1 Introduction

In brachytherapy, sealed radioactive sources are used to deliver a prescribed dose to a relatively small volume of tissue while sparing the normal tissue surrounding the target. The sources are implanted or placed in close proximity to the irradiated tissues. All developments in technology, dosimetry, oncology and mainly quality assurance-as described in the present book-aim at reducing the risk of complications to the patient. As the staff is concerned, radiation oncologists, physicists, nursing staff and technicians, the three general principles of radiation protection should be followed: justification, ALARA (As Low As Reasonably Achievable), and individual dose limitations (3). For the staff, as radiation workers, the annual dose limits are 20 mSv for the effective dose, and 500 mSv for the doses at the extremities (hands). A special group of persons was recently identified: members of the family or other persons like volunteers, that "knowingly and willingly" accept radiation exposures higher than the limit for the general population (i.e., 1 mSv per year) in order to help patients treated with radioactive sources.

In the past, and especially when radium sources only were available, the doses to the staff were high, often higher than the annual limits accepted at those times. With the introduction of the artificial nuclides in combination with more and more efficient afterloading systems the doses to the staff were dramatically reduced and, in many centres, are nowadays not significantly higher than the doses received in external beam therapy.

2 Techniques and Materials

The sources used in brachytherapy are always of a sealed source type. Most commonly, the rigidity of the source is determined by its non-radioactive encapsulation, which also serves to prevent spread of the radioactive material. This is for example the case for the sources with the nuclides cesium-137 and radium-226. The nuclide iridium-192 is often applied in the form of wires, in which the radioactive iridium is encapsulated with a platinum-iridium alloy. As these wire sources are cut to the desired length to the need of the individual patient, strictly speaking the definition of a sealed source type is not applicable, but they are treated as such.

Modern remote afterloading technique makes use of micro-electronic controlled equipment to control the position of the source or sources and has replaced many of the former manual implantation techniques. Besides the ability to optimise the dwell time of a source at a given position or for a whole catheter, the main advantage of such systems is the radiation protection for the people surrounding the patient. This equipment allows interruption of the treatment for nursing care, for visiting the patient, or even for fractionation of the prescribed dose. There is a strong reduction of the radiation dose to the staff in departments where the remote afterloading equipment is introduced.

When the dose rate to a prescription point is 12 Gy·h\(^{-1}\) or higher, the technique is called a high dose rate (HDR) technique. Dose rates below 2 Gy·h\(^{-1}\) are called low dose rates (LDR), while the intermediate dose rates are indicated with the term medium dose rate (4). Only a few nuclides can be used for HDR systems due to the required high specific activity. For brachytherapy HDR techniques the radionuclide iridium-192 is predominantly utilised.
The high activity of this source, e.g., up to 370 MBq, can only be used in a well designed remote afterloader with proper shielding inside. Any manual manipulation of these highly radioactive sources must be avoided (see Fig 3.1).

Fig 3.1: The tungsten container for the safe position of the high dose rate iridium-192 source in a high dose rate afterloader is clearly visible when the covers are removed.

If there is a defect in the sealing, e.g. caused by damaging of the sealed source, there is a risk not only of external irradiation of the person manipulating the source, but also of ingestion or inhalation of the radioactive material. The individual risk can be substantial in those cases. Early detection of source damaging and leakage of radioactivity is therefore required and forms an essential part of a QA programme.

The national authorities prescribe in detail in the license which measures have to be taken for a safe application of brachytherapy sources to the patient and for the protection of the radiological workers, the nursing staff and other members of the community. The responsibility for the safe operation of the equipment and for the radiation protection lies with the medical physicist. Normal operation procedures must be available in written form and the structure of the responsibilities in the department must be made clear. Quality control procedures must be described and the results of regular QC checks must be logged in a logbook.

3 External Irradiation by Brachytherapy Sources

The dose to the individual due to irradiation by a gamma source or by a set of sources is determined by the strength of the source(s), the time of irradiation and the distance. The modern quantity to indicate the strength of a source is the reference air kerma rate, RAKR. The RAKR of the source is expressed in the unit μGy·h⁻¹ at 1 m. The product of the reference air kerma rate of all sources i used in combination in a treatment (or during an exposure) for a given duration tᵢ is called the total reference air kerma, TRAK = Σ (RAKRᵢ • tᵢ). This product thus gives us a quantity that can easily be
used in radiation protection calculations at any distance, simply by using the inverse square law relative to the distance of 1 m: \( K_\alpha = \text{TRAK} / r^2 \), for the air kerma \( K_\alpha \) at a point at distance \( r \).

If the strength of the source is known in the activity unit MBq, then the reference air kerma rate can be determined using: \( \text{RAKR} = \Gamma_\delta \cdot A \). The quantity "activity" is still widely used, especially for the purpose of legal and administrative procedures. Values of \( \Gamma_\delta \) are specific for the source type and can be found in tabulated form in the textbooks. For a number of source types values of \( \Gamma_\delta \) are given in table 3.1.

Table 3.1: Values of \( \Gamma_\delta \) for a number of nuclides. Note that values in the literature may differ somewhat depending on the source encapsulation (most data taken from (1); see also chapter 2, Radiophysics).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>( \Gamma_\delta ) in ( \mu GY \cdot h^{-1} \cdot MBq^{-1} \cdot m^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{198}\text{Au} )</td>
<td>0.0548</td>
</tr>
<tr>
<td>(^{60}\text{Co} )</td>
<td>0.309</td>
</tr>
<tr>
<td>(^{137}\text{Cs} )</td>
<td>0.079</td>
</tr>
<tr>
<td>(^{125}\text{I} )</td>
<td>0.034</td>
</tr>
<tr>
<td>(^{103}\text{Pd} )</td>
<td>0.035</td>
</tr>
<tr>
<td>(^{192}\text{Ir} )</td>
<td>0.1157</td>
</tr>
<tr>
<td>(^{226}\text{Ra} ) (0.5 mm Pt)</td>
<td>0.197</td>
</tr>
</tbody>
</table>

The influence of shielding is entered into a dose calculation by using a correction factor for the transmission through the shielding material. The overlying tissue of the patient may cause a dose reduction, but generally the shielding is deliberately placed for that purpose. A transmission factor \( T \) is used in the calculation, which depends on the thickness of the material, the density, the effective atomic number and the photon energy of the emitted gamma rays. In table 3.2 the “first half value layer”, HVL, in lead for the same sources of table 3.1 is given. The half value layer is the thickness of a given material for which the value of the transmission factor \( T \) equals 0.5. Also the thickness of lead and of concrete is shown for these source for which \( T \) equals the value 0.1, i.e. a reduction to 10% of the unshielded intensity, the TVL or tenth value layer.

Table 3.2: Radiation protection data for a number of nuclides (most data taken from (1)).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Average energy (in MeV) of the emitted photons</th>
<th>Half life</th>
<th>First HVL in lead (in mm)</th>
<th>TVL in lead (in mm)</th>
<th>TVL in concrete (in cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{198}\text{Au} )</td>
<td>0.42</td>
<td>2.7 d</td>
<td>3</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>(^{60}\text{Co} )</td>
<td>1.25</td>
<td>5.3 y</td>
<td>12</td>
<td>42</td>
<td>22</td>
</tr>
<tr>
<td>(^{137}\text{Cs} )</td>
<td>0.66</td>
<td>30.2 y</td>
<td>6.5</td>
<td>22</td>
<td>17.5</td>
</tr>
<tr>
<td>(^{125}\text{I} )</td>
<td>0.028</td>
<td>59.4 d</td>
<td>0.025</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(^{103}\text{Pd} )</td>
<td>0.021</td>
<td>17 d</td>
<td>0.02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(^{192}\text{Ir} )</td>
<td>0.38</td>
<td>74.0 d</td>
<td>6</td>
<td>16</td>
<td>14.7</td>
</tr>
<tr>
<td>(^{226}\text{Ra} )</td>
<td>0.83</td>
<td>1600 y</td>
<td>16</td>
<td>45</td>
<td>23.4</td>
</tr>
</tbody>
</table>

For a better estimation of the shielding effects of concrete walls such as those used for construction of brachytherapy treatment rooms, it is sometimes more convenient to use data taken from graphical representation of \( T \) vs. the thickness. These graphs can be found, e.g., in ICRP Publication 21, Supplement to ICRP Publication 15 (2). Examples are shown in Fig 3.2 and 3.3.
Fig 3.2: Transmission factor $T$ for broad beam attenuation as a function of the thickness of a concrete shielding wall, density 2.35 g.cm$^{-3}$, for various radionuclides (2).

Fig 3.3: Transmission factor $T$ for broad beam attenuation as a function of the thickness of the lead shielding, density 11.35 g.cm$^{-3}$, for various radionuclides (2).

Reduction of the dose due to external irradiation by brachytherapy sources can be obtained by a combination of the following principles:

(i) Reduce the time of exposure, as the total dose is proportional with time. Tools used for source preparation must be set ready. Procedures must be practised with non-active,
dummy material to gain experience. Potential obstacles must be removed before the sources are taken out of the container.

(ii) Keep the distance as large as possible. Sources should not be touched by hand. It is recommended to use long forceps or tweezers to manipulate the source. The inverse square law is most effective to reduce the dose.

(iii) Reduce the amount of source material. Each source must be manipulated separately. Because often several sources are used for treatment of the patient, measures must be taken to reduce the exposure from sources that are not manipulated at that time. Those sources must always be stored in a shielded container and put aside at some distance.

(iv) Use the shielding material that is available. Examples are the shields at the preparation table or movable shields besides the bed of the patient.

4 Contamination by Radioactive Materials

The determination of the dose due to contamination with radioactive material is much more difficult to perform than the dose due to external irradiation. Measures are taken to avoid as much as possible the risks of contamination. Organs at risk are the skin, especially the skin of the hands, the digestive tract due to ingestion, and the lungs due to inhalation. Depending on the chemical substances, other organs can be involved.

Beta and alpha radiation emitting sources lead to a very low risk with regard to any external irradiation and usually only the skin is involved as the irradiated organ. However, when the radioactivity has entered the body the barriers are missing and this can lead to significant high doses to internal structures. This internal contamination can have different origins:

(i) Damaging of the sealing of the sources. Needle sources are sometimes bent, and especially the strontium-90 sources with a thin window are vulnerable.

(ii) Cutting iridium-192 wire sources on a preparation table can lead to loss of very small pieces of material that can hardly be seen. A contamination detector, however, can show their presence.

(iii) Small cracks, even invisible to the eye, in the source sealing can lead to contamination. For example, the gaseous radon-222 as a daughter product in the radium-226 source can leak through such tiny cracks.

(iv) In a brachytherapy department often patients are hospitalised and nursed from the department of nuclear medicine, using open sources as iodine-131 and phosphor-32. By definition these patients are a possible source of internal contamination of all personnel involved.

To reduce the risk the following steps should be considered.

(i) The surface of each source must be checked regularly for visible damaging. In case of preloading or manual afterloading it is recommended to have a quick look after each use, and preferably also before each insertion into the patient. If the source(s) is part of a closed afterloading system, such an inspection should be done when sources are replaced or for instance twice a year as part of a QA procedure; see also (iii). The locally responsible person (the physicist) must be warned when there is any suspicion after this inspection. Especially the tubes or needles used for bladder implants need careful verification that no damage has occurred.

(ii) Radium sources cannot be sterilised at high temperatures due to the risk of increased gas pressure, which may lead to leakage.

(iii) Sealed sources need periodic checks. In most countries a yearly check is obligatory. A wipe testing procedure may indicate freedom of leakage of the source. The results must be documented in a logbook.
(iv) The same wipe test must be performed regularly at the inner surface of the vault where the sources are stored or at parts of the source transport system (tubes) where activity might be expected in case of a contamination; see also (vi).

(v) Sources with a very thin sealing surface, such as the strontium-90 applicators cannot be touched for wipe testing. The wipe test must be performed on the inner surface of the vault.

(vi) Sources, which are too highly active to be touched, such as the iridium-192 and cobalt-60 sources of HDR afterloaders, cannot be reached safely. In general the verification for leakage is performed by placing the catheters, filters, tubes or other parts of the afterloader that are in contact with the source into a well-type chamber or the NaI crystal in the department of nuclear medicine.

(vii) Instruments used for cutting iridium-192 wire sources should not be used for any other action but should be kept apart instead. The instruments themselves can be contaminated. The preparation table should have a separate section for this work. A surface contamination detector can easily show even the smallest amount of radioactive material. The verification of the absence of radiation on the working area of the preparation table should be a routine task.

(viii) Eating, drinking, smoking and the application of cosmetics are forbidden in the area where radioactive sources are used. Ventilation of the preparation room should be sufficient to quickly reduce the presence of gaseous radioactive products. Gloves, materials for decontamination and contamination detectors must be available. The use of these materials must be practised.

A useful tool to detect radioactive contamination to the extremities, or to evaluate the efficiency of decontamination procedures, is a thin-window survey detector of the type used in a hand- and foot monitor, which is usually available in the radionuclide laboratory of the nuclear medicine department.

5 Manipulation of Sources

5.1 The preparation room

Radioactive sources cannot be left unattended. When not in use, sources have to be locked away safely in a storage container. For different source types different containers should be used. Storage containers must be fire resistant and carefully locked against unauthorised persons. Safety regulations will generally require a maximum exposure rate at 10 cm distance from the container surface of less that 1 µSv.hr⁻¹. They should have the official and clearly visible radiation symbols.

The storage containers are usually placed in a source storage and preparation room on or close to a preparation table. The manipulation of the sources on the table is preferably done behind lead screens and lead glass windows, giving protection to the body. Sometimes, a mirror system is used. Especially in those cases where radium sources are stored the ventilation system of the room must be adequate to avoid a high concentration of radon gas in case of a leaking source. The room must be locked when not in use.

In the room a radiation detector must be present to permanently show the radiation level. Other detectors must be available and suitable to detect small amounts of contamination on the surface of the table or for checking the waste after the work has been done. Only in case that no contamination is found, the garbage may leave the preparation room.
Fig 3.4: Example of the shielding on a preparation table in the storage room of a brachytherapy department.

For each type of work separate sets of instruments should be used, for example for preparing the iridium wires for manual afterloading techniques. The instruments should be prepared before the sources are taken out of the storage container. At return, the sources are visually inspected for bending and damaging before putting them back into the safe. Cleaning must be done carefully, e.g. using an ultrasonic bath behind a radiation shield. If present, the colour coding must be checked.

5.2 Registration of sources

All sources available must be registered. The register must contain information on the radionuclide and the activity on a given date, the source type (e.g., tube or needle, the size) and eventually the id number, the position in the storage container, the dates and the results of the checks (e.g. the radon leakage tests), the date and result of the periodic inventory of the vault, the admission of new sources or the removal of the old ones.

A logbook must show the date of intended use for a patient and the estimation of the treatment duration, including the identification of each source, the destination of the sources such as the patient and the patient’s room number. The date of return of the source must be registered as well.

This latter information must also be available at the transport container used to transport the source or sources from and to the preparation room. The radiation level at 1 m from the container surface should be less than 1 mSv.hr⁻¹ and at the surface less than 2 mSv.hr⁻¹. Radiation symbols at the outer side of the container must indicate their use. These transport containers may not be left unattended and the exposure of other persons during transport must be avoided as much as possible.

The container can stay with the patient during the duration of the treatment and can serve as a safe depot for the sources in case of emergency. Therefore, also a set of instruments must be available immediately near the patient’s room. After treatment, the sources must be returned to the preparation
room as soon as possible for cleaning and verification, after which they can be put into the storage container.

### 6 Nursing Care

In case remote afterloading equipment is used, the radiation exposure to the staff member that starts the treatment and to the nursing staff is minimal. For patients where remote afterloading is utilised, the treatment can, in general, be interrupted for nursing care. The sources are withdrawn into a safe position and the control timer is stopped. Technical measures such as an audio signal should give a warning during interruption to indicate that the treatment must be resumed. In cases without remote afterloading the attitude to the patient must be to keep distance, to stay as short as possible in the radiation area, and to use radiation shields as much as possible.

During manual insertion of sources one must take the necessary precautions and preparations in order to have a fast and efficient procedure. The instruments should be all ready and suitable for the type of work, e.g., using long tweezers to keep the sources at a distance from the body. Other staff involved in the application should be at the largest possible distance.

Staff members should visit the patient’s room only for necessary care. The presence of an audio/video system for contact from outside the room is recommended. Foods and drinks for the patient should be prepared outside the room. Only the highest necessary cleaning of the room should be allowed while the patient is loaded. The nurse should stay behind the radiation shield whenever possible. When not in use with the patient, those shields can be placed close to the door to have additional shielding at what is generally the weakest shielding position. Lead aprons can only be useful for the radionuclides that emit low energy photons i.e. iodine-125, paladium-103 and gold-198. For the high-energy gamma ray emitters the shielding obtained by a lead apron is almost negligible. Then, the use of an apron can even lead to an increased exposure to the staff because the time of care-giving may be increased.

During and after treatment no material may leave the room without verification that there is no radiation or contamination. In each room the laundry must be collected separately from the other rooms. Immediately after removal of the sources the patient must be checked with a radiation monitor to verify that all sources are removed from the patient. Sources are transported back to the preparation room using the transport container or stored inside the storage container of the afterloader.

When the patient with the sources has to be moved or replaced during treatment, for example from the operation theatre to the treatment room, or from the room to the simulator to make a set of radiographs for the reconstruction of source positions for dosimetry, only skilled radiological workers are allowed to accompany the patient. The shortest possible route must be used and the persons involved should keep their maximum distance from the implanted area. If an elevator is used no other persons are allowed to enter. The source data should be available with the patient using a transportation form. The bed should be marked with a radiation sign. It is recommended to have a small set of instruments and a small lead container with the patient for emergencies. Waiting times in the open hospital area must be avoided by making the proper appointments.

Generally, visitors should not be allowed to enter the patients’ room during treatment, even when using an afterloading system. However, in some circumstances, e.g. in case of a very long treatment time or in case of a poor psychological condition of the patient, there can be a reason to allow a limited visiting scheme. Then, only close relatives are allowed to enter, but never children or pregnant women. The duration of the visit that can be allowed should be based on an estimation of
the received dose with a limitation of 0.1 mSv per week for the visitor. When a remote afterloader is used such a dose limit will never be reached.

7 Special Treatments

7.1 Permanent implants using iodine-125 or palladium-103 seeds

Permanent implants, for example of the prostate, using iodine-125 or palladium-103 seed sources form a relatively low risk for the personnel involved in performing the application or in nursing the patient. The photon energy is very low, 0.028 MeV and 0.021 MeV respectively. Therefore the tissue surrounding the implant largely absorbs the emitted radiation from the sources. In general only those persons who handle the bare sources during the calibration procedure, the preparation of the source trains, or the insertion of the source trains into the implanted needles have an increased dose due to external irradiation. There is no radiation protection reason to keep the patient in the hospital longer than needed for nursing care. The patient and the family will receive instructions how to deal with certain problems after leaving the hospital, such as the risk of loss of seeds with the urine within the first few days after implantation. Due to the half life of iodine-125 sources of 60 days, several precautions must be made in case the patient dies within a period of 1 year after implantation. A funeral is allowed, but the body can only be cremated if the seeds are removed at autopsy.

7.2 Strontium-90/yttrium-90 (and ruthenium-106) ophthalmic applications

In this chapter on safety aspects of quality control in fact only gamma ray sources are considered. If a nuclide in a sealed source emits not only gamma rays but also beta particles, these are usually absorbed in the encapsulation of the source. In some source types the beta emitting nuclide is applied to make use of the specific properties of the beta radiation, such as in the strontium-90 eye applicators. These are used for treatment of small superficial tumours, mostly on the surface of the eye. Their use is, however, not very widespread.

The beta decay of strontium-90 is in equilibrium with the daughter nuclide yttrium-90 of which the maximum energy of the emitted beta radiation is about 2.3 MeV. Such beta particles penetrate to a maximum depth of about 12 mm in materials with a density of 1 g.cm\(^{-3}\). The beta radiation is quite easily shielded in a storage place by surrounding the source with such an amount of shielding material. To avoid the production of bremsstrahlung, low-Z material must be used close to the source, while some lead shielding must be applied to reduce the produced bremsstrahlung photons. As strontium is chemically similar to calcium, there is a serious risk from ingested radioactive material if a source leakage occurs. Careful inspection of the source applicators, which usually have a very vulnerable layer of sealing material, after each treatment must demonstrate any damage at an early stage.

Sometimes the nuclide ruthenium-106 is used as an alternative to strontium-90. Ruthenium-106 emits beta particles with a maximum energy of 3.55 MeV. The thickness of the shielding should be increased correspondingly.

7.3 Radium-226 and radon-222 sources

Alpha particles are not used in brachytherapy. If alpha particles are emitted in the radioactive decay of a source, such as with the nuclides radium-226 and radon-222, these particles are fully absorbed in the wall. Even very thin layers of material can be used as effective shields for the alpha radiation. After a number of years of use of these source types, some helium gas is formed inside and a gas pressure is present within the sealing of the source. Radioactive material in the form of the gaseous radon-222 may come free when the source encapsulation is damaged. Due to the risks involved with
contamination from damaged sources, the storage room must be well ventilated. For these sources wipe testing is essential in a department. If a contamination of the source is demonstrated, e.g. with the wipe test, putting it into a small container must immediately isolate the source. Any action that can lead to further spread of the possible contamination must be avoided. Eating and drinking is forbidden and the hands should not touch the nose and mouth until it is clear that there is no surface contamination. The medical physicist must be warned directly to take any further action. Because of the extreme long half life of the radium nuclide of more than 1600 years, such source types form a special problem for long term storage or for discharging. The nuclide is presently to be considered obsolete for use in brachytherapy applications and will only be found as curiosity or for calibration purposes. For all these reasons, the use of radium and radon sources is nearly abandoned. It should be strongly discouraged and when possible forbidden.

7.4 Californium-252 as a neutron emitting source

Californium-252 is one of a very few neutron emitting sources used in brachytherapy, but the clinical use of such sources is very limited. The aim is to make use of the higher radiobiological effectiveness of the neutron radiation, especially in low oxygenated tissues. Nevertheless, for radiation protection purposes, one must take into account the high value of the radiation weighting factor (\(W_R = 10\)) to evaluate the effective dose of the staff exposed to californium neutrons. In some afterloaders the californium-252 sources are present in the form of strings of sources. The safe storage position of such equipment must be heavily shielded with a primary shielding with a high-Z material container, which is surrounded by a low-Z material, such as polystyrene or other low-Z compounds, for further shielding the neutrons.

8 References