Nuclear Disaster after the Earthquake and Tsunami of March 11

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We would like to explain the effects of radiation on human health and discuss the actual effects of the contamination with radioactive material present in Tokyo. Currently, external exposure doses are within the allowable range in Tokyo and will have no adverse health effects on adults or children. As for internal exposure doses, there will likely be no problems as regards our ordinary dietary intakes. However, hot spots of Cs-134, Sr-90 and others should be monitored further. (Keio J Med 61 (1) : 28–34, March 2012)

***Keywords*: nuclear disaster, earthquake, tsunami, Japan**

Introduction

First, we offer our deep condolences to the victims of the Great East Japan Earthquake of March 11, 2011. It is our hope that all afflicted areas will steadily recover from this devastating event. As for the health effects of the Fukushima nuclear disaster, many people are now giving their opinions from a variety of viewpoints. Media reports may sometimes be exaggerated, thereby arousing excessive anxiety in the Japanese public. Herein, we would like to explain the effects of radiation on human health and discuss the actual effects of the contamination with radioactive material present in Tokyo.

Basic Issues

Units used for measuring radiation

There are four aspects to consider when measuring radiation: radioactivity, exposure dose, absorbed dose and effective dose (**Fig. 1**). Radioactivity is the spontaneous emission of ionizing radiation as a consequence of a nuclear reaction or directly from the breakdown of an unstable nucleus. The standard unit of radioactivity measurement is the becquerel (Bq), and 1 Bq is equivalent to the disintegration of one nucleus per second. Radiation is capable of ionizing substances, and the exposure dose is a measure of how much the radiation emitted from a radioactive material ionizes the air. The SI unit for exposure dose is coulomb per kilogram of air (C/kg). The absorbed dose is the amount of energy absorbed by an object from ionizing radiation. The absorbed dose unit is the Gray (Gy), and 1 Gy is equivalent to 1 Joule of absorbed energy per kg material (J/kg). The effective dose reflects the total overall effect on various tissues and organs throughout the human body, and the SI unit is the sievert (Sv). Commonly reported units are Bq and Sv in relation to the effects of the Fukushima nuclear disaster. The effective dose coefficient is a conversion factor[1] that is used to determine the biological effects of radiation based on the amount of radioactivity taken up by the human body. For example, assume that we eat 100 g of spinach every day for one year and that 10,000 Bq of I-131 is detected in 1 kg of the spinach. The exposure dose is 1000 Bq per 100 g of spinach and the effective dose coefficient is 2.2 $\times 10^{-8}$ Sv/Bq. Thus, the following calculation can be carried out: $1000 \times 2.2 \times 10^{-8} \times 365 = 0.00803$ Sv =8.03 mSv, and approximately 8 mSv of I-131 will be taken up in the body in a year through consumption of such spinach. As I discuss later, however, the effective dose coefficient is known to vary depending on age, as well as radiation quality, and to be approximately 10 times higher in children than in adults.[1]

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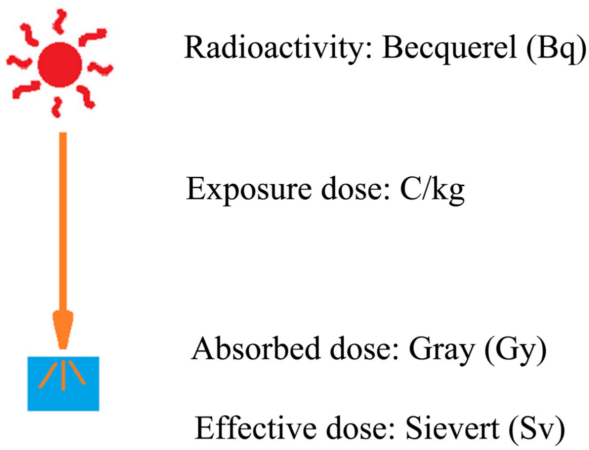

Fig. 1 Radiation units.

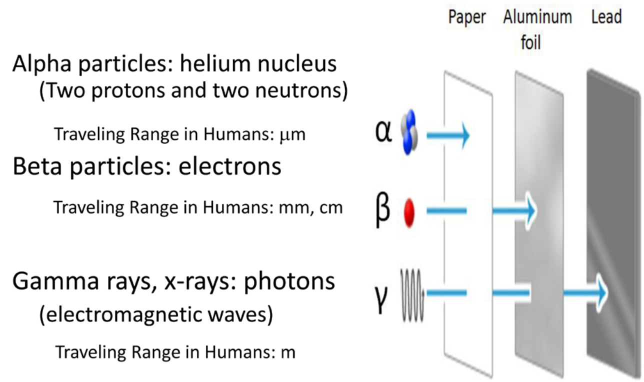

Fig. 2 Radiation types.

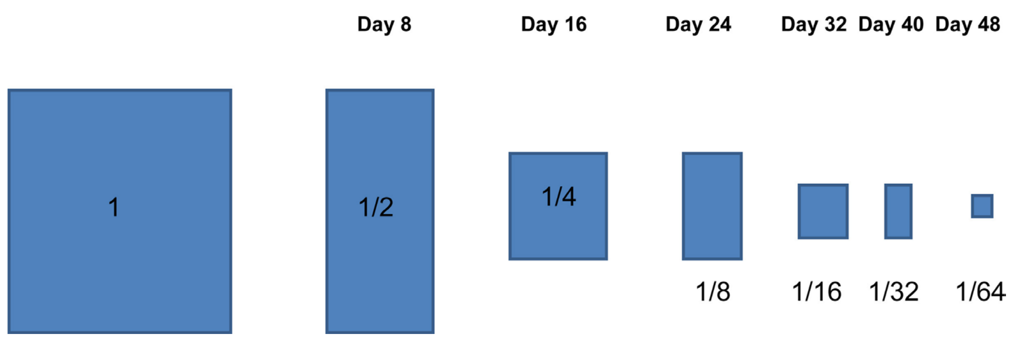

Fig. 3 Meaning of the half-life of radioactive materials.
Half-life refers to the amount of time needed for the radioactive emission of a radionuclide to decrease to half its original level. I-131 has a half-life of 8 days. Thus, emissions are reduced to 1/16 of the original level 32 days (one month) later. Meanwhile, because Cs-137 has a half-life of 30 years, emissions are reduced only to 1/4 even after 60 years have elapsed.

Types of radiation

I-131, which is a major radionuclide of current concern in relation to the Fukushima nuclear disaster, emits beta particles. Cesium, another radionuclide of concern, emits strong gamma rays; these gamma rays are generated by the production of Ba-137m via the decay of Cs-137 and by the production of Ba-134 via the decay of Cs-134. Strontium-90, which was recently detected in Fukushima city, although at a low level, emits beta particles. To date, fortunately, neither neutrons created by the decay of U-235, the essential component of nuclear fuel in the Fukushima nuclear power plants, nor alpha particles generated by the production of Am-241 via the decay of Pu-241, found in radioactive wastes from nuclear power plants, have been detected. Beta particles are essentially electrons and they travel from several millimeters to several centimeters within the human body. In contrast, gamma rays are photons (electromagnetic waves), similar to x-rays, and the range of gamma rays in the body is in terms of meters. The biological effects of both beta particles and gamma rays can be determined employing a similar calculation. When beta particles (such as those from I-131) travel from several millimeters to several centimeters and are taken up in the body, internal exposure becomes an issue in terms of health hazards. Meanwhile, because gamma rays (such as those from Cs-137) have a range of meters, not only internal but also external exposure poses a threat to human health (**Fig. 2**). Radionuclides deposited internally through respiration and food, i.e., internal exposure, are of concern in regions far from Fukushima ground zero. For areas surrounding the crippled nuclear power plants, not only internal but also external exposure is a major issue.

Half-life

Physical half-life refers to the amount of time needed

Table 1 Radionuclides have physical and biological half-lives

	Physical half-life	Biological half-life
131_{I}	8 days	120 days
137_{Cs}	30 years	70 days
^{90}Sr	29 years	49 years

Biological half-life: how long the radionuclide is retained in the body.

for radioactivity to fall to half its original level. For example, the half-life of I-131 is 8 days, i.e., the amount of I-131 is reduced to 1/2 after 8 days have elapsed and to 1/4 after 16 days (**Fig. 3**). It has almost disappeared (1/16 of its original level) approximately one month later. In contrast, the physical half-life of Cs-137 is as long as 30 years. This means that it takes 60 years to reduce the amount to 1/4 of the original level. For Sr-90, the physical half-life is 29 years. Radionuclides also have a biological half-life, which refers to the elimination of internal radioactivity via urine, feces and perspiration. I-131 is retained in the thyroid for a long time, and its biological half-life is 120 days. Cs-137 is widely distributed in the body with a biological half-life of approximately 70 days. Sr-90 is taken up in bone, and its biological half-life is very long at 49 years. The radionuclides of concern after the present nuclear disaster are I-131 and Cs-137. I-131 has a short physical half-life, although it is retained in the thyroid for a long time. Meanwhile, although Cs-137 is widely distributed in the body and its physical half-life is long, it is eliminated in a relatively short period, with a biological half-life of approximately 70 days. Sr-90 is taken up in bone and is hazardous because of its very long physical and biological half-lives, although it has been minimally detected, to date, since the Fukushima nuclear disaster (**Table 1**).

Radiation effects on DNA

The biological effects of radiation start with DNA damage (breaks in DNA strands). Humans have 46 chromosomes, which are essentially made of double-stranded DNA helices (**Fig. 4**). When radiation is absorbed by the body, it results in ionization, thereby generating a highly energetic electron. This electron may directly damage DNA itself, which is referred to as a direct action, or it may generate hydroxyl radicals (active oxygen) via water molecules and thereby damage DNA, which is referred to as indirect action (**Fig. 5**).[2] When one DNA strand is broken, it is called single-stranded DNA damage; when two DNA strands are broken, it is called double-stranded DNA damage. When DNA is separated by double-stranded damage at the same position, it is called a double-stranded DNA break (**Fig. 6**). DNA breaks can result in the binding of different another different sites,

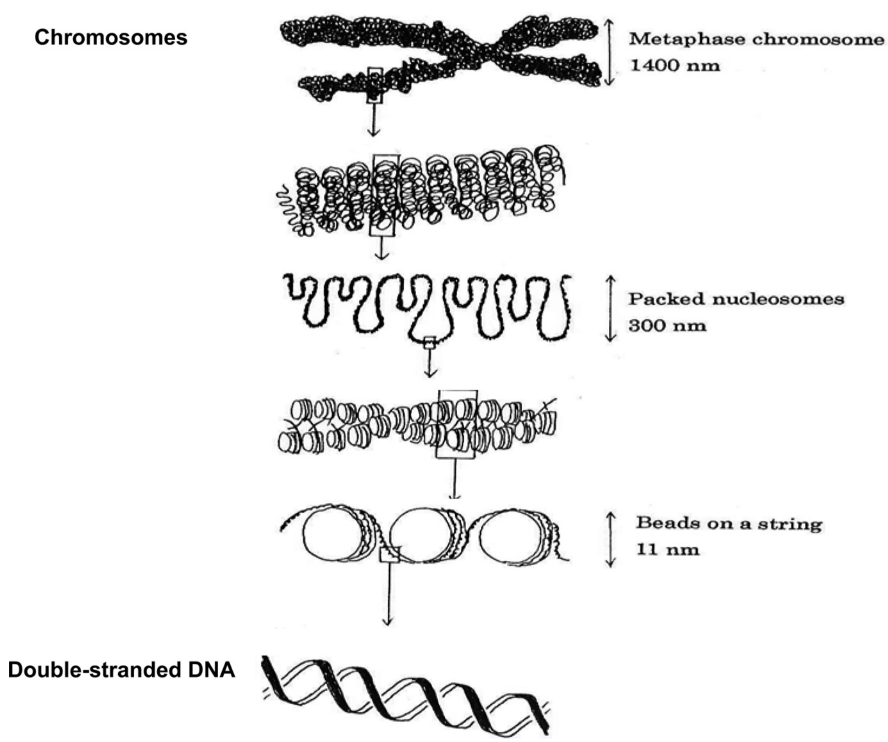

Fig. 4 Chromosome structure.
Humans have 46 chromosomes, made up essentially of double-stranded DNA helices.

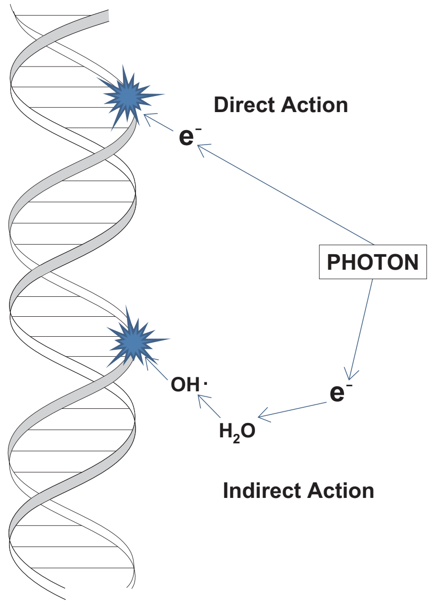

Fig. 5 Mechanism of DNA damage by radiation.
When radiation is absorbed by the body, it produces ionization, thereby generating an energetic electron. This electron can directly damage DNA itself (direct action) or it can generate hydroxyl radicals via water molecules, which then damage DNA (indirect action).

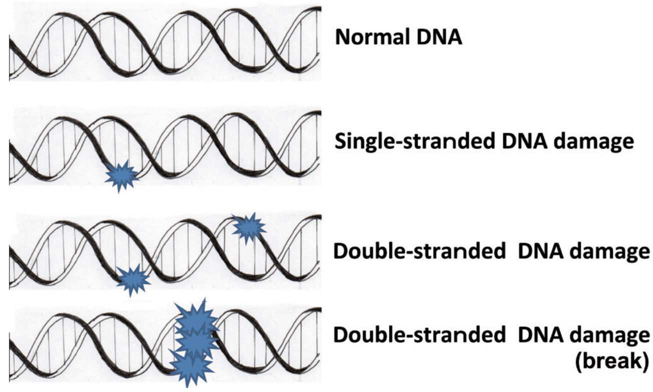

Fig. 6 Radiation-induced DNA damage.
When one DNA strand is broken, it is called single-stranded DNA damage; when two DNA strands are broken, it is called double-stranded DNA damage. When DNA is separated by double-stranded damage at the same position, it is called a double-stranded DNA break.

thereby forming abnormal DNA (chromosomes), which in turn causes cell death. If many cells die, tissue death results, ultimately leading to somatic death. Early radiation effects are associated with the above DNA damage processes. DNA damage is often repaired when it is limited to one of the two strands (a single-stranded break) or two broken strands that are far from each other. However, if DNA repair is not achieved (or DNA is miss-repaired), secondary carcinogenesis or genetic effects of radiation can occur. Radiation effects in humans fall into two categories: effects on individuals exposed to radiation (somatic effects) and effects on offspring of exposed individuals who were not themselves exposed (hereditary effects). Somatic effects are further divided into early and chronic effects: early effects manifest as early complications (e.g., burns, immunosuppression, gastrointestinal ulcers) within a few months after exposure, and chronic effects manifest as delayed complications (e.g., cancer, cataracts) from a few months onwards. Hereditary effects and carcinogenic effects resulting from minor DNA damage are called stochastic effects, and others are called deterministic effects. Stochastic (carcinogenic and hereditary) effects sometimes manifest spontaneously and can also be accelerated with small amounts of radiation. Meanwhile, deterministic effects have a certain exposure dose (threshold) that leads to cell death (**Fig. 7**).[2]

Dose limit

According to the International Commission on Radiation Protection (ICRP) recommendation, the maximum allowable radiation dose for the general public is 1 mSv per year. For medical professionals, the maximum dose is 100 mSv/5 years (which is obtained by an average of 20 mSv for 5 years) or a maximum 50 mSv per year. Thus, a dose of 20 mSv/year is considered to be the dose limit.[3] This level was also considered to be allowable for the general public at the time of the emergency after the Fukushima disaster; however, this level remains controversial. Exposure to this level raises the question of whether it carries a risk of secondary carcinogenesis. Data from individuals exposed at Hiroshima and Nagasaki showed cancer incidences to have increased at 5–10 years after exposure for leukemia, at 10–15 years for thyroid cancer, at 15–20 years for breast and lung cancer, and from 20 years onwards for gastrointestinal cancer.[4] The level of 1 Sv is a significant risk factor for increased cancer occurrence, and raises cancer occurrence by 50%. Given that cancer occurrence is associated with stochastic effects of radiation, when individuals are exposed to 100 mSv, 1/10 of 1 Sv, for a year, cancer occurrence is theoretically predicted to increase by 5% (**Fig. 8**).[4] However, after actual exposure to this level of radiation, it is still controversial whether the incidences of cancers, including leukemia, will increase (**Fig. 9**).[5] This may be explained by the involvement of various other confounding factors. A survey conducted by the National Cancer Center revealed the relative risk for cancer occurrence to be 1.05 for exposure to 100 mSv, 1.6 for smoking, 1.4 for excessive alcohol consumption, and 1.2–1.3 for leanness or obesity

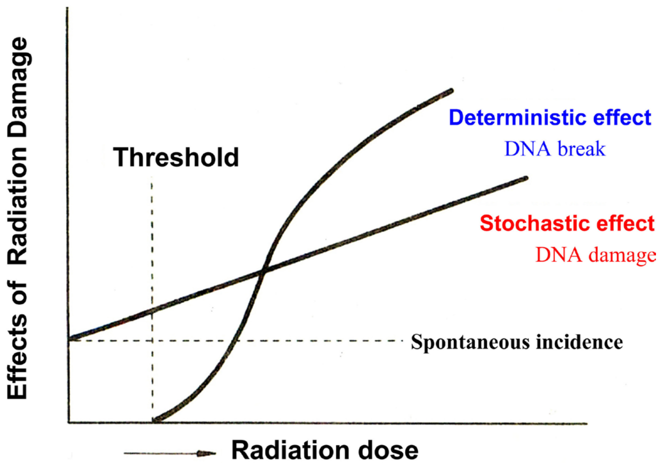

Fig. 7 Classification of radiation effects.
Carcinogenic effects resulting from minor DNA damage and hereditary effects of radiation are called stochastic effects, and others are called deterministic effects. Stochastic (carcinogenic and hereditary) effects sometimes manifest spontaneously and can also be accelerated as a result of even a very small amount of radiation. Meanwhile, deterministic effects have a certain exposure dose (threshold) that leads to cell death.

(**Table 2**). This reveals that the relative risk for developing cancer is far higher for smoking than for this level of radiation exposure. Thus, real radiation effects are likely to be masked by these confounding factors. Taking the confounding factors into account may also raise the possibility that exposure to 100 mSv/year is not significantly hazardous to human health.[6]

Actual Radiation Exposure

External exposure in Tokyo

A level of 0.8 μSv/h was detected in Tokyo on March 15. This was calculated to be 16 times the usual level (around 0.05 μSv/h). In addition, approximately 81,000 Bq/m^2 of I-131 fallout was observed in Tokyo from 21 through 23 March. Thus, the entire Tokyo metropolitan area should have been a radiation-controlled area for the aforementioned week. However, we are constantly exposed to environmental radiation from space and the ground and are sometimes exposed to medical radiation in our daily lives. Japanese people are exposed to a level of around 3.75 mSv (3750 μSv) per year. Assuming that we continue to be exposed to the present level of 0.8 μSv/h for a year, the exposure dose will be 7 mSv in a year. This level is two or three times higher than the actual annual exposure level of the general public, although it is 16 times higher than that of environmental radiation. Moreover, even if we are exposed to a level of 7 mSv in a year, no symptoms manifest nor are any abnormalities detected by examinations. (This may be explained by the fact that the dose limit is 20 mSv/year even for the general public, as stated previously.) In addition, radiation monitoring conducted on March 17 showed the level to have fallen to 0.05 μSv/h. I-131 fallout also rapidly fell and was zero in June and thereafter. Given the half-life (8 days) of I-131, the level of I-131 is speculated to have fallen to an acceptable level in April and thereafter. In total, approximately 7000 Bq/m^2 of Cs-137 fallout was observed in March, but this radionuclide was undetectable from May 15 onwards. Given its half-life of 30 years, the effect of cesium is considered to persist (**Fig. 10**). In fact, however, no human health hazards have been reported as a result of nuclear weapons testing in the latter half of the 20th century, despite several thousand Bq/m^2 of Cs-137 fallout being detected in the atmosphere.

Exposure in Tokyo

The radionuclides raising concern after the Fukushima disaster are I-131 and Cs-137. At first, I-131 was the major problem to be dealt with because it is deposited in the thyroid gland. According to news releases, I-131 exceeded the standard level, as indicated by cow's milk (1000 Bq/kg), vegetables including spinach (10,000 Bq/kg) and drinking water at Kanamachi water purification plant (210 Bq/kg). Using the effective dose coefficient, the following exposure doses of I-131 are obtained when a person eats 100 g of spinach or drinks 500 mL of cow's milk or 2000 mL of tap water every day: 8 mSv/year for spinach, 4 mSv/year for cow's milk and 3.4 mSv/year for tap water. These are below the allowable level of 20 mSv/year. Considering that I-131 fallout has not been detected since June and that tap water at the treatment plant had a level below the standard the next day, it can be concluded that the above levels are not a matter of concern for the general public, including children.

Cs-137 has a long half-life and was also detected in tea leaves and beef soon after the Fukushima disaster. Subsequently, cesium levels were monitored in various foods, and the radioactivity of this radionuclide has become a common topic of discussion. In a September 2011 news release on cesium, the level was 30–50 Bq/kg for rice, about 100 Bq/kg for peaches and grapes, and 1000–2000 Bq/kg for beef, fish and mushrooms. These levels have become an issue. However, assuming that we eat 2 measuring cups (about 360 mL) of rice every day, 500 g of beef twice a week, and 150 g of *sashimi* (raw fish) three times a week, we can calculate internal exposure doses using the effective dose coefficient. The following doses are thereby obtained: 0.05 mSv/year for rice, 0.5 mSv/year for beef, and 0.2 mSv/year for *sashimi*. These levels do not exceed the annual dose limit of 20 mSv and therefore pose no threat to human health.

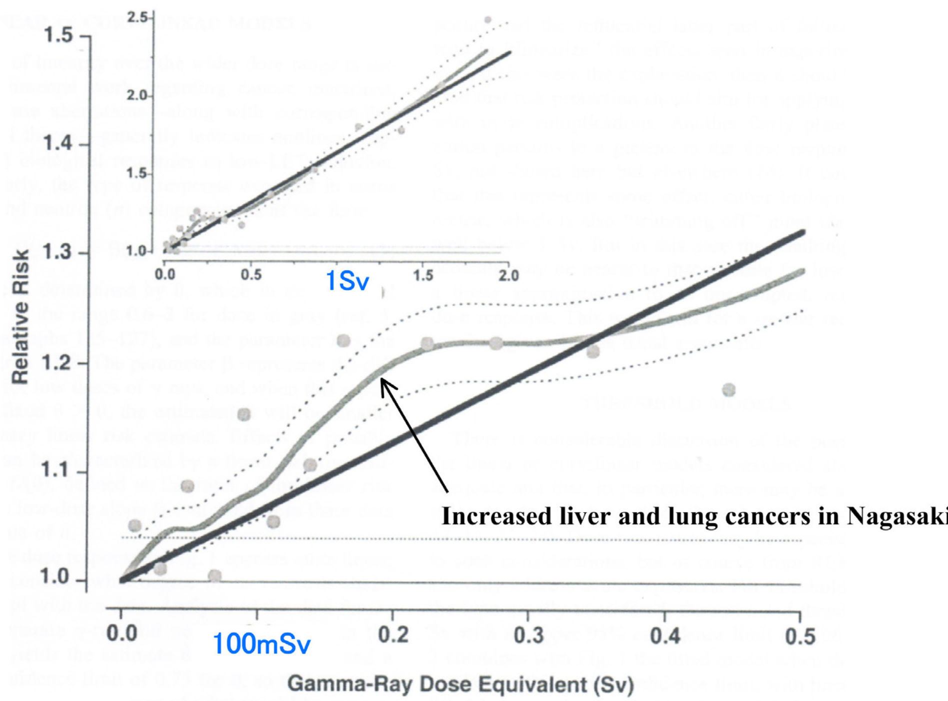

Fig. 8 Exposure doses and their associated carcinogenesis risks in Hiroshima and Nagasaki.
A level of 1 Sv represents a significant cancer risk factor, and raises cancer occurrence by 50%. Given that cancer occurrence is associated with stochastic effects of radiation, when individuals are exposed to 100 mSv, 1/10 of 1 Sv, over a year, cancer occurrence is theoretically predicted to increase by 5%. (Reproduced from Fig.1, ref 4)

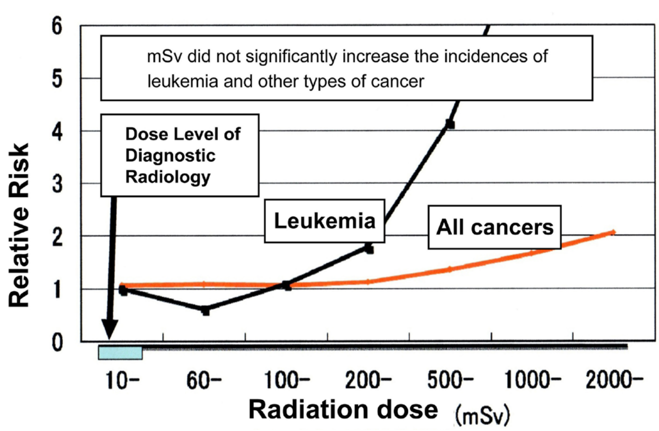

Fig. 9 Exposure doses and their associated carcinogenesis risks in Hiroshima and Nagasaki.[5]
Real exposure to 100 mSv did not significantly increase the incidences of leukemia and other types of cancer. Thus, levels exceeding 100 mSv are considered to be hazardous to human health.

Table 2 Relative risk of cancer occurrence for each factor

Factor	Relative risk
Smoking	1.6
Excessive alcohol consumption	1.4
Leanness (BMI < 19)	1.29
Obesity (BMI > 30)	1.22
High salt intake	1.13
Insufficient intake of vegetables	1.06
Radiation exposure (100 mSv)	1.05

Above all, we imagine that pregnant women and mothers of young children worry about radiation effects on human health after a nuclear disaster. It is true that fetuses and infants are highly sensitive to radiation; however, we do not have enough data to determine the radiation effects for them. This aspect of the effects of radiation is clearly a topic for further discussion.

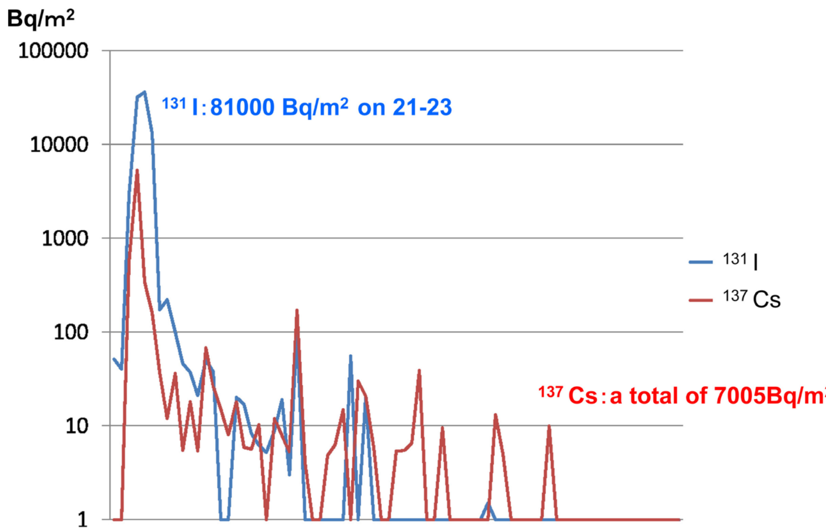

Fig. 10 Radiation doses of fallout (e.g., in rain) in the Shinjuku area of Tokyo. Considerable amounts of radioactive materials poured into the atmosphere from March 20 through approximately May 20, but have been undetectable since June.

Summary

At present, external exposure doses are within the allowable range and will have no adverse health effects on the population of Tokyo, including children. As for internal exposure doses, the authorities have halted shipments of affected produce. Thus, there are no problems as regards our ordinary dietary intakes. However, hot spots of Cs-134, Sr-90 and others, which have recently become an issue of concern, need to be further monitored.

Conclusion

Finally, we would like to express our deep admiration for the courageous workers at the Fukushima nuclear power plants and also to express our sincere condolences to people in the evacuation zone. We had hoped to be able to present an analysis of what is going on in the areas surrounding the Fukushima nuclear power plants, but that has not proved possible. We believe that Tokyo, as a part of the Kanto district, is recovering and that people are thus living normal lives again. Our wish is that all Japanese people will act together to support reconstruction after the Great East Japan Earthquake.

Acknowledgments

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References

1. ICRP Publ 72, Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5, Compilation of Ingestion and Inhalation Dose Coefficients. 1995.
2. Physics and chemistry of radiation absorption, DNA strand breaks and chromosomal aberrations. In: Hall E, Giaccia AJ, Radiation biology for the radiologist. 7th ed. Lippincott Williams & Wilkins, 2010; 5–29.
3. ICRP Publ 103, Recommendations of the ICRP. 2007.
4. Pierce DA, Preston DL: Radiation-related cancer risks at low doses among atomic bomb survivors. Radiat Res 2000; **154**: 178–186. [Medline] [CrossRef]
5. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) Report 1994.
6. Epidemiology and Prevention Division: Research Center for Cancer Prevention and Screening: National Cancer Center. (http://epi.ncc.go.jp).