Practical Radiation Protection

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Fourth, completely revised edition

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Preface

Like in the preceding editions, in this fourth edition we want to give a systematic insight in the hazards of applying ionising radiation and in the work methods to control these hazards, resulting in an acceptable risk.
In the Chapters 9, 10 and 11, we describe the measures the worker himself can take, for sealed sources and X-ray equipment, for open sources and for medical applications.
The preceding chapters treat successively the physical backgrounds, the measurement apparatuses, the quantities and units used in radiation protection, the hazards of ionising radiation, and the measures that are already taken by the Government and the formulas to assess your own dose.
The appendices give some mathematical background and exercises.

This book is also suitable for two other target groups:

- It also contains the topics necessary for the Radiation Protection Officer dispersible radioactive substances, level D (TMS-VRS-D) and for the Radiation Protection Officer medical applications (TMS-MT).
- Chapters 1 to 8, and where applicable 9 and 10, can be seen as a basis for the other seven training courses for the Radiation protection supervisor.

In this edition the following changes have been made.
In Chapters 1 and 3, we have split the text on half-life and half-thickness into a part without mathematical formulas and part with the precise formulas. It is expected that on one hand, this will clarify the treatment and on the other hand this will ensure that these important items will also be accessible for people without a mathematical background.
Chapter 2, the overview of the applications, now only contains only a brief overview of the medical applications; its extensive description is now included in Chapter 11.
In Chapter 4, on measuring equipment, a Section is added on tips for doing the actual measurements.
In Chapter 5, on quantities and units, the new tissue weighting factors are listed.
Chapter 6, on effects and risks, is virtually unchanged.
Chapter 7 is the most changed chapter. It describes the rules and regulations as from February 2018, when the new radiation protection basic safety standards 'Euratom Directive' is implemented in the Dutch law. An extra section on security is included.

The regulations on radioactive waste, previously in the separate Chapter 11 on radioactive waste, are now a section in this Chapter 7. Finally, a section on ethical aspects of regulation is added.
Chapters 8 and 9 have changed places. In Chapter 8, about assessing a dose, for external radiation we use for the sections the headings ' time, distance, shielding '. The h(10), the ambient dose rate constant, is introduced and the formulas are described in terms of half-lives and half-thicknesses, so not using the decay constants and the attenuation coefficients.
The rules of thumb for β radiation have changed.
Chapter 9, on sealed sources and X-ray equipment and Chapter 10, on open sources, are virtually unchanged; Chapter 9 focuses on applications outside of the medical setting.
The contents of the former Chapter 11, on radioactive waste, is now included in Chapter 7 on regulations, and in Chapters 10 (laboratories) and 11 (medical applications).
The new Chapter 11 describes the practical radiation hygiene in a medical setting.

The practice questions are all the same. The open questions are mainly intended for the Radiation protection supervisor.

This is a translation into English of the eight edition of the book *Praktische stralingshygiëne*. Small corrections have been carried out, and Section 8.6 was added.

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The content of this book is the responsibility of the authors and not of the institutions where they work or the colleagues that have provided comments.

Where in the book 'he' is used, 'he or she' is meant.

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difference, the net value, will be relatively large. This error can be calculated using the law of propagation of errors. A more extensive treatment, for those who are interested, can be found in appendix B.
The concept of sensitivity can be defined as the minimal amount of activity that can be detected. From the text above, it follows that the sensitivity depends on the relative error in the measurement. So, a long counting time and the lowering of the background will improve the sensitivity.

Example 1

A counter has a mean background of 36 pulses per minute. According to the text above, one needs to count at least $\sqrt{36} = 6$ pulses in 1 minute above that background count rate before one may speak of a measurable activity. But when we count for 10 minutes, then we need to count an excess of $\sqrt{360} = 19$ pulses. That are less than 2 pulses per minute, and therefore an activity about thrice as small becomes measurable. That makes sense, since the measuring time is ten times larger, making the measurement $\sqrt{10} = 3.2$ times more sensitive.

Through better shielding of the abovementioned counter, the background is limited to 9 pulses per minute. The minimal excess number of counts, necessary to determine if there is measurable activity present (when counting for 10 minutes), then becomes $\sqrt{90} = 9.5$ pulses. That is about 1 pulse per minute. By reducing the background by a factor of 4, the sensitivity has improved by a factor of $\sqrt{4}$) .

In summary: the sensitivity of a measurement can be improved by lowering the background. And counting for a longer time reduces the counting error as well as it improves the sensitivity.
With a monitor with a dial, the swinging of the needle during the background measurement is the determining factor for the sensitivity. Only when the position of the needle, at a place where the presence activity is to be expected, is clearly beyond the background (plus the amount of swinging), we may conclude there is some activity present, mostly in the form of a contamination.

Example 2

Above a clean surface, an analogue contamination monitor indicates a mean value of 8 pulses per second (cps = counts per second), with the needle swinging back and forth around that value by ±3 cps. So, there is a contamination present if the needle indicates at least 11 cps. If, for example, it is indicated on the device that for ^{125}I, a reading of 1 cps equals a surface contamination of 0.3 Bq/cm^2, then the minimum surface contamination we can detect is $3 \cdot 0.3 \approx 1$ Bq/cm^2.

4.7 Overview of detectors and their field of application

One should always use monitors only after consulting a radiation expert. Choosing the wrong type may lead to a false feeling of safety, because using the wrong detector may (wrongly) lead you to believe that there is no radioactivity present, while a suitable detector would have indicated otherwise.

Table 4.1
Detectors and their applications

	Measurement of β radiation	*Measurement of photon radiation*
Ionisation detectors		
GM tube (thin window)	contamination*	dose rate
GM tube (thick window)	dose rate	dose rate
Proportional counter (thin window, xenon filled)	contamination*	contamination with low-energy γ's like ^{125}I
(HP)Ge, Ge(Li)	–	spectrum (complex) identification of nuclide
Scintillation detectors		
NaI(Tl)	–	contamination spectrum (simple)
Anthracene or ZnS	contamination*	–
TLD	personal dose meter	personal dose meter
Scintillation liquid	contamination	soft γ-radiation

*) also α radiation

4.8 Recommendation for measurements in practice

4.8.1 Before starting to work at a new department

1. At the introduction to the work place, inquire about the different monitors present there, and for what use they are intended.
2. Also, inquire for what use they are *not* intended. In particular, ask if the monitors can also measure low-energy radiation, for example of 20 keV, sensitively. Some monitors only can measure with a sensitivity of only a few per cent in that area. Since the secondary radiation of a 40 kV X-ray diffraction tube will largely consist of radiation with an energy around 20 keV, and since some radionuclides are emitting their most important radiation around this energy, you will be unable to detect the most important component of this type of radiation.

For weakly penetrating radiation one takes the equivalent dose on 0.07 mm depth in that phantom. In the literature, these quantities with the symbols are specified with $H^*(10)$ and $H^*(0.07)$ respectively.
These quantities are called *ambient dose equivalent.*
In this book we use a simplified notation for the ambient dose equivalent $H^*(10)$; we will in short write H, for the effective dose, The unit for the ambient dose equivalent is the sievert.

The effective dose caused by external radiation of a radioactive source (so the equivalent dose at 10 mm depth) is determined by the activity A of the source and

- the duration of exposure
- the distance to the source
- the physical properties of the source
- the shielding.

In the following Sections these aspects are worked out, and summarised in Formula 8.5.

8.2.2 Duration

The duration of the application, t, determines the effective dose H:

$$H = \dot{H} \cdot t \tag{8.1}$$

The point on top of the H specifies that a rate (i.e. the dose rate) is involved.
In the formulas in the following Sections, this time aspect is not further elaborated; those formulas relate to the dose rate and not the dose.

8.2.3 Distance: the inverse square law

A beam of ionising radiation spreads in space in such a way that the intensity of the radiation becomes less as the beam is further away from the source. The dose rate is lower when you are on larger distance from the source. However, the dose rate is not inversely proportional to the distance. As long as the source is small in size (point source), the *inverse square law* holds. This law states that the dose rate is inversely proportional to the square of the distance (r). That this proportionality is quadratic, can be made plausible by imagining a sphere with a radius of 3 cm around the point source and a sphere with a radius of 10 cm. Through the sphere with the radius of 3 cm all radiation passes through a surface area of the sphere of $4\pi \cdot 3^2$ cm^2, and for the sphere at a distance of 10 cm all radiation passes through a surface area of $4\pi \cdot 10^2$ cm^2. One can conclude that the 'amount of radiation' (the fluence) decreases quadratically, see Figure 8.1.

For a point source the following formula holds, when there is no shielding:

$$\dot{H} \quad constant \quad \frac{A}{r^2} \tag{8.2}$$

where:
$\dot{H}$ = effective dose ($Sv \cdot h^{-1}$);
A = activity (Bq)
r = distance to the source (m)

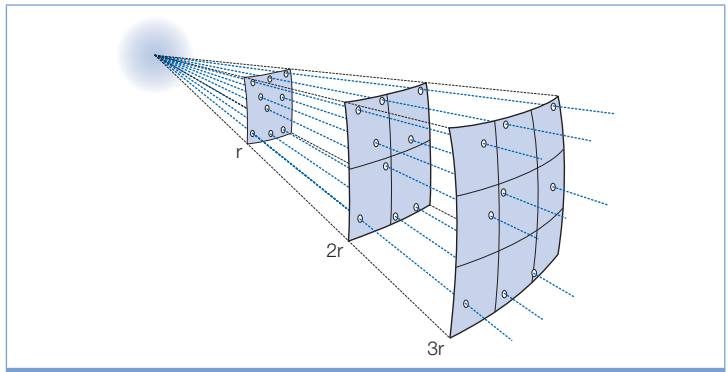

Figure 8.1

The number of photons through a unit of surface area decreases quadratically with distance.

8.2.4 Physical properties of the source

The constant in Formula 8.2 is defined by the physical properties of the source; the constant for a nuclide that emits low-energy radiation is different from the constant for a nuclide that emits high-energy radiation: each nuclide has its own constant. It is called the *ambient dose rate constant* and is written as $h(10)$. The number 10 in $h(10)$ indicates that it holds for a depth in the phantom of 10 mm.
The formula for the effective dose is, still for a situation in which there is no shielding:

$$\dot{H} = h(10) \cdot \frac{A}{r^2} \tag{8.3}$$

In Table 8.1 the ambient dose rate constant is given for some radionuclides. When using values for this constant, pay attention to the dimensions. Using the $h(10)$ values from Table 8.1 the activity must be inserted in MBq and the distance in metres: the result is then in $\mu Sv \cdot h^{-1}$.

For the risk calculation, it is assumed that the administration takes place in liquid form (giving a 'sip'), that in the event of an incident 10% of the activity is released and that 0.1% of this is released into the air. Nowadays, instead of giving a 'sip', a capsule is given, so that the chance of a dose caused by spilling of the sip is zero. The calculation indicates an upper limit for the risk of inhalation in the event of possible incidents in Nuclear Medicine.
Finally one can assume that the ventilation is such that one breathes in a fraction of 10^{-3} of the activity spread in the air, the inhalation fraction. This fraction of 10^{-3} can be substantiated by calculating how many litres of air a person inhales during the incident based on the fact that a person inhales 1.2 litres per minute; however, this calculation is beyond the purpose in this context.
An inhalation fraction of 10^{-3}, an incident fraction of 10% and a release fraction of 0.1% results in a total fraction of 10^{-7} of the applied activity in the body. Thus $10^{-7} \cdot 5500$ MBq $= 5.5 \cdot 10^{-4}$ MBq is being inhaled. Because $e(50)$ = 11 mSv per MBq (see Table 8.2), the inhalation dose is $6.1 \cdot 10^{-3}$ mSv (6 μSv).

With two administrations per week, i.e. about one hundred administrations per year, the expected collective annual dose, i.e. the dose of all those involved during this application, is around half a millisievert.
In applications with other nuclides, much less activity is used; they are also less radiotoxic (except, for example, ^{223}Ra; but this is used much less often), so the contribution to the collective annual dose will be lower.

Finally, it is useful to point out that when using the A_{max} formula 10.1 (assuming that $p = -2$, $q = 1$, $r = 0$ and $e(50) = 11$ mSv/MBq) the maximum activity allowed in the syringe is 0.2 MBq; that is a factor 28,000 times less than the 5500 MBq that is actually applied. According to the *pqr-formula* this procedure (syringe application) must take place in a B-laboratory in a fume hood. The A_{max}-formula must therefore only be applied in laboratories and their supplementary spaces. The big difference is due to the fact that in 1985 the Health Council when deriving the A_{max}-formula 10.1 assumed a much larger fraction that enters the air, and after that a safety margin has been applied on the calculations of the Health Council.

B.2.3 Needlestick injuries

To determine the dose as a result of a *needlestick injury* it is generally assumed that the worker receives a fraction of 10^{-3} of the administered activity. However, an estimate of the dose by that intake is not possible with the data in Table 8.2, because the $e(50)$-values of Table 8.2 are not applicable here; these values concern a pure radioisotope and when administered to a patient it usually concerns a labeled protein that spreads differently

through the body than the pure radioisotope. However, the dose for the worker is 10^{-3} of the dose for the patient. This means that in the case of a needlestick injury with a syringe intended for a patient, the dose for this worker as a result of internal contamination will be in the order of millisieverts.

B.2.4 External irradiation of the body

To assess the importance of the measures to control external radiation, one should focus on the administration of ^{18}F, due to its relatively high $h(10)$ of 0.17 μSv/h per MBq at 1 metre distance (see Table 8.1), the relatively high activity that is administered each time (400 MBq) and the many administrations that are performed annually (in the example below we assume a thousand administrations per year) .

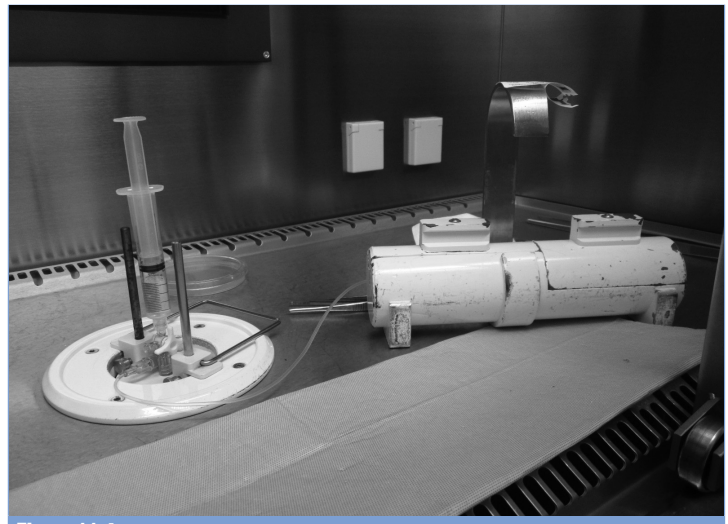

Figure 11.4

Preparing the ^{18}F-syringe.

We assume that a syringe fill station is used to safely fill the syringe with ^{18}F . This system is shown in Figure 11.4. The syringe is originally empty in the lead cylinder, the radioactive supply under the table in a lead-shielded container. The liquid is drawn into the syringe and the operator is only exposed without shielding during the short moment that the liquid passes through the visible plastic tube. Afterwards, that tube is flushed clean with non-radioactive fluid that is in the visible vertical syringe.

The calculation (see below) shows that the collective effective dose from external radiation in regular applications for a department can be around 13 millisieverts per year. This amounts to the collective dose as registered on the TLD badges in a Department of Nuclear Medicine.