524 Base on lessons learned from this accident, the radiation emergency hospital system
525 had been enhanced particularly focusing on work-related accidents with high dose
526 radiation exposure²², however, not for such large-scale natural disasters as
527 Fukushima.¹⁹ Accordingly, 2 referral hospitals were designated as the tertiary radiation
528 emergency hospitals where advanced treatment for ARS or severe internal
529 contamination was provided. Seventy-four hospitals in prefectures where NPPs were
530 located were also designated as primary or secondary radiation emergency facilities
531 where patients were triaged and treated, then transferred to tertiary hospitals when
532 indicated. Of note, 38 of these hospitals were located within a 30 km radius of NPPs,
533 meaning these hospitals may lose their function if a severe nuclear accident mandates
534 evacuation from the area.

535

536 ***Panel 2: Protection of emergency workers from radiation exposure***

537

538 Most national regulations for radiation protection are based on the 1990
539 Recommendations of the International Commission on Radiological Protection (ICRP).¹
540 International standards, such as the International Basic Safety Standards, various
541 international labor conventions, and European directives on radiological protection, are
542 also based on those recommendations. The ICRP revised its recommendations and
543 updated them as ICRP Publication 103 in 2007.²⁵ According to the new publication, the
544 dose limit for occupational exposure is 100 mSv over 5 years and 100 mSv for emergency
545 work. Occupational exposure of workers occurs during the performance of duties
546 involving radiation, such as those conducted after an accident by workers regularly
547 employed at the plant and by other workers engaged in recovery and rescue operations.
548 Many workers need to be involved in on-site mitigation and other activities. Such
549 workers are subject to internationally established limits for occupationally exposed
550 workers. However, a small number of skillful workers are expected to be involved in
551 emergency tasks. Thus, the dose limits are 500–1000 mSv as reference levels to avoid
552 the occurrence of deterministic effects for workers in an emergency situation.

553 ***Panel 3: Injuries of emergency and recovery workers in response to the accident***

554

555 By the end of September 2014, 754 workers had sought medical treatment at the site.
556 Five deaths were observed: three workers developed cardiac arrest owing to acute
557 myocardial infarction; there was one case of aortic dissection, and another person
558 suffered from asphyxia caused by a landslide during the construction of a pile
559 foundation. Among the workers, there were only 12 cases of contamination with
560 radioactive substances—all of which occurred in March 2011. There was an increase in
561 heat illness in May to July. In all, 88 workers suffered from heat illness; however, no
562 severe cases, such as heat stroke, were reported. To coordinate efforts for emergency
563 medical care and provide an adequate working environment for NPP personnel, the
564 Emergency Medical System Network was established: its purpose is to examine
565 occupational environments, institute preventive medicine, particularly in summer to
566 avert heat stroke, and conduct follow-up of workers with chronic illnesses and mental
567 health problems.²⁷

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- 846

847 Table and Figure legends

848

849 **Table:** Summary of past major nuclear accidents

850 * Prefixes of the SI unit; T (tera): 10^{12} , Bq: becquerel

851 **The INES at nuclear facilities is classified on the scale of seven levels based on the
852 radiation doses to people and widespread release of radioactive materials, violation of
853 radiological barriers and control within an installation, and dysfunction of accident
854 preventing measures.²

855 INES Level 7: major release of radioactive material with widespread health and
856 environmental effects requiring implementation of planned and extended
857 countermeasures

858 INES Level 6: significant release of radioactive material to require implementation of
859 planned countermeasures

860 INES level 5: limited release of radioactive material to require implementation of some
861 planned countermeasures, severe damage to reactor core

862

863 **Figure 1:** Location of Fukushima Daiichi Nuclear Power Plant¹⁷

864

865 **Figure 2:** Irradiation dose and number of workers involved with the emergency and
866 recovery operations at Fukushima Daiichi Nuclear Power Plant (March 11, 2011 to
867 August 31, 2013)²⁴

868 *Max: 678.08mSv (external exposure, 88.08mSv; internal exposure, 590mSv)

869 (29,332 workers were engaged in operations)

870

Figure**Table**

	<i>Kyshtym accident</i> ^{10,11}	<i>Windscale Piles accident</i> ^{11,12}	<i>Three Mile Island accident</i> ^{13,14,15,93}	<i>Chernobyl accident</i> ^{4,5}	<i>Fukushikma accident</i> ^{6,19,30,71}
Location	Southern Urals, Russia	Sellafield, UK	Pennsylvania, USA	Chernobyl, Russia	Fukushima, Japan
Year	1957 Sep	1957 Oct	1979 Mar	1986 Apr	2011 Mar
Type of accident	Chemical explosion of the containment tank of liquid radioactive wastes at the military installation	Fire of the nuclear reactor at the military installation designed to produce plutonium	Partial core melt at the civilian nuclear reactor	Core explosion and fire at the civilian nuclear reactor	Core melt-through 3 reactor cores damaged 3 reactor buildings damaged by the hydrogen explosions
Release of radioactivity	100,000 TBq (Ce-144+Pr-144: 66%, Zr-95+Nb-95: 24.9%, Sr-90;Y-90: 5.4%)	I-131: 740 TBq	Noble gases (mainly Xe-133): 370,000 TBq I-131: 0.55 TBq	I-131: 1,760,000 TBq Cs-137: 85,000 TBq	I-131: 100,000-500,000 TBq Cs-137: 6,000-20,000 TBq
Contaminated area	Area contaminated with Sr-90 > 74 kBq/m ² (2 Ci/km ²) : 1000 km ² > 3.7 kBq/m ² (0.1 Ci/km ²): 15000 km ²	Milk distribution was banned in an area stretching from 10 km north of Windscale Works to 20 km to the south.		Area contaminated with Cs-137 > 560 kBq/m ² : 10,000 km ² > 190 kBq/m ² : 21,000 km ²	Area contaminated with Cs-137 > 560 kBq/m ² : 600 km ² > 190 kBq/m ² : 2,000 km ²
INES level	6	5	5	7	7
Affected population	10,180 residents evacuated 270,000 lived in the area contaminated		195,000 residents living within 20 miles evacuated voluntarily	115,000 residents evacuated in 1986 (subsequently 220,000 evacuated) 270,000 population lived in "strict control zone" (contaminated area)	213,000 residents evacuated (20,000 evacuated voluntarily)
Dose estimates	Average effective dose of residents: 170mSv preceding evacuation, 520mSv in effective dose equivalent	Maximum estimated thyroid doses of residents Adults: the order of 10 mGy Children: conceivably 100 mGy	Maximum effective dose: 40 mSv (emergency worker) Effective dose of residents living within 50 miles Average: 0.015 mSv Maximum: 0.85 mSv	Workers with acute radiation sickness <2.1 Gy: 41 persons, 2.2 - 4.1 Gy: 50 persons, 4.2 - 6.4 Gy: 22 persons, 6.5 - 16 Gy: 21 persons Average thyroid dose of residents Evacuees: Adults: 349 mGy Pre-school children: 1548 mGy Residents in contaminated area: Adults: 138mGy Pre-school children: 449 mGy	Maximum effective dose: 678 mSv (emergency worker) Maximum thyroid dose: 12 Gy (emergency worker) Maximum effective dose of residents: 25 mSv (external) Maximum average thyroid dose of infants in the most affected district: 80 mGy
Implications	Restriction of information on the accident by the government	Poor preparedness before the accident	Scarcity of information about plant condition and evacuation plan No effective plan for hospital and nursing care facility evacuation	Restriction of information on the accident by the government Delay in implementation of public protection Long-term psychological issues	Severe health consequences in evacuation and relocation of hospitalized patients and elderly people requiring nursing care Psycho-social issues after the accident Risk communication

Figure 1

