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Journal of Radiology & Radiation therapy

Review Article

Radiation is a Double-edged Sword—a Historical Review of Radiological Protection

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Submitted: 24 March 2023
Accepted: 17 April 2023
Published: 19 April 2023
ISSN: 2333-7095

Keywords
- Justification
- Optimization
- Dose limits
- Reference levels
- Acute radiation syndorms

Abstract

While the author has engaged in nuclear medicine practices and research for over half a century, he has opportunities to serve to ICRP, UNSCEAR, IAEA and Radiation Council of Japan, through which he closely acquainted with radiation protection. He experienced 2 big events of nuclear accidents in Japan and involved in dealing with the aftermath of the accidents. Based on those experiences this historical review emphasizes the importance of appropriate education on radiation and its effects and protection in every level of schooling in order that people may take appropriate actions and behaviors based on correct judgements in receiving medical radiology and radiation therapy as well as in case of radiation and nuclear emergencies. In particular medical professionals need to be familiar enough with radiation and its effects to guide the general public to take appropriate actions.

INTRODUCTION

It all began in 1895 when Wilhelm Conrad Roentgen (1845-1923) discovered a new type of radiation that is X-ray. Discoveries of radioactivity by Henri Becquerel (1852-1908) and radium by Marie Curie (1867-1934) followed in 1896 and 1897, respectively. Radiology as a new discipline of medicine began by application of X-ray and radium to the human body with the purposes of diagnosis and therapy of diseases. The radioactive tracer technology developed in 1913 by George de Hevesy (1885-1966) was applied to human body in 1927 to start nuclear medicine [1]. All these scientific achievements were awarded Novel prize, which stimulated the evolution of quantum physics in the 20^{th} century.

Remarkable developments and progress of diagnostic radiology and radiation therapy since 1970's have been known not only by medical professionals but also by the general public who have experienced the progress as a patent. The utilization of radiation and radioisotopes have been expanded to industry, agriculture, biochemical research and contributed a lot to the convenient human lives.

Radiological protection which has progressed in parallel with medical application of radiation but has been much less noticeable is the subject of this historical review. It is important for those engaged in medical practices, using radiation in particular, to be ready to explain patients and the general public hazardous effects of radiation and the ways to mitigate the effects. In case of radiation and nuclear accidents they are expected to take initiatives to protect people in the most appropriate ways in the situation.

Double-Edged Sword

X-ray skin burn was reported in 1896 as a hazardous effect of X-ray. Radium skin burn was also noticed soon after its discovery. Radiation is a double-edged sword. Along with rapidly prevailing medical application of X-ray and radium, many workers dealing with those radiation suffered from radiation injuries, including skin lesions, bowel disorders and hematological disorders due to bone marrow suppression. In 1937 German Roentgen Society built a memorial plaque in the city of Bremen, on which several hundreds of victims are named.

Many incidents and accidents involving radiation and radioisotopes have been reported including those severe events experienced in Japan, that is Attack by Atomic bombs in 1945, Happy Dragon fishermen who exposed to radioactive fall outs of nuclear weapons testing in 1954, criticality accident in JCO in 1999 and Fukushima number 1 (DAIICHI) nuclear power plant (F1NPP) accident in 2011 which followed the Great East Japan Earthquake and gigantic tsunami. The author was involved in the aftermath of the latter 2 accidents of which experiences are described in this article.

Roles of ICRP in the International Framework

In the 2^{nd} International Congress of Radiology held in 1928 the International X Ray and Radium Protection Committee (IXRPC) was started with Rolf Sievert as chairman. At that time radiation sources were limited to X ray and radium. The target of the protection was occupational exposures mainly in the medical practice. The introduction of new radiation sources such as accelerators, nuclear reactors and man-made radionuclides changed the exposure situations. IXRPC changed its name to International Commission on Radiological Protection (ICRP) in 1950. ICRP as non-governmental organization has always played advisory roles recommending concepts and principles of radiological protection.

Under the cold war the radioactive fallouts due to nuclear weapons testing caused concern for increased radiation exposures of members of the public. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 with the mandates to collect data on radiation sources and exposures as well as hazardous effects. UNSCEAR presents reports on the effects of radiation exposures to the UN General Assembly after reviewing the scientific soundness of the data and information. International Atomic Energy Agency (IAEA) was established in 1957 as a UN related organization. By now the international framework of radiological protection has been established (Figure 1).ICRP makes recommendations on concepts and principles of protection on the basis of scientific reports issued by UNSCEAR. Based on the ICRP recommendations IAEA issues more detailed standards such as international basic safety standards, or BSS in cooperation with other international academic and industrial organizations. Each country makes its regulations on handling radiation and radioisotopes incorporating those recommendations and standards. The present regulations on safe managements of radiation and radioisotopes in Japan are mainly based on ICRP 1990 recommendations. The latest general ICRP recommendations was published in 2007 [2]. ICRP is now preparing the new general recommendations to be published between 2028-2031.

Two Types of Radiation Health Effects

Adverse health effects of radiation are classified into 2 general categories. ① harmful tissue reactions or deterministic effects due to the killing of cells and malfunction of tissues and organs following exposures to high dose radiation. The tissue reactions or deterministic effects do not occur unless the exposure doses exceed certain threshold dose for each symptom and sign. The threshold doses are typically higher than 1000 mGy, though transient decrease in peripheral lymphocyte may occur with minimum of 500 mGy. ②Stochastic effect that is carcinogenesis of surviving somatic cells with mutation after exposures.

Figure 1 International framework of radiological protection.

Schematic expression (Figure 2 curve a)of a tissue reaction demonstrates rapid increase of frequency as well as severity of a symptome as the dose increases above threshold.

There is a radiation effect that is distinct from above mentioned tissue reactions or deterministic effects. It is radiation-induced cancers that is observed after both high and low doses. In the low dose range of less than 100mGy epidemiology or human studies cannot provide statically meaningful answer for dose effect relation because of extreme statistical limitations. For the purpose of radiological protection ICRP assumes linear relation extrapolating the fitted line in higher dose domain, which is called linear no-threshold or LNT model (Figure 2 curve b).

Figure 3 shows dose-effect relation obtained by life span study of A-bom survivors for all solid cancers combined. The increased cancer risk becomes statistically significant at a dose of 100 to 200 mSv or higher. The risk of radiation induced cancer at low doses of less than 100 mSv is uncertain or low enough to be hidden in the 10% range of regional differnce of backgorund cancer incidences. The frequency of cancers among the A-bomb survivors increases by about 10% per 1Gy as compared with the

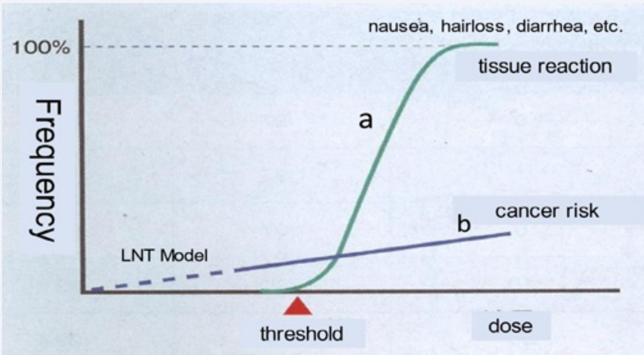

Figure 2 Two types of Radiation health effects, dose effect relation.

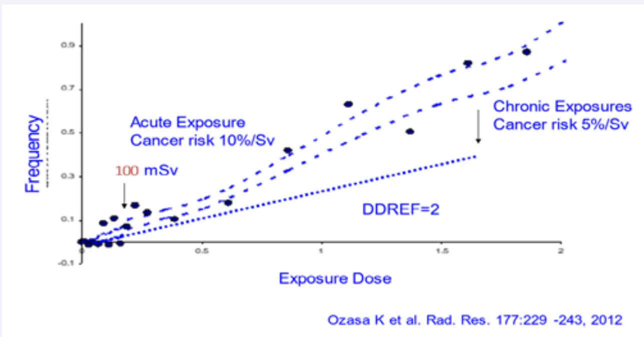

Figure 3 Stochastic effect dose effect relation in acute and chronic exposures. DDREF: Dose and Dose Rate Effectiveness Factor

control group. Radiation exposure from the atomic bomb was an example of instant acute exposure. In case of chronic exposures, the risk is lower than acute exposures. ICRP assumes the risk of chronic exposure is one half of the risk of acute exposures and applies dose and dose rate effectiveness factor or DDREF of 2. Consequently, nominal risk of cancer from chronic exposure is estimated as 5% per Sv.

The System of Radiological Protection

In the early days the system of radiological protection aims at defending workers from adverse effects of radiation that is deterministic effects or tissue reactions.

In 1955 excess leukemia and later solid cancers among A-bomb survivors in Hiroshima and Nagasaki was reported in Life Span Studies (LSS)of Radiation Effects Research Foundation (RERF). By the recognition of radiation cancer induction or stochastic effects the argument of existence or non-existence of threshold doses was facilitated. Eventually linear no-threshold (LNT) model for cancer and hereditary effects was adopted by ICRP together with the effective dose Sv to indicate risks of stochastic effects, which became the central protection quantity.

After recognition of stochastic effects, the aims of radiological protection became 2 holds, that is, to avoid deterministic effects and to minimize stochastic effects, that is, induction of cancer as heritable effects have not been reported in humans. Nakamura et al. [3], recently published an article speculating 3 major reasons why transgenerational effects of radiation are difficult to detect in humans.

The 2007 recommendations of ICRP distinguish 3 types of exposure situations, that is, planned, emergency and existing exposure situation, which covers all conceivable circumstances. The system of radiological protection is recommended to be applied to each exposure situation. The commission also distinguishes 3 categories of exposure, that is, occupational exposure, public exposure and medical exposure of patients. Each category of exposure is dealt with separately, when a same person is subject to different categories of exposures.

Three principles of radiological protection recommended by ICRP are justification, optimization and dose limits. Justification implies "no practice shall be adopted unless it produces a net benefit. Or do more good than harm." Under optimization process "all exposures shall be as low as reasonably achievable, or ALARA, economic and social factors taken into account, and "doses to individuals shall not exceed limits."

Type pf situation	Occupation exposure	Public exposure	Medical exposure
Planned exposure	Dose limit Dose constraint	Dose limit Dose constraint	Diagnostic reference level (Dose constraint)
Emergency exposure	Reference level	Reference level	N.A.
Existing exposure	N.A.	Reference Level	N.A.

Table 1: Indices to be used in ICRP system of radiological protection

The restrictions of doses in each exposure situation and each category of exposures are recommended as shown in Table 1. The system of radiological protection has been evolving in accordance with the progress of scientific knowledge, developments of protection technology, changes of societal values and experiences including accidents (Table 2).

Personal Experiences with a Criticality Accident

A criticality accident, the first in Japan, occurred on Sept. 30, 1999 in a uranium processing factory, JCO, Ltd. in Tokai village, Ibaragi Prefecture (Figure 4). Three workers were being engaged in the work to make 20 % enriched ^{235}U solution. While workers A and B were pouring uranyl nitrate into a precipitation tank a chain reaction of nuclear fission occurred and reached the critical level, which lasted the following 20 hours. The solution in the tank emitted a flash of blue light and the alarm siren went off. The 3rd worker C, who was in the corridor next to the room immediately ordered the other two to evacuate.

As radioactivity was detected in a local national hospital where they were taken by ambulance. In accordance with radiological emergency preparedness arrangements at that time they were transferred to National Institute of Radiological Sciences (NIRS) in Chiba by a helicopter.

In 1997 NIRS was officially designated as specially assigned hospital in charge of medical treatment for victims of radiation or nuclear accidents in the basic national plans for disaster prevention. This assignment was decided by the Central Disaster Prevention Council on the ground of the Basic Act on Disaster Counter Measures.

Three victims of the accident were hospitalized in Medical Care Unit for Radiation Emergency, where the initial examinations revealed no sign of body surface radioactive contaminations. Instead, radioactive ^{24}Na was detected in the venous blood as well as wrist watches and cell phones worn by workers. This indicated that a criticality accident had happened. Continuously emitted neutron beams caused activation of sodium in the blood and the metals. Dose estimations were performed using different methods including signs of prodrome symptoms, radioactivity

Past		Present
Protection of workers in medicine	All workers	All exposures
protection of human	assume environments are protected	protection of environments (non-human biota)
avoid deterministic effects	recognize stochastic effects	avoid deterministic effects, minimize stochastic effects
practical advices	dose limitation	optimization and constraints

Table 2: Changes of radiological protection standards, from 1928 to 2007.

Figure 4 Criticlity accident at JCO. Positions of 3 workers when the accident occurred.

in the blood, changes of peripheral blood cell count, whole body counting and chromosome aberration analysis (Table 3).

The initial dose assessments revealed minimum of 16GyEquivalent of worker A, 6 for B and 2 for C [4]. Those doses suggested possible death in 2-4 weeks, although all 3 looked healthy with little signs and symptoms on the following morning that was Oct. 1. The 3 workers develop acute radiation syndromes (ARG) following 1-3 days of latent or asymptomatic periods (Table 4).

If a person's entire body receives high-dose radiation either instantaneously or over a relatively short period of several weeks, the person is likely to suffer with such symptoms as nausea, vomiting, diarrhea, headaches, skin burns, hair loss, fever, dizziness, etc., together with physical signs such as a reduction in the number of white blood cells and platelets, which are known as acute radiation syndrome. These signs and symptoms appear earlier and more intensely as the received dose increases. It is characterized that the signs have a latent period, from the initial exposure until their appearance.

Medical staff of NIRS hospital, which had been dedicated to heavy ion radiotherapy using HIMAC or Heavy Ion Medical Accelerator in Chiba, started the treatment of 3 workers with cooperation and support of many physicians and nurses from other hospitals mainly in the framework of the Council for Radiation Emergency Medicine established in the previous year advocated by NIRS. Worker A was transferred to the University of Tokyo Hospital and received peripheral blood stem cell transplantation from his sister with fully matched HLA typing. Worker B was transferred to the hospital of the Institute of Medical Research affiliated to the University of Tokyo and received cord blood stem cell transplant. The born morrow transplants were successful. The worker C spent in a clean room

Method	Worker		
	A 35yoM	B 39yoM	C 54yoM
Initially estimated doses	18	10	2.5
Report of the Criticality Accidents Investigation Committee (December 24, 1999)	16~20 or over 20	6~10	1~4.5
① Prodromes	over 8	4~6 or over 6	less than 4
② Blood components (mainly lymphocyte counts)	16~23	6~8	1~5
③ Chromosome analysis	16~ over 30	6.9~10	2.8~3.2
④ Specific activity of ^{24}Na in the blood (neutrons and gamma rays : Gy)	(5.4, 9.9)	(2.9, 4.1)	(0.81, 1.5)
④ Total dose (assuming RBE = 1.7)	19	9.0	2.9
⑤ Human counter (neutrons and gamma rays : Gy)	-	-	(0.62, 1.1)
Currently estimated doses	16~25	6~9	2~3

NIRS-5-47 Final Report on Dose Estimation for Three Victims of JCO Accident, 2002

Table 3: Estimated doses to 3 workers using various methods. Doses are in terms of Gy/Eq that is biologically equivalent gamma ray doses.

EXPOSURE → Time

	PRODORMAL	LATENT	MANIFEST	DEATH RECOVERY
	· Anorexia · Nausea · Vomiting · Diarrhea	· Asymptomatic		· Return of Prodromata · Infection · Hemorrhage
A	strong	1 day UTH	BM transplant Skin graft	died 83 rd day
B	medium	2days IMS → UTH	BM transplant Skin graft	died 211st day
C	Almost none	3 days NIRS H	Clean room	Recover 82 nd day

Table 4: Stages of acute radiation syndromes with treatments and outcome of 3 workers.

in NIRS hospital during born marrow suppression and recovered without bone marrow transplant.

In workers A and B the skin burn appeared first in the part of the body where the dose was the highest and gradually aggravated to extend eventually all over the body. They received various type of skin grafts when skin burn increasingly aggravated. Damages to mucous membranes in the intestines and respiratory tracts continuously aggravated which required huge numbers of saline infusions, blood transfusion and anti-biotics.

In spite of vigorous efforts made by the medical team worker A died of multiple organ failure on the 83rd day after having fought heroically against ARG. Worker B as well died of multiple organ failure on 211th day. Worker C was discharged from NIRS hospital on 82nd day.

Facing the death of 2 heavily exposed workers the medical team mentally collapsed after having fought against newly appeared symptoms and signs day by day. The clinical courses and pathological findings were reported in the international symposium dedicated to the medical aspects of the accident held at NIRS [5].

Personal Experiences with F1 NPP Accident

On March 11, 2011 an ultrahigh tsunami followed a great earthquake of magnitude 9 which attacked the north east of Japan. The waves were estimated to reach up to 14 meter, which literary wiped off towns and villages in the wide areas. One hour after the earthquake tsunami reached the Fukushima nuclear power plant (F1NPP) and the site was flooded by the very high tide beyond anticipation. The flood made emergency power supply facilities inoperable in addition to loss of offsite power supply broken by the earthquake resulting in blackout of the station. The water pumps were stopped, which caused cooling failure of reactor cores and spent fuel pools. The rising temperature caused decrease of water level in reactors. Uncovering the reactor core caused generation of hydrogen by the reaction of zirconium cover of the fuel rods with water. Fuel rods were supposed to be melted down somewhere in this stage in spite of vigorous efforts to continue cooling. In order to avoid elevation of pressure in the containment vessel "vent" were started on March 12, which released large numbers of radioisotopes of relatively low boiling temperature. On March 12 hydrogen explosion occurred in the operation floor of the Unit 1, which destroyed reactor outer building and released radioisotopes into environments. Similar hydrogen explosion took place in unit 3 on March 14.

The system for prediction environmental dose information with the acronym of SPEDI showed that the highly contaminated air plume moved toward northwest of the Fukushima nuclear power plant causing heavy contamination in the towns and villages located under the plume (Figure 5a). The plume also went toward south along the east coast of the Pacific Ocean causing much less contaminations in these areas.

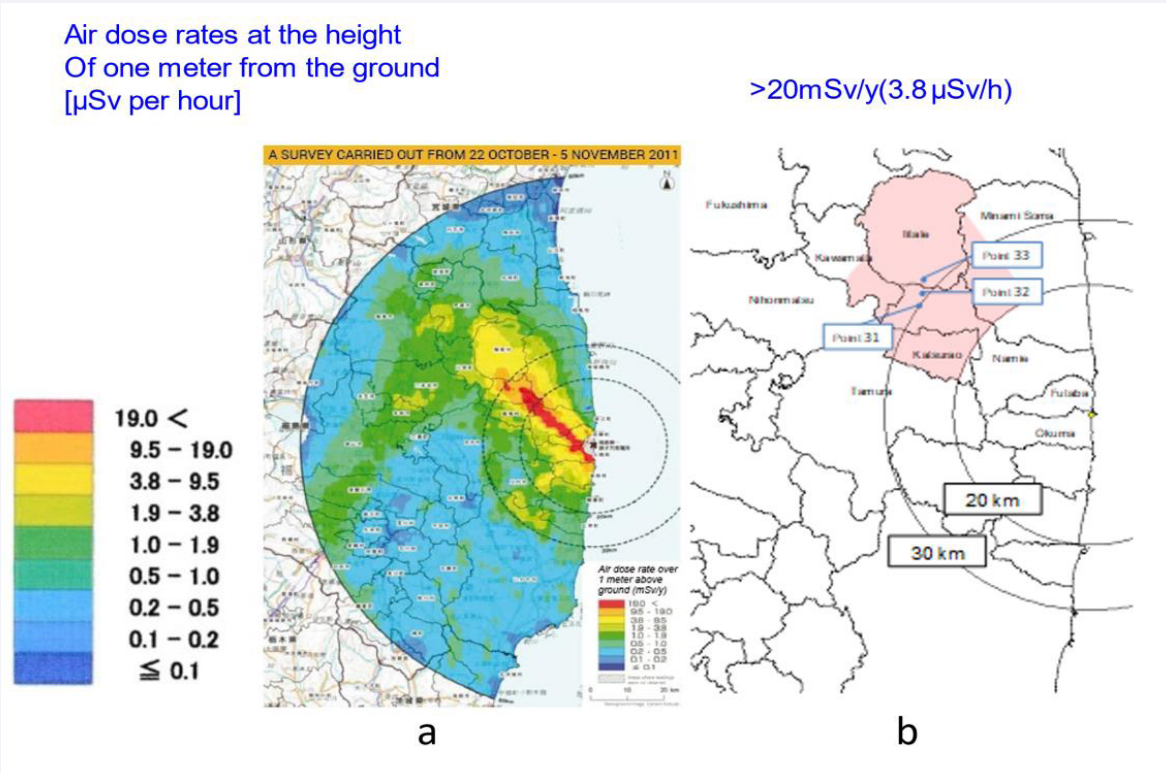

Figure 5 Movement of contaminated air(a) and additional protective action areas(b).

On March 12 the government decided to evacuate inhabitants first from 10 km radius and later 20 km radius from F1 nuclear power station. People living between 20 km and 30 km zone were first advised to stay inside houses. On March 25 people in this zone were advised to voluntarily evacuate. Having selected a reference level of 20mSv per year in accordance with ICRP recommendations the government set an additional evacuation zone covering the area outside the 30 km radius (Figure 5b).

ICRP has recommended protection of the public in emergency and its recovery phase. ICRP publications such as publ. 96 [6], 109 [7] and 111 [8] describe applications of 2007 recommendations to those situations in detail.

These recommendations are based on the scenarios in which the worst event happens all of a sudden, which is controlled within several days, in the Fukushima nuclear crisis vigorous efforts have been made to avoid the worst to happen. This situation had continued for 8 months until the government declared in December, 2011 that the reactors were fully in control of stopping with low temperature. This is a protracted emergency situation in which time scale of the initial event is prolonged from days to months (Figure 6.).

ICRP proposes 3 bands of doses to be used for optimization of protection. In emergency situation it is recommended to use the highest band of 20 to 100 mSv annual or acute dose in which an appropriate reference level is selected. The band of 1 to 20mSv is recommended to be used in which an appropriate reference level is chosen for public exposures in existing situation. The values for the reference level are to be chosen depending upon the prevailing circumstances of the exposure situation under consideration.

Contaminations of the air and soil with 1-131 and Cs-137 were the causes of concern for external exposures immediately after the release of radioactive materials from the nuclear reactors. After 10 to 14 days following the release contaminations of raw milk, drinking water and spinach and other vegetables were reported to exceed the provisional restrictions set by food sanitation law. The government ordered municipalities to ban shipment of contaminated foodstuff. Later the contaminations of tea leaves and beef with Cs-137 were reported.

Consumers became nervous about the internal exposures resulted from intakes of contaminated foods. In particular mothers of young children have got nearly panic trying to protect their children.

As of April 1, 2011 a group of 7 special advisors were appointed by the Cabinet Office to consult with administrators who were to make new rules and standards in regard to aftermath of F1 PP accident. The author served as a member of the group until it was dissolved in March 2021.

Fukushima health management survey started in May 2011. The survey includes basic and detailed surveys. The former is dose estimation based on the survey of actions taken by residents of Fukushima Prefecture. The latter cover thyroid screening for young people below age 18, comprehensive medical check-ups and mental health and life style survey for evacuees.

The dose estimation based on the behavioral records revieled that 93.8% of residents received less than 2 mSv during the 4 months after the accident, 99.8% less than 5 mSv. The estimated maximum dose to residents was 25 mSv. Individual monitering have been prevailed later and reviealed even lower doses than estimated doses.

The estimated radiation exposures of emergency responders in the F1 NPP shows that average dose received during 11 March, 2011 to 31 Oct. 2012 was 12 mSv with the highest of 679 mSv. No one exceeded 1000 mSv to show tissue reaction or deterministic effects. Around 20,000 workers have been followed up for their health conditions, especially for cancer.

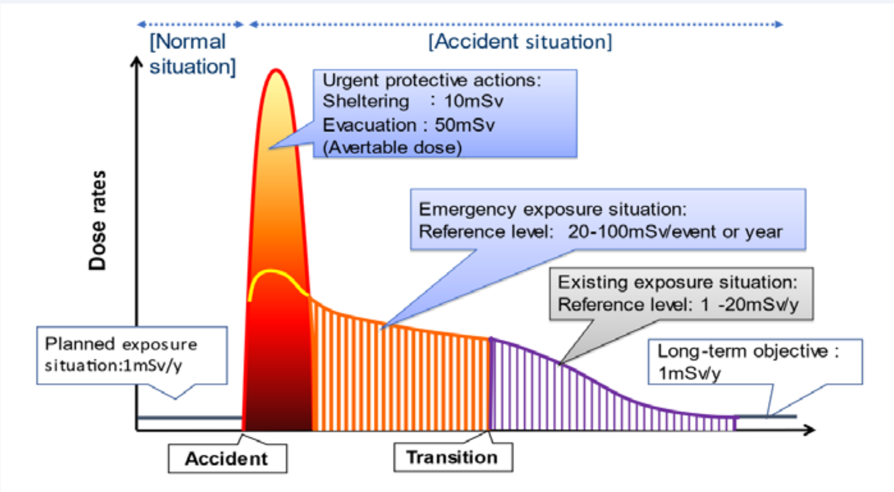

Figure 6 Protracted emergency situation

People concerned that thyroid cancer among children may increase, as it happened in Chernobyl accident in 1986. In the first round about 300 thousand children 18 years old or younger at the time of the accident were examined by ultrasound. Thyroid noodles suspected of cancer were found in 113 children. 99 of them received operation and 98 were confirmed as cancer (Table 5).

Unexpectedly high incidence of thyroid cancer caused hot arguments. Official view of the health managements survey committee is that it is unlikely to be due to radiation exposures with conceivable several reasons. It is more likely to be the result of screening using highly sophisticated recent US technology. There are different views such as Dr. Tsuda who insists the increase is caused by radiation exposure due to the F1NPP accident.

Many people suffer from non-radiological problems such as due to discordance among family members and communities, life style related problems including forced changes of farming, cattle breeding and forestry, mental health problem as well as stigma and segregation.

Features of F1 NPP accident [10,11], can be summarized as multiple disasters, protracted accident, no discernible early and late health effects due to radiation predictable either on workers or inhabitants.

In spite of those features serious mental and psychological effects continues. The effects are attributable to lack of common knowledge on radiation and its effects as well as lack of trust on specialists and authorities. Health effects caused by forced changes of life style have been observed.

Lessons Learned

We have learned many things from the 2 different types of nuclear/radiological accidents to be prepared for future similar emergencies. The author would like to emphasize the following important issues: Appropriate knowledge on radiation, its effects and protection should be prevailed in everyday life through education in every level of schooling, Secure use and control of radiation sources, Research for regeneration of tissue damage caused by high radiation exposure need to be promoted to cure the acute radiation syndromes, research for better understanding of mechanisms of health effects caused by low dose exposures need to be promoted. It is of extreme importance to obtain and nurture human resources who can fight and manage the emergency events that occur only rarely.

Objects : ～370,000 children ≦ 18 y.o. at 3/11/2011

Examined : 300,476 (81.7%)

Confirmatory exam. 2,294 (0.8%)

Possible or confirmed cancer 113 (0.038%)

Surgery 99 PTC 95, PDTC 3, Benign N.1

(Source : Suzuki, S. Clinical Oncology (2016) 28(4) 263 -71)

Table 5: Fukushima health management survey. Results of thyroid screening by ultra sounds.

Contraversies Related to LNT Model

Possible dose-response curves describing the excess risk of stochastic health effects at low doses of radiation is shown in Figure 7. Research evidences exist to support each curve. There are strong supporters for hormesis effects. French government announced practical existence of threshold values. For the purpose of radiological protection ICRP has adopted linear fit for more than 40 years. The commission considers LNT model is scientifically plausible to be used for protection purposes. ICRP publication 99 [12], reviewed epidemiological data obtained by 2005. The new epidemiological data were reviewed by National Council of Radiation Protection and Measurements or NCRP and supported LNT to be used radiological protection purposes in NCRP Commentary No.27 [13], published in 2018.

However, LNT model has been controversial. For example, 3 petitions were submitted in 2015 to U.S. Nuclear Regulatory Commission (NRC) by nuclear medicine professionals opposing the use of LNT for the standard of radiation regulations [14]. Vigorous arguments went on in the communities of radiology and nuclear medicine in the U.S., Europe and Japan [15-20].

The NRC officially denied the petitions in August 2022. It is said that future approaches should attempt to integrate biology and mechanistic studies with the epidemiology to go beyond what epidemiology might be able to alone [21].

DISCUSSION AND CONCLUSION

The world community of radiological protection have learned lots from the experiences of F1NPP accident. In 2020 ICRP published Publication146 as update of ICRP Publications of 109 and 111, Radiological Protection of People and the Environment in the Event of a Large Nuclear Accident [22], based on the experiences of F1NPP accidents. Radiation protection specialists from Japan contributed a lot to this publication. Recently ICRP announced "Advice for the Public on Protection in Case of a Nuclear Detonation". It says "although we hope this information will never need to be put into action, ICRP has summarized publicly available information on protection in case of nuclear detonation here and has made ICRP Publication 146."

It is hard to believe that what was happened in Hiroshima and Nagasaki 78 years ago would ever be repeated [23]. But the threat exists in the real world. We have to be prepared to act properly in case of possible exposures to high doses and low doses of radiation. In either case people may get panic. As radiologist we must be familiar enough with radiation protection measures to be able to act correctly and guide people to behave properly both in everyday practices of medicine and in cases of emergency.

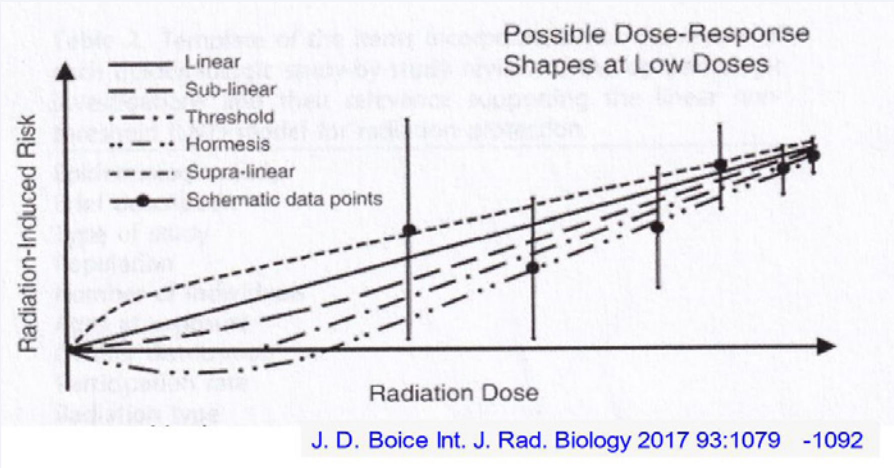

Figure 7 Possible dose-response relations at low doses.

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