X-ray Training Course Textbook

Kumamoto university

1. Ionizing Radiation and X-rays

Particles or electromagnetic waves that directly or indirectly ionize atoms are called ionizing radiation. In the Ordinance on the Prevention of Ionizing Radiation Hazards, ionizing radiation is categorized into the following four groups.

Group a) α rays, deuteron beams and proton beams
These are flows of positively-charged particles in which nuclei of light atoms move with a large amount of energy. The flow of helium atoms emitted by atomic nuclei during the decay of a radioisotope is called an α ray, the flow of deuterium nuclei is called a deuteron beam, and the flow of hydrogen nuclei is called a proton beam.

Group b) β rays and electric beams
The flow of negatively-charged electrons is called an electric beam, and the flow of electrons emitted by atomic nuclei is called a β ray.

Group c) Neutron beams
The flow of neutrons emitted by the nucleus during a nuclear reaction, such as atomic fission, is called a neutron beam.

Group d) X-rays and γ rays
These are both electromagnetic waves with short wavelengths. Although their nature is exactly the same, they are categorized into X-rays (atom-derived) and γ rays (nucleus-derived).

X-ray: an electromagnetic wave generated when an electric beam collides with metal. Its generation is attributed to the electrons outside the nucleus.
γ ray: an electromagnetic wave generated accompanying the decay of a nucleus. Its generation is attributed to the nucleus.

The relationship between a wavelength and the energy of an electromagnetic wave is shown in Figure 1. An X-ray is an electromagnetic wave, like an infrared ray, a visible ray or an ultraviolet ray. As is indicated by Figure 1, the wavelength of an X-ray is within a range from 0.001 to 10 nm, with the long-wavelength side making the transition to an ultraviolet ray and the short-wavelength side overlapping with a γ ray. As the wavelength becomes shorter, the X-ray's power to penetrate matter becomes stronger and, as the wavelength becomes longer, it retains more heat. An X-ray is invisible to the human eye and has very strong energy that can penetrate the human body.

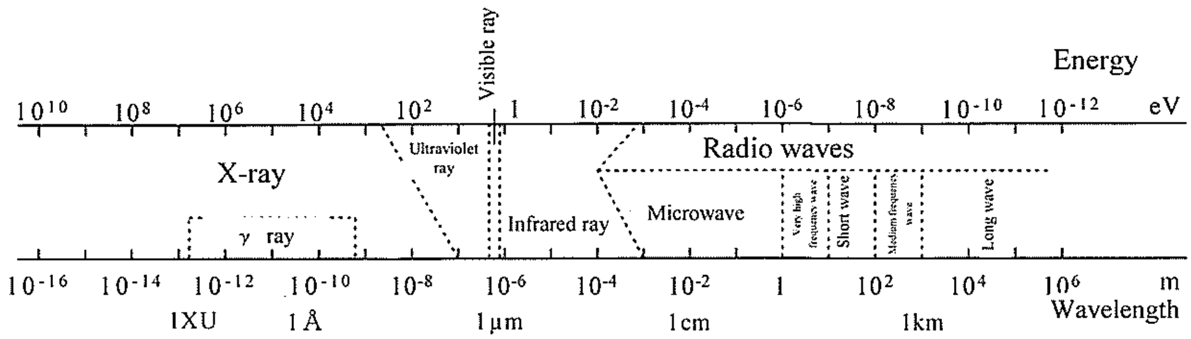

Figure 1. The relationship between a wavelength and the energy of an electromagnetic wave

2. Generation of an X-ray

The structure of an X-ray tube is shown in Figure 2. An X-ray tube has a cathode and an anode, and when an electric current is applied to the tungsten filament of the cathode, electrons are discharged into a vacuum. When high voltage is applied between the cathode and the anode, electrons accelerate from the cathode to the anode, and electrons having large kinetic energy collide with the metal on the anode, generating X-rays.

The point where the accelerated electrons collide with the target on the anode and at which X-rays are generated is called the real focus, and the same point viewed from the side using an X-ray beam is called the effective focus. In order to take a radiograph with high image quality in a radiographic test, it is better to make the dimensions of the effective focus small.

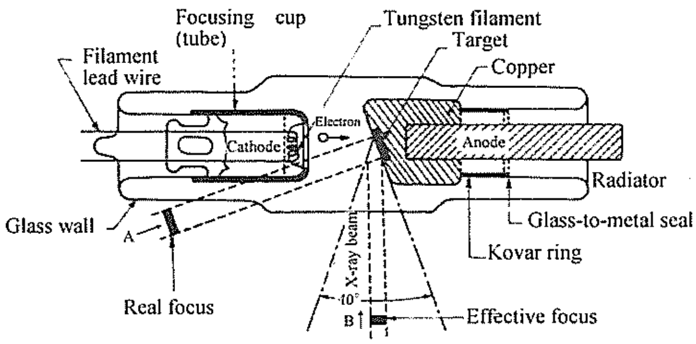

Figure 2. Structure of an X-ray tube

The relationship between a wavelength and the strength of the X-rays generated from the X-ray tube shows spectra as described in Figure 3. The spectra consists of a continuous X-ray spectrum showing a continuous wavelength distribution and the characteristic X-ray spectrum showing a spectrum characteristic to the target element

Continuous X-rays

When the accelerated electrons collide with the anode, they decelerate. The kinetic energy of the electrons for the decelerated amount is converted into X-rays. Generally, the process in which charged particles receive a great amount of acceleration while passing through a strong magnetic field (electrical field) and discharge a portion of their kinetic energy in the form of magnetic waves is called bremsstrahlung. Since the degree of deceleration differs depending on each electron, X-rays with varying amounts of energy are generated. X-rays that consist of these X-rays continuously overlapping one another are called polychromatic X-rays or bremsstrahlung X-rays

It has been experimentally confirmed that there is a relationship as described in equation (1) between the total intensity I of the continuous X-rays and X-ray tube current I, X-ray tube voltage V, atomic number X, and proportionality constant k.

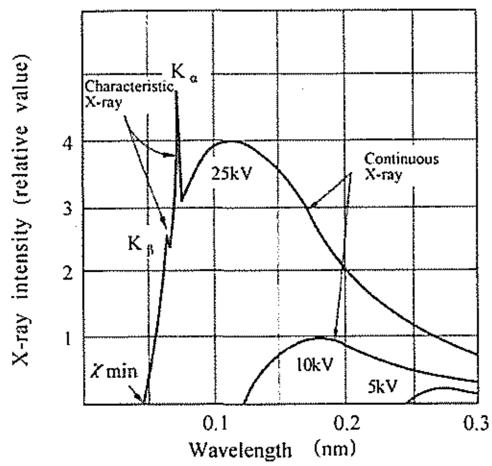

Figure 3. X-ray spectrum when various tube voltages are applied to an X-ray tube with a Molybdenum target

$$I = k\,i\,V^2 Z \qquad (1)$$

Characteristic X-rays

When electrons accelerated in the X-ray tube collide with the anode, some electrons may knock out a shell electron of the target atom. Since an atom in such a state is very unstable, an electron in an outside shell will fill the vacancy. At this point, energy corresponding to the energy level difference between the two shells is discharged as a characteristic X-ray. The wavelength of a characteristic X-ray does not change when the X-ray tube voltage is increased, but is specific to the target element. In general, a wavelength of a characteristic X-ray becomes shorter as the atomic number of the target element becomes greater.

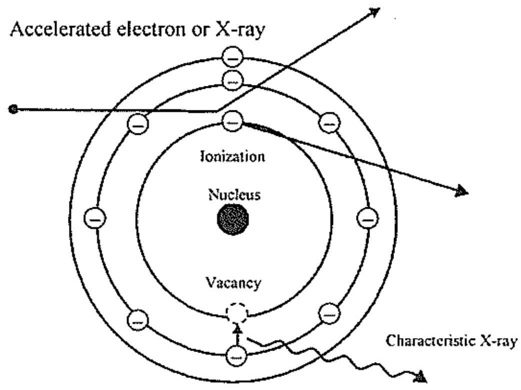

Figure 4. Generation mechanism of a characteristic X-ray

3. Interaction of X-rays with Matter

When X-rays pass though matter, they interact with it in various ways. During the interactions, they change their strength or propagation directions. Though there are various ways in which X-rays interact with matter, the following four are the major forms of interaction.

Photoelectric effect

A photoelectric effect is a phenomenon in which an X-ray photon gives energy to an orbital electron and ejects it outside of the atom, while the photon itself loses its energy and disappears (Figure 5).

Elastic scattering (Rayleigh scattering)

This is a phenomenon in which an X-ray photon elastically collides with an orbital electron and changes its direction (Figure 6). Elastic scattering does not change the wavelength (energy).

Inelastic scattering (Compton scattering)

This is a phenomenon in which an X-ray photon collides with an orbital electron and ejects the electron outside of the atom, while the photon itself changes the direction of its motion (Figure 7). The ejected electron is called a Compton scattered electron. The energy of the photon decreases by an amount corresponding to the energy of this electron.

Pair production

This is a phenomenon in which an X-ray disappears when it passes near a nucleus and a pair consisting of a positive electron and a negative electron is generated (Figure 8). The positive electron is bound again with the negative electron in a short period of time, and it disappears after emitting two gamma rays with an energy level of 0.51 MeV. Therefore, this phenomenon can only occur in an X-ray with a high energy level of 1.02 MeV or greater.

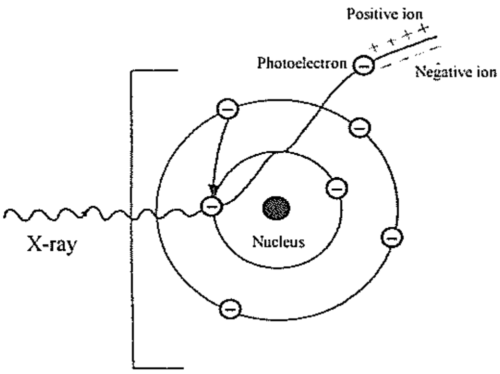

Figure 5. Photoelectric effect

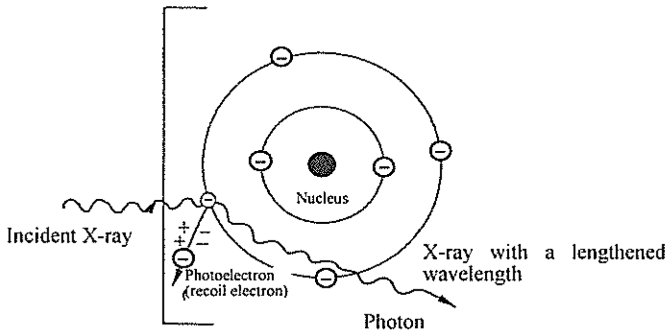

Figure 7. Inelastic scattering (Compton scattering)

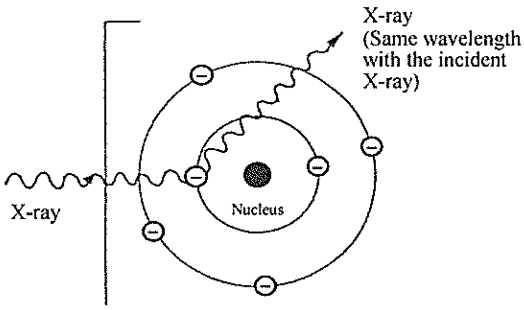

Figure 6. Elastic scattering (Rayleigh scattering)

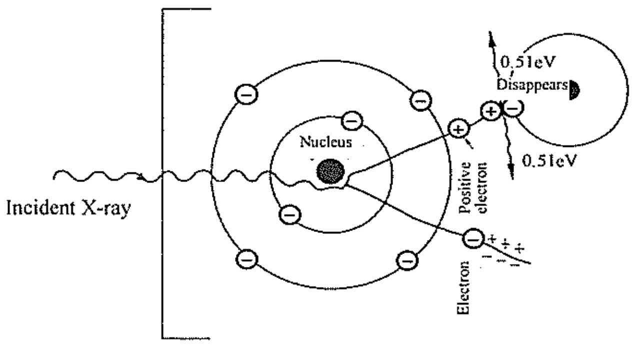

Figure 8. Pair production

4. X-ray Beam Quality

When an X-ray passes through matter, it attenuates due to interaction with the matter. When the intensity of a monoenergetic X-ray after passing through matter is denoted by I, I can be expressed by the following equation (2):

$$I = I_0 e^{-\mu x} \qquad (2)$$

In the above equation, x denotes the thickness of the matter, I_0 denotes the intensity of the X-ray when the thickness of the matter is 0, and μ denotes the attenuation coefficient. The attenuation coefficient expresses interaction by the matter, and when the coefficient of attenuation by the photoelectric effect is denoted by τ, the coefficient of attenuation by Rayleigh scattering is denoted by σ_R, the coefficient of attenuation by Compton scattering is denoted by σ_C、 and the coefficient of attenuation by pair production is denoted by κ, μ is expressed by the following equation (3):

$$\mu = \tau + \sigma_R + \sigma_C + \kappa \qquad (3)$$

In Figure 9, the attenuation coefficient of iron, divided into the coefficients of attenuation by the four types of interaction by the matter, is shown. The horizontal axis expresses the X-ray energy in a logarithmic scale, and the vertical axis expresses the attenuation coefficient in an ordinary scale. τ and σ_R abruptly decrease when the X-ray energy increases. Attenuation at around 0.5 to 1 MeV is mostly attenuation by σ_C. In addition, when the X-ray energy is 1 MeV or greater, attenuation due to pair production becomes significant.

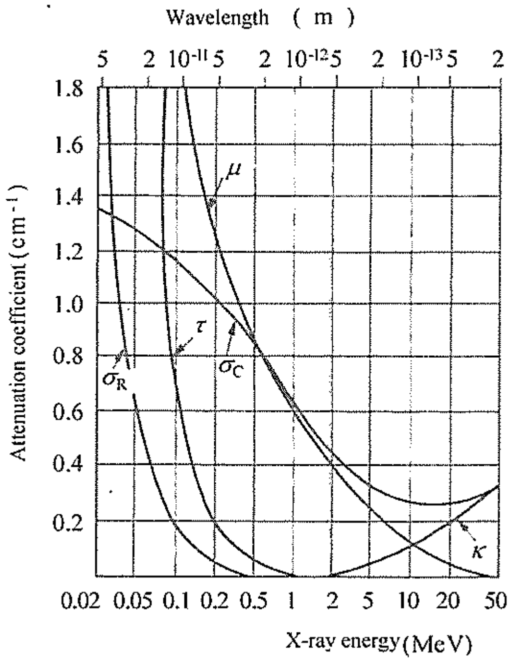

Figure 9. Relationship between each attenuation coefficient of iron and X-ray energy

In Figure 10, the attenuation coefficient μ for various metals is shown, with respect to X-ray energy and wavelengths. It is indicated in the figure that the attenuation coefficient decreases as X-ray energy increases. The discontinuous part of the attenuation coefficient of lead (Pb) at around 90 keV is called the K-absorption edge, which corresponds to the excitation voltage of a K-characteristic X-ray of lead (Pb).

As an indication of whether or not an X-ray can easily pass through matter, X-rays with high penetration power are called "hard X-rays" and X-rays with low penetration power are called "soft X-rays", to express the quality differences of X-rays.

5. Utilization of X-rays

Methods for utilizing X-rays can be largely divided into transmission, scattering, diffraction and spectroscopy. In Table 1, X-ray equipment is shown that uses these methods, categorized according to application.

Transmission

The degree of penetrative power of an X-ray changes depending on the type, thickness, or density of the target matter; therefore, it is possible to check defect conditions, changes of thickness, distribution conditions of the mixture, or the internal structure of an assembly from changes in transmitted X-ray intensity.

Scattering

When a material is irradiated with an X-ray, scattered radiation will be generated from the matter. Among the scattered radiation, those having an angle of 90 degrees or greater between the incident X-ray are called backscattered radiation. The intensity of this backscattered radiation increases with the increase in thickness of the matter.

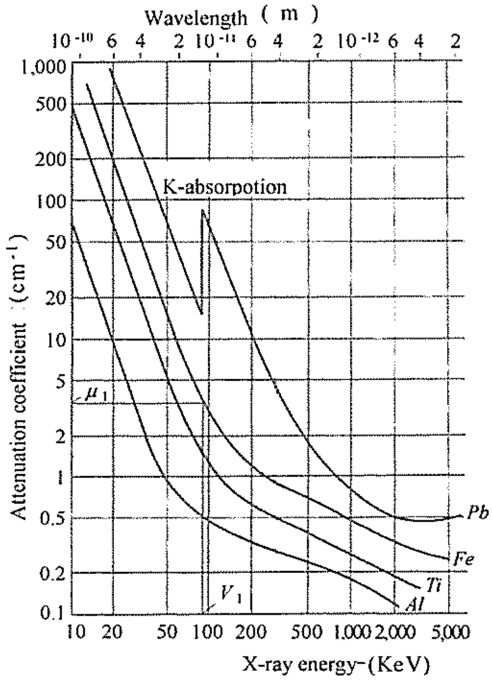

Figure 10. Relationship between the X-ray energy and the attenuation coefficients of various metals

Scattering is a method for measuring the thickness of matter using this property.

Diffraction

Many types of matter consist of crystals, and atoms or ions are regularly aligned inside crystals to form a lattice. Since intervals at which atoms line up are definite according to the type of matter, microscopic crystal structures of the matter that makes up the specimen can be made clear using an X-ray diffractometer. Moreover, by measuring the peak intensity of the diffracted X-rays, a quantitative analysis of the mixture or compounds constituting the specimen can be performed.

Spectroscopy

Spectroscopy is a method in which the lattice spacing of an atom is obtained by injecting a characteristic X-ray, generated when injecting an X-ray into the specimen, into a spectroscopic crystal of which the spacing of atomic planes has been obtained. X-ray fluorescence spectrometers can analyze matter quickly and nondestructively, with high accuracy.

Table 1. X-ray generator classification by application

Field	Name	Principle	Application
Science and engineering	X-ray radiographic testing equipment	Transmission (absorption)	Radiography, fluoroscopy, detection of material defects, etc.
	X-ray diffractometer	Diffraction	Crystal structure analysis, qualitative and quantitative analysis of matter
	X-ray stress analyzer	Diffraction	Measurement of residual stress of metals due to welding, heat treatment or casting
	X-ray fluorescence spectrometer	Spectroscopy	Qualitative/quantitative analysis of elements
	X-ray microanalyzer	Spectroscopy	Analysis of elements in micro region
	X-ray thickness gauge	Absorption, scattering	Measurement of metal thickness
Medicine	Diagnostic X-ray equipment	Transmission (absorption)	Radiography, fluorography, fluoroscopy
	Therapeutic X-ray quipment	Transmission (absorption)	Surface and deep X-ray therapy

6. Units of X-ray Doses

Absorbed dose

This is the amount of energy obtained as a result of absorption of radiation by a unit mass of matter. Its unit is defined as Gy (=J/kg).

Exposure dose

This is the amount of ionization of air, caused by an X-ray. It unit is C/kg.

Air kerma

Kerma is defined as the sum of the initial kinetic energy of all charged ionizing particles liberated into a unit mass of a tissue or organ by uncharged radiation (neutron ray, X-ray or gamma ray). The unit for kerma is J/kg or Gy. Air kerma is a quantity which expresses a field of indirectly ionizing particles using kerma for air, with the purpose of dose measurement.

Effective Dose and Equivalent Dose (Unit: Sv)

When categorizing the effects of radiation on the human body into probabilistic effects and non-probabilistic effects, the quantity for assessing the probabilistic effects is called the **effective dose**. The amount for assessing the non-probabilistic effects is called the equivalent dose, which expresses doses in a certain tissue of the human body.

Operational Quantity (Unit: Sv)

1 centimeter dose equivalent (H_{1cm})

This is a quantity used as an index for assessing the effective dose received by human tissues due to external exposure and the equivalent dose received by human tissues, excepting skin, due to external exposure. It is the quantity corresponding to a dose at a depth of 1 cm from the skin surface.

70 micrometer dose equivalent ($H_{70\mu m}$)

This is a quantity used as an index for assessing the equivalent dose received by the skin due to external exposure. It is the quantity corresponding to a dose at a depth of 70 μm from the body surface.

7. Three Principles of Radiation Protection

For protection from external exposure, (1) increasing distance from the radiation source, (2) reducing the time of exposure, and (3) providing appropriate shielding are important.

Distance

When the radiation source is a point source, the radiation dose per unit area is inversely proportional to the square of the distance from the radiation source.

Time

When the dose rate is constant, radiation exposure is proportional to the time of exposure.

Shielding

The transmittance of X-rays in air is shown in Figure 11. X-rays of 10 keV or less are attenuated to ½ or less with 1 m of air; however, 10 m of air is required for an X-ray of 20 keV. Therefore, X-rays between 50 and 100 keV, which are normally used, will not be attenuated at all by the air in a room, and shielding is necessary.

When an X-ray contacts matter, various types of interactions, as described in Figure 12, occur. The commonly used method for protecting experimenters from X-ray exposure is to shield the surroundings of the X-ray equipment with plates made from lead, iron or lead glass, or with clear plastic plates containing heavy metals, such as lead, etc. Examples of shielding effects are shown in Figure 13.

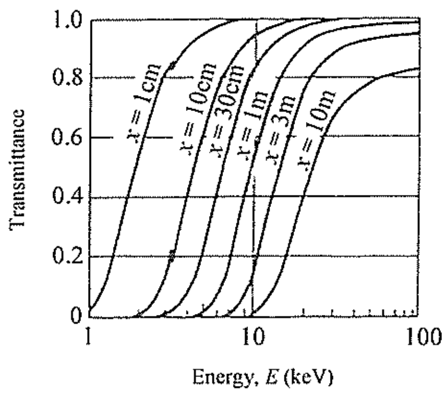

Figure 11. X-ray attenuation by air

Heavy metals are effective for shielding X-rays, and lead is particularly effective. The higher the metal density, the more effective the shielding effect, though the absorption spectrum will become rather complex, having sorption edges.

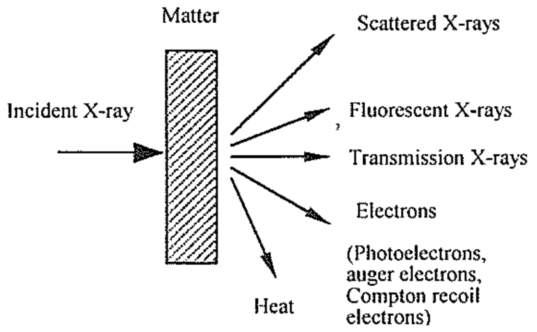

Figure 12. Interaction of X-rays with a matter

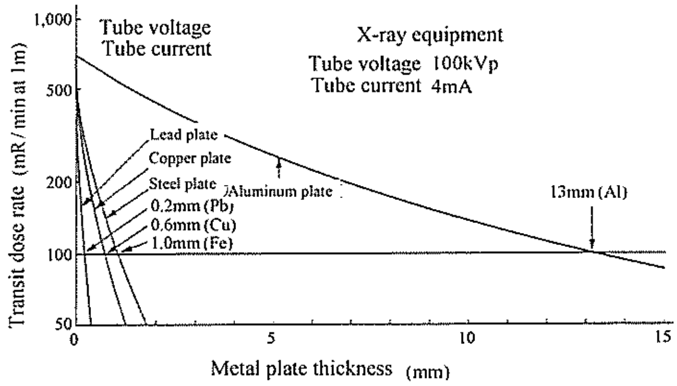

Figure 13. Thickness at which the transit doses become equal when different materials are used

8. X-ray Safety

(a) As is shown in Figure 14, transmitted radiation, leakage radiation and scattered radiation escape from X-ray equipment. In order to protect workers from exposure, the surroundings of the X-ray equipment are shielded by lead, lead glass, or plastic plates containing heavy metals, such as lead.
(b) Any body area should not be placed in the path of the useful beam.
(c) Equipment must be turned off while performing replacement of the specimen.
(d) In cases where the above are impossible, replacement must be performed after confirming that the shutter is closed.
(e) In order to avoid unnecessary exposure, improvement of work procedures and the equipment should be considered for reducing operation time.
(f) Concerning equipment in which targets can be replaced, an inspection for leakage X-rays must be performed using a survey meter at each replacement.

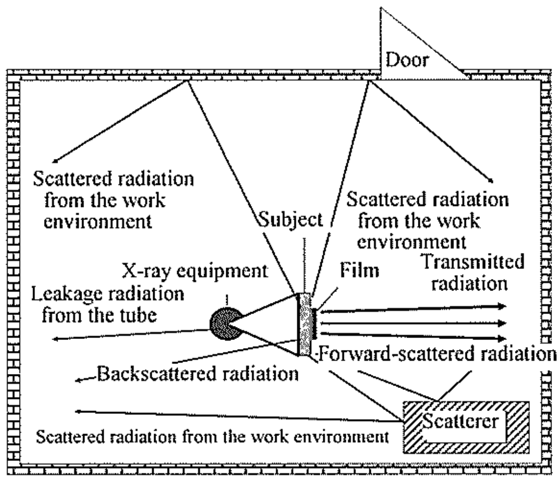

Figure 14. Transmitted radiation, scattered radiation and leakage radiation escaping X-ray equipment

9. Leakage from Major X-ray (Electron Beam) Equipment and Protection Against It

X-Ray Diffractometer

X-ray diffractometers produce an exceedingly large amount of primary X-ray doses. In addition, they make up a majority of X-ray equipment for researches and have many users. Consequently, they are the cause of many cases of radiation damage. For this reason, it is necessary to perform sufficient examination of operational procedures and provide appropriate shielding, while keeping in mind the following.

(1) The dose rate of primary X-rays is high. Figure 15 illustrates variations of primary X-ray doses, when the distance from the X-ray tube window was changed. Lead, molybdenum and cobalt were used as the targets. When molybdenum was used, the dose rate was 10 Gy/m at the position 10 cm from the shutter. At around 15 cm, where there is a risk of exposure at the time of adjustment or specimen replacement, the dose rate was 6 Gy/m, and 1 minute of exposure could cause symptoms such as erythema or alopecia. Moreover, as is indicated in Figure 16, X-ray diffractometers produce a great amount of scattered X-ray doses. At a position of 30 cm away from the specimen center, where the operator is most likely to be positioned, the dose rate was 100 μGy/h.

(2) Narrow beams become an issue. Though the local dose rate becomes an issue for narrow beams, a survey meter will show low measurement values. Beams with a large cross-section are necessary for accurate measurement of dose rates.

(3) X-ray irradiation and leakage largely vary depending on equipment. There are various forms of X-ray diffractometers. Nowadays, many of them are automated and highly safe. However, some of them require adjustments of specimens while they are being irradiated with X-rays, due to the characteristics of the experiments. In addition, in some places, older equipment is still used. Since much equipment is highly safe, it is all the more necessary to exercise extreme caution when using them.

(4) In Table 2, examples of accidents occurring in universities while using X-ray diffractometers are shown. Since an X-ray diffractometer is a piece of equipment that is used on a daily basis, users tend to lack awareness that they are using equipment that generates radiation. In particular, many accidents have occurred related to the opening and closing of the shutter; therefore, it is necessary to check the shutter each time. In addition, the area of the glass batch used when measuring personal exposure doses may change depending on the direction. Therefore, as is shown in Figure 17, it is necessary to check the direction and make sure that it is placed on the front side of work wear, on the chest for a male and on the abdomen for a female.

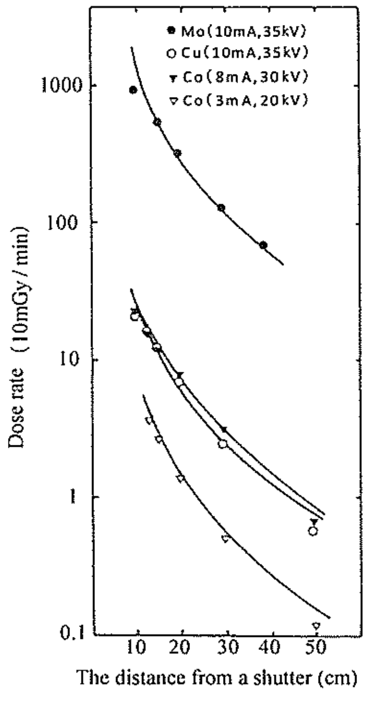

Figure 15. Primary X-ray dose rate of an X-ray Diffractometer (Konishi et al., 1982)

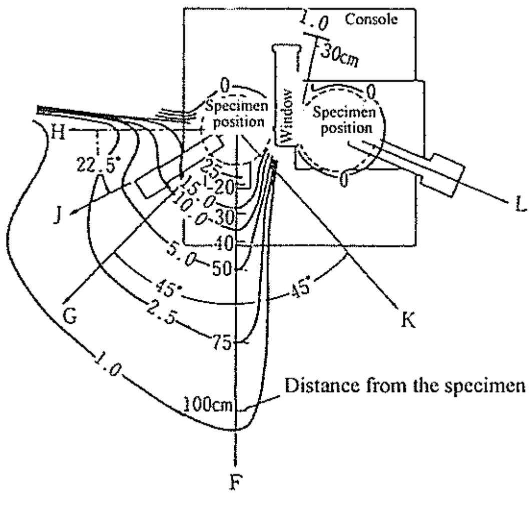

Figure 16. Distribution of leaked scattered X-ray dose from an X-ray generator (unit: 10 μGy)
(Co target, 30 keV, 20 mA, lead specimen)

Table 2. Examples of accidents occurring in universities while using X-ray diffractometers (Konishi, et al., 1982)

No.	Party involved	Number of people	Method used	Clue for finding the accident	Main exposure area	Estimated exposure dose	Cause
1	Student	3	Camera method	Clinical symptoms	Fingers	Approx. 9 Gy	The party was playing with the equipment to look at their bones through the fluoroscope.
2	Student	1	Camera method	The party noticed the accident.	Eyes	<0.2Gy	The lead glass of the beam viewer was not set.
3	University staff	2	Camera method	Information on the film badge	Chest, face	0.9mGy< 9mGy<	Same as above
4	Student	1	Camera method	The party noticed the accident.	Eyes	3-11mGy	Forgot to set the beam viewer.
5	University staff	1	Camera method	Same as above	Eyes	1mGy<	Same as above
6	Student	1	Camera method	Same as above	Fingers	200mGy	The party mounted the specimen without realizing that the shutter was open.
7	Student	1	Camera method	Same as above	Face	40-130mGy	The party adjusting the optical axis without realizing that the shutter was open.
8	Student University staff	4 1	Automatic recording method	Information on the film badge	Chest	0.5-1mGy	The shutter on the side not being used was closed for a long period of time.
9	Student	1	Automatic recording method	The party noticed the accident.	Fingers, chest, face	0-1Gy	The party mounted the slit without realizing that the shutter was open.
10	Student	1	Automatic recording method	Same as above	Abdomen	3mGy	The party turned the equipment on, misidentifying the shutter as being closed.
11	Student	1	Automatic recording method	Information on the film badge	Chest	4.9mGy	Unknown
12	Student	1	Automatic recording method	Same as above	Chest	1.8mGy	Unknown
13	University staff	1	Automatic recording method	The party noticed the accident.	Back of the hand	25mGy	The party mounted the specimen without realizing that the shutter was open.

Table 3. Causes for X-ray leakage from an electronic microscope (Konishi, et al.,, 1982)

Cause for leakage	Explanation	Leakage point
Gap at a joint	Due to deterioration, wear or loss of tightening force of the packing	Electron gun, specimen chamber, observation window frame
Lack of barrier thickness	Lead equivalent in the lead glass is insufficient. The barrier directly under the beam is thin.	Observation window, lower part of the camera chamber
Defect of a shield	The shield structure allows gaps to exist alongside the mirror body.	Lower part of the condenser lens
Inappropriate use of a shield	A portion of the shield was taken away due to a failure.	Lower part of the console

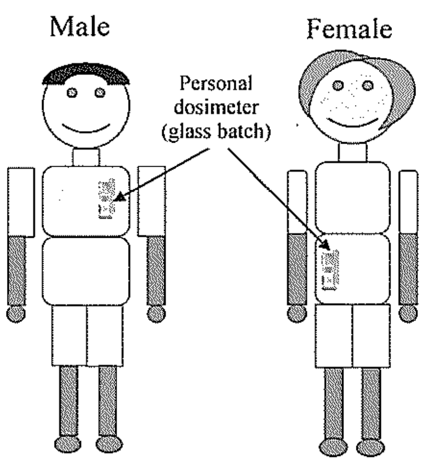

Figure 17. Positions in which the personal dosimeter (glass batch) should be placed

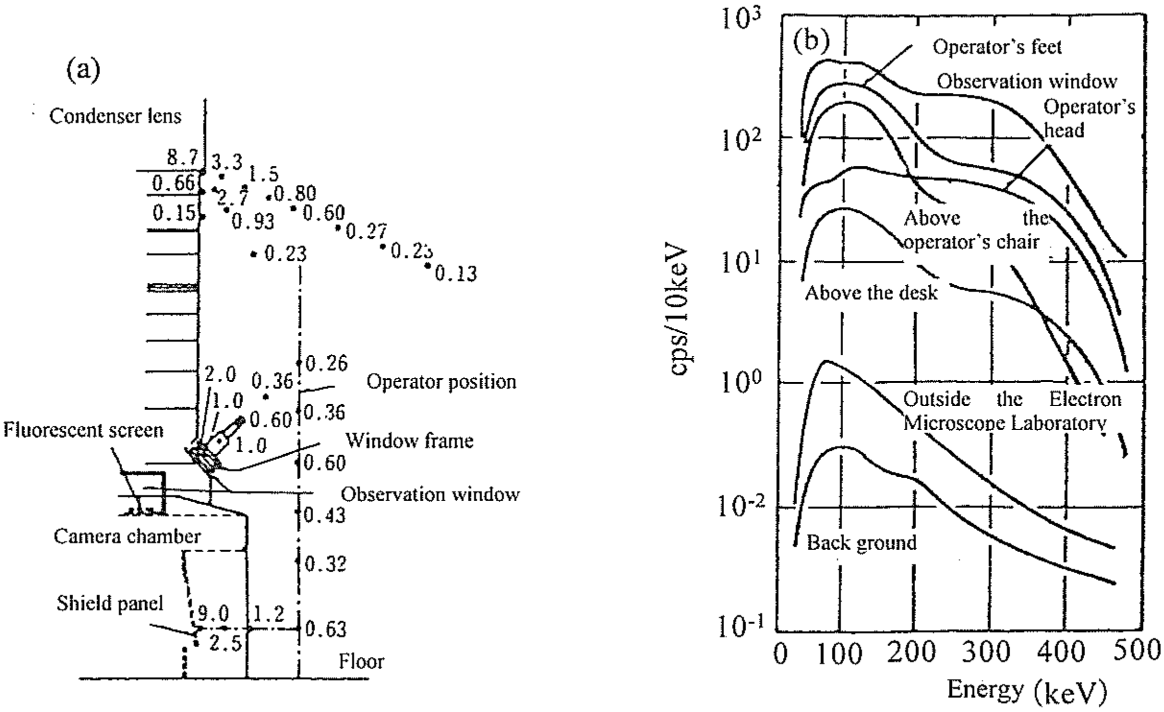

Figure 18. X-rays leaked from a large-scale electronic microscope (500 kV, 19 μA)
(a) dose rate of the vertical section, (b) energy spectra (NaI)

Electronic Micrometer

Although electronic micrometers do not directly use X-rays, X-rays are generated when electron beams are decelerated by the lens or specimen. The types and energy of leaked X-rays are shown in Figure 18. The major leaking points are the electron gun, specimen chamber, observation window, camera chamber, etc. The causes for leakage are items listed in Table 3.

10. Radiography

When taking a radiograph using X-ray equipment, the X-ray tube voltage, X-ray tube current and exposure time are set as the radiographic conditions. Changes in the characteristics when the tube voltage is changed are shown in Table 4. The contrast of a radiograph in X-ray radiography becomes lower as the tube voltage becomes higher. An example of taking a radiograph of the human body using different tube voltages is shown in Figure 19. In a high radiograph under high voltage, the contrast is a little weaker than that of a radiograph under a normal voltage.

Table 4. Changes of the characteristics in response to tube voltage

Tube voltage	Radiation quality	Penetrating power	Absorption in the human body	Amount of scattered radiation	Radiography contrast
High	Hard	Strong	High	Many	Weak
↕	↕	↕	↕	↕	↕
Low	Soft	Weak	Low	Few	Strong

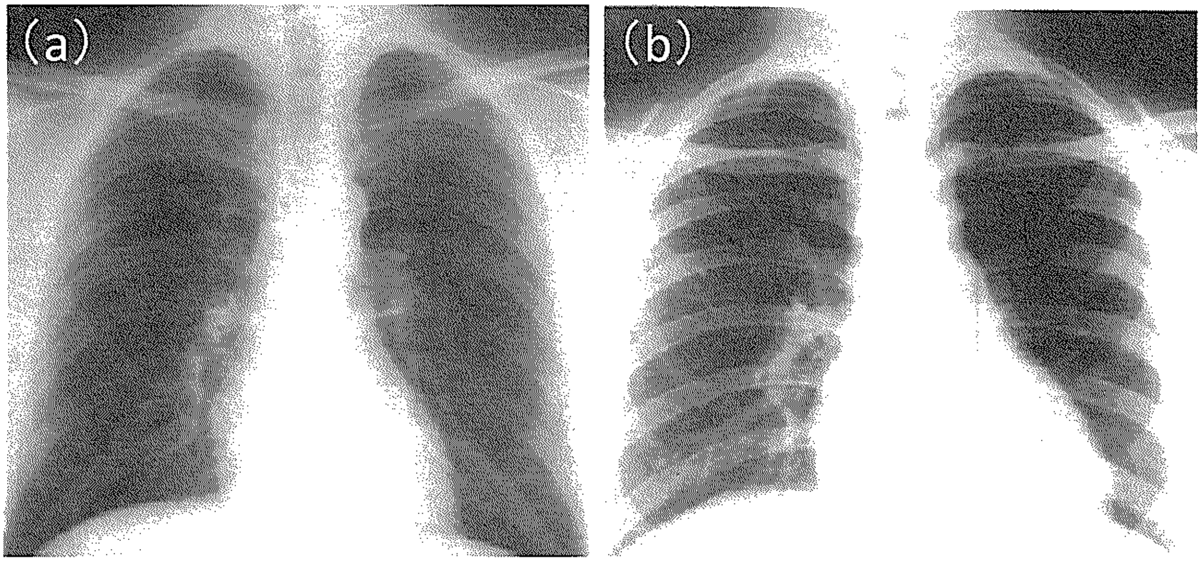

Figure 19. High voltage radiograph and normal voltage radiograph, (a) high voltage radiograph (tube voltage 140,000 V) (b) normal voltage radiograph (tube voltage 70,000 V)

References

"Authorized Chief X-ray Inspection Engineers Training Course Textbook", edited by the Electron Science Institute, Kosaido Co., Ltd., 2001.

"X-ray Operation Training Course Textbook", Radio Isotope Center, Kyushu University.

11. Taking a Radiograph

When taking a radiograph using X-rays, the irradiation cone and diaphragm are attached to the X-ray tube, as is shown in Figure 1, to limit the range from which X-rays come out. Scatter radiation is mixed in X-rays that transmit through the subject, lowering the image contrast; therefore, an X-ray grid is often used to remove scatter radiation. In Figure 2, cassettes in which film are contained are shown. There are various sizes of cassettes according to their purpose. Figure 3 is an opened cassette. The cassette contains a bluish-colored film in it, and there is a white intensifying screen on the left of the film. There is another intensifying screen underneath the film that the film is held between for exposure.

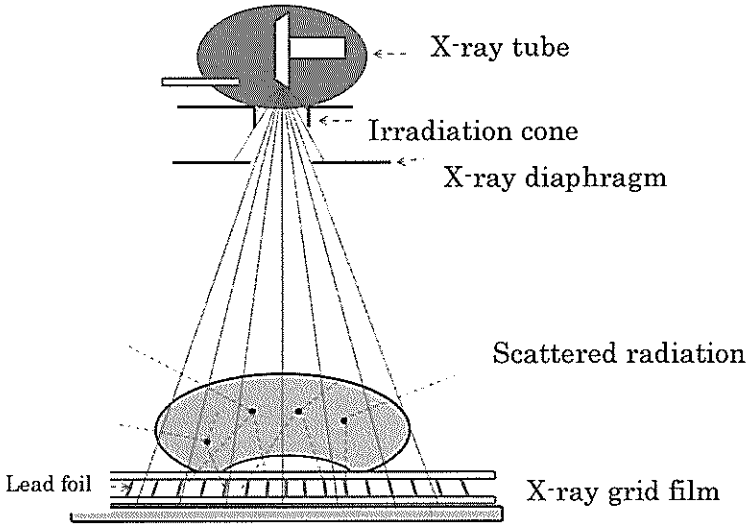

Figure 1. Geometric configuration of X-ray radiography

Figure 2. Cassette types

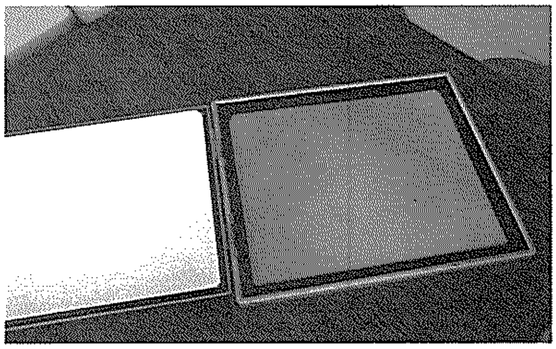

Figure 3. Cassette and film

Until more than 10 years ago, radiography using an analog X-ray intensifying screen-film system, which directly exposes film, as was described above, was the mainstream. However, today, a digital system using a computer has become the mainstream. The digital system digitalizes X-ray data using systems such as Imaging Pate (IP) or Flat Panel, without using film. As is shown in Figure 4, images are broken down into pixels and displayed. The smaller the pixel size (a), the more detailed the displayed data However, as the pixel size becomes smaller, the number of pixels increases, increasing the load on the computer.

As a result of the development of computer technologies, practical application of the digital X-ray radiography system has been promoted. The benefit of digitalization is that easy-to-view images can be generated through image processing and that images can be used for systems such as CAD (Computer Aided Diagnosis), which assists doctors in making diagnoses by detecting focal regions. Moreover, images stored on the server can be exchanged within the network, which brings benefits such as saving users the time and effort of saving or searching for film.

In addition, through image processing, it is possible to provide images with optimum density regardless of the amount of irradiated X-ray dose by adjusting the image density. Although this is a benefit in the sense that it can reduce the number of takes, it has another aspect in which it makes it difficult to grasp the exposure doses of patients; therefore, it is necessary to exercise greater control of X-ray doses.

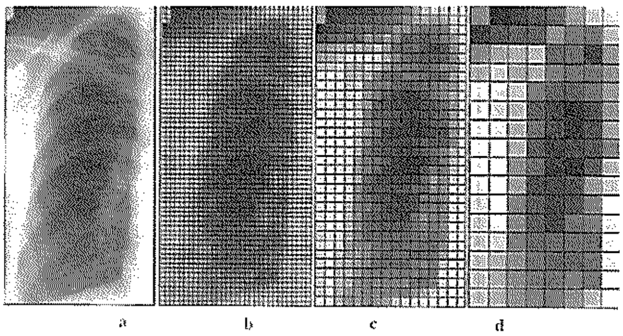

Figure 4. Pixels of the digital system
(a has the smallest pixel size, and d has the largest pixel size.)

Effects of Radiation

on Human Health

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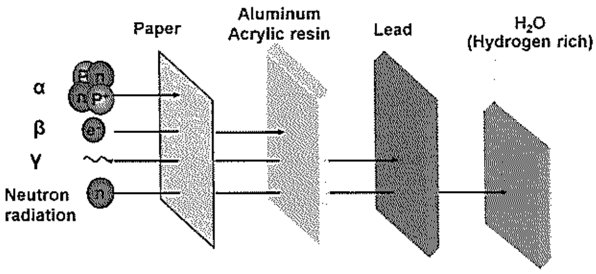
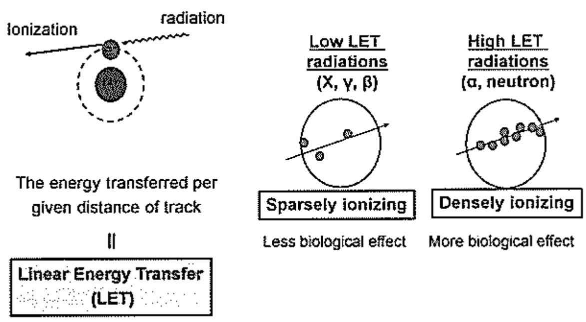
Factors that relate to biological effects

1. Penetrating ability
2. Linear Energy Transfer (LET)

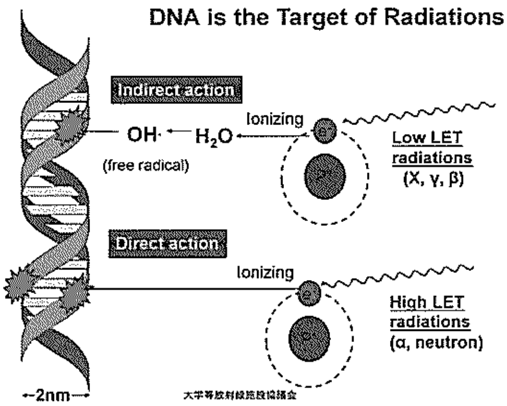
1. Penetrating Ability of Radiations



2. Linear Energy Transfer (LET)



DNA is the Target of Radiations



Classification of Biological effects of Radiations on the Human Body

- Acute Effects vs. Late Effects
- Deterministic Effects vs. Stochastic Effects
- Somatic Effects vs. Genetic Effects

Classification of Biological effects of Radiation on the Human Body

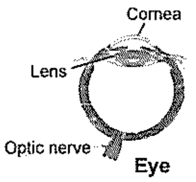
- Acute Effects vs. Late Effects
- Deterministic Effects vs. Stochastic Effects
- Somatic Effects vs. Genetic Effects

Acute Effects

Symptoms of acute effects and dose delivered (Whole body, single exposure to gamma rays (or X-rays))

Dose (Gy)	Symptoms
0.25 or less	Almost no clinical symptoms
0.5	Temporary reduction of white blood cells (lymphocytes)
1	Nausea, vomiting, whole-body languor, substantial reduction of lymphocytes
1.5	Radiation sickness to 50%
1	Death to 5%
4	Death to 50% within 30 days
6	Death to 90% within 14 days
7	Death to 100%

Late Effects



Cataracts: clouding of the lens of the eye
- Latent period: several years to a few decades
- Do not occur below a single exposure dose of 2 Sv

Cancers
- Latent period: several years to a few decades

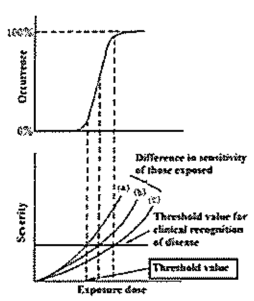
Genetic effects
- Could be
- But not verified in human beings so far

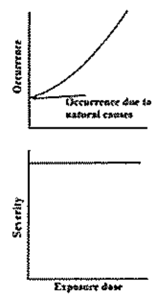
Use a appropriate shield in front of your eyes

Classification of Biological effects of Radiation on the Human Body

- Acute Effects vs. Late Effects
- Deterministic Effects vs. Stochastic Effects
- Somatic Effects vs. Genetic Effects

Deterministic Effects vs. Stochastic Effects





Deterministic Effects
- Acute effects
- Cataract

Stochastic Effects
- Cancer, leukemia
- Genetic effects

Deterministic effects

Projected threshold estimates of the acute absorbed dose for 1% morbidity after whole body gamma ray exposures

Effect	Organ/Tissue	Time to develop effect	Absorbed dose (Gy)
Temporary sterility	Testes	3-9 weeks	~ 0.1
Permanent sterility	Testes	3 weeks	~ 6
	Ovaries	< 1 week	~ 3
Depression of blood forming process	Bone marrow	3-7 days	~ 0.5
Skin reddening	Skin (large areas)	1-4 weeks	< 3-6
Skin burns	Skin (large areas)	2-3 weeks	5-10
Temporary hair loss	Skin	2-3 weeks	~ 4
Cataract (visual impairment)	Eye	Several years	~ 1.5

ICRP publication 103, pp168, Table A.3.4, 2007

Deterministic effects

Projected threshold estimates of the acute absorbed dose for 1% mortality after whole body gamma ray exposures

Exposed population	Organ/Tissue	Time to develop effect	Absorbed dose (Gy)
Bone marrow syndrome			
without medical care	Bone marrow	30-60 days	~ 1
with good medical care	Bone marrow	30-60 days	2-3
Gastro-intestinal syndrome			
without medical care	Small intestine	6-9 days	~ 6
with good medical care	Small intestine	6-9 days	> 6
Pneumonitis	Lung	1-7 months	6

ICRP publication 103, pp168, Table A.3.4, 2007

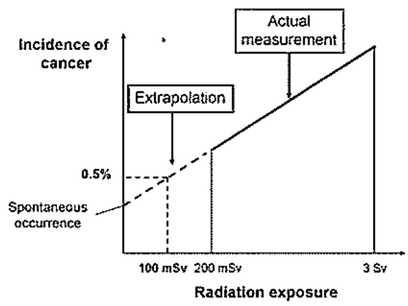
Stochastic effects

Detriment-adjusted nominal risk coefficients after exposure to radiation at low dose rate

Exposed population	Cancer	Heritable effects	Total
Whole population	5.5×10^{-2}/Sv	0.2×10^{-2}/Sv	5.7×10^{-2}/Sv
Adult workers	4.1×10^{-2}/Sv	0.1×10^{-2}/Sv	4.2×10^{-2}/Sv

ICRP publication 103, pp53, Table 1, 2007

Risk Estimate for Cancers (Stochastic Effect)



Classification of Biological effects of Radiation on the Human Body

- Acute Effects vs. Late Effects
- Deterministic Effects vs. Stochastic Effects
- Somatic Effects vs. Genetic Effects

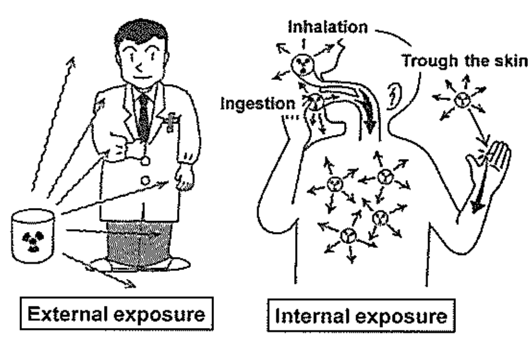
Somatic Effects

Effects of radiation limited to the exposed individual, as distinguished from genetic effects, that may also affect subsequent unexposed generations.

Genetic Effects

The radiation induced change in the DNA of germ cells resulting in the passing of the altered genetic information to future generations.

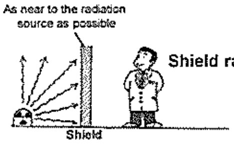
External Exposures vs. Internal Exposures



Protecting Against External Exposure

3 principles

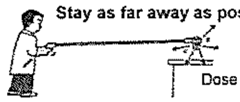
Shielding



Shield radiation sources.

Distance

Stay as far away as possible.



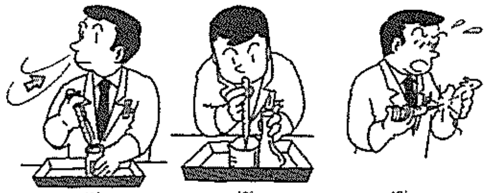
Dose rate = K/ R^2
K: constant
R: distance

Time

Keep exposure time short !

Protecting Against Internal Exposure

Intake routes of radioisotopes

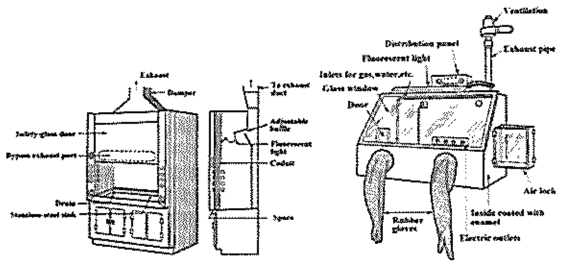


(1) **Inhalation**

(2) **Ingestion**

(3) **Through the skin (wound)**

To Prevent the inhalation of radioisotopes



Oak Ridge-type hood

Glove box

Prohibited Matters

Eating or drinking

Smoking

Wearing make-up

Radiation-Related Quantities and Units

Absorbed Dose : Gray (Gy)

- The energy absorbed per unit mass of the material
- A fundamental dosimetric quantity (physical unit)
- Regardless of the kind of radiation
- 1 Gy = 1 J/ kg
- Dose not reflect the degree of biological effects

To calculate the risk of irradiation to the human body

Equivalent Dose : Sievert (Sv)

Effective Dose : Sievert (Sv)

Equivalent Dose & Effective Dose

Equivalent Dose (H_T) : Sievert (Sv)

- a measure of biological effects on a particular tissues or organs
- $H_T = \sum_R w_R \cdot D_{T,R}$

w_R : Radiation weighting factor
$D_{T,R}$: Mean absorbed dose for a tissue or organ (Gy)

Radiation weighting factor (w_R)

Radiation	Weighting Factor
γ rays & X rays	1
Beta rays	1
Proton	2
α rays, fission fragments, heavy ion	20
Neutrons	Continuous function of the energy

(ICRP 2007)

Equivalent Dose & Effective Dose

Effective Dose (E) : Sievert (Sv)   Stochastic effects

- a measure of biological effects throughout the body (cancers or genetic effects)
- $E = \sum_T w_T \cdot H_T = \sum_T w_T \cdot \sum_R w_R \cdot D_{T,R}$

H_T : Equivalent dose for tissues and organs

w_T : Weighting factor for organs or tissues

Annual average dose per person

Doctors	0.24 mSv
Nurse	0.12 mSv
Radiotherapy technicians	0.68 mSv
Those engaged in research	0.01 mSv
Nuclear power plant worker	1.3 mSv

Tissue weighting factors

Tissue/Organ	Weighting factor
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Breast	0.12
Gonads	0.08
Bladder	0.04
Esophagus	0.04
Liver	0.04
Thyroid	0.04
Bone	0.01
Brain	0.01
Salivary gland	0.01
Skin	0.01
Others	0.12

(ICRP 2007)

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Effective Dose Limits and Tissue Equivalent Dose Limits for Radiation Workers (including Researchers)

Effective dose limit	50 mSv/year; 100 mSv/5years
Women	5 mSv/3 months
Pregnant women*	1 mSv as internal exposure
Tissue equivalent dose limit	
1) Lens of the eye	150 mSv/year
2) Skin	500 mSv/year
3) Abdomen of pregnant women*	2 mSv

*From the confirmation of pregnancy to delivery

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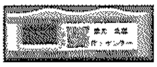
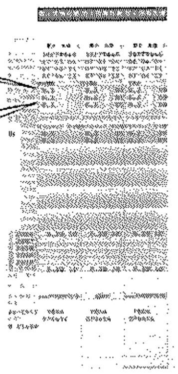
Personal Radiation Monitoring

Personal monitoring instrument



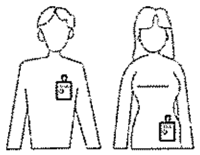
Radiation exposure report



Effective dose (実効線量)

Equivalent dose (等価線量) for the lens, skin and abdomen

Where should a monitoring instrument be worn on?



Men   Women

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End of slides

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Applicable law
Ordinance on Prevention of Ionizing Radiation Hazards

1. Radiation is a double-edged blade

Use of radiation always entails both benefits and damages. Benefits refer to the advancement in scientific research through the use of radiation which makes it possible to contribute to society; damages mean radiation hazards caused by overexposure to radiation.

Achieving a balance between benefits and damages needs to be borne in mind when using radiation.

2. History of radiation hazards

X-ray was discovered by W. K. Roentgen in 1895. Because of its high penetrating power, it began to be used for medical use. Shortly after the start of its medical use, however, symptoms such as X-ray skin irritation or eye pain started to be seen. Cases of skin cancer and leukemia were also reported.

For this reason, the X-ray and Radium Protection Committee was established in England in 1921, which started activities to protect researchers from overexposure to radiation and radioactivity. Recommendations issued by this Committee were used as international standards for some time.

In 1924, the International Congress of Radiology (ICR) was held in England, where the need for international activities in relation to radiation units and measurements was emphasized. The International Commission on Radiation Units and Measurements (ICRU) was established by the Congress, which started activities to propose internationally-agree-upon units for radiation/radioactivity and standardize procedures for measurements.

The Second ICR was held in Stockholm, Sweden, in 1928, where the International X-ray and Radium Protection Committee (which is the predecessor of ICRP) was established and recommendations titled "X-ray and Radium Protection" were issued. These recommendations targeted radiologists, X-ray technicians and nurses and mainly concerned the improvement of working environment at hospitals, the issues of X-ray shields, and the prevention of electric shock caused by X-ray equipment.

At the Sixth ICR held in London in 1950, ICRU became an independent organization and was renamed as the International Commission on Radiological Protection (ICRP) . The renamed commission expanded the scope of targeted radiations from traditional X-rays and radium to include all ionizing radiations.

3. ICRP (International Commission on Radiological Protection)

International Commission on Radiological Protection is an international organization which provides recommendations on radiological protection from specialists' points of view. Established by the Second ICR held in 1928, it consists of four specialized committees, which give consideration to the basic idea of radiological protection, protection standards, and the measures for radiological protection. The results of consideration are published as recommendations or publications, which are used as the model for radiological protection standards in countries around the world.

4. Relationship between the ICRP recommendations and domestic laws

In response to ICRP's 1985 recommendations (publ. 1), the Act on Prevention of Radiation Disease Due to Radioisotopes, etc. was established in Japan in 1960.

Since then, laws in Japan have been modified in response to the 1977 recommendations (publ.26) and 1990 recommendations (publ. 60). The introduction of the 2007 recommendations (publ. 103) to domestic laws is now under consideration.

As mentioned above, the idea of radiological protection has always had its basis in the global standards.

5. Goals for radiological protection

Applicable laws are not to unfairly limit the use of radiation. Their goal is to allow the use of radiation for the advancement of society by controlling damages to acceptable levels, first by ensuring people's safety; second, by preventing critical effects; and third, by taking measures to reduce stochastic effects.

6. Radiological protection system

The basis for radiological protection is to ensure public safety.

Let us consider the example of an X-ray equipment room. In the X-ray equipment room, radiation is used to pursue scientific research to make contributions to society. While conducting a research, radiation users can get exposed to a certain amount of radiation leaking from X-ray equipment.

The amount of radiation leakage can be increased or decreased by the tube voltage and tube current of X-ray equipment as well as by the use of shielding partitions. Reducing the exposure dose of radiation users by controlling the amount of radiation leakage can also lead to the reduction in the public exposure dose.

The basic idea for radiation use in ICRP's radiation dose control system is as follows:

a) Any actions shall not be introduced unless such actions generate net positive benefits.

It is to ensure that activities causing radiation exposure are not always unjustifiable in terms of their benefits or benefits from possible alternative measures.

b) All radiation exposure shall be kept as low as reasonably achievable while taking the economic and social factors in consideration. The realization of this is optimization.

c) Any radiation exposure shall not exceed the dose limit value indicated by the ICRP.

Personal dose equivalent shall not exceed the limit recommended by the ICRP according to each circumstance.

In case of exceeding the dose limit, it will be handled as an "accident."

7. Laws regarding radiation safety in Japan

The Atomic Energy Basic Act forms the basis for the atomic energy use in Japan.

This law has a provision that establishes that "a separate law shall be established in connection to the prevention of radiation diseases." In response to this provision, the Act on Prevention of Radiation Disease Due to Radioisotopes, etc. was established.

Other laws have been established according to the specific circumstances such as business categories that handle radiation. More than 20 laws have been established: for example, the National Public Service Act provides for provisions regarding health and safety of public servants; the Industrial Safety and Health Act provides for provisions regarding workers' safety and health; and the Civil Aeronautics Act provides for provisions regarding the safe transport of radioisotopes.

8. Ordinance on Prevention of Ionizing Radiation Hazards

Article 1: The employer shall endeavour to minimize the exposure of workers to ionizing radiation as low as possible.

This article defines the basic principle of the Ordinance since the possibility of having stochastic effects cannot be denied even if the radiation dose to human body is below the amount established under the Ordinance.

While radiation has health effects to human body, it could also have a lot of benefits. The use of radiation is, therefore, socially permitted within the extent of its benefits. Therefore, when using radiation, it is best to minimize the exposure to radiation as low as possible to achieve the objectives.

This Ordinance consists of 62 articles; Chapter I provides for General Provisions; Chapter II is on Controlled Area, Limit and Measurement of Dose; Chapter III is on Protection against External Radiation; Chapter IV provides for Protection of Contamination; Chapter IV-II is on Control of Special Work; Chapter V provides for Emergency Measures; Chapter VI provides for Operations Chief of Work with X-rays and Operations Chief of Work of Transmissive Photography with Gamma Rays; Chapter VI-II provides for Special Education; Chapter VII is on Working Environment Measurement; Chapter VIII provides for Medical Examination; and Chapter IX provides for Miscellaneous Provisions.

The X-rays we will be handling is defined as one of the ionizing radiations in Article 2 of this Ordinance.

9. Safety control system, workers' safety control, and equipment safety measures

Regarding the safety control system, in pursuant to Article 10 of the Industrial Safety and Health Act, the Ordinance establishes that the employer shall staff each office with a health supervisor and an industrial physician to manage and supervise the implementation of measures to prevent occupational risks and health problems, the provision of safety and health education and medical examinations, the investigation of causes of occupational accidents, and the establishment of measures to prevent recurrence of such accidents.

Article 48 of the Ordinance on Prevention of Ionizing Radiation Hazards sets forth that the employer shall select an operations chief of work with X-rays for each controlled area from among those who have been granted the license for operations chief of work with X-rays, to instruct and supervise workers on safety when handling X-ray equipment.

For workers' safety control, the Ordinance obliges the employer to provide special education, medical examinations, and exposure dose measurements. However, medical examinations and exposure measurements are only provided for those workers who enter the controlled area.

The Ordinance also sets forth that special education shall be given once before having the workers engage in radiation work, and then periodically at least every one year, in terms of the predetermined subjects and for longer than the designated hours.

The Ordinance also establishes that medical examinations shall be provided once before having the workers enter the controlled area, and then periodically at least every six months, in terms of the predetermined checkup items.

Radiation exposure dose shall be measured on a continuous basis during the period the workers enter the controlled area.

Results of the medical examinations and exposure dose measurements shall be kept for a period of 30 years after records have been taken.

Regarding safety measures involving X-ray equipment, the Ordinance sets forth that, according to Article 88 of the Ordinance on Industrial Safety and Health, an installation or modification plan for X-ray equipment must be submitted to the competent supervising agency for labor standards at least 30 days prior to such work, in order to ensure safety. The plan needs to include the analysis of radiation exposure dose, the placement of signs and precautions, and the installation of alarm devices. The Ordinance obliges the employer to take measurements of radiation leakage and ensure safety before using the installed X-ray equipment; the Ordinance also obliges the employer to take measurements of the amount of radiation at the border to the controlled area periodically at least every six months.

10. Radiation equipment room

X-ray equipment shall be, by principle, installed inside a special room (radiation equipment room).

A designated sign must be placed at the entrance to the radiation equipment room, and unauthorized persons shall not be allowed to enter the room.

The following is the requirements for installing X-ray equipment at locations other than the radiation equipment room as exceptions:

(1) Equipment whose dose rate (H1cm) at its outer side is shielded at less than 20μSv$\cdot h^{-1}$;

(2) When moving radiation equipment as needed while in use; and

(3) When installing radiation equipment inside the radiation equipment room precludes its intended use or when such installation is considerably difficult for work operation.

11. Controlled Area

A controlled area is the area where there is a possibility for radiation exposure and where workers' health control is required. It is defined as the area where the exposure dose for 3 months exceeds or is likely to exceed 1.3 mSv.

Designated signs and precautions must be placed at the controlled area, and unauthorized persons shall not be allowed to enter the area.

12. Electron Microscope

An electron microscope is "equipment that accelerates electrically-charged particles" and is accompanied by secondary generation of X-rays; however, it does not fall under the category of "X-ray equipment" under the Ordinance on Prevention of Ionizing Radiation Hazards.

However, it is necessary to set up a controlled area if there are areas where the exposure dose of secondarily generated x-rays exceeds or is likely to exceed 1.3 mSv.

Even when there is no need to set up a controlled area, the exposure dose must be controlled so that it does not exceed the public annual limit of 1 mSv.

13. Special Education

As workers who will engage in work to undertake transmissive photography with X-ray equipment or gamma-ray radiating equipment are required to have sufficient knowledge to carry out the work safely, the employer must provide special education in terms of the predetermined subjects and for designated hours before having the workers engage in such work.

14. Medical examination

Medical examinations are provided to enhance industrial safety and health of workers who engage in work involving radiation, by continually checking their health condition.

The employer must provide medical examinations by a physician of the following checkup items to those workers who regularly engage in the radiation work and enter the controlled area, at the time of employment, before the transfer to such work, and then periodically every six months:

(1) Previous exposure and its analysis
(2) Examination of white blood cell count and white blood cell percentage
(3) Examination of red blood cell count, hemoglobin content and hematocrit value
(4) Examination of eyes for cataract (this may be omitted depending on the type of radiation sources)
(5) Dermatological examination

In regular medical examinations, all or part of the checkup items (2) through (5) may be omitted if deemed unnecessary by the physician. Medical examinations for workers whose effective dose of the previous year does not exceed 5 mSv in the regular medical examinations, and also whose effective dose is unlikely to exceed 5 mSv over the year in which the said medical examination is scheduled to be carried out, shall not require the inclusion of items (2) through (5) if deemed unnecessary by the physician.

At the time of medical examination, the employer shall submit to the physician the data showing the dose to which said workers were exposed since the last medical examination.

15. Dose limit by location

Dose limits by location are established by law. Exposure dose should be minimized as low as possible, but it shall be controlled and used so that the dose limit will be below the following limits at a maximum:

(1) Areas where people enter at all time: 1mSv/week

(2) Border to the controlled area: 1.3mSv/3 months

(3) Border to the business facility: 250 μSv/3 months

(4) Patient's room at hospital or clinic: 1.3mSv/3 months

16. Dose limit for workers engaged in radiation work

Dose limits are established at which health effects of radiation exposure is socially acceptable. These limits must not be exceeded at any time except for emergency.

(1) Effective dose

5-year accumulated dose 100mSv/5 years

Annual dose 50mSv/year

Women 5mSv/3 months (except for those who expressed that they have no intention to get pregnant.)

Women 1mSv/during pregnancy

(2) Equivalent dose

Lens of the eye 150mSv/year

Skin 500mSv/year

Women's abdomen 2mSv (during pregnancy)

17. Emergency Response

Emergency situation is when shields unexpectedly get damaged and/or when the X-ray radiation cannot be stopped immediately. Areas where the effective dose is likely to exceed 15 mSv shall be established as restricted zones, and people must immediately evacuate from these zones.

18. Penalties

In case of violating laws such as the Industrial Safety and Health Act, the violator as well as the legal entity will be punished.

The penalties are as follows:

(1) Examples of imprisonment of 6 months or less, or a fine of 500,000 yen or less:

When the operations chief of work has been selected, but the violator failed to assign him/her the work required by the ministerial ordinance of the Ministry of Health, Labour and Welfare;

When measures necessary to prevent radiation health hazards were not taken;

When no special education was provided; or

When measurements were not taken for working environment or the results of the measurements were not recorded.

(2) Examples of a fine of 500,000 yen or less:

When X-ray equipment was used without registration, or the main part of it was altered.