방사선 사고의 물리학적 기초

원자력병원 핵의학과
김 은 희

Introduction

Radiation accident is defined as a situation in which there is an unintentional exposure, either actual or suspected, to ionizing radiation or radioactive contamination. Radiation accident can occur in the followings: nuclear reactors, isotope production facilities, irradiation facilities, material testing (sealed source, x-ray device), diagnostic/therapeutic devices, transportation, etc. The mode of radiation exposure for different radiation sources/origins is summarized as follows:

Source	External exposure	Internal exposure
Critical assembly	Yes	Yes
Reactor	Yes	Yes
Fuel element manufacturer	Yes	Yes
Radiopharmaceutical manufacturer	Yes	Yes
Particle accelerator	Yes	Yes/No
X-ray generator	Yes	No
Sealed source (intact)	Yes	No
Sealed source (leaking)	Yes	Yes
Nuclear medicine laboratory	Yes	Yes
In-vitro assay laboratory	Tes	Yes

Radiation Characteristics

Radioactivity is defined as the disintegration of a nucleus releasing energy in the form of radiation. The unit of radioactivity is the becquerel (Bq). One becquerel means that one radioactive isotope disintegrates in one second. One of the elements describing radioactive characteristics of a radionuclide is *half-life* that is defined as the time for half the radionuclei to disintegrate. Radiation affects the target by ionization. During interaction with matter, radiation produces ions by ejecting electrons from atoms and disrupts molecular structures, resulting in cellular injury. Radiation acts in different types: (1) alpha particles (=helium nucleus), which are weakly penetrating and, therefore, hazardous only in internal exposure, (2) beta particles (=energy-spectral electrons), which are penetrating tissue up to a few mm, (3) gamma-rays, which can pass through the human body, and (4) neutrons, which can induce radioactivity within the body.

Radiation Dosimetric Quantities

Exposure is defined for gamma- and x-rays in terms of the amount of ionization they produce in air. The unit of exposure is Roentgen. The primary physical quantity used in dosimetry is the *absorbed dose*, defined as the energy absorbed per unit mass from any kind of ionizing radiation in any target. The unit of absorbed dose is Gray (= Joule/kg) or rad (= 100 erg/g). The identical dose value does not always imply the equivalent biological effect induced. The efficiency of different types of radiations in inducing biological effect is included in dosimetric quantity named *equivalent dose,* which is defined by

$H_T = \Sigma_R \; w_R \; D_{T,R}$

where H_T = equivalent dose to the tissue or organ T in rem or Sievert,
w_R = radiation weighting factor, and
$D_{T,R}$=absorbed dose averaged over the tissue or organ T, due to radiation R

The RBE (Relative Biological Effectiveness) value and QF (Quality Factor) are the quantities adopted as the radiation weighting factors. The following radiation weighting factors are recommended in ICRP 60.

Photons, electrons	1
Neutrons	5, 10, or 20
Protons	5
Alpha particles, heavy ions	20

The overall radiation impact on the whole body is determined by every tissue or organ impact. The relative contribution of the tissue or organ to the total detriment is expressed by tissue weighting factor. The *effective dose,* or the total impact on the body, is determined by

$E = \Sigma_T \; w_T \; H_T$

where E=effective dose to the whole body in rem or Sievert,
w_T=tissue weighting factor, and
H_T=equivalent dose.

The following tissue weighting factors are recommended in ICRP 60.

Tissue or organ	Tissue weighting factor
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder*	0.05

* composed of adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus

Biological Effect

The biological effect is categorized into (1) *deterministic effect,* the probability of whose occurrence is zero below threshold or one above the threshold and whose severity increases with dose or (2) *stochastic effect,* the probability of whose occurrence increases with the increments of dose with no threshold and whose severity is not affected by the dose. When enough cells in an organ or tissue are killed or prevented from reproducing and functioning normally, there will be a loss of organ function (*deterministic effect*). A modified somatic cell still retaining its reproducibility gives rise to a clone of modified cells that may result in a cancer (*stochastic effect*; somatic effect). A modified germ cell may transmit incorrect hereditary information and cause severe harm to the descendants (*stochastic effect*; *hereditary effect*).

The possible subcellular targets are enzymes, cell membrane, and chromosomal DNA. Alterations in structure *of enzymes* can affect the cell's metabolism. Alterations in proteins that form part of a membrane's structure can cause changes in its permeability to molecule. Radiation affects cells primarily by damage to the chromosomal DNA.

Radiation impact is through direct or indirect action. A secondary electron may interact with DNA to produce an effect (*direct action*). The secondary electron may interact with a water molecule to produce free radical, which in turn produces damage to DNA (*indirect action*). The radiolysis of water produces free radicals. A free radical is defined as an atom or molecule carrying an unpaired orbital electron in the outer shell. An atom or molecule with an unpaired electron has a high chemical reactivity. The OH free radical plays a major role in indirect radiation action to the cell.

Radiation Protection Principles

No practice involving exposures should be allowed unless: (1) all use has a net positive benefit (*justification*); (2) all exposure is as low as is reasonably achievable (ALARA)(*optimization*); and (3) exposures does not exceed the limits (*limitation*). ALARA means making every reasonable effort to maintain exposure to radiation as far below the dose limit as is practical taking into account economic, societal, and other considerations.

Radiological protection aims at (1) preventing deterministic effects by setting dose limits below their threshold and (2) reducing stochastic effect in frequency by suppressing dose below acceptable level.

Dose Limits

Radiation exposure types are categorized into *occupational exposure* (all exposures as a result of work), *medical exposure* (exposures of persons as part of diagnosis or treatment), *or public exposure* (the others). Even though the largest public exposure comes from the natural sources, the artificial sources are the main subject in radiation protection due to their ready controllability. The following dose limits are recommended in ICRP 60.

Application	Annual dose limit	
	Occupational	Public
Effective dose	20 mSv averaged over 5 years	1 mSv
The lens of eyes	150 mSv	15 mSv
The skin	500 mSv	50 mSv

Radiation Accident Dose Criteria

The situation in which the actual or suspected dose is over the following criteria indicates the "radiation accident".

Condition	Criteria (mrem/mSv)
Whole body dose (blood-forming organs or gonads)	25,000/250
Skin/extremity dose	600,000/6,000
Tissue/organ dose by external source	75,000/750
Internal burden	1/2 NCRP max. organ burden