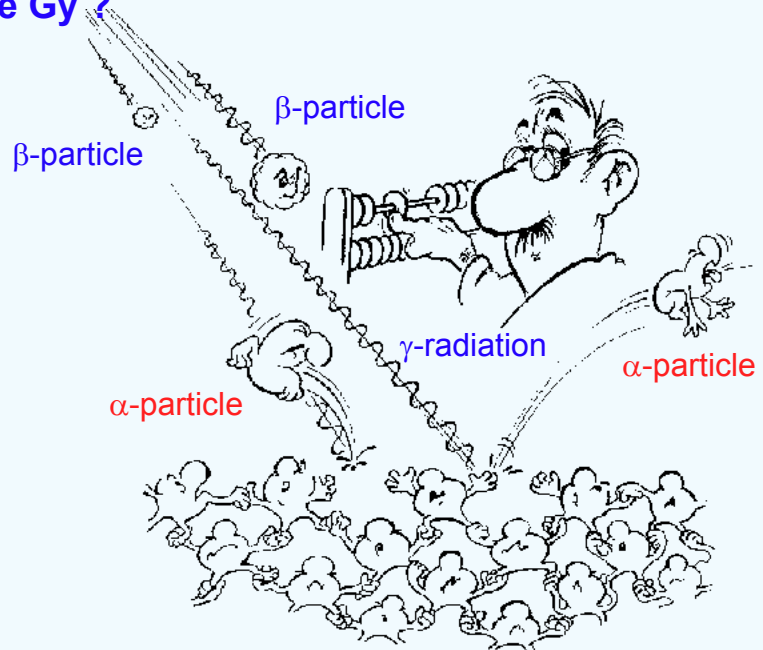


How to count Bq and measure Gy ?

You can not measure Sv !

You
need more
than eyes
and abacus.



Chapter 6

The Measurement of Radiation

Introduction

In this chapter, the equipment and methods used for measuring ionizing radiation will be discussed. There are two types of instruments: counting equipment (used to determine number of becquerels and the radiation quality) and dosimeters (used to determine radiation dose). Both types of equipment require that *the radiations result in observable changes in a compound* (whether gas, liquid or solid).

Measuring equipment consists of two parts that usually are connected. The first part consists of a *sensitive volume*, consisting of a compound that experiences changes when exposed to radiation. The other component is *a device that converts these changes into measurable signals*.

The qualities of radiation that we want to measure are:

- **Activity.** The activity or intensity of a source is measured in becquerel. It can be given as the total activity or given in Bq/kg (solid), Bq/l (liquid) or Bq/m³ (gas). In considering pollution of an area Bq/m² is used. Some countries still use Ci/km².
- **Type of radiation.** It is important to distinguish between α - or β -particles, x- or γ -rays and neutrons.
- **The energy.** The energy is usually measured in the unit electron volt (eV). The energy of the particles or photons is important.

- **Dose** is the absorbed radiation energy measured in gray (Gy).
Correct measurement of dose is important in radiobiological experiments and within radiation therapy. We shall also discuss measurements of doses from natural sources.

Measuring equipment can vary in size and price. The equipment chosen depends on the purpose of the measurement, the sensitivity desired, and the precision necessary. The simplest type of measurement is to observe the amount of radiation hitting the sensitive volume or detector of the counter. If the sensitive volume is covered with plates of different thicknesses and composition, information may be obtained on the type of radiation. These instruments may be used to monitor radiation areas.

Exact measurements of radiation energy are more complex and different equipment is required. The energy of the radiation may be used to identify a particular isotope. If several isotopes are mixed together (for example, fission products), it is possible to identify the separate isotopes by an accurate determination of the energy of the particles or photons emitted. For that purpose, equipment is needed which has *good energy resolution*.

X-and γ -rays that hit the sensitive volume may pass through it without being absorbed. Consequently, the sensitive volume must be large enough to absorb sufficient amounts of this type of radiation. The greater the energy, the larger the volume. If a significant fraction passes through the sensitive volume without interacting, and therefore without detection, the equipment has a *low efficiency*.

If the sensitive volume contains heavy atoms, the possibility of interaction, and thus the probability of being detected, is greater. Heavy atoms are most effective in stopping x -, γ -, α -, β -, and cosmic-rays. When heavy charged particles hit a metal box, they create an electric current that can be measured.



On the next page are given 7 different physical effects that are utilized to measure radiation.

Ionization, scintillation, semiconductors and film are extensively used to observe individual particles. All of them can be used to determine radiation doses.

In addition to these effects we may also use biological changes, such as chromosome aberrations for dose determination.

For the sake of simplicity, it is important to have a response that is directly proportional to the dose, i.e., the dose-effect relationship should be linear. This is usually accomplished for physical effects, whereas biological changes such as chromosome aberrations seem to follow a linear-quadratic curve .

Detection methods and instruments

In this section we describe a number of different types of radiation measuring instruments. Consider the different physical events that can be utilized to make a measurement.

1. **Film.** Most people have seen an x-ray picture. The picture is the result of radiation hitting a photographic film. The more radiation exposure, the more blackening of the film. In radiation diagnostic, film has been the detection method. Furthermore, film-badges have been used by people working with radiation in hospitals or in research, keeping track of how much radiation exposure the workers have received. All x-ray pictures are now digitalized.
2. **TLD.** These initials stand for “*Thermo Luminescence Dosimetry*”. A crystal such as LiF containing Mn as an impurity is used. The impurity causes traps in the crystalline lattice where, following irradiation, electrons are held. When the crystal is warmed, the trapped electrons are released and light is emitted. The amount of light is related to the dose of radiation received by the crystal.
3. **Ionization.** Radiation results in the formation of positive and negative ions in a gas as well as in all other materials. Ionization can be used both for Bq measurements as well as for dose measurement. With knowledge about the energy needed to form an pair of ions – the dose can be obtained. The famous Geiger-Mueller tube, commonly called a Geiger counter, is designed to measure the electrical response produced by the newly formed ions.
4. **Scintillation.** A number of compounds have the property that they will emit light when exposed to radiation. The intensity of the emitted light depends on the radiation exposure and the light intensity is easily measured.
5. **Semiconductors.** Radiation produces an electric current in semiconductors that can be measured.
6. **Free radicals.** Radiation produces a class of chemical species known as free radicals. Free radicals by definition contain an unpaired electron and, although they are very reactive, they can be trapped in some solid materials. The number of trapped free radicals is a measure of the radiation dose.
7. **Redox products.** Radiation either reduces (by electron addition) or oxidizes (by electron abstraction) the absorbing molecules. Although these changes are initially in the form of unstable free radicals, chemical reactions occur which ultimately result in stable reduction and oxidation products.

In the following we shall see in more detail into the different detection methods and give a few examples which hopefully give you some information about detection techniques. In no other fields you can measure so tiny amounts as radioactivity – and may be this is the reason for the general fear among people for radiation. Let us start by giving an example.

How little radioactivity can be observed ?

Is it possible to measure 1 gram of I-131 if it is spread out over the entire world?

We have one gram of the radioactive isotope I-131. This isotope is a fission product (it is released in all the reactor accidents such as Chernobyl and Fukushima).

I-131 has a half-life of 8.04 days – it is a β -particle emitter and has a γ -photon with an energy 0.364 MeV. We use the γ -radiation with its particular energy for identification.

One gram I-131 is 1/131 mole of the compound. Since a mole contains $6.022 \cdot 10^{23}$ atoms (Avogadro's number) the number of I-131 atoms in 1 gram is $4.6 \cdot 10^{21}$.

The activity of 1 gram of I-131 (the number of atoms that disintegrate per second) is $4.59 \cdot 10^{15}$ Bq. This is found from the decay laws discussed in chapter 3 and the number is found by combining two of the equations discussed in chapter 3 (pages 36 and 37)

$$A = -\frac{dN}{dt} = \lambda N = \frac{\ln 2}{t_{1/2}} N = 4.59 \cdot 10^{15} \quad N = 4.6 \cdot 10^{21} \text{ atoms.}$$
$$t_{1/2} = 8.04 \text{ days} = 6.95 \cdot 10^5 \text{ seconds}$$

The area of the world – $4 \pi R^2$ – is approximately $5.1 \cdot 10^{14} \text{ m}^2$. For an even distribution of the I-131 gram it would be an initial activity of 10 Bq per m^2 . With good counters (like a germanium counter) **this activity can be observed and identified even in a mixture of other radioactive isotopes.**

You can measure 1 gram of I-131 even if it is distributed all over the world !



We can conclude that we have very sensitive equipment for measuring radioactivity. In the case of I-131 the activity in 1 gram is high because of the rather short half-life. The activity is closely connected to the half-life. For isotopes with longer half-lives, larger amounts are required.

For example Cs-137, with a half-life of 30 years and with 1 gram distributed all over the world, would have a specific activity of only 0.007 Bq per m^2 . This would not be detectable.

The total amount of Cs-137 released in the Chernobyl accident was according to UNSCEAR (1996) about 26.5 kg. If this amount was distributed evenly around the world the activity would be 185 Bq per m^2 . In some regions in Scandinavia the fallout reached 100 kBq per m^2 and near the reactor the activity was about 10 times larger.



On the following pages we give some more information about the different types of equipment used for measuring ionizing radiation – both counters and dosimeters. However, much more information can be found in textbooks and papers dealing with different types of measurements.

Film

We start this short review of detection methods with film – which has played an important role through the first hundred years of x-ray diagnostic. The first picture on film was presented already in 1895. Today film is on the way out of the hospitals since new digital methods have been introduced.

Ionizing radiation interacts with film pretty much like ordinary light. The sensitive compound consists of silver halides (mainly silver bromide mixed with small amounts of silver iodide). The radiation would split the molecules, leading to the formation of metallic silver particles. Since the silver particles are black, it implies that the radiation dose increases with the darkness of the film

A film used for x-ray diagnostic is built up by several layers like the base, the emulsion, and the protective coating. The detection layer is only about 10 μm thick and it is only the radiation that is absorbed in this layer that can give a picture. Consequently, in order to obtain a good picture it was necessary to increase the exposure and the dose.

The exposure time and consequently the radiation dose can be reduced by introducing so called "intensifying" screens – consisting of a layer of fluorescent crystals such as calcium tungsten and/or rare earth atoms. The point is that these screens absorb x-rays and yield light that in turn can expose the film.

The film has to be developed (which takes some time) and it represents a storage problem. Furthermore, very little can be done to the final picture. Since new digital techniques have been introduced x-ray film is already out of the hospitals.



It is difficult to analyze chest x-ray pictures since several organs are exposed. Lung pictures was important in the treatment of tuberculosis.

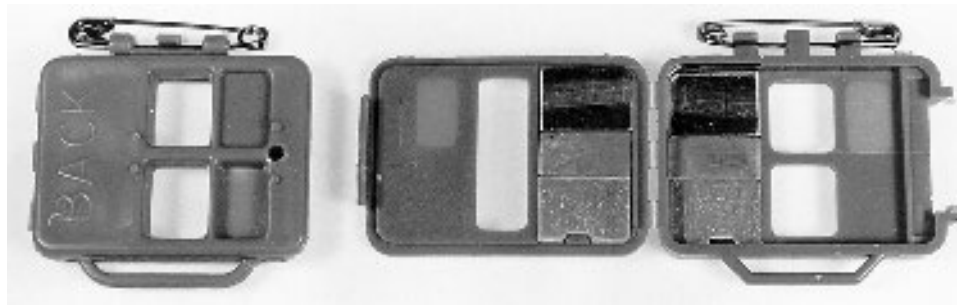
Dose determination by film

Workers who are potentially exposed to radiation often use film as a personal dosimeter (an example is given in the figure on the next page). It is worn on work clothes (sometimes on the lapel or belt).

The film is contained in a plastic holder that has small absorption plates of lead, tin, cadmium and plastic. In addition, there is an open window that makes it possible for weaker radiations to reach the film. The blackening behind the different plates depends on the energy and type of the radiation.

If the radiation contains neutrons of low energy, called thermal neutrons, the film behind the cadmium plate will show some extra blackening because of reactions between neutrons and cadmium – it is so called (n,γ) reactions.

This personal dosimeter is integrating – i.e. it adds up the radiation through a period like a week or a month. The blackening in all windows must be measured. The blackening of the film is linear to the dose, and doses up to about 10 Gy can be measured.



A picture of a film dosimeter. To the right, the plastic holder is opened to show the construction. In addition to an open window you can see several areas covered with absorption plates of different types.

Thermoluminescence-dosimeter (TLD)

This method is based on the fact that several crystals may trap imperfections like holes and electrons when irradiated. When such crystals subsequently are heated the trapped electrons receive enough energy to escape from the trap and fall to the ground state, emitting light photons. Since warming is a requirement, the technique is called thermoluminescence. ***The intensity of the luminescence is a measure of the dose.***

Small crystals of LiF (lithium fluoride) are the most common TLD dosimeters since they have the same absorption properties as soft tissue. The amount of light emitted at 200 °C due to the radiation is proportional to the dose in soft tissue.

TLD may be used as a personal dosimeter for β - and γ -radiation because it is independent of the energy of the radiation. Lithium has two stable isotopes, Li-6 (7.4 %) and Li-7 (92.6 %). Li-6 is also sensitive to neutrons. Consequently, if there is a combination of neutron and γ -radiation, the light emitted from a LiF crystal with Li-7 is a measure of the γ -radiation, whereas the light emitted using Li-6 yields the total dose from both neutrons and γ -radiation.

In the case of neutron detection, the efficiency of the detector depends on the energy of the neutrons. Because the interaction of neutrons with any element is highly dependent on energy, making a dosimeter independent of the energy of neutrons is very difficult.

Detectors Based on Ionization

An ionization chamber consists of a gas volume in an electric field between two electrodes. Radiation entering this volume results in the formation of ions. The positive ions will be attracted to the negative electrode, and negative ions will be attracted to the positive electrode. Ions with high enough energies may ionize even more molecules on their way to an electrode. This means that when the voltage across the electrodes increases, the number of ions increases. For a certain voltage (the proportional region), the number of ions at the electrode is proportional to the radiation energy deposited in the gas volume, resulting in a qualitative measure of the radiation energy.

If a very high voltage is used (called the Geiger-Mueller region), each ionization yields a cascade of ions that results in a pulse. Regardless of the energy of the radiation, the same size pulse is formed.

A large variety of detectors have been made where the basic physical event is the ionization. Both dose measurements as well as counting instruments have been made. We shall mention a few instruments based on the ionization process:

The proportional counter.

For this instrument the voltage across the electrodes is adjusted to let the number of ions that reach the electrodes be equal or proportional to the number of ions induced by the radiation. Thus, the pulse size reflects the energy deposited by the incident radiation in the detector gas. As such, it is possible to distinguish the larger pulses produced by alpha particles from the smaller pulses produced by betas or gamma rays. We have counters both with and without windows. The window less gas flow counters can be used to detect the very weak β -particles from tritium.

The gas used in the counters is usually a noble gas (mainly argon). For special purposes other mixtures of gases have been used, such as a tissue equivalent gas mixture consisting of 64.4% methane, 32.4% carbon dioxide and 3.2% nitrogen. For neutron detection He-3 and BF₃ (Boron Trifluoride) are the most commonly employed gases.

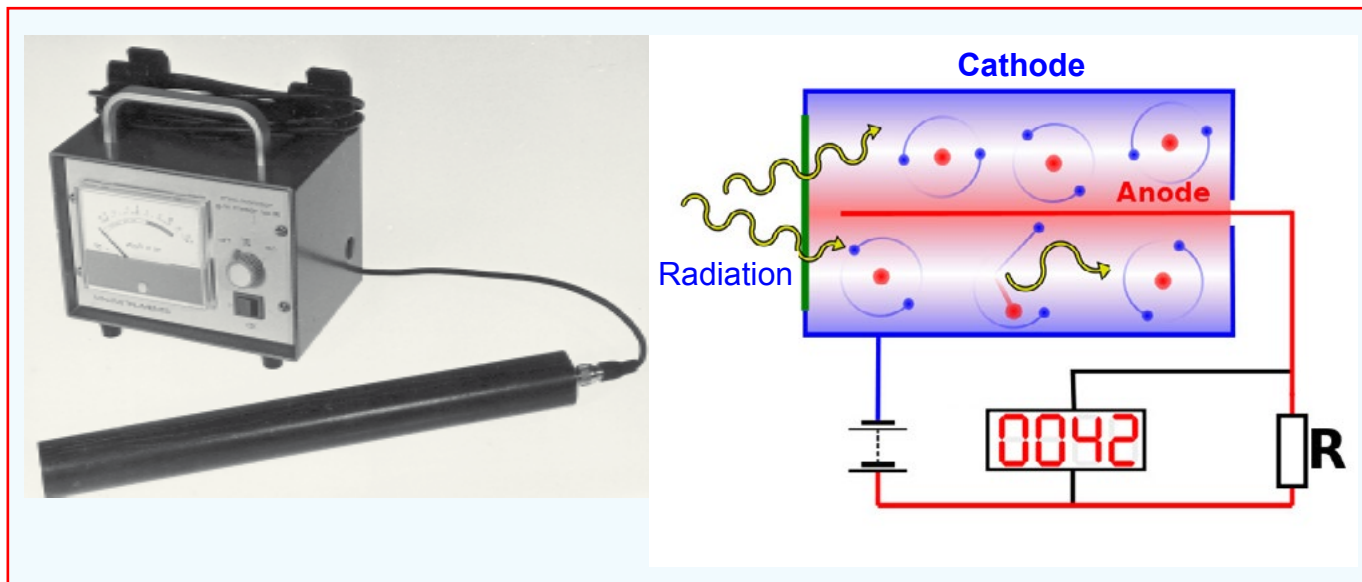
Geiger-Mueller counter.

This famous instrument is named after the two physicists who invented the counter in 1928. Mueller was a student of Hans Geiger.

The counter consists of a gas volume with two electrodes that have a high voltage between them. Very often the detector element is cylindrical in shape with the cylinder wall serving as the negatively charged (ground) electrode and a thin metal rod running along the middle axis serving as the positively charged electrode.



Hans Wilhelm Geiger
(1882 - 1945)



A Geiger-Mueller counter. To the left is a picture and to the right an illustration. The sensitive volume is a tube which is connected to a pulse counter. The counter yields information about the radiation intensity.

Ionizing radiation passing through the gas volume produces ions in the gas. The voltage is high enough for each electron attracted to the central electrode to make a cascade of new ions. This results in a pulse which is detected by a counter system and may also be sent to a speaker which produces an audible click.

The counter can be used as a warning instrument. It does not, however, yield information about the type of radiation or its energy.

The requirement that the radiation should reach the sensitive gas volume may be difficult for α -particles. The G-M counter is well suited to localize β - and γ -emitting radioactivity in connection with accidents.

The Scintillation Counter

The scintillation counter is based on the principle that light is emitted when a scintillator is exposed to radiation. Both solid and liquid scintillators can be found. Several organic compounds, such as benzene and anthracene, can be used. Crystals of sodium iodide (NaI) have been used in many experiments. The light pulse produced when radiation interacts with the scintillators is recorded by a photomultiplier tube.

Single crystals of NaI can be made with volumes of several liters. Hospitals all over the world have gamma-cameras which use NaI crystals in the form of large plates with diameters of more than 40 cm.

The light emitted when the crystal is irradiated is proportional to the γ -energy deposited. Consequently these counters are suited to measure the energy of γ -radiation and, therefore, can be used to identify γ -emitting isotopes.

Semiconductor Counters

Transistors and other components in electronic equipment are made of semiconducting materials. When electrons are released in these semiconductors, the current can be measured with great accuracy.

Solar cells are made of thin silicon crystals. They give rise to an electric current when hit by solar light. In a similar way a current can be induced by ionizing radiation. A large, clean and almost perfect semiconductor is ideal as a counter for radioactivity. The released electric charge is closely related to the radiation energy. ***These counters are employed to measure the energy of the radiation and for identification.*** The crystals are made of silicon or germanium. However, it is difficult to make large crystals with sufficient purity. The semiconductor counters have, therefore, low efficiency, but they do give a very precise measure of the energy. In order to achieve maximum efficiency the counters must operate at the very low temperatures of liquid nitrogen (-196°C).

The Energy of the Radiation – Isotope Identification

It is very important to have sufficient information about the energy of the radiation. ***With information about the energy and the type of particle observed, it is possible to identify a radioactive isotope.*** This may have great importance with regard to the storage and handling of radioactive sources.

Both semiconductor counters and scintillation counters produce pulses which are a measure of the radiation energy deposited in the sensitive volume. The number of pulses is a measure of the activity of the source. Before they are measured, the pulses are electronically amplified and filtered and grouped according to their size. They are then converted to numbers in an analog to digital converter (ADC). A computer sorts out the numbers and presents the results.

Example

In the figure on the next page is given the result for the Cs-137 isotope when observed with a sodium-iodide scintillation counter and a germanium semiconductor counter.

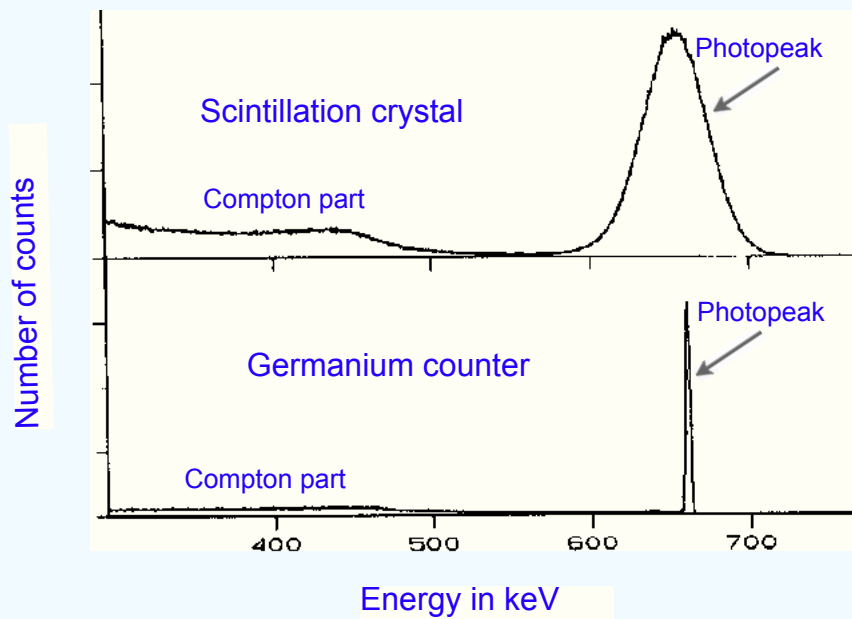
The radiation energy is given along the abscissa and the count number is given along the vertical axis. The curve attained is called a γ -spectrum.

Cs-137 emits both a β -particle (which is not observed in this case) and a γ -photon with an energy of 662 keV. The figure demonstrates how the two counters react when hit by the γ -photon.

The interpretation of the γ -spectrum is as follows: The γ -ray energy is absorbed either *completely* (the photoelectric effect) or *partly* in a Compton process. Consequently, the high energy peak in the spectrum, which has an energy of 662 keV, is called the "*photopeak*". The partly absorbed energy is seen in the left part of the spectrum – the *Compton part*.

It is the photopeak that is used for identification of the isotope. It is therefore important that the peak is narrow (good resolution).

Cs-137



The γ -ray spectrum for Cs -137 measured with a sodium iodide scintillation crystal and a germanium semiconductor counter. The γ -radiation has a peak at 662 keV (the photopeak). This is important for identifying the different isotopes. (Courtesy of Finn Ingebretsen, Inst. of Physics, Univ. of Oslo)

The curve is usually called the response function of the counter. If a radioactive source emits several photons with different energies the spectrum will consist of several photopeaks.

The above two spectra demonstrate that a scintillation counter yields much broader lines compared to the germanium counter. Generally, it is easier to identify different isotopes with a counter that has good energy resolution, such as the germanium counter.

Several isotopes in a mixture

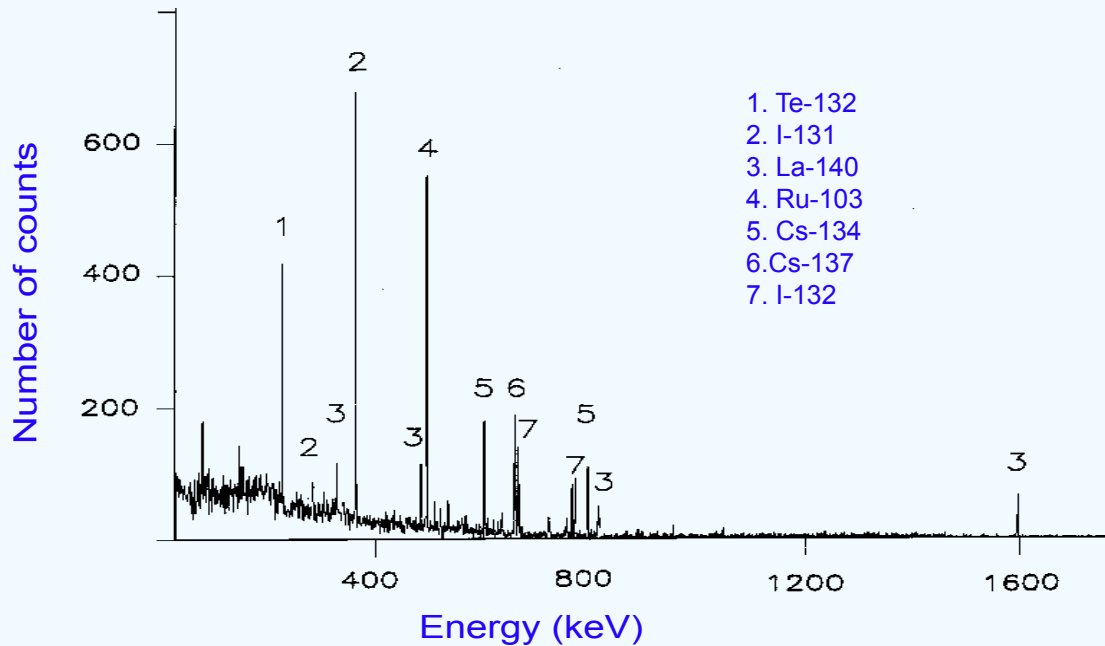
An example with several isotopes (some with more than one γ -photon) would yield a much more complicated spectrum. An example of this is given by the figure on the next page.

The fallout from the Chernobyl accident in April 1986 was observed several places around the world. Rather heavy fallout was observed in Scandinavia and in the figure (next page) is given an example. The sample (taken about two weeks after the accident) consisted of grass from the lawn outside the University of Oslo (about 2,000 km away).

The γ -spectrum shows that a number of isotopes were released. The isotopes that emit γ -radiation can be identified – and from the figure we can identify 7 isotopes.

See table next page.

A sample with isotopes from Chernobyl collected outside Blindern



This is an example with an unknown mixture of isotopes. The sample, consisting of grass from the lawn outside the University of Oslo, exhibits the fallout from the Chernobyl accident.

The sample is taken about two weeks after the accident and contains therefore some of the short lived isotopes in addition to the Cs isotopes. A germanium counter was used and you can see a number of photopeaks which makes it possible to identify seven different isotopes. The inset and the table below give the 7 isotopes.

(Courtesy of Finn Ingebretsen, Inst. of Physics, Univ. of Oslo)

Number in figure	Isotope	Half-life	Energy of gamma photons
1	Te-132	77 hours	0.23 MeV
2	I-131	8.04 days	0.364 MeV
3	La-140	40.2 hours	0.33, 0.49, 0.82, 1.6 MeV
4	Ru-103	40 days	0.498 MeV
5	Cs-134	2.1 year	0.57, 0.60, 0.80 MeV
6	Cs-137	30 year	0.662 MeV
7	I-132	2.29 hours	0.673, 0.78 MeV

Chemical Separation can be used to identify isotopes that do not emit γ -radiation. Such methods made it possible to identify the isotopes present in the fallout from the nuclear tests in the 1960s. For example, it was found that the amount of Sr-90 (a pure β -emitter) was equal to the amount of Cs-137. Sr-90 is also in the fallout from the Chernobyl accident, but most of it was concentrated to the region around the reactor. Furthermore, Sr-90 can not be detected in experiments like that above.

Dose Measurements

The strength of a radioactive source (in Bq) and the energy of the emission (in eV) can be measured. This is, however, not a dose measurement.

The radiation dose is the energy deposited in the irradiated compound.

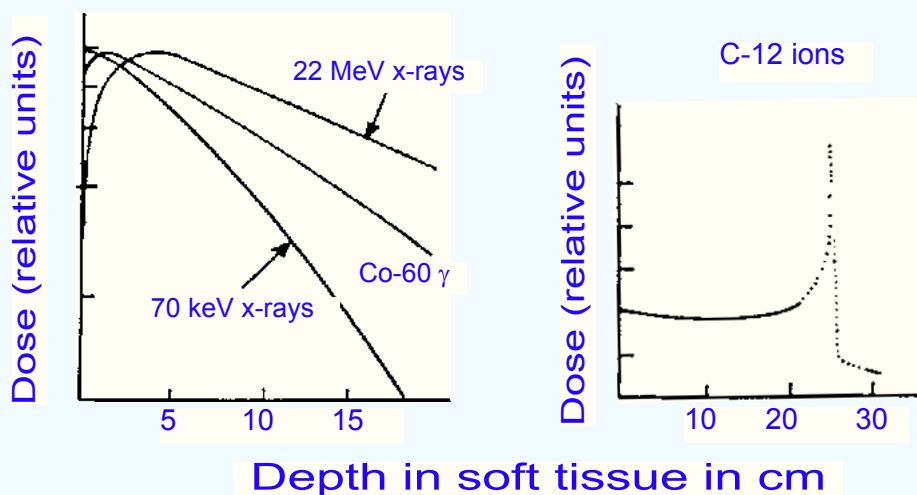
If the radiation hits a human being, the dose is defined as the energy deposited in the human body. The amount of energy deposited is almost always different from the amount of energy coming from the source. Deposited energy determines the dose.

Counters observe particles or photons sequentially. In dose measurements, the concern is not with the individual particles or photons but with the **total energy absorbed** in the exposed materials (e.g., tissue). It is difficult to observe energy absorption in tissue. Two of the problems are:

1. An exposure to one roentgen (1.0 R) of x- or γ -radiation can be measured with ionization chambers. This results in a radiation dose to soft tissue of approximately 9.3 mGy. The precision can be no better since the roentgen unit is based on the radiation absorption in air, whereas doses to a biological system (soft tissue or bone) are based on the energy absorbed in that system.

The absorption increases with the electron density of the exposed material and is therefore larger in bone compared with soft tissue. Furthermore, the energy absorption increases with decreasing radiation energy. Since these properties *are not* the same for air, soft tissue and bone, the doses delivered by a 1 R exposure are different.

2. When the radiation strikes a body, the dose changes with depth (i.e., the distance the radiation traverses in the body). One illustration is given in the figure below. Here different types of x-rays as well as a beam of charged particles (C-12 ions) are shown.



Depth dose curves for soft tissue. The dose is measured from the surface of the skin. On the left are data for x- and γ -rays as indicated. To the right is shown the dose curve for high energy charged particles. In this example carbon atoms, with all 6 orbital electrons stripped away, were used. The energy of the carbon ions when they hit the soft tissue is 5,688 MeV. The Bragg-peak strongly depends on the energy of the particle – otherwise similar curves are obtained.

3. In order to use radiation for cancer treatment it is important to have knowledge of the depth dose curves. As you can see from the figure above, the region for maximum dose can be changed by changing the x-ray energy. For tumors positioned deeper than 6 cm into the tissue, x-rays with an energy of more than 20 MeV should be used. The goal is to give a high killing dose to the tumor while minimizing the dose to the surrounding healthy tissue.

Charged particle radiation has a striking depth dose relationship (see page 27, 28). The dose peaks at the end of the track (called the Bragg peak). The Bragg peak occurs at a depth which depends on the energy of the particles. High energy protons, and more recently carbon-ions, have been used for cancer treatment. It requires large accelerators and it is, therefore, quite expensive. No such treatment is available in Norway today.

Fricke dosimetry

In experiments with chemical solutions the radiation dose can be determined by the chemical changes induced by the radiation. A well-known chemical reaction is based on the oxidation of Fe^{2+} to Fe^{3+} . It was the Danish chemist Hugo Fricke, who introduced this reaction for dosimetry in 1929.

We know that absorbed energy can convert Fe^{2+} ions to Fe^{3+} . The energy needed to convert one ion is 6.45 eV. The Fricke dosimeter consists of air-saturated 1 mM Fe^{2+} at pH 0.46. The conversion of Fe^{2+} to Fe^{3+} is measured by a spectrophotometer. The accepted yield – the number of ions formed per 100 eV absorbed, that is $G(\text{Fe}^{3+})$ is 15.5 for low LET radiations.

Some other aqueous systems utilized as radiation dosimeters include bromide ion, ceric sulfate, ferrocyanide, formic acid, ethanol, and ultrapure water.



Hugo Fricke
(1892 – 1972)

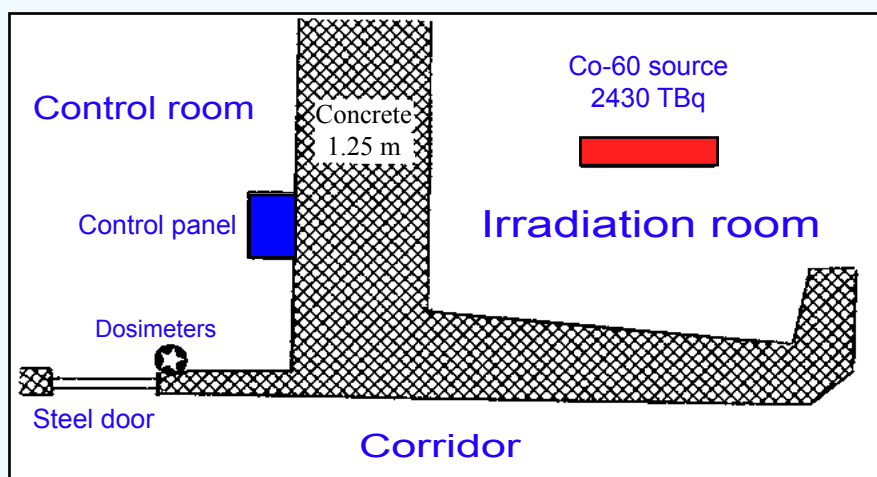
Free Radical Dosimetry

Among the highly reactive products formed in materials by radiation are free radicals. By definition, a free radical is a molecule that has an unpaired electron. Some examples are the hydroxyl radical (OH), the methyl radical (CH_3), and nitrous oxide (NO). Radicals are very unstable in aqueous systems such as in a living cell, but their lifetimes can be very long in solid materials. Consequently, trapped free radicals in solid materials can be used to obtain the radiation dose. The number of radicals formed and trapped is proportional to the radiation dose. The number of radicals is measured by the *Electron Spin Resonance* (ESR) technique.

This type of dosimetry started more or less by chance in 1982 connected to a fatal reactor accident in Norway. We shall therefore start by giving you some details about this accident and the dose determination.

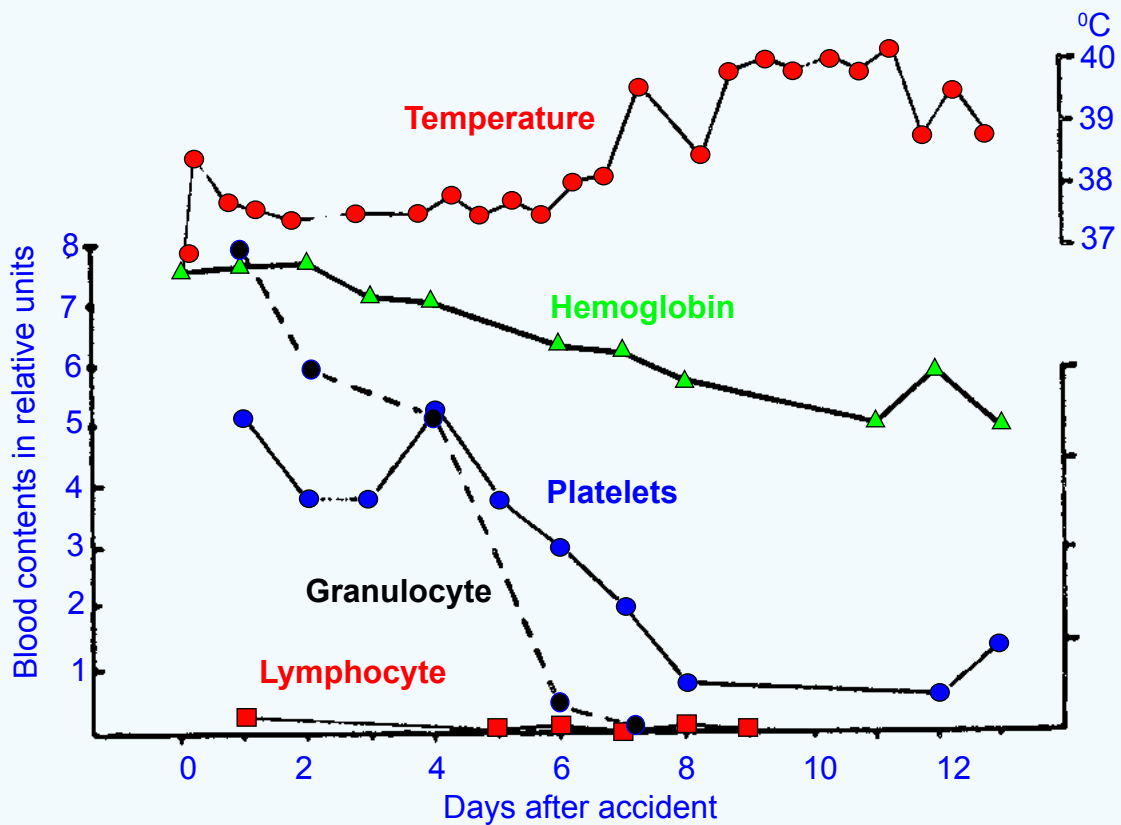
A radiation accident

In September 1982 a fatal radiation accident occurred in a laboratory for radiation- induced sterilization of medical equipment in Norway. An employee was exposed to a large γ -dose. He was the only person at work when the accident happened. A coincidence of technical failures with a safety lock and an alarm light, together with neglect of the safety routines, resulted in the fact that he entered the room with the source in the exposure position. The drawing below shows the radiation facility. The source is Co-60 with an activity of 2430 TBq.



The employee was found outside the laboratory in the early morning with clear signs of illness. Since he had heart problems (angina pectoris), it was first assumed that he had a heart attack and he was hurried into the hospital. However, it became clear that he had been exposed to radiation. The man had *acute radiation syndrome* with damage to the blood forming tissue as shown in the figure below.

You can see from the figure that his blood counts went down dramatically – in particular the lymphocytes. The lymphocytes are of fundamental importance in the immune system. His temperature was about 38 degrees for a few days and then increased to about 40. He was all the time treated with antibiotics and several blood transfusions, but died 13 days after the accident.



In the figure is given the body temperature (upper curve with temperature axis to the right) and the different blood values for the technician involved in the radiation accident in Norway. The lymphocytes were already knocked out after 24 hours. He was treated with antibiotics. It can be mentioned that in 1982 it was not possible to think on solutions such as bone marrow transplantation.

What was the radiation dose?

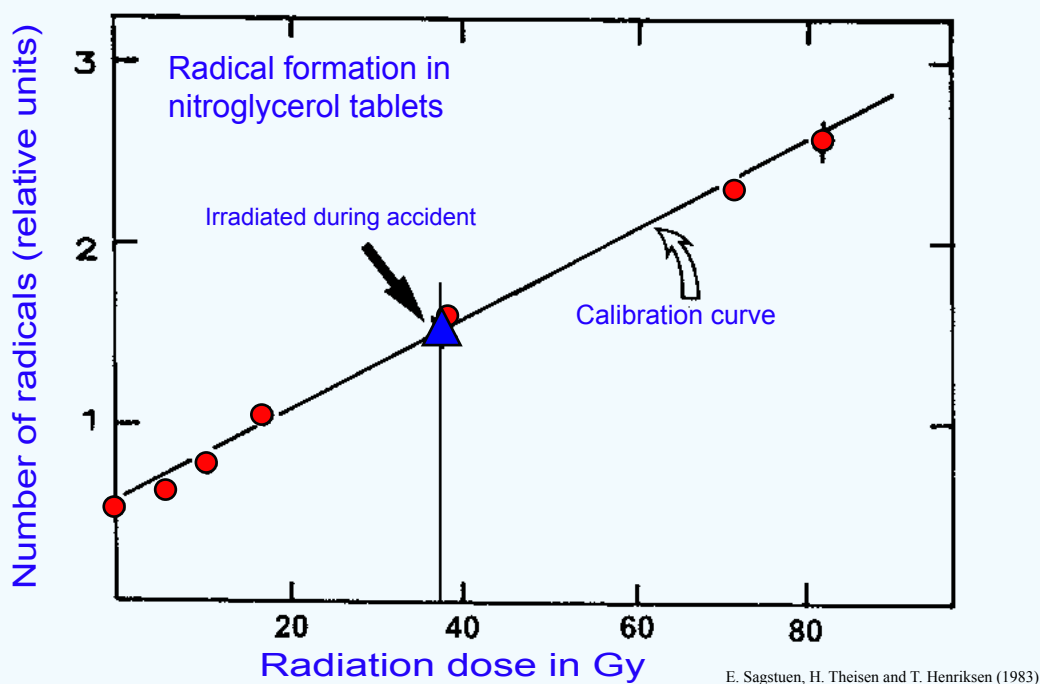
It is important to get information about the dose involved in this accident. We usually have very small opportunities to arrive at the dose in similar accidents. In this case the victim used a film badge as required for all employees. However, when developed, the film was black and could not give the dose involved.

Attempts were also made to interview the victim about the time spent in the irradiation room. The dose calculated from this was a couple of Gy and should be observed by the film badge. It was obvious the the dose must have been larger. What other possibilities were available?

The radiation authorities in Norway asked the ESR-group at the University of Oslo about the possibilities to use electron spin resonance to determine the dose. This turned out to be a challenging task and a hunt for objects containing radicals that were induced together with the victim. Induced radicals were found in the cloths (shoes and buttons) and in the nails of the victim. However, it was not possible to use these materials for a proper dose determination. The solution was found more or less by accident. The victim used nitroglycerol tablets because of heart problems. He always carried a small box containing these tablets – which turned out to solve the problem.

The nitroglycerol tablets consists mainly of sugar (lactose) which is the part in which the radicals are formed. The tablets from the accident was loaded with radicals. In order to use this system for a dose determination, it was necessary to work out a dose-effect curve (a calibration curve).

Tablets of the same type were irradiated with Co-60 γ -rays with doses from 1 to 80 Gy, as determined by thermoluminescence dosimetry. With a calibration curve in hand, the tablets irradiated with the victim could be determined as shown in the figure below.



The accidental dose was determined to be 38.5 Gy. Then, measurements were made with a phantom which was placed in the exposure room at the same position as the victim. A number of TLD dosimeters were used and it was found that a dose of 38.5 Gy to the position of the box with the nitroglycerol tablets (in his pocket) yielded an average whole body dose of 22.5 Gy. The bone marrow dose was 21 Gy, whereas the dose to the brain was calculated to be 14 Gy.

Conclusion: ESR spectroscopy can be used for dose determinations, even after an accidental exposure.

Note: The accident occurred in 1982. The tablets have been stored since and used as a laboratory exercise for students in radiation biophysics every year. In the fall of 2008 (26 years after the accident) 4 different groups of students measured the dose again. The average value found was 38.5 Gy!

ESR - dosimetry

ESR (sometimes called EPR after Electron Paramagnetic Resonance) – dosimetry has developed during the last two decades. It was known already in the early 1960-ties that stable radicals were formed in crystalline organic compounds such as simple amino acids. The energy absorbed in order to form one radical was in the range from 5 to 50 eV, i.e. similar to the energy necessary to form an ion pair in a gas.

Crystalline organic compounds have qualities that is necessary for dosimetry such as:

1. Radicals are formed in high yields.
2. The radicals are stable for days, – even years.
3. The sensitive volume made of organic compounds can be made tissue-like.
4. The sensitive volume can be small – comparable to TLD dosimeters.
5. The dose-effect curves seem to be linear up to kGy-region.

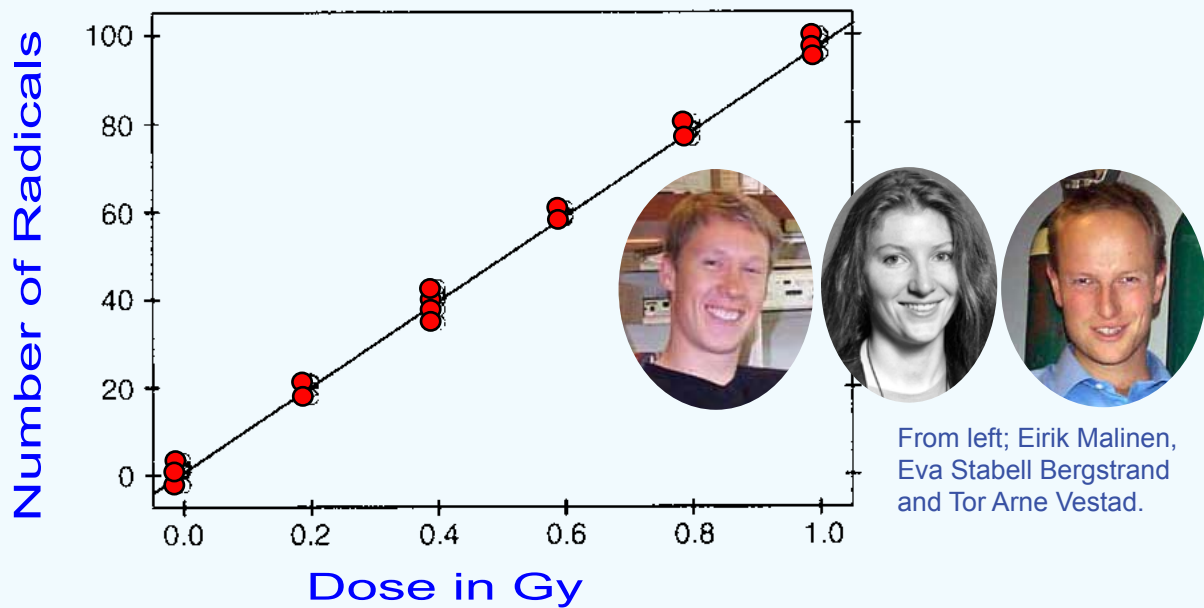
The drawback during the 1960 – 1970-ties was that the ESR-spectrometers available could not be used unless the radical number exceeded a certain level – implying that the radiation dose had to be above a few Gy.

Another drawback that can be mentioned is that the radical yield decreases rapidly with LET for values above 10 keV/ μ .

For a long time the amino acid L- α -alanine in polycrystalline form has been used for ESR dosimetry. It has an atomic composition that makes it near tissue (and water) equivalent with respect to energy absorption. The radical yield is high (about 13 eV per radical), and the radicals produced are quite stable. The dose–response relationship is linear in the region between 2 Gy and 5–10 kGy. Alanine is very accurate when measuring high radiation doses (kGy), but it is not well suited for determining doses below a few Gy unless very cumbersome precautions and procedures are followed. As a consequence, alanine is not suited for clinical applications where doses down to 0.5 Gy should be easily detectable with high precision. This has motivated researchers to search for new sensitive ESR dosimeter materials that can do the job when alanine is inadequate.

Formates (salts of formic acid, HCOOH) were suggested as alternatives to alanine a few years ago by Anders Lund and coworkers in Linköping, Sweden. Ammonium and lithium formate both have properties similar to water with respect to absorption and scattering of radiation, and they show promising potential for accurate dose estimation at low radiation doses. Lithium formate has a sensitivity that is about 6 times as high as L- α -alanine, and it has the propensity to measure radiation doses down to at least 50 mGy. Under normal temperature and humidity conditions the radicals are stable for many months, and the dose–response shows almost no dependence on radiation qualities and energies at low LET. A dose–response curve for the 0–1.0 Gy region is displayed in figure on the next page.

Other materials that have been used for standard EPR dosimeters and for accident or retrospective EPR dosimetry include calcified tissues, various sugars, quartz in rocks, and sulfates.



The figure gives the dose–response curve for lithium formate ESR dosimeter in the dose range 0 – 1.0 Gy. The results are from Ph. D. theses of students like Eirik Malinen, Eva Stabell Bergstrand and Tor Arne Vestad in the biophysics group at the University of Oslo.

Summing up

The "**dose rate**" is usually given when describing the intensity of the radiation being absorbed by the target, i.e. the radiation dose per unit time. The total dose is then obtained by a simple multiplication of the dose rate by exposed time.

In order to measure the dose to soft tissue exposed to γ -radiation, the walls of the instrument as well as the compound in the sensitive volume (whether a gas or a solid) must have a composition that has an absorption similar to soft tissue.

Thermoluminescence dosimeters (TLD) are frequently used for dose measurements. TLDs are well suited for different types of radiation as well as for large and small doses and dose rates. If LiF-crystals are used, x- and γ -rays yield a response which is proportional to the dose to soft tissue. If crystals with calcium are used, the response is proportional to the bone tissue dose.

Since the TLD crystals are small, they are well-suited for measurement of doses to patients. They can be placed on and in the body.

The recent development with ESR-dosimetry is promising. ESR-dosimeters can be given the same qualities as the TLD-dosimeters.