Photo from 1957

Louis Harold Gray

He is honored by calling the physical dose unit "gray*" – abbreviated Gy

Bq = becquerel
Gy = gray

(Sv = sievert)

Chapter 5

Activity and Dose

The activity of a radioactive source

When an atom disintegrates, radiation is emitted. If the rate of disintegrations is large, the radioactive source is considered to have a high activity.

The unit for the activity of a radioactive source was named after Becquerel (abbreviated Bq) and is defined as:

1 Bq = 1 disintegration per sec.

In a number of countries, the old unit, the curie (abbreviated Ci and named after Marie and Pierre Curie) is still used. The curie-unit was defined as the *activity in one gram of radium*. The number of disintegrations per second in one gram of radium is 37 billion. The relation between the curie and the becquerel is given by:

$1\ Ci = 3.7 \cdot 10^{10}\ Bq$

The accepted practice is to give the activity of a radioactive source in becquerel. This is because Bq is the unit chosen for the system of international units (SI-units). But one problem is that the numbers in becquerel are always very large. Consequently the activity is given in kilo (10^3), mega (10^6), giga (10^9)and tera (10^{12}) becquerel. If a source is given in curies the number is small.

For example; when talking about radioactivity in food products, 3,700 Bq per kilogram of meat is a large number and consequently considered to be dangerous. If however, the same activity is given in Ci, it is only 0.0000001 curie per kilogram – "*nothing to worry about?*".

Intensity of radioactive sources

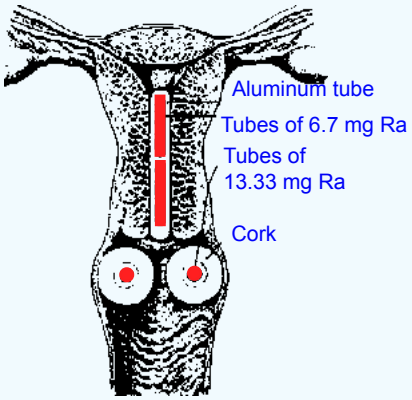
Most people are used to measuring the amount of a substance in kilograms or liters, not in becquerels or curies. If we are using the best balances in the world, we can accurately measure down to about one microgram of substance (10^{-6} gram). By using our knowledge of radioactive detection, amounts more than a million times smaller than this can be measured. Radioactive sources as small as 10 – 100 Bq can be readily measured; which corresponds to only about 10^{-14} gram.

Some examples

Around 1930, radium sources were introduced in many hospitals and used for cancer therapy. In spite of the fact that radium and its daughter nuclides emit α-particles and β-particles, it is the accompanying γ-radiation that is used for treatment. Examples are given below.

In the first example the source consists of a number of needles filled with radium (in the milligram range). In the other example all radium is in one source (3 gram radium). This gives rise to the two types of treatment; brachytherapy and teleteraphy.

An example of brachytherapy

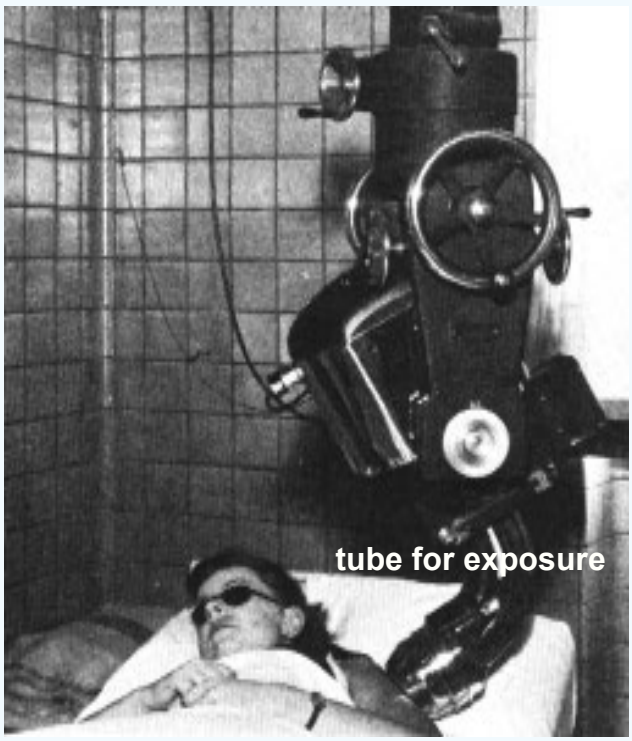


The drawing to the left is from 1931 and demonstrates the treatment of a cervical cancer by using small needles containing radium. The needles can be placed in quite close contact with the tumor.

Cork containers are used for the vaginal sources and a cylindrical tube for the uterine sources. The source in the example is all together 40 millicurie – or 1480 mega Bq (MBq) – 1.48 million Bq.
In some cases, the needles with radium were melted into solid paraffin and placed directly on the skin of the patient.

An example of teletherapy

In the period from 1930 up to about 1960, radium was used for cancer treatment. Then the radium sources were exchanged with Co-60 or Cs-137 sources – and high energy accelerators (Betatrons and Linear accelerators). In the period with radium, a number of hospitals around the world, were called Radium Hospitals. In Norway the Radium hospital was opened in 1932 – based on a radium source of 4 gram. One gram was divided in a number of small needles and used for brachytherapy. The rest – 3 gram – was used for teletherapy – and was called "*The radium cannon*". See picture next page.

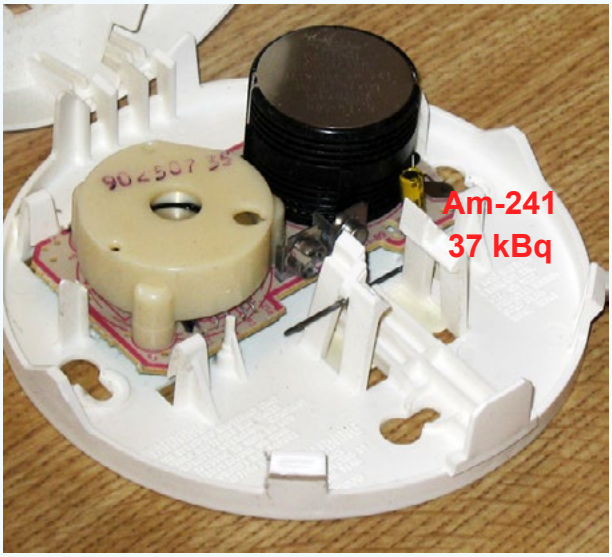


The source consisted on 3 gram radium; that is 3 Ci or 111 GBq (1 GBq = 10^9 Bq).

The source was kept in a lead container when not in use. For treatment the source was brought into the exposure position – approximately 10 cm from the skin. A treatment lasted for about 45 minutes. The dose given was of the order 2 Gy (see later in this chapter).

The treatment time was quite long for the patients since they could not move out of position during the treatment. With stronger sources the treatment time was reduced considerably.

Smoke detectors



To the left you see a modern smoke detector. The detector (the round black box) consists of a radioactive source – which emits α-particles into a small air chamber between two electrodes. The particles ionizes the air and a current of ions go from one electrode to another.
When smoke particles come into this small air chamber, they will absorb the α-particles. The number of ions formed as well as the current will go down and the alarm goes!

The radioactive source consists of Am-241 with an intensity of about 35 kBq. Americium is a transuranic element with atomic number 95. The isotope Am-241 decays via an α-particle (energy of about 5 MeV) and some very weak γ-rays. The half-life is 432 years. We can write this decay as follows:

$$^{241}_{95}Am \Rightarrow {}^{4}_{2}He + {}^{237}_{93}Np$$

It is seen that americium decays into neptunium – which in turn is a radioactive isotope. However the half-life for the neptunium isotope is 2.2 million years – which implies that this isotope in practice is stable.
The isotope used in smoke detectors is harmless to people (unless you eat it) and also harmless to the environment.

Specific Activity

Specific activity is the activity per mass or volume unit. For example, the radioactivity in meat is given as ***Bq/kg***. For liquids the specific activity is given in ***Bq/l*** and for air and gases the activity is given as ***Bq/m³***.

In the case of fallout from a nuclear test or accident, the activity on surfaces can be given either as Bq/m² or as Ci/km². Both are used to describe radioactive pollution. The conversion between them is:

$$1 \text{ Ci/km}^2 = 37{,}000 \text{ Bq/m}^2$$

It is necessary with information – and you still have a long way to go in order to calculate radiation doses and risk factors associated with these specific activities. The information must include the specific activity along with the various types of isotopes, their energies, physical and biological half-lives and methods of entry into the body. After considering all of these factors, a determination of risk can be estimated.

Radiation Dose

So far we have discussed the intensity of a radioactive source – i.e. the number of Bq. Radioactive sources represents no biological risk as long as they are isolated from the environments. However, when people (or another biological system) are exposed to radiation – a radiation dose is delivered.

It is therefore important to distinguish between the activity of a radioactive source (measured in becquerels) and the radiation dose which may result from the source. The radiation dose depends on the location of the source with regard to those exposed. Furthermore, the radiation dose depends upon the type of radiation, such as whether it is α-, β- or γ-rays and the energy of the radiation.

Although people can neither see nor feel radiation, it is known that radiation deposits energy to the molecules of the body. The energy is transferred in small quantities for each interaction between the radiation and a molecule and there are usually many such interactions.

For anything that is irradiated, the temperature rises. Additional radiation increases the temperature further. The temperature increase occurs because the radiation energy is transformed into heat. Even though it is generally very difficult to detect the rise in temperature, the realization that heat is generated by radiation is a key element in understanding the concept of *radiation dose.*

Radiation dose measures the amount of energy deposited in an irradiated compound.

Radiation dose is measured in units of gray (Gy)

1 Gy = 1 joule absorbed energy per kg

L. Harold Gray (1905 - 1965) was one of the great pioneers in radiation biology. He obtained his PhD in 1930 at the Cavendish Laboratory under Rutherford at a time when the laboratory was a world centre for fundamental research in atomic physics. Gray`s first paper was "*The absorption of penetrating radiation*".

Gray worked as a physicist at Mount Vernon Hospital, and became interested in the effect of oxygen on radiosensitivity. Cells with a low content of oxygen (hypoxic cells) are less sensitive to radiation compared to normal cells. This behavior has caused problems for the treatment of cancer, because most tumors contain regions with hypoxic cells.

The LH Gray Memorial Trust was set up in 1967 to honour the memory of Hal Gray. Also L. H. Gray Conferences and Workshops have become established as prestigious meetings at which a high level of presentation and discussion take place.

A private picture from 1957. Here we are outside Grays institute at Mont Vernon hospial – from left; John Boag, Målfrid Henriksen (wife of the author) and Hal Gray.

Dose Units and Their History

In the course of the 100 years of dealing with ionizing radiation, several different dose units have been used. Some of these units are still used in different countries. It is useful, therefore, to consider some of these units and to see the relations between the old units and the gray unit (Gy).

- ***Skin erythema dose***

It was discovered early that radiation exposure resulted in reddening of the skin. For a long period this reddening was used to quantify the radiation. This was called the *skin erythema dose*. This unit was quite uncertain since the reddening of the skin varied from one person to another. Another drawback was that the reddening appeared some time *after* the exposure.

In the case of ultraviolet radiation, this dose unit (along with the attending uncertainties) is still in use. The smallest UV-dose resulting in the reddening of the skin is called **MED**, which is an abbreviation of *minimum erythema dose*.

- ***The Roentgen unit***

People who worked with radiation around 1920 began searching for a more precise dose unit and in 1928, the *roentgen unit* (abbreviated R) was adopted. This unit can not be used for the dose itself since it is actually a measure of radiation exposure, i.e. the ionization of air molecules.

In the original definition 1 R means the amount of x- or γ-radiation that is required to liberate positive and negative charges of one electrostatic unit of charge (esu) in 1 cm^3 of dry air at standard temperature and pressure (STP). This corresponds to $2.58 \cdot 10^{-4}$ coulomb per kg of ions generated in air.

To calculate the radiation dose (in Gy) from an exposure of 1 R depends on the energy of the x- or γ-radiation and the composition of the irradiated material. For example, if soft tissue is exposed to γ-radiation of 1 R, the radiation dose will be approximately 9.3 milligray (mGy).

- ***The Rad Unit***

In 1953, the dose unit *rad* was developed. This is an abbreviation for *radiation absorbed dose* and is defined as:

The amount of radiation which yields an energy absorption of 100 erg per gram

(i.e. 10^{-2} joule per kg).

The rad unit is still used in several countries.

From this you can easily see that both gray and rad are defined as energy absorbed – the relation between the two are:

1 gray = 100 rad

In this book, the gray is used most of the time. But use of the rad is difficult to avoid due to its pervasive use in the older literature. The SI-system of units uses the gray.

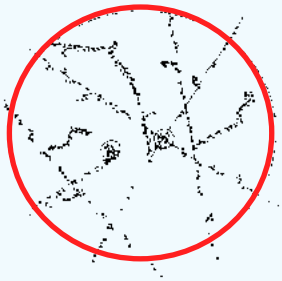
Relative biological effectiveness (RBE) and equivalent dose

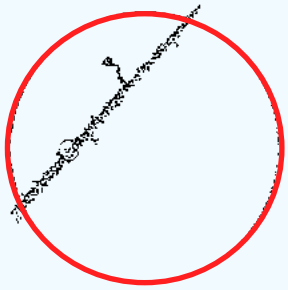
When a ***biological system*** is irradiated with different types of radiation (x- and γ -radiation, α -particles, neutrons and/or heavy ions) the biological end result – ***for the same dose given in Gy*** – may vary. This is a puzzle, since the primary products, ions and excited molecules, are the same.

The answer to this puzzle is connected to the spatial distribution of the primary products. Thus, for x- and γ -rays the primary products are evenly distributed, whereas in the case of protons, α -particles and heavy ions, the primary products are found along the ***track of the particle***. An illustration of this is found below. (See also Chapter 2, pages 28 – 29).

The distribution of ions and excited molecules vary with the type of radiation

Electrons,
x-rays and γ-rays





Track of an
α-particle

In the illustration above the ions and excited molecules are indicated by dots – i.e. the dots represent small amounts of energy absorbed. To the left is presented the situation for x-rays, β -particles and γ -rays, whereas to the right is given the situation for an α -particle. In this case the ions are formed along a track – with smaller tracks branching off from the main track (they are called δ -tracks).

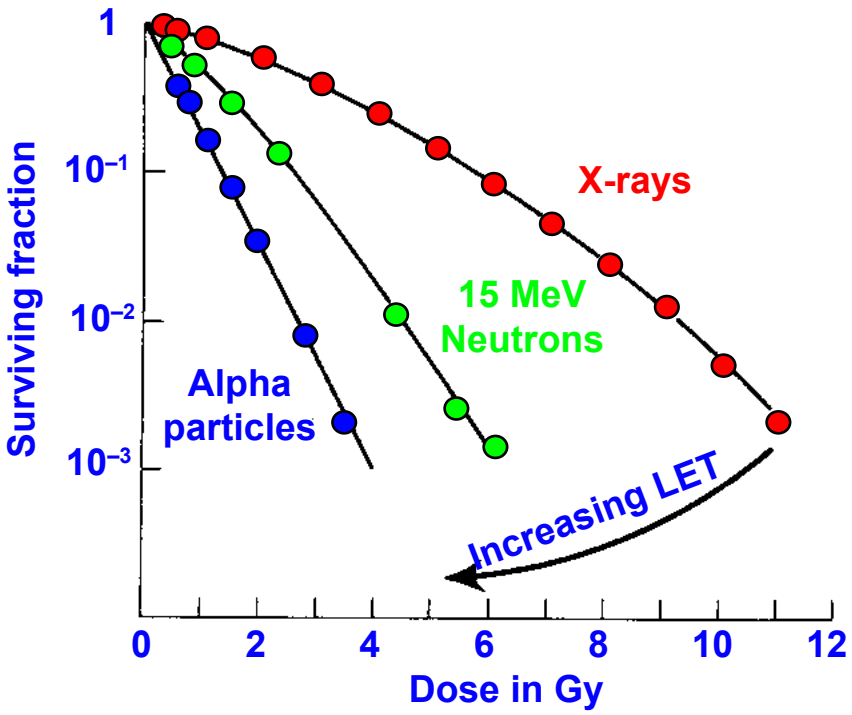
*The number of dots within the two circles is the same, indicating the **same** radiation dose measured in Gy. However, the distribution of dots is different. The situation to the left is an illustration of **low LET** (linear energy transfer); i.e. sparse ionization along the γ -ray track. The circle to the right is an illustration of **high LET**; i.e. a dense path of ionizations along the track.*

How can we find RBE ?

For the most simple biological end point, such as cell killing, we can do straight forward experiments.

A summary of such experiments are given on the next page. The reference radiation is x-rays with maximum energy 250 keV. Also Co-60 γ-radiation has been used (γ-energies of 1,17 and 1,33 MeV). For a given biological effect (for example 10 % killing), RBE is calculated from the following formula:

$$\text{RBE} = \frac{D_{x-rays}}{D_{test}}$$



In this illustration is a summary of cell killing experiments. It is clear that the cell killing depends on the LET of the irradiation. Thus the efficiency increases with LET, going from x-rays to heavy ions. This is important for radiation therapy when protons and heavy ions like carbon ions are used.

You choose a certain end point, such as the 10 % survival (or another value) and give the x-ray dose to reach this endpoint and compare with the test radiation. Since most survival curves follow a linear quadratic curve, the RBE ***decreases with increasing dose.***

Since we now use protons and other heavy ions in radiation therapy, it is important to have information of RBE (this will be more discussed in Chapter 10 on radiation therapy).

With regard to the mechanism for cell killing it seems to be a close connection between double strand DNA breaks and cell death. Consequently, the RBE yield information about the LET-dependence of double strand breaks.

What is the situation for other deleterious effects?

If we go to other biological endpoints it appears to be more difficult to determine the RBE. In the case of humans, most interest has been concerned on; a) genetic effects and b) cancer. For both these effects we assume that the start point is a DNA-damage. We do not know the particular type of damages and it is of course not possible to do experiments.

In the case of genetic effects a lot of work has been carried out with mice. Similarly, experiments have been carried out for radiation induced cancer in mice, rats and rabbits. However, no experiments include two or more different types of radiation (with different LET), and we have very little information about what the RBE-values to use.

The radiation authorities such as ICRP (*International Committee on Radiation Protection*) has solved the problems with RBE by introducing a new dose unit – "***the equivalent dose***".

The units within this system are called ***rem*** (in the cgs-system) and ***sievert (Sv)*** in the SI-system. The latter unit is given to honour the Swedish scientist Rolf M. Sievert.

The history of rem and Sv

The observation that cell killing efficiency depends on LET have in many ways changed the dosimetry. The radiation organizations discussed already in 1945 – just after the second world war, that it would be useful to introduce a new unit. The physical dose unit used then was the roentgen unit (R, see above). In 1947 the rem-unit was introduced. This unit was in 1950 defined as:

that dose of any ionizing radiation which produces a relevant biological effect equal to that produced by one roentgen of high voltage x-radiation.

In 1962 ICRP used rem as equivalent dose for the unit rad (see above).

In the 1970-ties the SI-unit system was adopted by the radiation world. Consequently, the radiation dose was given in Gy (gray) and the rem-unit was changed to Sv (sievert). The Sv unit should take care of the LET-dependence. Thus;

$$Sv = w_R \cdot Gy$$

w_R is a weight factor assigned to the radiation in question,

it is the RBE (relative biological efficiency).

The use of Sv

It should be remembered that Sv is not a physical dose unit that can be measured with dosimeters. The radiation dose is measured in Gy – and if a reliable RBE-value exists the equivalent dose in Sv can be observed.
If the radiation in question consists of x-rays, γ -rays, β -particles or a mixture of them (this is the case in most situations with radioactive isotopes) the RBE-value would be close to 1.0 – and this value is adopted by ICRP. If however α -particles or high energy particles of protons, neutrons and heavy ions are included we can obtain reliable RBE-values for cell killing. However, we have very little information about RBE-values in the case om other deleterious effects such as cancer.

For radiation protection, ICRP has worked out a system that is used all over the world – and which will be given below. In this system are given dose units such as; ***equivalent dose, effective dose and collective dose.*** *It has to be pointed out that the system is based on the LNT-model (linear with no threshold) for the biological radiation effects on humans.*

RBE-values given by ICRP

Radiation type	Weighting factor w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy

The curve for neutrons has, according to the previous recommendation (ICRP 1991) a value of 5 for energies below 10 keV, a value of 10 in the energy range 10 – 100 keV, – a value of 20 in the range 100 keV to 2 MeV, and finally a value of 5 for energies above 20 MeV.

It is very difficult to estimate the equivalent dose for a mixture of neutron energies as found for the cosmic radiation.

ICRP – UNSCEAR – Sievert

Rolf M. Sievert
(1896 - 1966)

Rolf M. Sievert played a significant role in establishing the international committees ICRP (International Commission on Radiological Protection) and UNSCEAR (United Nations Committee on the Effects of Atomic Radiation). He served for several years as director of the Swedish National Institute of Radiation Protection.
Sievert constructed an ionization chamber for depth dose measurements (called Sievert chamber).

Sievert is honored for his work in dosimetry (the measurement of absorbed dose) by naming the unit for equivalent dose *sievert* (abbreviated Sv).

Effective Equivalent Dose

In some cases, only a part of the body is irradiated. For example, mainly the bronchi and lungs are involved in the case of radon and radon decay products. Different organs and types of tissue have different sensitivities with regard to what is termed the *late effects* of radiation. Late effects are biological responses that are only observed after a substantial amount of time has passed, often years. Induction of cancer is a late effect. In order to compare the risk for late effects of different types of radiation, the so-called *effective dose* is used.

If one part of the body (*e.g.*,the lungs) receives a radiation dose, it represents a risk for a particularly damaging effect (*e.g.*, lung cancer). If the same dose is given to another organ it represents a different risk factor.

In the LNT-model it is possible to calculate a dose given to the whole body that yields the same risk as that from the much larger dose given to one particular organ.

This calculated dose is called ***the effective dose*** (often shortened to simply *the dose*) and is designated *E*. It is defined in the following way:

$$E = w_1H_1 + w_2H_2 + \ldots\ldots\ldots$$

Here w_1 represents a weighting factor for organ 1 and H_1 is the equivalent dose (given in Sv) for organ number 1, and so on. The weighting factors represent the sensitivity of a particular organ.

It can be noted that the "*effective dose*" involves two different weight factors;

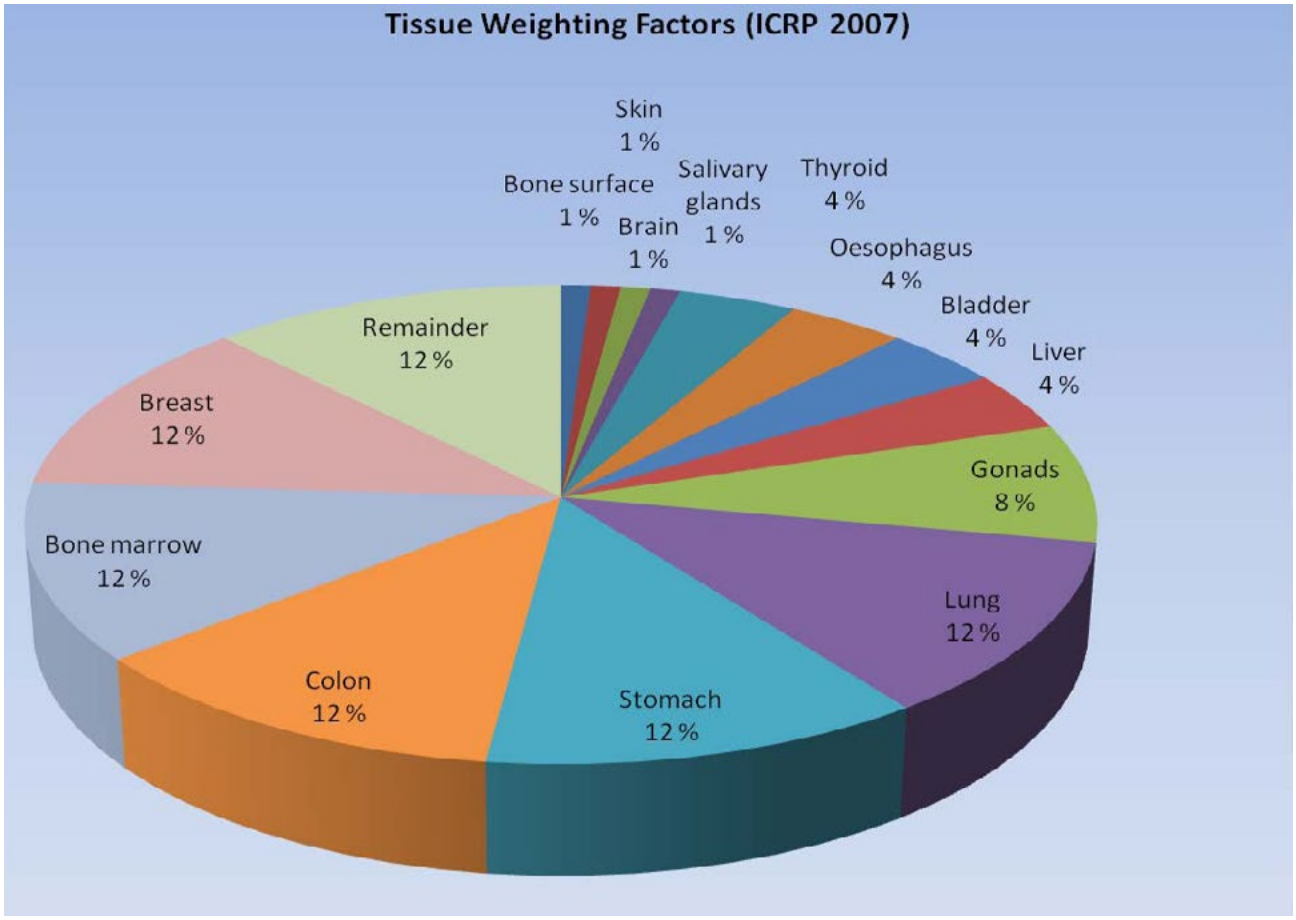
- First, the radiation weight factor w_R and
- Second, the tissue weight factor w_T.

Both factors that are in use, are proposed by ICRP.

The ICRP values for the radiation weight factors w_R from 2007 are given in the table above. The tissue weight factors, suggested by ICRP in 2007, are given by the diagram on the next page.

The body has been divided into 15 different organs – each with a weighting factor w_T . If you add up all the weighting factors, you find that the total is 1 or 100 %.

One organ or tissue is called "remainder". The notion is used for the combined contribution from 14 different tissues – 13 for each sex and in addition prostate (for men) and uterus/cervix (for women).



Other Dose Units used by ICRP

In addition to the units already defined, there are some other concepts used in radiation protection such as "***collective dose***" and "***committed equivalent dose***".

The above units together with the LNT-hypothesis have, in recent years been used by lay people, journalists, environment organizations and politicians in combination with assumptions of the total health effect of radiation accidents such as Chernobyl and Fukushima.

In the following we shall give a brief overview of the concepts used when working in radiation protection.

Collective dose.

The collective dose is the sum of all individual doses in a group of people. It can be obtained by the product of the average individual dose with the number of people in the group. For example in combination with mammography to a large group, the collective dose is calculated as the product of the single dose and number of women.

The unit used for the collective dose is ***person-sievert*** (person-Sv) or sometimes ***man-sievert***.

Collective doses and the LNT theory always give scaring results. We shall return to this point when we discuss the radiobiology.

Committed equivalent dose

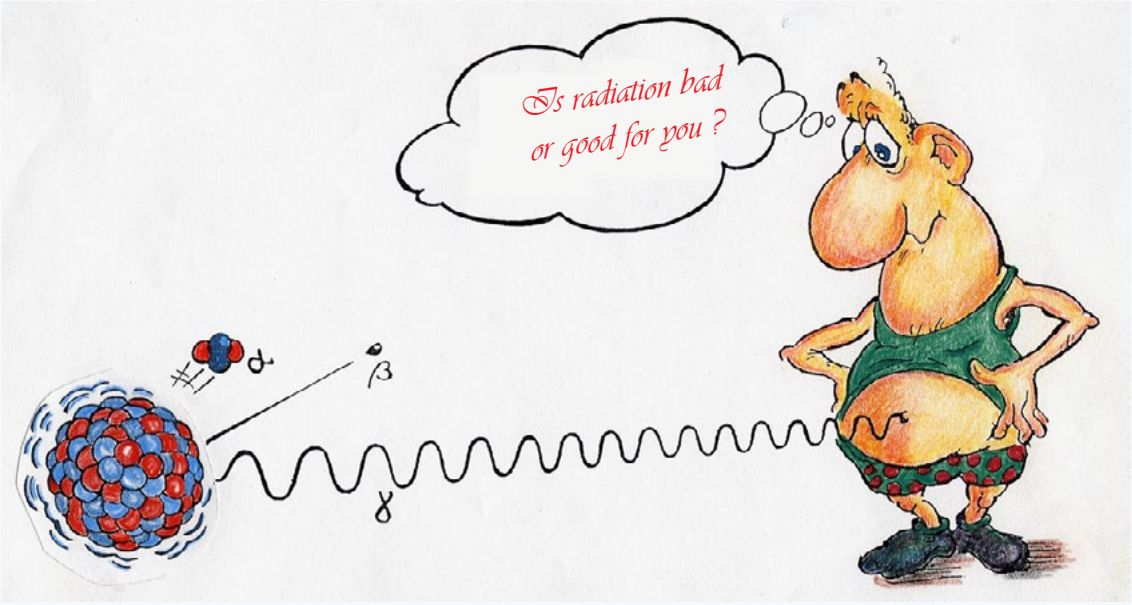
When a radioactive compound enters the body, the activity will decrease with time, due both to physical decay and to biological clearance, as noted earlier. The decrease varies from one radioactive compound to another. Accumulated dose over a certain period of time, usually 50 years, is called the committed equivalent dose.

Conclusion on Sv

1. The Sv unit is connected to man. It can not be used in biological experiments on animals, fish, plants, insects, etc.

2. The dose can not be measured in Sv-units. A large number of articles and opinions have been published where the dose is given in Sv. This is not possible!

3. The Sv (rem) units are concerned with "deleterious effects on man" and are based on the LNT-hypothesis. This hypothesis is rather doubtful – and recent radiobiological experiments are not in line with the LNT-view. Consequently, the present author would like to use the Gy (rad) units throughout the book.



Radiobiological work during the last 20 years have revealed that biological systems have a number of defense mechanisms such as ***repair***, ***apoptosis*** and ***adaptive response***. Furthermore it appears that these processes may be stimulated by radiation – particulary small doses given at a low doserate. May be that we should be happy with the radiation around us – and may be we would profit on a higher background level. These interesting issues will be discussed.