4. Dose and Exposure

In order to protect people from ionizing radiation, or to calculate the risk/benefit ratio for exposing a patient to possibly necessary radiation, it is obviously necessary to measure radiation to which the subject is exposed. Within a radiation field close to a radiation source there will be a *fluence* of particles that has been defined as dN/da where N is the number of particles incident on a sphere of cross-section a. The unit of exposure used to be the roentgen (R) that was defined as “That quantity of radiation that will release an electrical charge of 2.58×10^{-4} coulombs in one kilogram of dry air.” This is equivalent to about 1.3×10^{15} electrons. The new unit has no name (this is the actual truth), but is just given as 1 R = 2.58×10^{-4} C kg^{-1} dry air.

A more useful measure is derived from the concept of *radiation dose*, which describes the dose of radiation absorbed by human tissue. Another measure is the *dose equivalent*, which takes into account the fact that some types of radiation are more damaging than others.

The absorbed dose is measured in terms of the energy absorbed per unit of mass of tissue. Energy is measured in joules, and mass in kilograms. The unit of dose is the ‘gray’ (Gy) where

$$1 \text{ Gy} = 1 \text{ J kg}^{-1} \text{ of tissue}$$

There is an old unit of dose that is still used, the rad (radiation absorbed dose), that is related to the gray by

$$1 \text{ rad} = 0.01 \text{ Gy} = 0.01 \text{ J kg}^{-1} \text{ of tissue}$$

As an illustrative (hopefully) example, if 1000 quanta (particles) are completely absorbed in 1 kg of tissue, then the energy absorbed by the tissue will be 1000 times the energy of each particle. Radiation energy is usually measured in keV (or MeV), but you can convert these energies to joules:

$$1 \text{ J} = 6.2 \times 10^{18} \text{ eV}$$

A dose of 1 Gy means that 6.2×10^{18} eV of energy have been absorbed in 1 kg of tissue. This could arise from 6.2×10^{12} X-ray photons of energy 1000 keV, or other combination of numbers.

Absorbed dose is difficult to measure. It is first calculated be measuring the exposure and then calibrating from knowledge of mass absorption coefficients for air and tissue (more later).

4.1 Dose equivalent

The unit of dose equivalent is that dose that gives the same risk of damage or detriment to health whatever the type of radiation. This unit is called the sievert (Sv):

$$1 \text{ Sv} = 1 \text{ J kg}^{-1} \text{ tissue x } \textit{constant}$$

The constant, called the radiation weighting factor, depends on the type of radiation. There is an old unit that is still used, the rem, that is related to the sievert by

$$1 \text{ rem} = 0.01 \text{ Sv} = 0.01 \text{ J kg}^{-1} \text{ tissue x } \textit{constant}$$

The dose equivalent in Sv is obtained by multiplying the dose in Gy by a constant:

$$\text{dose in Sv} = \text{dose in Gy x } \textit{constant}$$

The radiation weighting factor for X-rays and γ-rays is unity (1), for neutrons the constant is 10, and for α particles the constant is 20. Therefore, if you had your choice, you would rater be radiated by X-rays than α particles. Table 4.1 gives some idea of the sizes of the units of dose.

Table 4.1 Typical figures for X-ray doses for five different conditions

Dose due to background radiation in 1 year (in Iowa)	1 mSv=0.1 rem
Level set as the maximum dose to the general population in 1 year (a larger dose is sometimes allowed in 1 year provided the 5-year average does not exceed 1 mSv).	1 mSv = 0.1 rem
Level set as the maximum dose to people who work with radiation (50 mSv is the maximum any one year)	20 mSv = 2 rem
Dose exposure that will cause nausea, sickness, diarrhea in most people	0.5 Gy = 50 rad
Dose exposure that will kill many people in a few months following exposure	6 Gy = 500 rad

4.2 Maximum permissible levels

Maximum permitted doses set in the various codes of practices are expressed in units of dose equivalent. The International Commission on Radiological Protection (ICRP) recommends maximum annual dose equivalent for radiation workers as 50 mSv (5 rem), with a 5-year average less than 20 mSv per year. Larger doses are allowed to specific body parts. For members of the public, the recommended whole-body dose is 1 mSv (0.1 rem) averaged over 5 years.

Table 4.2 Maximum permitted doses from ICRP

Condition	**Dose**
Radiation worker	50 mSv = 5 rem (5-yr average < 20 mSv = 2 rem)
Public	1 mSv = 0.1 rem over 5 years

The US Nuclear Regulatory Commission has adopted standards that limit maximum exposure for the general public to 0.5 rem per year. Limits for occupational exposure are 1.25 rem/3 months for the whole body, and 18.75 rem/3 months for the extremities. Routine personal monitoring is usually done with film badges and ring-type finger badges.

The maximum permitted dose levels have been reduced over the last 70 years. In 1931, the maximum permitted level was 15 mSv (1.5 rem) PER WEEK. It is possible that further reductions will be made. The reason is that even small doses have long-term effects, and it is these effects that are the cause of continuing controversy in setting "safe" settings. The biological effects can only be expressed in statistical terms as the chance that a generic change, or a leukemia (or other cancer) might develop over a given period of time. The assessment of risk is complicated because there are also natural causes of these changes. The existence of long-term effects is the reason why young people, and particular the unborn fetus, are subject to the greatest risk for ionizing radiation, and thus are subject to their own specific maximum radiation exposure levels. For example, it is recommended that, under the "10 day rule," women are only exposed to diagnostic X-ray procedures during the 10 days following menstruation when pregnancy is unlikely.

4.3 Environmental dose

We are exposed to radiation from many different sources during our lives. Some of the sources are natural, some are man-made. Table 4.3 quantifies the body doses of various of these sources. You should compare these with the maximum allowed dose given above.

Table 4.3 The doses correspond to six different situations (values are approximate).

Cosmic radiation	200 µSv (20 mrem) over 1 year
Natural radioactive materials (e.g., ^{238}U)	300 µSv (30 mrem) over 1 year
Naturally occurring radioactive materials in the body (e.g., ^{40}K)	300 µSv (30 mrem) over 1 year
Chest X-ray	500 µSv (50 mrem) skin dose for one X-ray
Coronary angiogram	20 mSv (2 rem) skin dose for one procedure
Nuclear power station	< 1mSv (100 mrem) over 1 year 1 km from the station

4.4 Body parts – whole body dose

There is a maximum permitted dose of 20 mSv (2 rem) for radiation workers, and 1 mSv (0.1 rem) for the general public. The basis for these levels of is the risk of biological damage. Some feel that it is too easy to exaggerate radiation hazards when making comparisons with other hazards of life. For example Table 4.4 shows figures in terms of an equal risk of causing death on 1 year.

Table 4.4 All of these activities carry the same risk. They give a 1 in 20000 chance of causing death in 1 year (from E.E. Pochin, 1974)

Exposure to 5 mSv (0.5 rem) whole-body radiation
Smoking 75 cigarettes
Traveling 2500 miles by motor car
Traveling 12 500 miles by air
Rock climbing for 75 minutes
Canoeing for 5 hours
Working in a typical factory for one year
Being a man aged 60 for 16 hours
Being a man aged 30 for 20 days

The information in Table 4.4 is not meant to minimize in the engineer's mind the damaging effects of radiation; the information is meant to put the risk into perspective. Remember, these data are based on statistical models, and not on measured laboratory data.

Table 4.5 gives some typical doses obtained in clinical practice. Note that some of the doses are fairly close to the recommended limits (0.1 mSv averaged over 5 years for the general public).

Table 4.5 Doses for some common radiological examinations

Examination	**Dose (mGy)**
CC Breast	1.2
AP Chest	0.3
AP Lumbar spine	9.2
AP Pelvis	6.6
AP Skull	4.4

CC = Cranio-caudal view or projection
AP = Anterio-posterior view or projection

The ICRP have suggested the use of the quantity *effective dose equivalent*, which is a prescription for calculating the dose that, if given to the whole body, would produce the same detriment as the actual exposure received to the patient. The calculation of EDE is complicated and uses Monte-Carlo procedures, but the result is a number that represents the whole body "danger" of the clinical procedure. Each clinical procedure has an EDE – choose one with a low EDE (as if the patients really have a choice). Table 4.6 gives the effective dose equivalent and selected organ doses for various diagnostic procedures.

Table 4.6 Effective dose equivalent (mSv) and organ doses (mGy) for breast, red bone marrow, lung, thyroid, skin, ovaries, and testes for selected radiological examinations (from [Webb])

Examination		**Doses per Examination**						
	EDE	Breast	RBM	Lung	Thyroid	Skin	Ovary	Testes
Barium meal	3.8	2.2	2.6	8.7	1.1	2.1	3.6	0.3
Barium enema	7.7	0.7	8.2	3.2	0.2	5.1	16.0	3.4
IVP	4.4	0.7	1.9	7.0	0.2	1.9	0.8	0.1
Cholecystogram	1.0	0.4	0.8	1.6	0.1	0.8	0.4	0.0

The literature on ionizing radiation hazards is enormous. A general qualitative understanding for the situation can be gained, however, by consensus statements such as "the average risk of inducing a fatal malignancy in human tissue subjected to a dose of 10 mSv is in the region of 10^{-4}," or "the overall risk associated with a tissue dose, in the developing embryo or early fetus, of 10 mSv may lie in the range of 0-1 per 1000 for all serious malformations and cancers" [Webb]. **The message is to keep the dose as low as reasonably achievable, but especially for the very young.** Current practice leads to tissue doses in the range of 0.1-100 mSv per examination. Nuclear medical procedures often exceed this range. Procedures based on CT often exceed this range. We will investigate what this means for the medical imaging engineer.