Nuclear Engineering and Technology 49 (2017) 598—608

Available online at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Proposing a Simple Radiation Scale for the Public: Radiation Index

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ARTICLE INFO

Article history:
Received 21 July 2016
Received in revised form
23 September 2016
Accepted 3 October 2016
Available online 11 November 2016

Keywords:
Annual Background Dose
Exemption and Clearance Dose
Medical Exposure
Nuclear Accidents
Radiation Units

ABSTRACT

A new radiation scale is proposed. With empathy toward the vast majority of people who are not well versed in radiation and related matters, and thus suffering from misunderstanding that breeds unnecessary fear of radiation, the aim of proposing a new radiation scale, *radiation index* (*RAIN*), is to put the general public at ease with the concept of radiation. RAIN is defined in dimensionless numbers that relate any specific radiation dose to a properly defined reference level. As RAIN is expressed in plain numbers without an attached scientific unit, the public will feel comfortable with its friendly look, which in turn should help them understand radiation dose levels easily and allay their anxieties about radiation. The expanded awareness and proper understanding of radiation will empower the public to feel that they are not hopeless victims of radiation. The correspondence between RAIN and the specific accumulated dose is established. The equivalence will allow RAIN to serve as a common language of communication for the general public with which they can converse with radiation experts to discuss matters related to radiation safety, radiation diagnosis and therapy, nuclear accidents, and other related matters. Such fruitful dialogues will ultimately enhance public acceptance of radiation and associated technologies.

1. Introduction

Radiation remains a mysterious concept to a vast majority of people except for a tiny minority of experts who either specialize in it or work with it in their occupation. This misunderstanding breeds unnecessary fear of radiation. Muller [1] attempts to put radiation in proper perspective by giving some interesting examples of radioactive materials: books are radioactive; our body is radioactive (unless long dead); the United States Bureau of Alcohol, Tobacco, and

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http://dx.doi.org/10.1016/j.net.2016.10.005

Firearms requires that wine, gin, whiskey, and vodka should not be legally sold in the USA unless these products contain sufficient radioactivity; biofuels are radioactive, etc. Radiation is ubiquitous and needs to be understood properly by the public in friendly and familiar terms to help alleviate unfounded fear.

The public's fear of radiation is unnecessarily heightened because the terms and units that are used to measure the level of radiation are diverse and formidably complicated for the general public to understand [2,3]. The public and even many scientists and engineers are genuinely intimidated by the terms and units of radiation that seem to be monopolized by the experts. Efforts to explain radiation terms and units to the public are almost invariably met with blank stares, embarrassment, or even disdain, as ignorance can breed distrust. Radiation scientists and nuclear engineers have long since ignored the fact that their customers are not accustomed to the scientific terms and units of radiation. The absence of a common language between the public and the nuclear and radiation community has greatly hampered communication between these two groups, and as a result, public acceptance for nuclear power and radiation technology has been marginalized. The public's misunderstanding is amplified by the scientific jargon used by radiation experts and nuclear engineers when they communicate with the public. Many popular articles have been written that lament the public's ignorance about radiation and address the importance of and the need for public's correct understanding of radiation. Yet, there has not been a sincere attempt by the nuclear and radiation community to alleviate the public's fear by developing a common tool of communication that can facilitate the public's understanding. We attempt to improve this situation by introducing a new radiation scale in this study.

Communicating the matters related to radiation safety, nuclear accidents, and medical radiation in terms of scientific units such as Becquerel (Bq), Gray (Gy), Sievert (Sv), and their variations using micro and milli units has confounded and alienated the public, contributing enormously to elevating the public's anxieties about radiation due to mistrust rooted in discomfort with scientific verbiage.

Table 1 shows "SI derived units" defined by the Bureau International des Poids et Mesures (International Bureau of Weights and Measures) in the field of ionizing radiation. All radiation-related quantities or concepts in specific fields such as radiation science and radiation protection are based on these three SI derived units that are foreign to most people. To further complicate the situation, SI prefixes such as milli, micro, or kilo are used with any of these special names and symbols.

Table 2 lists various radiation dose concepts, all of which are basically a certain amount of energy imparted to a mass of target, but each describes a different concept, as defined in the table.

Additionally, previously other units, such as Roentgen, rem, rad, etc., were used to describe radiation doses [5,6].

To further complicate the matter, the kinetic energy of individual radiation particles is expressed by the units of eV, keV, or MeV, and the intensity of a radiation beam is often expressed by fluence (number of particles per unit area) or flux (number of particles per unit time to a given area) in radiation metrology.

These units are largely monopolized by radiation experts, and the public has extremely little interest in using them, let alone interest in learning the significance of all these units and conversions between them that are often necessary.

We propose a new radiation index that is friendly and simple for laymen to understand and use as a common tool of communication between them and the radiation community. In analogy with familiar units popularized in other areas, notably the seismic magnitude scale, acoustic intensity level, and hydrogen ion concentration in liquid (pH), all of which are dimensionless and simple, the new radiation unit proposed in this study should be friendly enough for the public to embrace it in their daily conversations when discussing radiation-related matters such as radiation safety, nuclear accidents, radiological medical diagnosis, radiation therapy, etc. The scale we propose will, therefore, be necessarily dimensionless and bear no scientific terminology. We will decide a reference point in the most proper manner and define any other level of radiation dose relative to this reference point as radiation index (*RAIN*), our new scale. That is, the new index will explicitly relate specific radiation levels to a commonly accepted reference radiation level via RAIN. In the following sections, the concept of RAIN will be developed, its relation to the scientific terms will be established, and applications in some practical areas will be exemplified.

2. Definition of the new concept, RAIN

We set some guiding principles in defining RAIN, which are as follows: (1) The new radiation index should be an international number, and easy to use in daily conversations and discussions among average people requiring little or no scientific knowledge of radiation and related subjects. (2) It should allow the general public to "feel" the meaning of the numbers expressed in the new scale in a similar manner to the popular seismic magnitude scale, acoustic intensity level (dB), and hydrogen ion concentration in liquid (acidity, pH);

Table 1 – SI derived units in the field of ionizing radiation [4].

Name	Symbol	Expressed in terms of other SI units	Expressed in terms of SI base units	Derived quantity
Becquerel	Bq		/sec	Activity referred to a radionuclide
Gray	Gy	J/kg	m^2/sec^2	Absorbed dose, specific energy (imparted), kerma
Sievert	Sv	J/kg	m^2/sec^2	Effective dose, ambient dose equivalent, directional dose equivalent, personal dose equivalent, etc.

Table 2 – Various concepts of radiation dose in radiation science and protection.

Dose concept	Definition	Units
Absorbed dose	Energy imparted to a specific mass of a material from radiation	Gy
Kerma (kinetic release of radiation in matter)	Absorbed energy imparted from the radiation (X-ray, gamma ray, or neutron) & converted into secondary particles	
Ambient dose equivalent	Dose equivalent produced by the expanded & aligned field at a specific depth in the ICRU sphere	Sv
Directional dose equivalent	Dose equivalent produced by the expanded field with a specific angle at a specific depth in the ICRU sphere	
Personal dose equivalent	Dose equivalent in soft tissue at a specific depth below a specified point in the body	
Equivalent dose	A new definition in ICRP 60 (1990) of the dose equivalent in ICRP 26 (1977)	
Committed equivalent dose	Total long-term equivalent dose of a specific body part of a specific person due to radionuclide intake	
Collective equivalent dose	Sum of equivalent doses of a specific group of persons	
Effective dose	Tissue-weighted sum of the equivalent doses in all specified tissues & organs of the human body, which represents the stochastic health risk to the whole body	
Committed effective dose	Total long-term effective dose of a specific person due to radionuclide intake	
Collective effective dose	Sum of effective doses of a specific group of persons	
Committed collective equivalent dose	Sum of committed equivalent doses of a specific group of persons	
Committed collective effective dose	Sum of committed effective doses of a specific group of persons	

ICRP, International Commission on Radiological Protection; ICRU, International Commission on Radiation Units and Measurements.

that is, the new radiation scale shall be a dimensionless number. (3) The difference between the ordinary background radiation dose level and the danger level can range from a hundred-fold to over a million-fold; the logarithmic transform thus shall be not only useful, but also necessary to express such a wide range of applications. (4) The new concept shall be a comprehensive one that can express the accumulated dose (mSv) over a finite duration. (5) The new concept must be based on the effective dose among various dose concepts given in Table 2, because it can be related to the detrimental effects and the probability of biological radiation hazard such as cancer induction and genetic effects of ionizing radiation. (6) To maximize the simplicity for the general public, the numerical value of RAIN shall retain no more than a single significant digit after the decimal point.

Following the above guidelines, we express the public radiation scale in terms of the newly defined measure of radiation level, RAIN, as follows:

$$RAIN \equiv \log_{10}\frac{D_1}{D_0} \quad (1)$$

Here, RAIN represents the logarithmic scale of radiation dose relative to a reference dose D_0. We will set D_0 value at 10 μSv in a year in this study, based on the exemption and clearance levels suggested by the International Atomic Energy Agency (IAEA) [7] and widely accepted and applied by the international regulation groups. Doses below the exemption and clearance levels shall not be considered at all in terms of its risk of biological hazards. In this context, a RAIN value of 0 does not mean zero exposure but signifies a negligible biological risk.

D_1 refers to the radiation dose level of interest. The subscript 1 refers to either an exposure situation involving a year-long chronic exposure from background radiation sources or a one-time single event associated with accidental, medical, or occupational exposure of various durations determined by the nature of the event in a given circumstance. For example, taking a chest X-ray takes less than a second, whereas evacuating from a city due to a nuclear power plant (NPP) accident may take a few days or months. Another example is a situation of a radiation worker who may need to work in a radiation environment for 2,000 hours in a year.

D_0 and D_1 defined loosely in this easy manner will serve well to facilitate and enhance much-needed communication between the nuclear/radiation community and the general public, as well as stimulate conversations among lay people.

Thus defined, RAIN is easily interpreted as *a measure of increment of radiation dose for any exposure case of interest above and beyond the reference radiation dose level for exemption*. Using this simple concept, the public can begin to "feel" and understand the meaning of the numbers and associate RAIN values with the events, measures, or experiences they may be more familiar with, such as medical computed tomography (CT) examination.

Some typical cases for which we need to estimate D_1 in order to compute the corresponding values of RAIN are shown in Table 3. The International Commission on Radiological Protection (ICRP) recommends 100 mSv as the maximum value for a reference level, incurred either acutely or in a year. This would mean that there is no difference in the biological effectiveness below 100 mSv regardless of temporal exposure conditions, i.e., either acute or chronic exposure. Readers interested in the technical basis for the above recommendation and details on other related issues such as dose and dose rate effectiveness factor are encouraged to refer to ICRP 103 [8].

3. Interpretation of RAIN

The simple concept of RAIN is easy to use in daily conversations between experts and laypersons, and the numbers are

Table 3 – Exposure types and representative cases to be considered in order to estimate D_1.

Exposure type	Representative cases
Continuous	Annual effective dose originating from living in a specific place for a year
	Internal-exposure-based effective dose due to consumption of radioactively contaminated food for a year
One time	Internal-exposure-based effective dose due to breathing of contaminated air for hours or due to intake of radioactive materials by accident or mistake for hours
	Medical exposure due to a one-time radiological diagnosis or treatment
	External-exposure-based effective dose from a radioactively contaminated environment or any radiation source by accident or incidence for a finite duration

friendly and nonintimidating to the general public. With repeated uses of the RAIN concept in casual conversations, the public will begin to appreciate the connection between the numbers and certain events or episodes in medical and other applications they may have experienced. Government authorities, when they must announce and inform the public of events or situations involving radiation, can use RAIN values to refer to the level of incremental radiation of such events. This will facilitate public understanding of the significance of situations involving radioactive exposure without resorting to scientific units such as mSv, μSv, etc. that can easily perplex the public. Until now, public announcements on radiation tended to be riddled with scientific jargon for which the public generally has no understanding of the physical meaning of the terms and units, thus unnecessarily heightening the fear and mistrust of radiation. Now, people can have a better understanding of the situation by interpreting the RAIN values in terms of their own personal episodes drawn from medical, environmental, accidental, or other circumstances they may be familiar with.

4. Applications of RAIN

4.1. *Natural background exposure*

In our daily life, we are continuously exposed to various levels of natural background radiation depending on our location on earth. Table 4 shows the radiation sources and average annual radiation exposure levels of the world and a few selected countries. The world average annual human dose due to natural background radiation sources is shown to be 2.4 mSv, and by coincidence the calculated RAIN value is 2.4. Hence, this value of 2.4 can serve as another convenient reference point in the RAIN system, as it is easy for the general public and radiation experts to remember.

For instance, when the public is told that a certain event resulted in a RAIN value of 2, they will know that the incremental radiation from the event is less than 2.4, which is the world average annual human dose level due to natural background radiation sources. If another event resulted in a RAIN value of 3.4, they can understand that the radiation level has increased by a factor of 10 above the natural background radiation exposure level.

Table 5 shows the average annual environmental radiation doses from terrestrial and cosmic radiation only. In the table, background environmental radiation dose for an hour due to terrestrial radiation from the ground and the cosmic radiation from space to the general public are also listed.

Table 6 shows the accumulated doses received from cosmic radiation due to a 10-hour flight at different altitudes and their corresponding RAIN values [14].

Table 4 – Average annual human exposure to natural ionizing radiation.

Radiation source	Annual dose (mSv)				Remarks
	World [9]	USA [10]	Japan [11]	Korea [12]	
Inhalation of air	1.26	2.28	0.40	1.41	Mainly from radon, depends on indoor accumulation
Ingestion of food & water	0.29	0.28	0.40	0.24	^{40}K, ^{14}C, U, Th, etc.
Terrestrial radiation from ground	0.48	0.21	0.40	1.00	Depends on soil & building blocks
Cosmic radiation from space	0.39	0.33	0.30	0.34	Depends on altitude
Total dose	2.4	3.1	1.5	2.99	(mSv)
RAIN	2.4	2.5	2.2	2.5	

Table 5 – Average environmental radiation dose (only from terrestrial radiation from ground and cosmic radiation from space).

Location	World	USA	Japan	Korea	Cities in Korea [13]			
					Seoul	Daejeon	Suwon	Busan
Annual dose (mSv)	0.87	0.54	0.7	1.34	0.95	1.09	1.33	0.97
Hourly dose (μSv/hr)	0.1	0.062	0.08	0.153	0.109	0.124	0.152	0.111
RAIN	1.9	1.7	1.8	2.1	2.0	2.0	2.1	2.0

Table 6 – Cosmic radiation exposure level depending on flight altitude.

Altitude (km)	Exposure rate (μSv/hr)	Dose for 10 hr flight (μSv)	RAIN
0–7	≤1	≤10	0.0
8[a]	3.7	37	0.6
15	13	130	1.1

RAIN, radiation index.
[a] This is the altitude of a typical international flight.

4.2. *Intake of radionuclide-contaminated food*

Radiation contamination in food has become a social issue ever since the Chernobyl and Fukushima accidents have greatly contributed to reviving and intensifying the debates. After the Fukushima accident, governments of Japan and Korea have tightened the safety regulation for radiation-contaminated food by lowering the allowable level of ^{137}Cs from 370 Bq/kg to 100 Bq/kg. Codex [15] issued guidelines on radiation-contaminated food imported from contaminated areas. The guidelines limit the acceptable radiation dose from food intake to the same level as the dose received by the general public over 1 year. This parameter, referred to as the intervention exemption level of dose), is set at 1 mSv, which is equivalent to the annual dose limit for the public recommended by ICRP.

The mean internal dose of the public due to annual consumption of imported contaminated food can be calculated by the following equation, and D should be smaller than the intervention exemption level of dose:

$$D = GL \times M \times e_{ing} \times IPF \quad (2)$$

where D = mean internal dose in the 1st year (mSv); GL = guideline level of contamination concentration in foods (Bq/kg); M = mass of food consumed in a year (kg); e_{ing} = ingestion dose coefficient (dose per unit intake, mSv/Bq); and IPF = import/production factor (dimensionless).

M is based on the assumption of an average adult's annual food intake of 550 kg and an average infant's annual food intake of 200 kg. IPF is the ratio of import to production factor set at 0.1 (from Codex); e_{ing} depends on the dose conversion coefficient for each specific radionuclide, which is related to radiation type, energy, radioactive half-life, and biological half-life, and depends on age.

For example, the mean doses for adults and infants consuming imported food contaminated with ^{137}Cs at 1,000 Bq/kg for a year are as follows:

For adults: $E = 1{,}000\ \text{Bq/kg} \times 550\ \text{kg} \times 1.3 \cdot 10^{-5}\ \text{mSv/Bq} \times 0.1 = 0.7\ \text{mSv}$

For infants: $E = 1{,}000\ \text{Bq/kg} \times 200\ \text{kg} \times 2.1 \cdot 10^{-5}\ \text{mSv/Bq} \times 0.1 = 0.4\ \text{mSv}$

We can also calculate the Codex GL level for ^{137}Cs in an adult's food intake from Eq. (2) by replacing D with the intervention exemption level of dose, which is 1 mSv, as follows:

$$GL = 1\ \text{mSv}/(550\ \text{kg} \times 1.3 \cdot 10^{-5}\ \text{mSv/Bq} \times 0.1) = 1{,}400\ \text{Bq/kg}$$

Table 7 shows four radionuclide types categorized by their toxicity and the guide levels of contamination concentration by Codex. Also listed are the mean internal doses in the 1st year of consumption and their estimated corresponding RAIN values.

In the background environment, the two most plentiful radioisotopes emitting gamma radiation are ^{40}K and ^{137}Cs, and their concentrations in food materials vary depending on regions and countries. The measured average ^{40}K and ^{137}Cs concentrations in about 300 fresh food materials in Korea are in the range of 21.5–681 Bq/kg and in the range from the undetected

Table 7 – Examples of radiation dose for adults due to ingestion of imported food contaminated by major radionuclides at the guide level of concentration [15].

Radionuclide type	Guide level of concentration (Bq/kg)	Radionuclide in food	Estimated dose in a year (mSv)	RAIN
I	10	^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Am	0.1	1.0
II	100	^{106}Ru	0.06	0.8
		^{131}I	0.1	1.0
		^{90}Sr	0.2	1.3
		^{235}U	0.3	1.5
		^{129}I	0.6	1.8
III	1,000	^{35}S, ^{103}Ru	0.04	0.6
		^{192}Ir	0.08	0.9
		^{89}Sr	0.1	1.0
		^{60}Co	0.2	1.3
		^{144}Ce	0.3	1.5
		^{137}Cs	0.7	1.8
		^{134}Cs	1.0	2.0
IV	10,000	^{3}H	0.02	0.3
		^{14}C	0.3	1.5
		^{99}Tc	0.4	1.6

RAIN, radiation index.

Table 8 – Measured average concentrations of ^{40}K and ^{137}Cs in common food materials of Korea [16].

Food materials	Milk	Pork	Beef	Bean	Rice	Cabbage	Mackerel
^{40}K (Bq/kg)	46.7	90.4	85.5	568	26.6	62.8	92.8
^{137}Cs (mBq/kg)	23.9	92.7	70.4	185	13.8	25.5	110
Annual average consumption (kg)	25.8	8.1	7.4	1.0	78.9	31.4	2.0
Annual average dose from ^{40}K (μSv)	6.05	3.68	3.18	2.85	10.53	9.90	0.93

level to 289 mBq/kg, respectively, and those of some representative food materials are listed in Table 8 [16]. Half-lives of ^{40}K and ^{137}Cs are 1.28×10^9 years and 30 years, respectively. The radioisotope ^{40}K is primordial, and ^{137}Cs has been produced artificially via atmospheric nuclear bomb tests in the 1940s to 1950s. As we see in Table 8, ^{40}K is much more abundant in food than ^{137}Cs. According to the US Environmental Protection Agency report [17], the conversion factor for 50 years committed effective dose equivalent due to ingested foods containing ^{40}K is 5.02×10^{-9} Sv/Bq. If a Korean consumes all the common food materials listed in Table 8, then the total radiation dose becomes 37 μSv/y, which is in the order of clearance and exemption level of IAEA, and its RAIN value becomes 0.6.

4.3. *Medical exposure*

In medical applications of radiation, the newly introduced radiation index will enhance the quality and quantity of dialogues between physicians and patients.

Applying the RAIN concept to medical diagnosis or treatment requires a careful interpretation of RAIN values, as the radiation doses in medical applications are not evenly distributed around some mean values over a prolonged period, but they represent concentrated peak values over a short duration. The contrast is better understood by referring to Table 4, which includes the RAIN values for the events assumed to be observed over sustained long periods (mostly 1 year in Table 4), whereas the RAIN values shown in Tables 9–11 represent narrowly concentrated peaks and therefore appear to be relatively high. The RAIN values for medical one-time exposures should be interpreted in this context to avoid any unnecessary alarm.

Table 9 – Average effective dose per radiological diagnostic examination in healthcare level I countries (1997–2007) [18].

Radiological examination type	Dose (mSv)	RAIN
Chest radiography	0.07	0.8
Head radiography	0.08	0.9
Pelvis & hip radiography	1.1	2.0
Abdomen radiography	0.82	1.9
Upper GI radiography	3.4	2.5
Lower GI radiography	7.4	2.9
Mammography	0.26	1.4
Chest fluoroscopy	2.1	2.3
CT	7.4	2.9
Angiography	9.3	3.0

CT, computes tomography; GI, gastrointestinal; RAIN, radiation index.

Table 10 – Average effective dose per nuclear medicine diagnostic examination in healthcare level I countries (1997–2007) [19].

Nuclear medicine examination type	Dose (mSv)	RAIN
Bone ^{99m}Tc	4.74	2.7
Cardiovascular ^{201}Tl	40.7	3.6
Lung perfusion ^{99m}Tc	3.52	2.5
Thyroid scan $^{131}I/^{123}I$	30.5	3.5
Renal	1.89	2.3
Brain	6.09	2.8
Liver	4.10	2.6
PET	6.42	2.8
PET-CT combined	7.88	2.9

CT, computes tomography; PET, positron emission tomography; RAIN, radiation index.

Tables 9 and 10 show the average effective doses converted into RAIN values for one-time medical exposures due to various medical diagnoses when typical patients are subjected to X-ray or nuclear medicine diagnostic examinations. These data are excerpted from the 2008 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report. In these tables, healthcare level I country means that it belongs to the group of countries having the best healthcare system. Less than a quarter of the world population lives in these countries. It is worthwhile to notice that the difference of RAIN values between chest X-ray and CT is about 2, which means that the difference in terms of dose is 100 times.

The radiation exposure data shown in Table 11 refer to the radiotherapy dose received by a typical patient at healthcare

Table 11 – Average radiotherapy dose to a patient in healthcare level I countries (1997–2007) [20].

Radiation therapy (cancer) type	Dose (Sv)	RAIN
Leukemia	16	6.2
Lymphoma Hodgkin's	33	6.5
Lymphoma non-Hodgkin's	40	6.6
Breast tumor	51	6.7
Lung/thorax tumor	60	6.8
Gynecological tumor	51	6.7
Head/neck tumor	61	6.8
Brain tumor	53	6.7
Skin tumor	54	6.7
Bladder tumor	55	6.7
Prostate tumor	67	6.8
Urological tumor	39	6.6
Tumor of colon & rectum	49	6.7

RAIN, radiation index.

level I. These data are based on the value averaged over 14 countries belonging to the healthcare level I countries.

4.4. *Industrial radiation exposure*

RAIN can also be applied to food and agricultural industries. In addressing the effect of radionuclide-contaminated foods and agricultural products, health authorities can use RAIN to communicate with the public and help alleviate possible overreaction by the public. Sterilization by radiation is very useful in many fields of industries such as long-term storage or transport of food, sterilization of surgical equipment, sterilization of male insects, etc. In 1981, the World Health Organization reported that "the irradiation of any food commodity up to an overall average dose of 10 kGy presents no toxicological hazard" [21], which corresponds to the RAIN value of 9.0. In 1999, the Study Group of the World Health Organization concluded that no upper limit of dose is required to be imposed. This means that "irradiated foods are deemed wholesome throughout the technologically useful dose range from below 10 kGy to envisioned doses above 10 kGy" [22].

4.5. *Accidental exposure*

Most governments set radiation levels to alert or warn the public when a radiation leak accident occurs from a nuclear facility, following the IAEA guidelines. These warning levels are determined based on hourly dose or dose rate because of the need for a quick decision on sheltering or evacuation. Table 12 shows the general criteria for protection actions in an emergency to reduce the risk of stochastic effects for the general public and fetus.

The most significant nuclear accidents are the Three-mile Island NPP accident in 1979, Chernobyl NPP accident in 1986, and Fukushima NPP accident in 2011.

Following the Chernobyl NPP accident on April 26, 1986, residents of Pripiyat and Yanov were forced to evacuate the next day by the Soviet government because it was projected that the environmental dose level might exceed 100 μSv/h. On May 3, the evacuation zone was set to a region within a 30 km radius from the accident site rather arbitrarily, but later in 1987 this 30 km zone was based on the revised dose level of 100 mSv. The three zones defined within 30 km are listed in Table 13. A total of 116,000 residents from 187 villages were finally evacuated by September 1986.

Evacuation of people from the vicinity of the Fukushima Daiichi NPP began in the evening of March 11, 2011, with the evacuation zone gradually extended from a radius of 2 km of the plant to 3 km and then to 10 km. By the evening of March 12, 2011 it had been extended to 20 km. Similarly, the area in which people were ordered to shelter was extended from within 3–10 km of the plant shortly after the accident to within 20–30 km by March 15, 2011. In the area within a 20–30 km radius of the NPP, the public was ordered to shelter until March 25, 2011 when the national government recommended voluntary evacuation. As a result of nuclear power plant facility conditions, difficulties in coordination, and insufficient preplanning, orders for evacuation and sheltering were modified several times within 24 hours, and eventually about 78,000 people living within a zone with a radius of 20 km were ordered to be evacuated. In some locations beyond the 20 km evacuation zone, dose rates of the order of a few hundred micro-Sievert per hour (μSv/h) were measured from March 15, 2011 onward [25].

In 2013, the evacuation areas were subdivided based on the more carefully estimated annual total dose to people inhabiting the area, if any. These areas are defined and illustrated in Table 14.

4.6. *Recommended limit of radiation for occupational and public exposure*

ICRP has continuously suggested and updated recommendations necessary for protection of people from radiation since 1928. Under ICRP Publication 60 in 1991 [27], the system of radiological protection is based on three principles: justification of practice, optimization of protection, and individual dose limits. The recommended individual dose limits, which are identical to those of ICRP 60, are given in Table 15, and newly added dose constraints in ICRP Publication 103 in 2007 [8], which will apply to a person in one of three exposure situations, are listed in Table 16. From Table 15, the 5-year average annual effective dose for occupational exposure is 20 mSv. Therefore, assuming 2,000 hours of working time, the average hourly dose will be 10 μSv/h, which can be a guide level to define the radiation work area in nuclear and radiation facilities in general.

4.7. *Biological effects of radiation exposure*

Radiation exposure to humans or living organs can cause short- or long-term biological effects, which are generally categorized into chronic effects and acute or deterministic effects. The former is also called a stochastic effect because its

Table 12 – General criteria for protection actions in an emergency to reduce the risk of stochastic effects [23].

Dose type	Dose (mSv)	Expected exposure period	Protective action		RAIN
Thyroid equivalent dose	50	7 d	Iodine thyroid blocking		3.7
Effective dose Fetus equivalent dose	100	7 d	Sheltering & evacuation	Prevention of inadvertent ingestion, restriction on food & water, contamination control, decontamination, reassurance of the public	4.0
Effective dose Fetus equivalent dose	100	1 yr Full period *in utero* development	Temporary relocation		4.0

RAIN, radiation index.

Table 13 – Three areas of 30 km evacuation zone in Chernobyl [24].

Zone	Exposure rate (μSv/hr)	Radial distance from the reactor (km)	Comment	Dose (mSv) for staying 1 wk	RAIN for staying 1 wk
Black zone	Over 200	Vicinity to reactor unit 4	Immediate evacuation. Evacuees were never to return	≥33.6	≥3.5
Red zone	50–200	10	Evacuation in the next day of accident. Evacuees might return once radiation levels normalized	8.4–33.6	2.9–3.5
Blue zone	30–50	30	Children & pregnant women were evacuated starting in summer of 1986	5.0–8.4	2.7–2.9

RAIN, radiation index.

Table 14 – Three areas of 30 km evacuation zone in Fukushima in 2013 [26].

Area	Estimated annual dose (mSv)	Comment	RAIN
Area 1 (green)	≤ 20	Area where evacuation orders were ready to be lifted	≤3.3
Area 2 (orange)	> 20	Areas in which residents were still not permitted to live	≥3.3
Area 3 (red)	> 50	Areas where it was anticipated that residents would not be able to return for a long time	≥3.7

RAIN, radiation index.

Table 15 – Recommended dose limits from ICRP Publication 103 [8].

Category	Dose types	Comment	Dose (mSv)	RAIN
Occupational exposure	Maximum annual effective dose	For a specific year	50	3.7
	Average annual effective dose	For 5 yr	20	3.3
	Annual equivalent dose	Lens of eye	150	4.2
	Annual equivalent dose	Skin, hands, feet	500	4.7
Public exposure	Average annual effective dose	For 5 yr	1	2.0
	Annual equivalent dose	Lens of eye	15	3.2
	Annual equivalent dose	Skin, hands, feet	50	3.7

RAIN, radiation index.

occurrence is very probabilistic, and it is a dominant effect at low dose rates and long-term exposure. A representative example is cancer occurrence and genetic effect. Radiation exposure may approximately increase additional cancer risk by a factor of 5%/Sv, but below the 100 mSv level, it is uncertain whether the cancer was induced by radiation or by other causes. The latter effect is called acute radiation syndrome, which normally occurs in a few minutes or weeks at most depending on the exposure levels. The important dose levels for acute radiation syndrome due to whole-body exposure are summarized in Table 17. Although the lethality after total-body irradiation is dependent on the dose and dose rate, the dose level for 50% lethality in 60 days ($LD_{50/60}$) can be defined based on the cumulative data on human radiation exposure. ICRP has reported that $LD_{50/60}$ is approximately 3.3–4.5 Gy without medical management and 6–7 Gy with medical management such as transfusion of antibiotics and/or blood [29].

4.8. *RAIN values for multiple-exposure events: addition and multiplication*

RAIN is a logarithmic scale similar to other scales such as seismic, acoustic, and acidity scales that are not additive. For example, earthquakes of magnitude 4 and 6 do not add up to give a magnitude of 10. However, RAIN can be calculated to describe the cumulative effect of multiple exposure events as follows:

$$RAIN \equiv \log_{10}\left(10^{RAIN_1} + 10^{RAIN_2} + \ldots\right) \quad (3)$$

Let us consider some limited cases, starting with a two-event case. In this case, if we define R as the ratio of the smaller RAIN value to the larger RAIN value, that is,

$$R = \frac{RAIN_2}{RAIN_1} \leq 1$$

then the total RAIN value will be:

$$RAIN = \log_{10}\left(10^{RAIN_1} + 10^{RAIN_2}\right) = \log_{10}\left[(1+R) \times 10^{RAIN_1}\right] = \log_{10}(1+R) + RAIN_1$$

Or simply,

$$RAIN = \Delta + RAIN_1 \quad (4)$$

If two RAIN values are equal, then $R = 1$, and hence the incremental part of Eq. (4), i.e., $\Delta = \log_{10}(1 + 1) = 0.3$. For example, the RAIN value for a single CT scan is 2.9, as shown in Table 9. Therefore, if the CT examination is taken twice, the

Table 16 – Dose constraints and reference levels recommended for individuals from single dominant sources for all types of exposure situations that can be controlled [8,28].

Maximum constraints (mSv in a year)	Situation to which it applies	RAIN
100	In emergency situations, for workers, other than for saving life or preventing serious injury or catastrophic circumstances, for public evacuation & relocation, & for high levels of controllable existing exposures. There is neither individual nor societal benefit from levels of individual exposure above this constraint.	4.0
20	For situations where there is direct or indirect benefit for exposed individuals, who receive information & training, monitoring, or assessment. It applies to occupational exposure, for countermeasures such as sheltering & iodine prophylaxis in accidents, for controllable existing exposures such as radon, & for comforters & caregivers to patients undergoing therapy with radionuclides.	3.3
1	For situations having societal benefit, but without individual direct benefit, there is no information, no training, & no individual assessment for the exposed individuals in normal situations.	2.0
0.01	Minimum value of any constraint.	0.0

RAIN, radiation index.

Table 17 – Acute radiation syndrome by gamma irradiation to whole body [30].

Dose (Sv)	Symptoms	Remark	RAIN
~0.25	None	No clinically significant effects	~4.4
0.25–1	Mostly none, a few may exhibit nausea & anorexia	Bone marrow damaged, no death is expected	4.4–5.0
1–3	Mild to severe nausea, malaise, anorexia, infection	Recovery probable although not assured	5.0–5.5
3–6	Severe effects as above, plus hemorrhaging, infection, diarrhea, epilation	Fatality may occur in this range without treatment	5.5–5.8
≥6	Above symptoms plus impairment of central nervous system	Fatality expected	≥5.8

RAIN, radiation index.

dose will be doubled and the total RAIN value will be $2.9 + 0.3 = 3.2$.

Clearly, the total RAIN value will be slightly larger than the bigger RAIN value (by 0.3 maximum), and it can be estimated quickly and easily using Table 18. As another example, let us consider the case that an ordinary man will receive an extra exposure of 1 mSv (RAIN value 2.0) in addition to the world average background dose of 2.4 mSv (RAIN value 2.4) in a particular year. Since the RAIN ratio R is $2/(2.4) = 83\%$, so, from Table 18, the incremental RAIN is then 0.3. Therefore, the total RAIN value will be $2.4 + 0.3 = 2.7$.

Since we suggest that the numerical value of RAIN shall retain no more than a single significant digit after the decimal point, the following tables may be helpful for quick conversion of mSv into RAIN values. For example, 1 mSv is equivalent to a RAIN value of 2, as shown in Table 19, and thus 5 mSv is easily converted to a RAIN value of 2.7 by Table 20.

Table 18 – Increment of RAIN values (R is the ratio of two RAIN values).

R (RAIN ratio)	≤12%	13–41%	42–76%	77–100%
Δ (incremental RAIN)	0	0.1	0.2	0.3

RAIN, radiation index.

4.9. *Summary of representative RAIN values*

Table 21 shows a summary of RAIN values representing some familiar events or cases exemplified in Sections 4.1–4.6. As a quick aid for the general public, the last column of Table 21 provides the three zones of RAIN values (green, yellow, and red zones), which are characterized by the degree of severity of radiation exposure.

The boundary between the green and yellow zones is determined to be a RAIN value of 3 (equivalent to 10 mSv) because this value corresponds to the boundary between the high level of annual natural radiation exposure at some residential area requiring active monitoring and regulation of radiation exposure and its risk. In the green zone, biological effect due to radiation exposure can be negligible in comparison with other natural hazards. However, in the yellow zone, cancer risk should be taken into account and a prudent approach for radiological protection is recommended.

The boundary between the yellow and red zones is determined to be a RAIN value of 5 (equivalent to 1,000 mSv), which can be considered as the threshold of acute radiation syndrome, such as vomiting, nausea, and hematopoietic changes. As the radiation exposure increases, the probability of lethality will increase in the red zone.

Table 19 – Table for conversion of dose in mSv into RAIN value.

Dose	1 mSv	10 mSv	100 mSv	1 Sv
RAIN	2	3	4	5

RAIN, radiation index.

Table 20 – Increment of RAIN values for multiplication of a dose.

Multiplication ratio	2×	3×	4×	5×	6×	7×	8×	9×
Δ (incremental RAIN)	0.3	0.5	0.6	0.7	0.8	0.8	0.9	1.0

RAIN, radiation index.

5. Conclusion

The general public is least familiar with the scientific units currently used to define the level or amount of radiation. It is fair to say that the public has largely been kept in the dark as far as radiation is concerned. Public ignorance about the meaning of radiation units greatly contributed to the public's distrust and fear of radiation even when radiation levels are negligibly small, as the scientific units typically have a range of many orders of magnitude and often the numbers tend to be large if expressed in terms of the smallest units (μSv, for instance). Spurred by the need to create a common language that can bridge the gap between the general public and the nuclear/radiation community, this study proposes a new scale for radiation level. This will strengthen the link between these two groups, which has thus far remained weak due to the misunderstanding and fear of radiation elevated by the difficult physical units the experts have preferred to use at the exclusion of the public.

The new scale is a dimensionless number, RAIN, based on a logarithmic scale analogous to the well-known concept of seismic scale. This study established the correspondence between RAIN and scientific units. Events resulting in a negative RAIN value do not have to be considered because they are below the exemption and clearance levels. The world average annual human exposure due to natural background radiation sources is 2.4 mSv and, by coincidence, the corresponding RAIN value has the same numerical value of 2.4, making it a convenient second reference radiation level. To further facilitate public understanding of the significance of RAIN values, we provide a simple reference guide by introducing three zones (green, yellow, and red zones) the boundaries of which are demarcated by RAIN values of 3 (equivalent to 10 mSv) and 5 (equivalent to 1,000 mSv or 1 Sv). Also shown are the radiation levels expressed in RAIN for a number of well-known episodes that happen in medicine, health physics, nuclear facilities, and other fields.

We hope that this new scale of radiation will serve as a common tool of communication to facilitate constructive discussions between lay people and nuclear and radiation experts without breeding misunderstanding about radiation that has led to unnecessary and exaggerated fear of radiation for so long. The new radiation scale is expected to familiarize the public

Table 21 – Scale of RAIN values for representative events in three zones.

RAIN	Representative events	Comment	Zones
0	Exemption	Exemption & clearance dose limit of IAEA (10 μSv)	Green zone—negligible (below RAIN 3 or 10 mSv)
1+	Chest X-ray	10 hr of international flight (50 μSv) Chest X-ray exposure (70 μSv) Guide level of radionuclide in food (0.2–1 mSv depending on RIs for 1 yr)	
2+	Annual background, CT, & PET	Additional public radiation dose limit (1 mSv for 1 yr) Fluoroscopy (2 mSv) Annual background average dose (2.4 mSv) PET (6.4 mSv), CT (7.4 mSv)	
3+	Radiation worker limit	Indoor sheltering (10 mSv for 2 d) Annual dose limit for radiation workers (50 mSv)	Yellow zone
4+	Cancer risk	Threshold for cancer pathogeny (100 mSv) Thyroid protection level (100 mSv) Blood cell reduction (250 mSv)	
5+	Acute radiation syndrome	Threshold for hematopoietic syndrome (1 Sv) Lethal dose 50/60 (50% will die in 60 d; ~4 Sv)	Red zone—fatal effect (above RAIN 5 or 1 Sv)
6+	Radiation therapy	Central nerve syndrome (10 Sv) Radiation therapy for leukemia (16 Sv)[a] Radiation therapy for prostate cancer (67 Sv)[a]	
7+		100–1,000 Sv	
8+		1°C increase of water (4.2 kGy)[b]	
9+	Sterility of food & surgical equipment	Limit of commercial food irradiation for sterility (10 kGy)[b]	
10		Irradiation level of surgical equipment for sterility (100 kGy = 10^5 Gy)[b]	

CT, computed tomography; IAEA, International Atomic Energy Agency; PET, positron emission tomography; RAIN, radiation index; RI, radiation intensity.

[a] Therapeutic dose for cancer cells. Exposure in normal tissues occurring during a general radiation therapy will be much smaller than these levels.

[b] Gy is used instead of Sv because the irradiated target is not a human tissue but an object.

with radiation and educate them on radiation properly without prejudice. When popularized, the new index will become as familiar as the seismic scale, and nonexperts will be able to use it comfortably in their daily conversations involving radiation, radiation safety, nuclear accidents, and radiation applications.

Conflicts of interest

There is no conflict of interest with KUSTAR-KAIST Institute.

Acknowledgments

G.C. and J.H.K. were supported by KUSTAR-KAIST Institute (grant number N11160010(00)) for this work.

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