Units of Radiation: Becquerel and Sievert

Becquerel (Bq)
Unit indicating the amount of radioactivity

One nucleus decays per second = 1 becquerel (Bq)

Radioactive materials

Sievert (Sv)
Unit of radiation exposure dose that a person receives
Associated with radiation effects

1 mSv from outside the body   1 mSv from within the body

Nearly equal effects on the human body
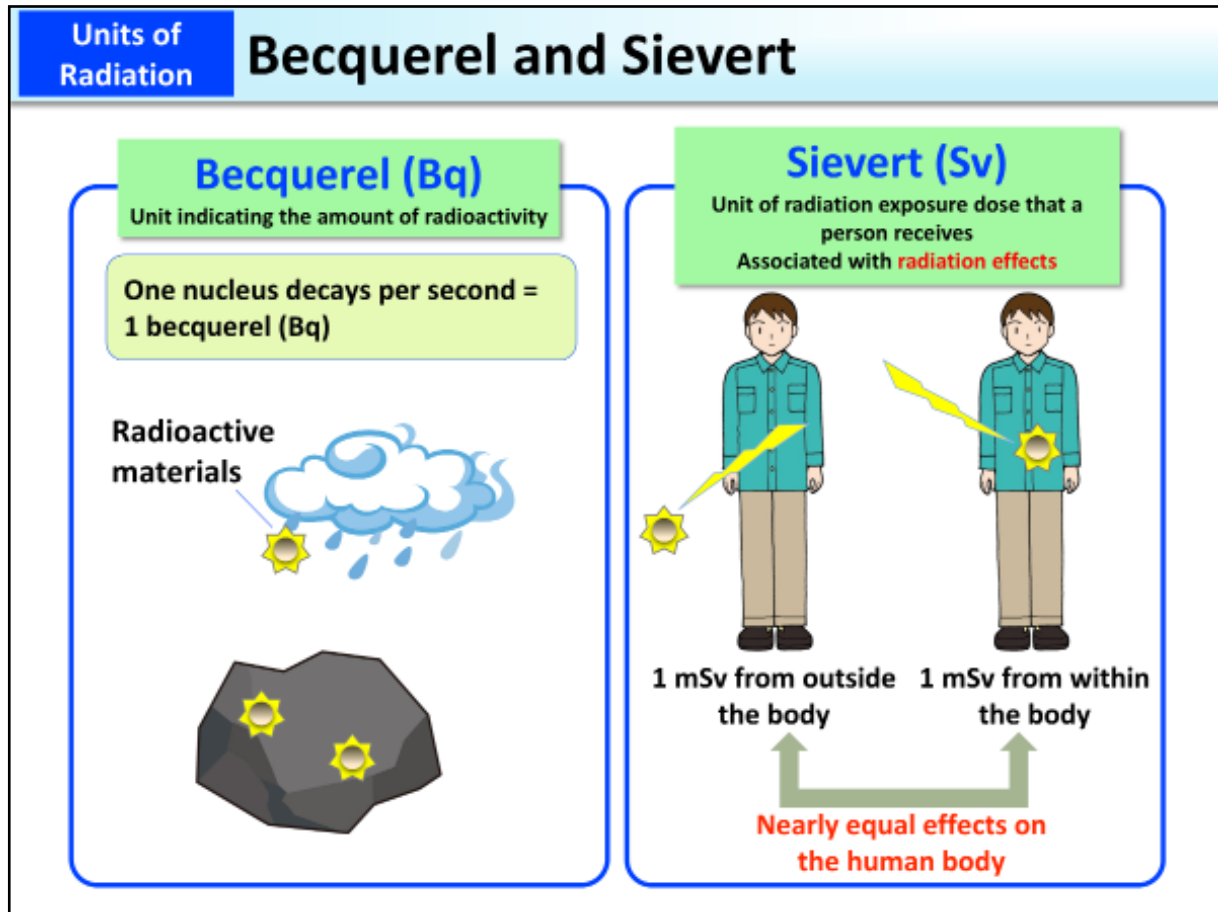
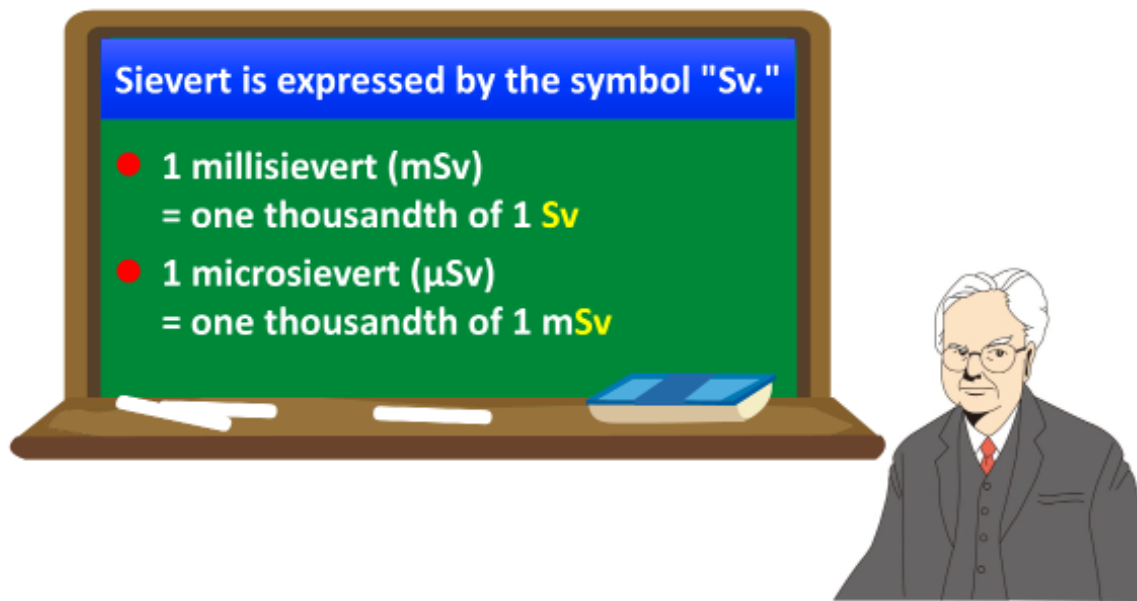"Becquerel" and "sievert" are the most common units of radiation. Becquerel is a unit of radioactivity and focuses on where radiation comes from. It is used to express the amount of radioactive materials contained in soil, foods, tap water, etc. The higher the value expressed in becquerels, the larger the radiation being emitted. Sievert is a unit of radiation exposure dose that a person receives and is used with regard to what is exposed to radiation, i.e. the human body. The larger the value expressed in sieverts, the larger the effects of radiation to which the human body is exposed (p.40 of Vol. 1, "Concepts of Doses: Physical Quantities, Protection Quantities and Operational Quantities").

The extent of radiation effects on the human body varies according to the types of exposure, i.e., internal or external exposure, or whole-body or local exposure (for details, refer to Vol. 1, "2.1 Exposure Routes"), and according to the types of radiation (for details, refer to Vol. 1, "1.3 Radiation"). By using sieverts to express all types of exposure, it is possible to compare their effects on human body.

External exposure of 1 mSv and internal exposure of 1 mSv are deemed to have equal effects on the human body. Exposure to 1 mSv of radiation from outside the body and exposure to 1 mSv of radiation from within the body mean exposure to a total of 2 mSv of radiation.

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Units of Radiation — Origin of Sievert

Sievert is expressed by the symbol "Sv."

- 1 millisievert (mSv) = one thousandth of 1 Sv
- 1 microsievert (μSv) = one thousandth of 1 mSv

Rolf Sievert (1896-1966)
Founder of the physics laboratory at Sweden's Radiumhemmet
Participated in the foundation of the International Commission on Radiological Protection

The unit "sievert" is named after Rolf Sievert, a Swedish researcher on radiological protection. He served as the chairman of the International X-ray and Radium Protection Committee (IXRPC), the predecessor of the International Commission on Radiological Protection (ICRP), and participated in founding the ICRP[1]. Millisieverts (one millisievert = a thousandth of sievert) and microsieverts (one microsievert = a millionth of sievert) are mostly used to express radiation doses that people receive in their daily lives.

Becquerel (unit of radioactivity), curie (former unit of radioactivity) and gray (unit of absorbed dose) are all named after researchers who made significant contributions to the study of radiation.
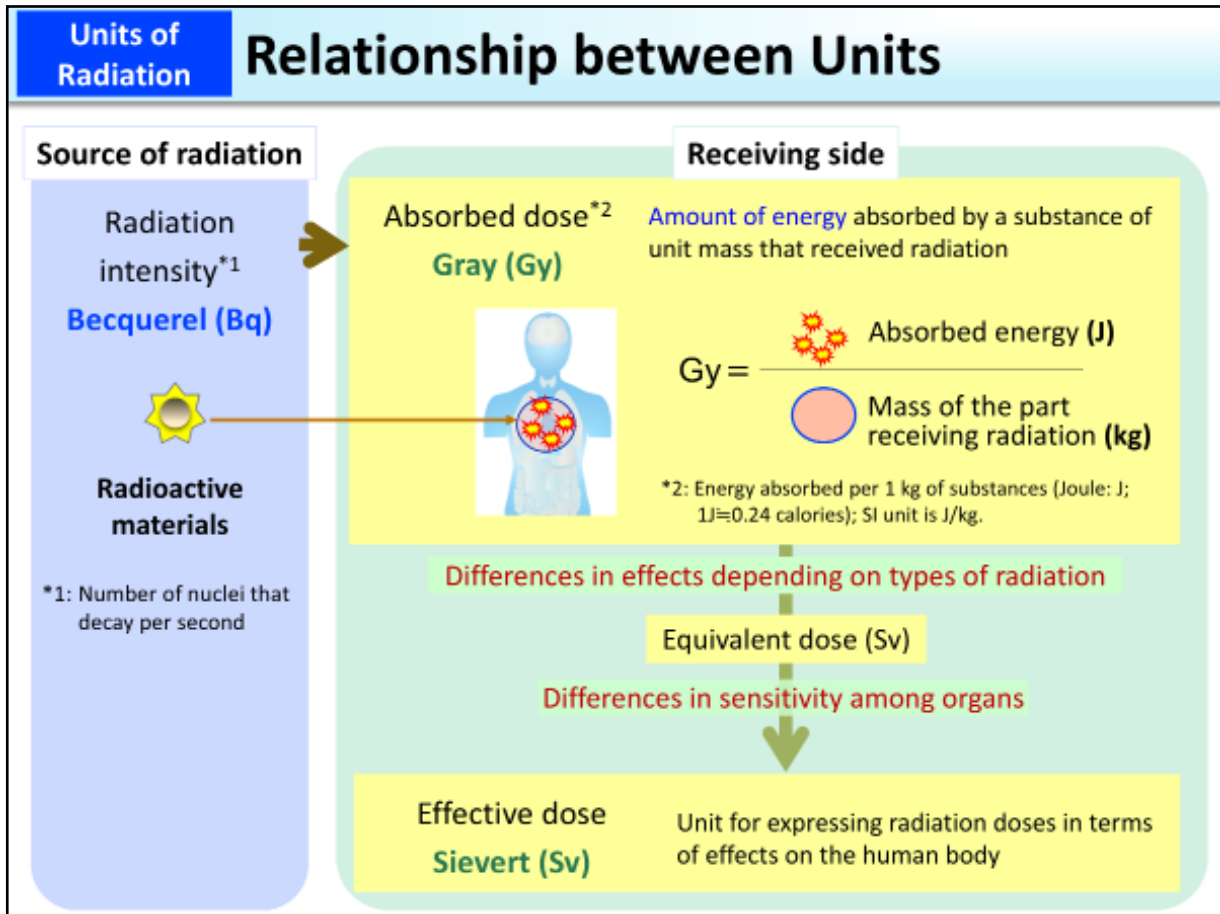
1. It is said that George Kaye at the National Physical Laboratory played a central role in founding the ICRP.
(Source: ICRP Publication 109, The History of ICRP and the Evolution of its Policies, ICRP, 2009)

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Units of Radiation — Relationship between Units

Source of radiation

Radiation intensity[1]
Becquerel (Bq)

Radioactive materials

[1]: Number of nuclei that decay per second

Receiving side

Absorbed dose[2]
Gray (Gy) — Amount of energy absorbed by a substance of unit mass that received radiation

$$Gy = \frac{\text{Absorbed energy (J)}}{\text{Mass of the part receiving radiation (kg)}}$$

[2]: Energy absorbed per 1 kg of substances (Joule: J; 1J≈0.24 calories); SI unit is J/kg.

Differences in effects depending on types of radiation

Equivalent dose (Sv)

Differences in sensitivity among organs

Effective dose
Sievert (Sv) — Unit for expressing radiation doses in terms of effects on the human body

Units of radiation can be broadly divided into units for sources of radiation and units for the receiving side. Becquerel, a unit of radioactivity, is used for sources of radiation. Units for the receiving side are gray and sievert.
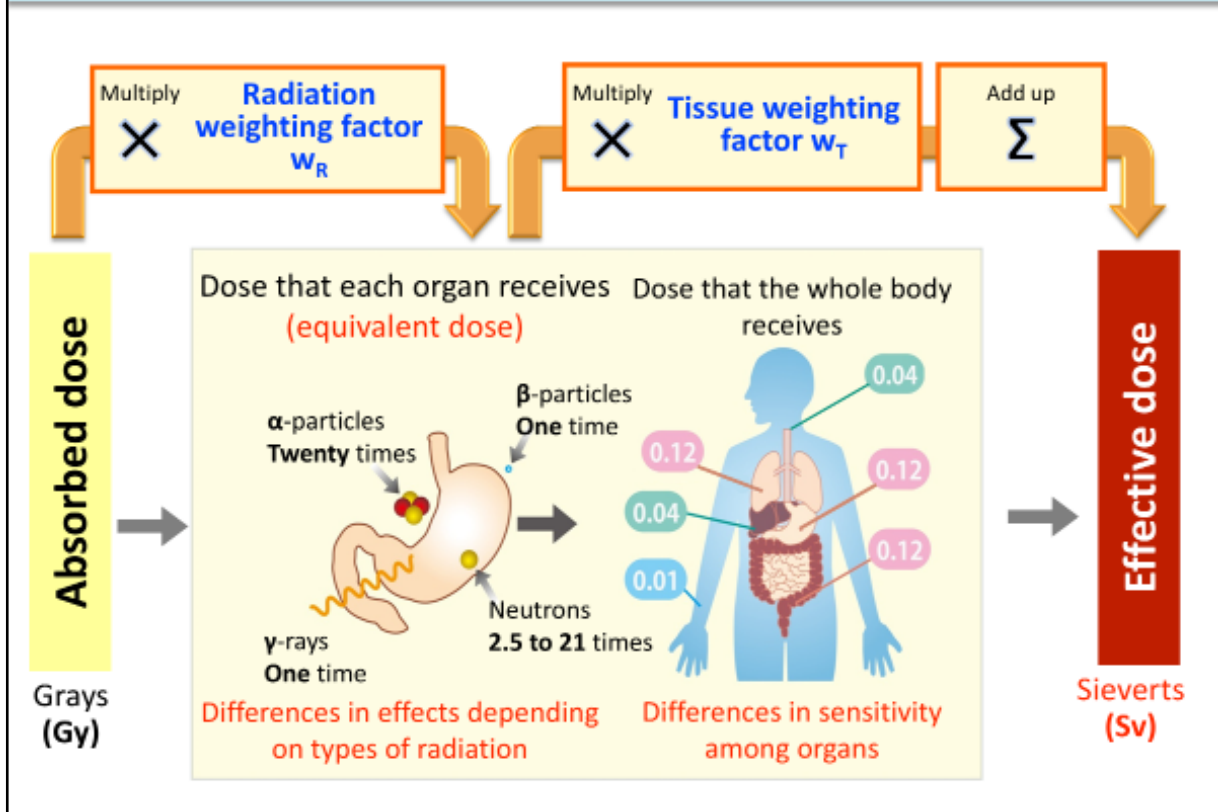
When radiation passes through something, its energy is absorbed there. Gray is a unit for indicating the absorbed dose.

The extent of effects on the human body varies depending on the types and energy quantities of radiation even if the absorbed doses are the same. Doses weighting health effects of respective types of radiation are equivalent doses (expressed in sieverts). The effective dose (expressed in sieverts) was developed for exposure management in radiological protection. In contrast to the equivalent dose, the effective dose weights differences in sensitivity among organs and tissues and sums them up to express the radiation effects on the whole body.

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Units of Radiation — Conversion from Gray to Sievert

Multiply × **Radiation weighting factor w_R**

Multiply × **Tissue weighting factor w_T**

Add up Σ

Absorbed dose — Grays (Gy)

Dose that each organ receives (equivalent dose)

α-particles **Twenty** times

β-particles **One** time

γ-rays **One** time

Neutrons **2.5 to 21** times

Differences in effects depending on types of radiation

Dose that the whole body receives

0.04 · 0.12 · 0.12 · 0.04 · 0.12 · 0.01

Differences in sensitivity among organs

Effective dose — Sieverts (Sv)

To calculate the effective dose that expresses the effects of radiation exposure on the whole body, it is necessary to first determine the absorbed doses of individual tissues and organs exposed. The equivalent dose (expressed in sieverts) is obtained by multiplying the absorbed doses of individual tissues and organs by their respective radiation weighting factors (W_R) for taking into account the types of radiation. The value of the radiation weighting factor is larger for the types of radiation having larger effects on the human body (α (alpha)-particles: 20; β (beta)-particles and γ-rays: 1).

Once the equivalent doses for individual tissues and organs exposed to radiation are determined, they are then multiplied by the respective tissue weighting factors (W_T) for taking into account differences in sensitivity among organs, and the products are summed. The tissue weighting factors are for weighting the radiation sensitivity of individual tissues and organs. Any organ or tissue where radiation is likely to induce fatal cancer is given a higher factor.

The tissue weighting factors summate to 1. Thus, the effective dose can be considered as the weighted average of the equivalent doses of all organs and tissues. Effective doses can be calculated similarly for both internal and external exposures.
(Related to p.38 of Vol. 1, "Various Factors")

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| Units of Radiation | **Various Factors** |

Equivalent dose (Sv) = Radiation weighting factor w_R × Absorbed dose (Gy)

Type of radiation	Tissue weighting factor w_R
γ-rays, X-rays, β-particles	1
Proton beams	2
α-particles, heavy ions	20
Neutron beams	2.5～21

Effective dose (Sv) = Σ (Tissue weighting factor w_T × Equivalent dose)

Tissue	Tissue weighting factor w_T
Red bone marrow, colon, lungs, stomach, breasts	0.12
Gonad	0.08
Bladder, esophagus, liver, thyroid	0.04
Bone surface, brain, salivary gland, skin	0.01
Total of the remaining tissues	0.12

Sv: sieverts; Gy: grays   Source: 2007 Recommendations of the ICRP

Recommendations issued by the International Commission on Radiological Protection (ICRP) in 2007 presented new radiation weighting factors and tissue weighting factors. It is stated that α (alpha)-particles have 20 times larger effects on the human body than γ-rays and β (beta)-particles with the same absorbed doses. Neutron beams are also given high radiation weighting factors and are expected to have 2.5 to 21 times larger effects on the human body than γ-rays and β-particles depending on the energy quantities (p.37 of Vol. 1, "Conversion from Gray to Sievert").

A survey on the health effects of radiation on atomic bomb survivors revealed which organs and tissues are more prone to the cancer-causing effects of radiation (p.114 of Vol. 1, "Tissues and Organs Highly Sensitive to Radiation"). These tissues are assigned high tissue weighting factors.

Surveys on the health effects of radiation were also conducted on the children and grandchildren of atomic bomb survivors but no heritable effects of radiation were observed (p.109 of Vol. 1, "Chromosomal Aberrations among Children of Atomic Bomb Survivors"). Therefore, the ICRP lowered the tissue weighting factor for the gonads from 0.2 in the 1990 Recommendations to 0.08 in the 2007 Recommendations. In this way, the factors used in the calculation of effective doses are updated to accommodate new findings.

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Units of Radiation — Calculation of Equivalent Dose and Effective Dose

Effective dose (sievert (Sv)) = Σ (Tissue weighting factor × Equivalent dose)

When the whole body is evenly exposed to 1 mGy of γ-ray irradiation

Effective dose =
    0.12 × 1 (mSv): bone marrow
  + 0.12 × 1 (mSv): colon
  + 0.12 × 1 (mSv): lungs
  + 0.12 × 1 (mSv): stomach
        :
  + 0.01 × 1 (mSv): skin
  = 1.00 × 1 (mSv)
= 1 millisievert (mSv)

When only the head is exposed to 1 mGy of γ-ray irradiation

Effective dose =
    0.04 × 1 (mSv): thyroid
  + 0.01 × 1 (mSv): brain
  + 0.01 × 1 (mSv): salivary gland
  + 0.12 × 1 (mSv) × 0.1: bone marrow **(10%)**
  + 0.01 × 1 (mSv) × 0.15: skin **(15%)**
        :
= 0.07 millisieverts (mSv)

Methods for calculating an effective dose when the whole body is evenly exposed to 1 mGy of γ-ray irradiation and an effective dose when only the head is exposed to 1 mGy of γ-ray irradiation are compared.

Since the radiation weighting factor (W_R) for γ-rays is 1, the whole body being evenly exposed to 1 mGy means that the whole body is evenly exposed to 1 mSv (1 gray × 1 (W_R) = 1 millisievert). That is, equivalent doses are 1 mSv for all organs and tissues. To calculate effective doses, the equivalent doses for individual tissues are multiplied by their respective tissue weighting factors and the products are summed. Bone marrow, colon, lungs, stomach and breasts are given a high factor of 0.12 because these are organs with high risks of radiation-induced fatal cancer. The skin of the whole body is assigned a factor of 0.01. Thus, when the equivalent doses for all organs and tissues are multiplied by their respective tissue weighting factors and the products are summed, the result is an effective dose of 1 millisievert.

If only the head is exposed to 1 mGy in radiation inspection, the organs and tissues in the head, such as the thyroid, brain and salivary gland, are entirely exposed to radiation, so equivalent doses are 1 mSv for all these organs and tissues. For organs and tissues that are only partly present in the head, such as bone marrow and skin, equivalent doses are obtained by multiplying by the ratios of their areas exposed to radiation (bone marrow: 10%; skin: 15%). When their equivalent doses are multiplied by their respective tissue weighting factors and the products are summed, the result is an effective dose of 0.07 mSv.
(Related to p.36 of Vol. 1, "Relationship between Units")

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Units of Radiation: Concepts of Doses: Physical Quantities, Protection Quantities and Operational Quantities

Physical quantities: directly measurable

Radiation intensity (Bq: becquerels)
Number of nuclei that decay per second
Radiation fluence ($s^{-1}m^{-2}$: fluence)
Number of particles incident on a unit area

Absorbed dose (Gy: grays)
Energy absorbed per 1 kg of substances
Irradiation dose (for X-rays and γ-rays) (C/kg)
Energy imparted to 1 kg of air

Doses indicating the effects of exposure on humans: not directly measurable

Defined based on physical quantity

Protection quantities

Equivalent dose (Sv: sievert)
indicates effects on individual human organs and tissues

Effective dose (Sv: sievert)
indicates effects on the whole body by combining effects on individual organs and tissues

Operational quantities

Ambient dose equivalent (Sv: sievert)
Directional dose equivalent (Sv: sievert)
Approximate value for protection quantity used in environmental monitoring

Personal dose equivalent (Sv: sievert)
Approximate value for protection quantity used in personal monitoring

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To control radiation effects on the human body, it is necessary to take into account the effects of exposure on multiple parts of the body and the effects of previous exposures. The equivalent dose and the effective dose were invented for that purpose.

The equivalent dose is obtained by weighting effects on individual organs and tissues according to the types of radiation.

The effective dose is obtained by converting the effects on individual tissues to a value for the whole body. It is not the simple average of equivalent doses for individual organs but the result of weighting according to differences in sensitivity to radiation among organs.

A factor for weighting radiation effects on individual organs is called the tissue weighting factor.

Thus, protection quantities are calculated based on doses for organs and tissues in the human body. They are therefore different from physical quantities such as the radiation intensity (unit: becquerel) and absorbed dose (unit: gray) and cannot be measured directly with instruments. To indicate effects on the human body, operational quantities are defined.

Some survey meters use sieverts in their readings. They do not directly measure a protection quantity but show approximate values defined based on measured physical quantities, i.e., operational quantities. Operational quantities include the ambient dose equivalent used in environment monitoring and the personal dose equivalent used in personal monitoring (p.41 of Vol. 1, "Dose Equivalents: Measurable Operational Quantities for Deriving Effective Doses").

To provide conservative (on the safe side) estimates of protection quantities, operational quantities are defined to assume slightly larger numerical values than the values of protection quantities in most cases.

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Units of Radiation — Dose Equivalents: Measurable Operational Quantities for Deriving Effective Doses

Dose equivalent = Absorbed dose at a reference point that meets certain requirements × Quality factor

To substitute for "effective doses" that cannot be actually measured, "operational quantities" that can be measured as conservative values or as nearly the same values as effective doses, such as an ambient dose equivalent and personal dose equivalent, are defined under certain conditions.

Ambient dose equivalent (1cm dose equivalent)

Dose equivalent is a dose that would be produced at a depth of 1 cm from the surface of an ICRU sphere, which is 30 cm in diameter and simulates human tissue, placed in a field where radiation is coming from one direction; Ambient dose equivalent is used in measurements of ambient doses using survey meters, etc.

Gamma-rays

ICRU sphere
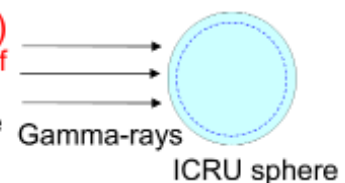
Personal dose equivalent (1 cm dose equivalent)

Dose equivalent at a depth of 1 cm at a designated point on the human body; Since measurement is conducted using an instrument worn on the body, exposure from all directions is evaluated while a self-shielding effect is always at work.

⇒ **Personal dose equivalents are always smaller than survey meter readings!**

ICRU slab
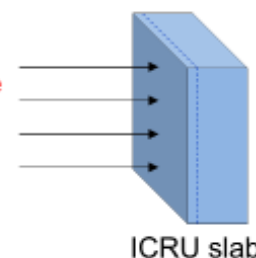
Operational quantities for approximating effective doses that cannot be actually measured (p.40 of Vol. 1, "Concepts of Doses: Physical Quantities, Protection Quantities and Operational Quantities") are defined, such as the ambient dose equivalent H*(d) (d is depth) for evaluating ambient doses in a work environment, etc., the personal dose equivalent H_p(d) for evaluating personal exposure, and the directional dose equivalent H' (d,α) (α is the angle of incidence) as a quantity for use when there is a need to evaluate the depth and directions of incidence as well, as in the case of exposure of the lens of the eye to β-particles or soft X-rays.

Generally, both the ambient dose equivalent and the personal dose equivalent are also called 1 cm dose equivalents because a depth of 1 cm is used in the case of exposure to γ-rays.

However, while the ambient dose equivalent is measured using measuring instruments that are less affected by directivity, such as a stationary ionization chamber and a survey meter, the personal dose equivalent is measured using a small personal dosimeter worn on the trunk of the body, so incidence from the back is evaluated while a self-shielding effect is always at work. Therefore, in the case of exposures only from the front direction, such as exposures in laboratories, the ambient dose equivalent and the personal dose equivalent are equal, but in the case of exposures from all directions, personal dose equivalents are always smaller than the values measured with a survey meter, etc. Calculation of an effective dose for incidence from all directions is made under the condition of "rotational irradiation" in which the human body is rotated, and the calculated value will be exactly the same as the personal dose equivalent. In other words, the calculated value will generally be larger than the effective dose.

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Units of Radiation

Difference between Values of Effective Dose and Dose Equivalent
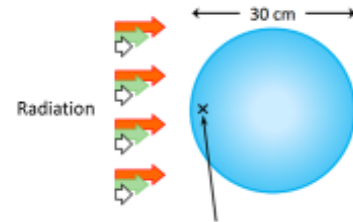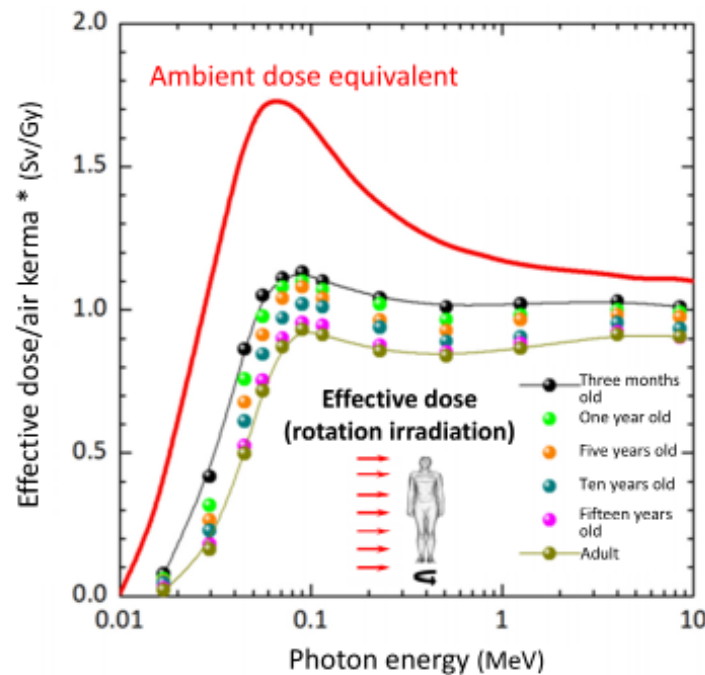
The ambient dose equivalent measured with a survey meter is defined as the dose equivalent at a depth of 1 cm from the surface of an ICRU sphere that is 30 cm in diameter. The ambient dose equivalent is also called 1 cm dose equivalent.

Source: Partially revised material 1 for the 9th meeting of the Atomic Energy Commission of Japan in 2012 (a report by Akira Endo of JAEA)

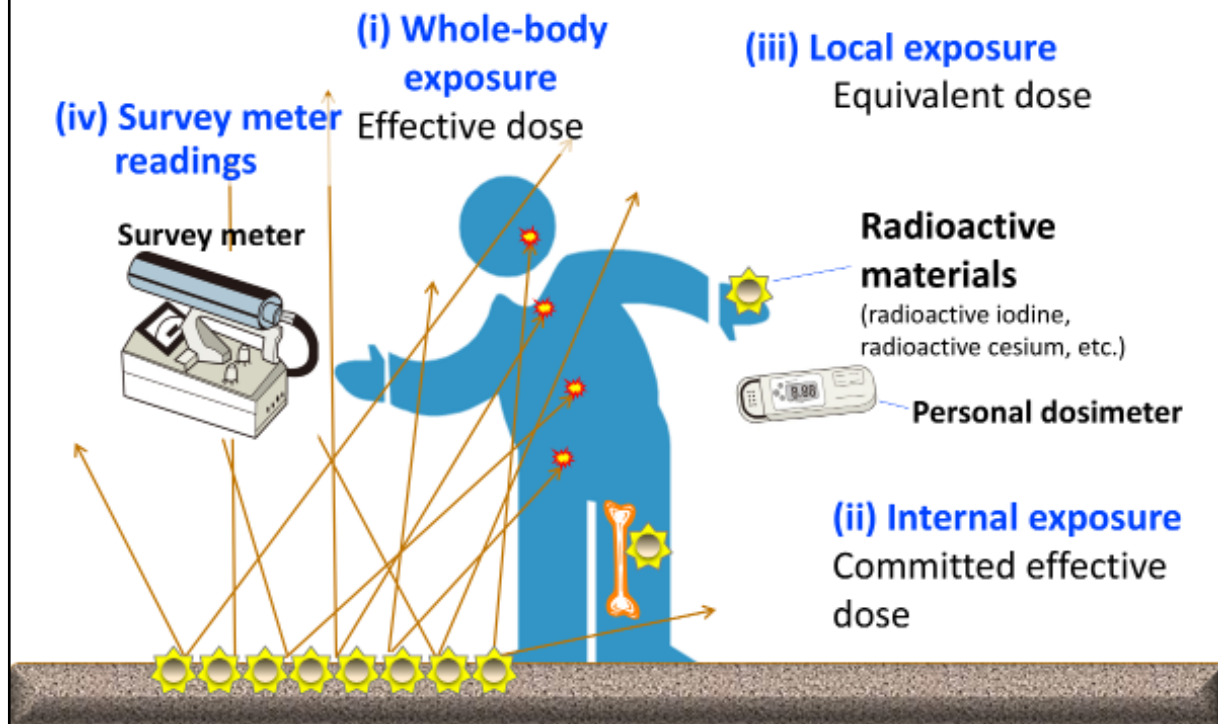* Air kerma is a unit of physical quantity.

The ambient dose equivalent measured with a survey meter is set to always indicate a larger value than the effective dose.

This is also the case for a personal dosimeter when measuring radiation incident only from the front. However, in a setting where a personal dosimeter is worn on the body and radiation sources are evenly distributed, measured value will be close to the value of "effective dose" because of the self-shielding effect of the human back, etc.

The graph above shows differences between effective dose (including the self-shielding effect of the back, etc. in the case of even irradiation by rotation) and ambient dose equivalent to the energy of incident γ-rays. While the degree of self-shielding slightly varies depending on differences in physique due to age, the value measured with a survey meter for Cs-137 γ-rays at 662 keV is shown to be about 30% larger than the effective dose for adults and the value measured with a personal dosimeter (personal dose equivalent).

(Related to p.41 of Vol. 1, "Dose Equivalents: Measurable Operational Quantities for Deriving Effective Doses")

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Units of Radiation — Doses in Units of Sieverts

(iv) Survey meter readings — Survey meter

(i) Whole-body exposure — Effective dose

(iii) Local exposure — Equivalent dose

Radioactive materials (radioactive iodine, radioactive cesium, etc.)

Personal dosimeter

(ii) Internal exposure — Committed effective dose

Sievert is used as the unit for (i) radiation dose to the whole body (effective dose) (p.42 of Vol. 1, "Difference between Values of Effective Dose and Dose Equivalent"), (ii) radiation dose due to internal exposure (committed effective dose) (p.56 of Vol. 1, "Committed Effective Doses"), and (iii) dose from local exposure, in which exposure to radiation is limited to a certain location (equivalent dose). They are common in that they all take into account the risks of cancer and heritable effects on individuals or tissues exposed.

Sievert may also be used for (iv) the readings of survey meters. The relevant value shows a value converted to an ambient dose equivalent (p.44 of Vol. 1, "Various Measuring Instruments").

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