After the earthquake and tsunami there was a shortage of monitoring equipment. At the early stage of the emergency response, groups of workers were provided with a single personal dosimeter and the resulting measurements were taken to be representative of the external doses received by all members of the group. Once monitoring equipment was available for all workers, external dose assessment was based on the measurements of the individual personal dosimeters.

Based on the results of the internal dose estimation, TEPCO concluded that workers with the highest internal doses were those working in a central control room. For these workers, ^{131}I was the major contributor to internal dose (e.g. 98% for the worker with the highest internal dose). Stable iodine tablets were distributed to emergency workers beginning 13 March 2011. So far, no health effects have been observed for workers exceeding the dose limits.

A summary of the percentages of workers for different effective dose ranges as reported by TEPCO is presented in Table 8. Figure 7 shows the mean effective dose distribution as a function of age for TEPCO workers and contractors. Further data provided by TEPCO are presented in Annex H.

Table 8. Summary of the percentages of workers having received different effective dose ranges. For more detailed information on workers doses, see tables provided in Annex H

Effective dose range (mSv)	Internal exposure (% of workers)	External exposure (% of workers)	Total effective dose (% of workers)
< 10 mSv	> 95%	68.69%	66%
10 – 50 mSv	4.5%	28.23%	30%
50 – 100 mSv	0.3%	2.71%	< 4%
100 – 200 mSv	< 0.05%	0.37%	< 1%
> 200 mSv	< 0.05%	0%	< 0.05%

4.2.4 Exposure scenarios for workers at the Fukushima Daiichi NPP

The HRA Expert Group considered that the preliminary HRA for workers should not be based on individual doses and that it would be more appropriate to assess health risks in a few plausible exposure scenarios. As a result, four exposure scenarios were developed as shown in Table 9 below. Health risks were determined for each of these four sets of doses.

- Scenario 1 represents a group of around two thirds of the emergency workers with a total effective dose of 5 mSv as a "reasonably conservative" value.
- Scenario 2 represents about one third of the emergency workers with a total effective dose of 30 mSv.
- Scenario 3 represents less than 1% of emergency workerswith a total effective dose of 200 mSv.
- Scenario 4 represents a few emergency workers with a total effective dose of 700 mSv who received high doses to the thyroid gland from ^{131}I intake and low to moderate doses to other tissues. This scenario can be taken to be representative of the maximum exposure of emergency workers.

Table 9. Exposure scenarios assumed for the workers' health risk assessment

Scenario	Total effective dose (mSv)	External exposure (mSv)	Internal exposure (mSv)	Comments
1	5	5	–	Around 70% of the workers have < 10 mSv total effective dose and many workers in this group may have much lower doses (close to zero or even zero), so 5 mSv effective dose was considered a reasonably conservative assumption for this scenario. These workers probably appeared on the scene later and were not exposed to high levels of ^{131}I. Therefore: the assumption is that any internal dose is due to inhalation of ^{134}Cs and/or ^{137}Cs. Irrespective of the relative contribution of internal and external exposure, it is assumed that organ doses are equal to effective doses.
2	30	24	6	A total effective dose of 30 mSv is assumed with external exposure as the major contributor (80%) and internal exposure (20%) being all due to ^{131}I.
3	200	200	–	There are 75 workers with external effective doses > 100 mSv (the highest reported external dose is 199 mSv). It is assumed that there is no internal exposure to iodine and that organ doses are equal to effective doses.
4	700	100	600	There are 12 workers with internal effective dose > 100 mSv. The maximum reported total effective dose is 678.8 mSv and the maximum reported internal dose is 590 mSv (highest dose scenario). It is assumed that internal dose is entirely due to ^{131}I.

An objective of the HRA Expert Group was to provide estimates of health risk for emergency workers at the Fukushima Daiichi NPP from doses received during the emergency phase. Because there is no precise date when the emergency phase ended and an existing exposure situation was reached, the experts considered a reasonable approach to assess worker exposure for the first year only.

Thus, the question to be solved was how to convert the effective doses provided into doses to specific organs. The organs being considered were colon, red bone marrow, and thyroid. This HRA considered only male workers. Two different approaches were used to calculate organ doses for each of the exposure scenarios and the results were very similar (see Annex I). Approach A included the contribution to total dose from external exposure from immersion in a cloud but it did not consider the external exposure from radioactive material deposited in the workplace or radiation sources within the damaged reactors. Approach B addressed only the estimation of absorbed doses from intakes of radionuclides. Results for the estimated organ doses are presented in Table 10 for the four scenarios. Note that scenarios 1 and 2 cover more than 99% of workers and are

therefore more representative for this HRA. Scenarios 3 and 4 represent an upper bound in terms of internal and external exposure and cover less than 1% of workers. Note that the organ doses are very similar to the effective doses for Scenarios 1, 2 and 3. This is not the case for Scenario 4 where the dose to the thyroid is very high (around 12 Sv) while the doses to red bone marrow and colon are lower than the effective dose. The reason is that Scenario 4 assumes that most of the dose is due to ^{131}I. This dose level is an upper bound consistent with data provided by TEPCO about high thyroid doses in two workers (Annex H, Table 23).

Table 10. Estimated organ doses for the four scenarios assumed for the NPP workers (rounded values)

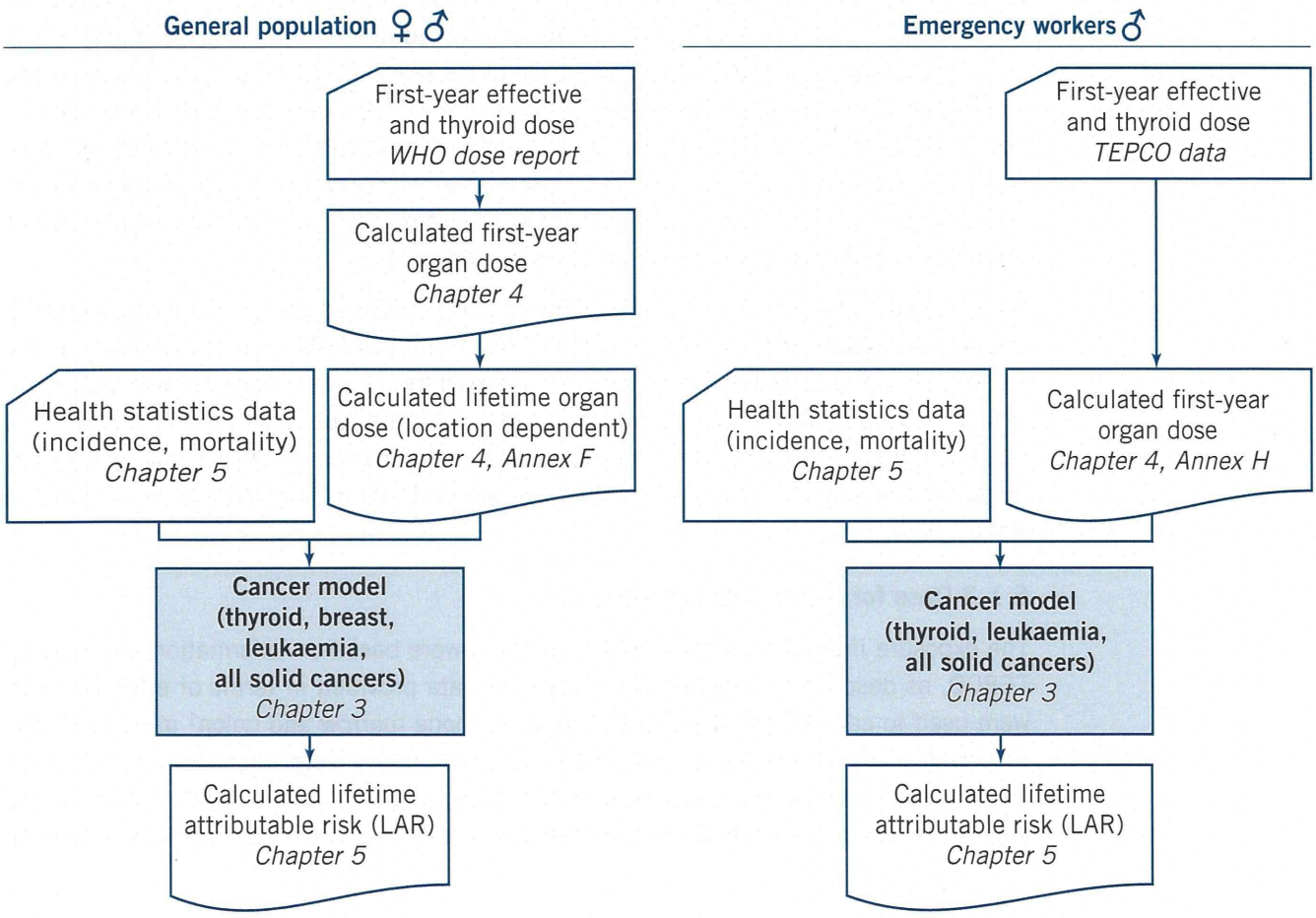
Scenario	Bone marrow (mSv)	Colon (mSv)	Thyroid (mSv)	Comments
1	5	5	5	This scenario covers around 69% of workers (~ 16 000 workers).
2	24	24	140	This scenario covers around 30% of workers (~ 7 000 workers).
3	200	200	200	This scenario represents less than 1% of workers (~ 200 workers).
4	100	100	11 800	This scenario represents an upper bound (a few workers).

5. Risk characterization

Risk characterization is the essential part of an HRA, where quantitative risk estimates are derived through the integration of the existing knowledge on the hazard (Chapter 2), the risk models (Chapter 3) and the dose estimates (Chapter 4). This last step in the risk assessment process is typically a quantitative statement about the magnitude and nature of risks derived by calculating the excess lifetime cancer risk associated with the estimated exposure (*102*). The general approach for the general population and for the workers is shown in Figure 8.

For this radiation risk characterization in particular, the aim is to provide estimates of radiation-related health risks derived from doses received by characteristic members of the general population and by workers occupationally exposed to radiation at the Fukushima Daiichi NPP, from the releases of radioactive material from 11 March 2011

Figure 8. General approach for characterizing the cancer risks for the general public and the workers



onwards, after the earthquake and tsunami in Japan. Cancer risks were quantitatively assessed and non-cancer risks were qualitatively discussed. The cancer sites considered for the risk characterization are leukaemia, thyroid cancer, female breast cancer, and all solid cancers. Risks are provided in terms of the probability of a premature incidence of a primary cancer from radiation exposure in a representative member of the public, a measure known as the lifetime attributable risk (LAR).

The general approach was to keep the risk assessment as simple as possible, given the uncertainty in dose estimates and the generally low doses involved. The next few sections give the full details of the input data and the results.

5.1 Input data

5.1.1 Dose for the general population

The exposure data used in this report are based on the levels of effective doses and thyroid doses calculated for the first year by the Dose Expert Panel that prepared the WHO Preliminary dose estimation report (*3*). The HRA Expert Group was provided with the detailed results of the exposure assessment including the point estimates, from which lifetime organ doses for thyroid, colon, breast and bone marrow were calculated (see chapter 4 for details). Lifetime organ doses D were used as input data to the cancer risk models for the calculation of LAR (see chapter 3). Distribution of lifetime organ doses were calculated on a year-by-year basis up to 70 years after exposure using the approach described in Chapter 4, section 4.1.4. Although for adults this 70-year period after exposure was enough to achieve the attained age of 89 years of age used in LAR, in the case of 1-year-old infants and 10-year-old children the 70-year period used for the calculation of their lifetime dose did not cover the entire period up to 89 years of attained age. However, the dose received beyond 70 years after exposure is very small (nearly zero) and will not influence the LAR calculations. An example of the temporal distribution of lifetime organ doses is presented in Figure 6, section 4.1.4.

As specified in section 4.1, the HRA Expert Group classified the geographical locations into four groups. It was agreed that health risks in terms of LAR would be calculated only for Groups 1 and 2, as the levels of dose estimated for all other locations were below the annual natural background level found in Japan, and the local variations in this level. It must be noted that the worldwide average annual effective dose from natural background radiation is about 2.4 mSv, with a typical range of 1–10 mSv in various regions of the world (*103*).

5.1.2 Dose for the emergency workers

The exposure input data for the HRA in workers were based on information provided by TEPCO, as described in section 4.2. Exposure data provided in terms of effective dose were used to calculate workers' organ doses for bone marrow and colon[1] in each of four assumed exposure scenarios. Only first-year organ doses were used as input data for the workers' HRA because the assessment is based on radiation doses related to the emergency exposure situation (i.e. emergency workers). Further occupational exposure

1. Organ doses for thyroid were already available as they had been included in the preliminary dose estimation.

to radiation beyond the first year will be considered under either an existing or a planned exposure situation, and will therefore be beyond the scope of this HRA.

5.1.3 Health statistics data

The following data are required as references for accurate calculation of LAR and LBR:

- age- and sex-specific all-cause mortality
- age- and sex-specific all cancer mortality (ICD 10 codes C00–C96)
- age- and sex-specific all cancer incidence (C00–C96)
- age- and sex-specific incidence for breast cancer (C50)
- age- and sex-specific incidence all solid cancers(C00–C89)
- age- and sex-specific incidence leukaemia (C91–C95)
- age- and sex-specific incidence thyroid (C73).

Mortality data for the general Japanese population (all-cause and cancer-specific) used to calculate overall survival $S(a)$ and cancer-free survival $S_{aj}(a)$ as a function of attained age a, were obtained from an official Japanese statistics website (http://www.e-stat.go.jp/SG1/estat/ListE.do?lid=000001082327). Cancer incidence data were taken from the 2004 Japan Cancer Surveillance Research Group compilation of 31 population-based cancer registries in Japan. Relying on data from 14 of those registries (excluding under-registered sites to avoid under-estimation), Matsuda *et al.* (*104*) published age-specific cancer incidence rates according to sex and primary site.

For the Fukushima prefecture and its cities and villages, no local cancer incidence rates were available at the time of this HRA, as the Fukushima cancer registry began data collection only in 2011. On the basis of the similarity of cancer incidence in two neighbouring prefectures for which cancer registries are available (Miyagi and Yamagata) and the other Japanese cancer registries, the HRA Expert Group agreed that cancer data from Fukushima were likely to be comparable to those from other parts of Japan (see section 6.2.2).

5.2 Cancer risk characterization in the general population

5.2.1 Overview of results

The HRA Expert Group assessed cancer incidence risk as (i) LAR assessed for the entire life (up to 89 years attained age) and (ii) cumulated attributable risks assessed over 15 years after exposure (AR_{15}). Tables 11–14 summarize the cancer risk estimates for the general population composed of both males and females exposed at 1 year of age, 10 years and 20 years.

As mentioned in section 4.1.2, the geographical locations were classified into four groups. Based on the estimated doses it was concluded that the risks in Groups 3 and 4 locations would be much lower than the temporal and spatial fluctuations of the baseline cancer incidence risks. It was therefore decided to calculate the LAR only in Group 1 and Group 2 locations.

The results are presented for leukaemia, female breast cancer and all solid cancer incidence in Table 11 and Table 13. For practical reasons the results for thyroid cancer incidence are shown separately in Table 12 and Table 14 because a slightly different grouping of locations was used. The complete set of results tables has been included in Annex J.

In this section several risk quantities are presented. The LBR, described in section 3.3.1, represents the accumulated baseline probability to have a specific cancer up to age 89 years. Some data about LBRs for infants, children and young adults of both sexes are provided in Annex L. The LAR expresses the probability of premature incidence of a radiation-related cancer. The concept of LAR has an implicit "cumulative" nature derived from the way LAR values are calculated: as an integration of the risk that could be attributed to radiation exposure, arising on a year-per-year basis (excluding the latency period). In this context, LAR is an "extra" lifetime risk that is added to an already existing baseline lifetime risk (the LBR). The LFR, defined as the ratio between LAR and LBR, reflects the relative increase in cancer risk that could be attributed to radiation exposure. Both LBR and LAR are represented by a number between 0 and 1 while LFR is provided here as a percentage (%).

5.2.2 Results of lifetime risk calculations

Figure 9a shows the LAR values for leukaemia incidence in two locations of Group 1 (highest estimated doses) and in one representative location of Group 2 for females of different ages at exposure. Leukaemia has the particularity that both LAR and LBR are higher for males compared with females. The LAR is greatest in male infants (4 in 10 000) in the most affected Group 1 location (Group 1a). The LAR for infant girls is estimated to be about two thirds of that for infant boys (female: male LAR ratio around 0.7) (Figure 10). It can be seen that LAR is higher for 1-year-old infants and 10-year-old children compared with adults (LAR ratios 2.7 and 1.3, respectively). In general, the LAR in Group 2 locations is about a quarter of that for the most affected Group 1 location. The LFR is greatest (6.6%) in the most affected Group 1 location, while it is less than 1.7% in Group 2 locations for all ages and both sexes.

Figure 9b shows the LAR values for all solid cancers[2] incidence in two locations of Group 1 and in one representative location of Group 2 for females of different ages at exposure. The LAR in the Group 1a location with the highest estimated doses is greatest in female infants at around 110 in 10 000, and is lower at around 60 in 10 000 for 20-year-old female adults. The LAR for Group 2 locations is less than 32 in 10 000. Unlike leukaemia, the LAR is higher for females while the LBR is smaller (female:male LAR ratio 1.5) as shown in Figure 11. In general, risks are higher for 1-year-old infants and 10-year-old children than for 20-year-old adults (LAR ratios 1.9 and 1.5, respectively). The LFR is greatest for infant boys in Group 1a (3.8%) while it is below 1% in Group 2 locations.

Figure 9c shows the LAR values for thyroid cancer in two locations of Group 1 and in one representative location of Group 2 for females of different ages at exposure. The LAR for thyroid cancer incidence is greatest in female infants in the most affected Group 1

2. The assessment of the risk of all solid cancers combined is intended to provide, together with the assessment of the risk of leukaemia, an overall indication of the lifetime risk of cancer. In circumstances where the tissue doses are highly heterogeneous such as the dose to the thyroid following an intake of radioactive iodine, the risk of all solid cancers combined will not fully account for the risk of thyroid cancer (See section 6.3.4).

location at 52 in 10 000 and it is around 9 in 10,000 for 20-year-old females. In Group 2 locations LAR is around 2 in 10,000 for 20-year-old females Both LAR and LBR are much higher for females than for males (female: male LAR ratio 4.6) as shown in Figure 12. Risks are much higher for 1-year-old infants and 10-year-old children than for adults (LAR ratios of around 6 and 3, respectively). The LFR in the most affected location of Group 1 is 68% and 11% for 1-year-old and 20-year-old females, respectively. In Group 2 LFR is 23% and 3% for females in the same age-at-exposure ranges.

Figure 9d shows the LAR values for female breast cancer in two locations of Group 1 and in one representative location of Group 2 for different ages at exposure. The LAR is greatest in female infants in Group 1 locations at 36 in 10 000, which represents a 6.4% increase over the LBR (Figure 13). In general the LAR for Group 2 locations is estimated to be about one third of that in the Group 1a location. For young women (20-year-olds), the LAR is one third of that in infant girls.

Comparison of the assessed risks for a given subgroup (i.e. sex, age-at-exposure, location) using the same scale results in a clearer identification of the relative contribution of the different cancer sites to the overall risks. For example, the LAR for all solid cancers, breast, thyroid and leukaemia for 1-year-old females in Group 1 and Group 2 locations shows a major contribution from all solid cancers, and dominance of breast and thyroid cancer risks compared with leukaemia (Figure 14). All solid cancers represent a pooling of a variety of cancers, including breast and thyroid cancer. The risk model for all solid

Figure 9. Lifetime attributable risk (LAR) in females of 1 year, 10 years and 20 years in different locations of Group 1 and Group 2 for (a) leukaemia, (b) all solid cancers, (c) thyroid cancer, (d) breast cancer.

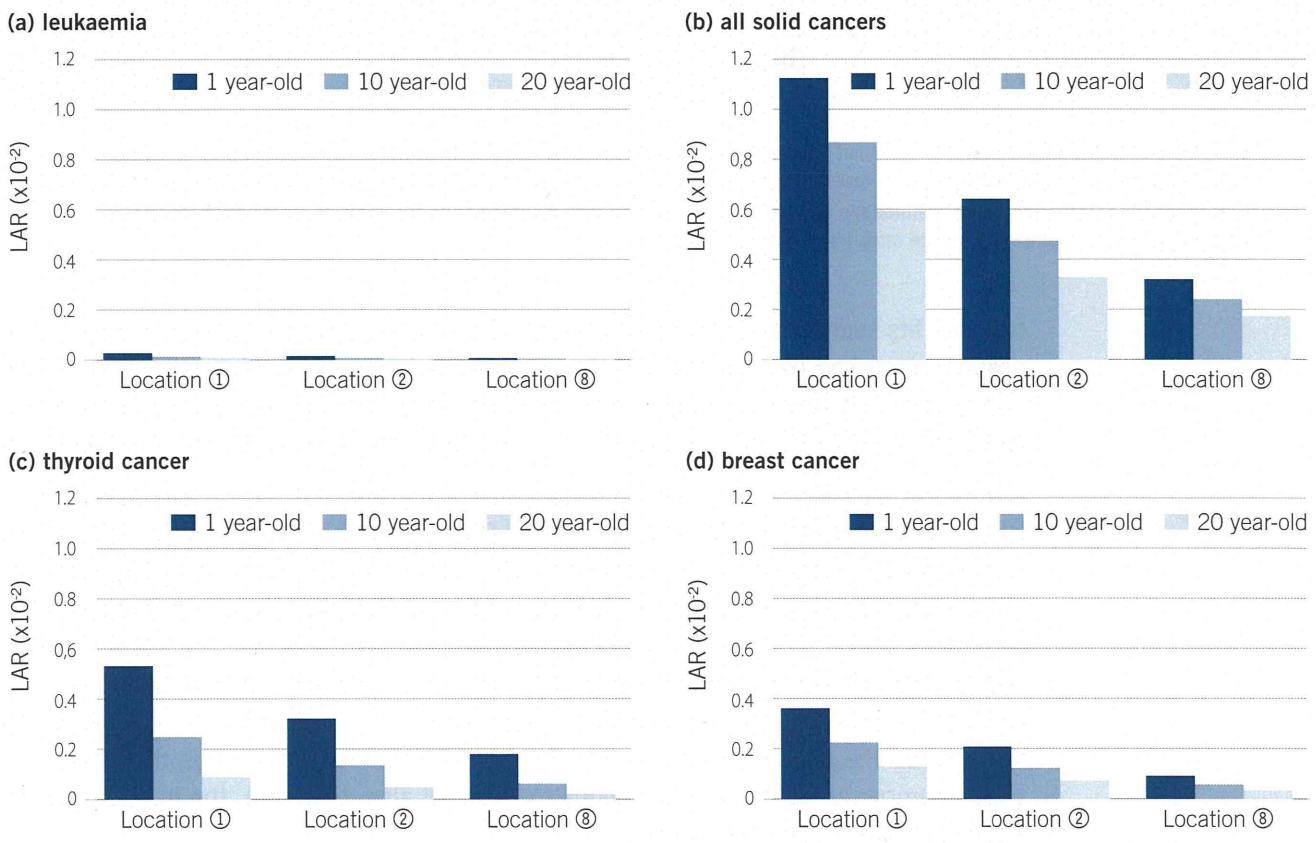


Table 11. Lifetime attributable risk (LAR) and lifetime baseline risk (LBR) up to attained age 89 for the general population (both sexes and three different ages at exposure) for all solid cancers, breast cancer and leukaemia incidence.

Location groups	Locations	Lifetime attributable risk (LAR x 10^{-2})					
		Males					
		Adults 20y		Children 10y		Infants 1y	
		All solid	Leukaemia	All solid	Leukaemia	All solid	Leukaemia
Group 1	①	0.394	0.015	0.568	0.020	0.730	0.040
	②	0.225	0.008	0.317	0.011	0.425	0.023
Group 2	③	0.093	0.003	0.124	0.004	0.160	0.008
	④	0.136	0.005	0.189	0.007	0.249	0.012
	⑤ to ⑨	0.115	0.004	0.159	0.006	0.208	0.010
	⑩ to ⑭**	0.115	0.004	0.159	0.006	0.208	0.010
Group 3	Rest of Fukushima prefecture (less affected)	*	*	*	*	*	*
	Neighbouring prefectures	*	*	*	*	*	*
	Rest of Japan	*	*	*	*	*	*
Group 4	Neighbouring countries	*	*	*	*	*	*
	Rest of the world	*	*	*	*	*	*
LBR (X 10^{-2}) for cancer incidence in Japan* **		**40.74**	**0.57**	**40.71**	**0.58**	**40.60**	**0.60**

* The HRA expert group agreed that mathematical calculations of health risks in terms of LAR would be not be performed for Group 3 and Group 4 locations, where the risks would be much lower than the normal temporal and spatial fluctuation of the baseline cancer incidence risks.

** For locations ⑩ to ⑭ no separate calculations were performed and LAR was assumed to be the same as locations ⑤ to ⑨.

*** Based on Japan 2004 cancer incidence rates from Matsuda et *al.* (*104*).

cancers, fits such a combination of diseases. In contrast, when breast and thyroid cancer risks are assessed by applying specific risk models for each of those cancer sites, their higher age-dependence becomes more evident. This explains why the LARs for breast and thyroid cancer do not necessarily sum exactly when compared with all solid cancer.

A different perspective is provided when considering the LFR, which expresses the relationship between the LAR and baseline (LBR). Figure 15 illustrates the LFR for the cancer sites mentioned above. While the LFR for all solid cancers is quite small, the LFR for thyroid cancer reaches a high value (around 70% for 1-year-old females). This dominant relative increase in thyroid cancer risk does not mean that the absolute risk is equally high. Even with a low number of "extra" cases of thyroid cancer (absolute risk), the very low baseline incidence of the disease results in a large relative increase as represented by the LFR. However, when the level of baseline incidence is that small, the actual number of "extra" cases is likely to be small also; therefore, the impact in terms of public health would be limited.

Lifetime attributable risk (LAR x 10^{-2})								
Females								
Adults 20y			Children 10y			Infants 1y		
All solid	Breast cancer	Leukemia	All solid	Breast cancer	Leukemia	All solid	Breast cancer	Leukemia
0.591	0.129	0.009	0.859	0.222	0.014	1.113	0.357	0.027
0.336	0.072	0.005	0.479	0.122	0.007	0.647	0.205	0.016
0.139	0.029	0.002	0.187	0.045	0.003	0.244	0.071	0.005
0.202	0.040	0.003	0.284	0.067	0.005	0.377	0.108	0.008
0.171	0.034	0.003	0.238	0.056	0.004	0.316	0.090	0.006
0.171	0.034	0.003	0.238	0.056	0.004	0.316	0.090	0.006
*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*	*
29.07	**5.55**	**0.40**	**29.09**	**5.54**	**0.41**	**29.04**	**5.53**	**0.43**

5.2.3 Temporal patterns of the risks

The results shown in the preceding graphs (i.e. LAR, LBR and LFR) provide a vision of the radiation risks integrated over the lifespan. In the context of this assessment, an infant who was 1 year old at the time of the Fukushima Daiichi NPP accident would typically reach the end of the lifespan at the turn of century (i.e. year 2100). Estimations over such a long duration carry a number of uncertainties associated with LAR and LBR that cannot be easily predicted or quantified (e.g. trends in cancer incidence rates, changes in demographic patterns, remedial actions, and increased early detection of diseases).

A way to lower the uncertainties is to use risk quantities over a shorter period of life. In the present assessment, the risks were also calculated over a 15-year period of life following the accident i.e. up to the year 2026. For the purposes of this report, such risk indicators are denoted as AR_{15}, BR_{15} and FR_{15}. In addition to reducing the associated uncertainties, these risk quantities appear more pertinent for priority setting when they