

Isotopes and delivery systems for brachytherapy

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1.1 Introduction

The aim of this chapter is to consider which radioactive materials might be suitable as brachytherapy sources, to describe some practical brachytherapy sources, and to consider how these sources may be applied to the patient in a controlled and safe way. It is assumed that the reader has some familiarity with the basics of radioactivity and the emissions from radioactive substances.

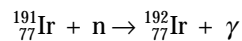
Radioactive sources for brachytherapy are now available with many radionuclides and in various shapes and sizes, and there is no such thing as an 'ideal' brachytherapy source. Different sources have different applications depending on their emission type and radiation energy and how they are constructed. However it is possible to state some basic requirements:

- 1 The radionuclide must have a half-life of a few days or more for permanent implants and preferably at least a few weeks for temporary implants. Large corrections for radioactive decay during a temporary implant should be minimized. A long half-life for stock sources will give them a useful working life. Very short half-lives (e.g. a few hours) are unsuitable.
- 2 The energy of the emitted radiation should be sufficient to treat the required application, but not so high that radiation protection becomes difficult. Charged particle emission should be absent or effectively screened (except for beta emitters). Most modern brachytherapy sources emit photons of between about 0.35 to 0.66 MeV, though there are low-energy exceptions to this.
- 3 The radioactive material should be in a physical form that is insoluble and non-dispersible and can normally be encapsulated into a structure to prevent dispersion of radioactive material.
- 4 The radioactive decay process should have no gaseous or liquid decay products.
- 5 The material should be available in a high specific activity.
- 6 The sources should be available at reasonable cost so that the treatment does not become financially prohibitive.

Most brachytherapy sources are termed ‘sealed sources’. These are constructed so that the radioactive material is encapsulated (often doubly encapsulated) in a container to minimize the risk of loss of radioactive material. Some sources, for example iridium wires, are not so encapsulated but nevertheless the risk of dispersal is very small; these are termed ‘solid sources’. Sealed sources have to be wipe tested for leakage on a regular basis ⁽¹⁾. Preparation equipment for solid sources has to be checked regularly for contamination, even though this hazard is unlikely in practice.

1.2 Production of radioactive materials

The radioactive materials used in brachytherapy sources are produced by either neutron activation or are a product of nuclear fission. In neutron activation, often called the ‘n- γ ’ reaction, a sample of a stable isotope of the element is placed in a neutron field in a nuclear reactor. Some of the nuclei of the element capture a neutron and become a radioactive isotope of the element, with the emission of gamma radiation. An example is the production of the radioactive iridium-192 from the stable iridium-191:



With this production method the product will contain a mixture of the stable isotope and the radioactive isotope. The activity of the product will depend on the neutron flux and energy, the probability of nuclei interacting with the neutrons, the length of time in the reactor, and the half-life of the product itself.

Some radioactive materials used in brachytherapy are fission products. The process of nuclear fission arises when large nuclei divide and produce new elements, which are radioactive. An example is caesium-137 which arises from the fission of uranium and therefore is a by-product of the fuel rods in a reactor. The desired product has to be separated from other fission products. A more detailed treatment of production methods and yield can be found in reference 2.

1.3 Radionuclides in brachytherapy

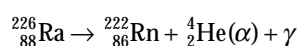
This section includes brief descriptions of some of the radionuclides used for brachytherapy and these are summarized in Table 1.1.

1.3.1 Radium-226

In the early days of brachytherapy radium-226 and its daughter product radon-222 were the only radioactive materials used. Radium-226 is part of the radioactive series starting with uranium-238 and ending with the stable isotope lead-210. It has a half-life of 1620 years and decays by alpha emission to radon-222.

Table 1.1 Physical characteristics of some radionuclides used in brachytherapy

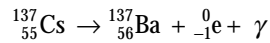
Source	Usual form	Production	Half-life	Emissions
Radium-226	Tubes, Needles	Naturally occurring	1620 y	2.45 MeV (max) gamma (from daughters when encapsulated)
Caesium-137	Tubes, Needles, Afterloading	Fission Product	30.17 y	0.662 MeV gamma
Cobalt-60	Tubes, Afterloading	Neutron activation	5.26 y	1.17, 1.33 MeV gammas
Iridium-192	Wires, Afterloading	Neutron activation	74 d	0.38 MeV (mean) gamma
Iodine-125	Seeds	Daughter of Xenon-125	59.6 d	27.4, 31.4, 35.5 keV X-rays
Palladium-103	Seeds	Neutron activation	17 d	21 keV (mean) X-ray
Gold-198	Grains	Neutron activation	2.7 d	0.412 MeV gamma
Strontium-90	Plaques	Fission Product	28.7 y	2.27 MeV beta particles
Ruthenium-106	Plaques	Fission Product	1.02 y	3.54 MeV beta particles



The daughter product radon-222 is radioactive and some of the subsequent daughter products decay by beta and gamma emission. The net effect is that an encapsulated radium source emits a complex photon spectrum with a maximum energy of 2.45 MeV, the alpha and beta particles being absorbed in the encapsulation. The radium in the form of radium sulphate powder was doubly encapsulated, usually in platinum, into tubes and needles and was also used in short distance teletherapy units. It was used extensively for treatment of cancer of the uterine cervix and implants. Dosimetry systems such as the Manchester System (see Chapter 2) were developed for it. However, it has several disadvantages, including the high photon energy requiring thick shielding, the risk of damage to a tube with consequent ingestion of the radium salt, and the biological harm that could result from accidental ingestion of the alpha emitting nuclides. The clinical use of radium has been discontinued in the UK and most other countries, as other more convenient radionuclides are now available.

1.3.2 Caesium-137

Caesium-137 is a product of uranium-238 fission. It decays by beta-minus emission with a half-life of 30.17 years and emits a photon energy of 0.662 Mev.



It can be incorporated into glass beads and made into a variety of radioactive sources by encapsulating in stainless steel. It became readily available in the 1960s and largely replaced radium during the mid 1970s. It was considered safer than radium as its lower photon energy eased the radiation protection requirements and its solid physical form and lack of alpha emission made it safer in the event of a tube being damaged. Figs. 1.1 and 1.2 show a typical caesium-137 tube used for manually inserted gynaecological applications and a spherical caesium-137 source as used in a low dose-rate afterloading machine respectively.

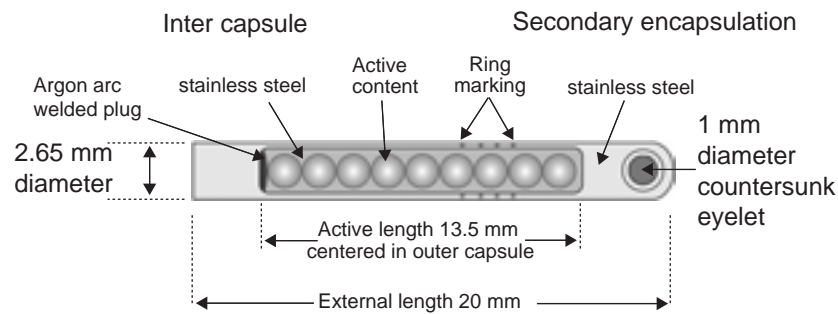


Fig. 1.1 Diagrammatic representation of a caesium-137 tube similar to an Amersham 'J-Type' tube.

Activity: Up to 1480 MBq (40 Ci) per pellet

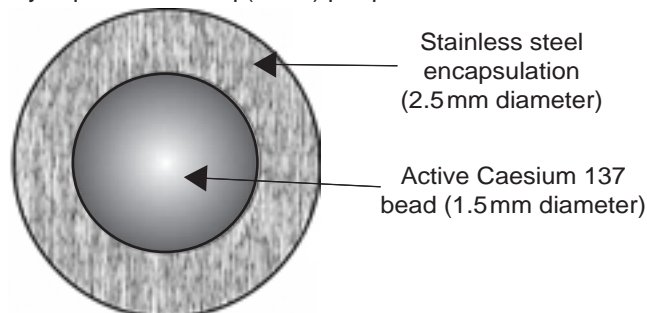
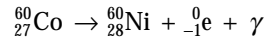


Fig. 1.2 Diagrammatic representation of an LDR afterloading caesium-137 pellet.

1.3.3 Cobalt-60

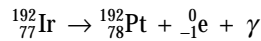
Cobalt-60 is produced by the neutron activation of the stable cobalt-59. It has a half-life of 5.26 years and decays by beta minus emission as shown below:



It emits gamma energies of 1.17 and 1.33 MeV. It has been used in tubes and needles, similar to radium and caesium tubes, but its relatively short half-life makes it inconvenient for this. Its main use in brachytherapy is in the form of pellets for high dose-rate afterloading machines. These are similar in appearance and size to the caesium pellets shown in Fig. 1.2.

1.3.4 Iridium-192

As mentioned in 1.2, iridium-192 is produced by the neutron activation of iridium-191. It has a half-life of 74 days and decays by beta minus emission:



The photon emission is a complex spectrum with a weighted mean of about 0.38 MeV. When freshly produced, iridium-192 is contaminated by small amounts of the radioactive iridium-194, which arises from the neutron activation of the stable iridium-193; however this has a half-life of 17 hours and rapidly decays to insignificance.

Iridium-192 is often used in the form of a wire, used for low dose-rate (LDR) manual implants. The central radioactive core is an iridium/platinum alloy surrounded by a 0.1 mm thick platinum sheath. It is available in 0.3 mm or 0.6 mm overall diameter as wires or pins (Fig. 1.3). The thin wire is normally

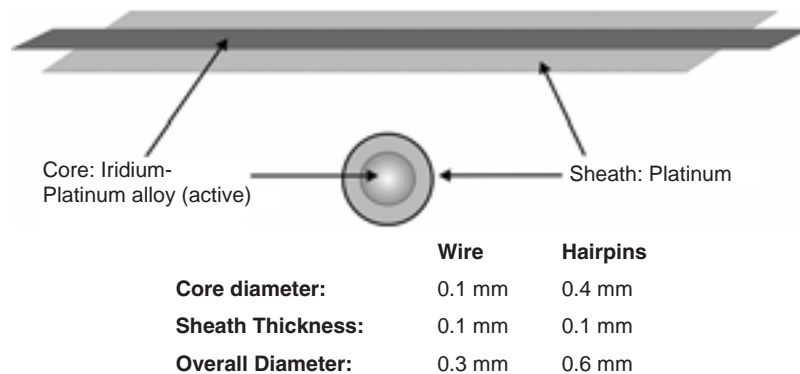


Fig. 1.3 Diagrammatic representation of iridium-192 wire.

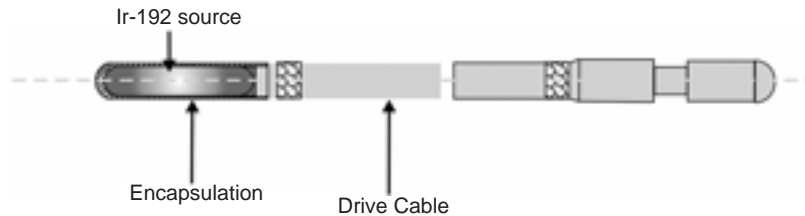
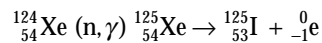


Fig. 1.4 Typical iridium-192 HDR afterloading source. Dimensions will depend on afterloader type.

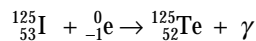
supplied in coils of 500 mm length and is cut to the required lengths by the user. A hairpin has two 'legs' each of 60 mm length and a crosspiece that measures 12 mm. Their use is described in Section 1.6.2.2. Its high specific activity permits a high activity source to have small dimensions. It is therefore also used for high dose-rate afterloading machines (Fig 1.4), which are described in Section 1.6.3.2.

1.3.5 Iodine-125

Iodine-125 used principally for prostate brachytherapy (see Section 1.6.1), is a daughter product of xenon-125 which itself is produced by the neutron activation of xenon-124:



Iodine-125 decays by electron capture and has a half-life of 59.6 days:



The gamma ray has an energy of 35.5 keV and characteristic radiation of 27.4 and 31.4 keV is also emitted. This low energy gives a half value thickness of lead of 0.025 mm, which makes radiation shielding highly effective.

For brachytherapy, iodine-125 is incorporated into implantable seeds. Several types of seeds are available from different manufacturers. As an example, Fig. 1.5 shows the structure of Oncura type 6702 and 6711 seeds. The 6702 seed has the iodine-125 absorbed on to an ion exchange resin but contains no radiographic marker. The 6711 seed has iodine-125 adsorbed on to a silver rod, which is encased in a titanium capsule. In this case the silver acts as a radiographic marker for imaging. The overall size of both seeds is 4.5 mm long and 0.8 mm diameter. The 6711 seed is the most commonly used type, particularly for prostate implants but the 6702 is sometimes used for temporary implants to other sites when a higher activity is desirable.

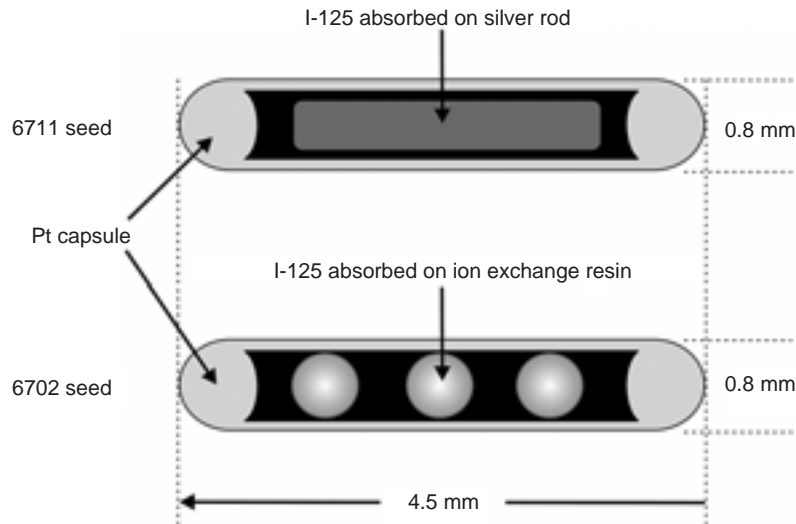
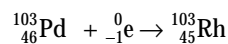


Fig. 1.5 Diagrammatic representation of two types of iodine-125 seed.

1.3.6 Palladium-103

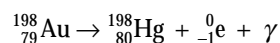
Production of this isotope is possible via several reactions including the neutron activation of the stable palladium-102 and the interaction of protons or deuterons on rhenium-103. It decays by electron capture with a half-life of 17 days:



Like iodine-125 it emits a mixture of gamma rays and characteristic radiation, but with a slightly lower mean energy of about 21 keV. It is encapsulated into seeds of the same dimension as iodine-125 seeds and used in a similar manner for prostate implantation. Some operators prefer it for faster growing tumours citing a radiobiological advantage for the shorter half-life (i.e. higher dose-rate) but this benefit is not universally accepted ⁽³⁾.

1.3.7 Gold-198

This is produced by the neutron activation of the stable gold-197. It decays by beta emission with a half-life of 2.7 days to an isotope of mercury:

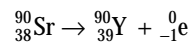


It emits a 0.412 MeV gamma photon (plus insignificant amounts of other energies). For many years gold-198 grains, consisting of gold-198 encapsulated

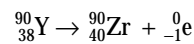
in platinum, were used for permanent implants, especially for the head and neck region. However the method has largely fallen into disuse and gold-198 grains no longer feature in UK suppliers' catalogues.

1.3.8 Strontium-90

Strontium-90 is a fission product and is used in brachytherapy as a beta emitter for superficial treatments. It decays by beta minus emission with a half-life of 28.7 years to yttrium-90:



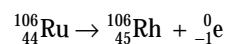
The beta energy from strontium-90 itself is too low to be useful for brachytherapy ($E_{\text{max}} = 546 \text{ keV}$) but the daughter element yttrium-90 (half-life 64 hours) also decays by beta minus emission with beta energy (E_{max}) of 2.27 MeV:



Therefore the combination of strontium-90 with its daughter yttrium-90 provides a source of 2.27 MeV (E_{max}) beta particles with an effective half-life of 28.7 years. This material has been used for surface applicators, particularly ophthalmic applicators where the beta particles provide the required surface dose with rapid fall-off beneath. They were made from a strontium compound incorporated into a silver sheet, which is then formed into an applicator, with shielding on the reverse side. A variety of shapes, sizes, and concavities were available. Although no longer available from a major UK supplier, they are still in use in some hospitals. The surface dose-rate is such that the treatment takes a few minutes.

1.3.9 Ruthenium-106

This material has largely replaced strontium-90 in surface applicators, probably as it emits higher energy betas. It is a fission product and decays by beta emission to an isotope of rhenium with a half-life of 1.02 years:



The beta energy E_{max} is 3.54 MeV. The plaques are similar to the strontium-90 plaques in that the active material is incorporated into a silver sheet, which forms the surface of the plaque. The dose-rate is such that the treatment takes a few days, so the plaque is provided with suture holes to allow it to be fixed. Several shapes and sizes are currently available.

1.3.10 Other radionuclides

Various other radionuclides have been used or proposed for use in brachytherapy, including californium-252, phosphorus-32, samarium-145 and tantalum-182. These will not be discussed further as they are not in common use. More information is available in reference ⁽²⁾.

1.4 Definitions

The following terms are frequently used in brachytherapy, and it is useful to define them before describing the delivery systems:

Intracavitary Therapy. The insertion of brachytherapy applicators and radioactive sources into an existing body cavity, for example the uterine canal or vagina.

Interstitial Therapy. The insertion of brachytherapy applicators and radioactive sources directly into tissue, for example a needle or wires implant to the breast, floor of mouth etc.

Intraluminal Therapy. The insertion of brachytherapy applicators and radioactive sources into a lumen, for example the bronchus or oesophagus.

Intravascular Therapy. The insertion of brachytherapy applicators and radioactive sources into an artery. This treatment is used for the prevention of restenosis and may be applied to coronary or peripheral arteries, though the treatment techniques for the two are different. For reasons of space this will not be discussed further in this chapter.

Low, Medium and High Dose-Rate (LDR, MDR, HDR). There is no universally accepted definition of these dose-rate categories; the various bodies such as ICRU ⁽⁴⁾, AAPM ⁽⁵⁾ the UK Guidance Notes ⁽¹⁾ suggest different boundaries between them. The reader is referred to reference ⁽⁶⁾ for further discussion of the various definitions. However, most users accept the following:

Low Dose-Rate (LDR). Dose-rates around $0.5 \text{ Gy}\cdot\text{hr}^{-1}$ to about $1 \text{ Gy}\cdot\text{hr}^{-1}$. These are the dose-rates obtained or aimed for in traditional manual brachytherapy and it is generally accepted that dose-rate corrections to the prescribed dose are not required in this range (though there could be some debate about the upper end of this range). ICRU puts the upper limit at $2 \text{ Gy}\cdot\text{hr}^{-1}$ but most users would regard this as being MDR (see below).

Medium Dose-Rate (MDR). Dose-rates between about $1 \text{ Gy}\cdot\text{hr}^{-1}$ and $12 \text{ Gy}\cdot\text{hr}^{-1}$. There is no sharp dividing line between LDR and MDR, but

these are dose- rates where, although the therapy is still continuous, a dose correction for dose-rate effects is required. Many HDR afterloading cervix treatments are treated at about 1.5 to 2 Gy.hr⁻¹.

High Dose-Rate (HDR). Dose-rates greater than 12 Gy.hr⁻¹ (0.2 Gy.min⁻¹). In practice most HDR machines operate at dose-rates much higher than this boundary, typically around 2 Gy.min⁻¹.

Pulsed Dose-Rate (PDR). This is a technique where high dose-rate 'pulses' of treatment (typically lasting five or ten minutes) are repeated at short intervals (typically once per hour). The intention is to simulate the radiobiological effects of LDR treatment using an HDR type machine. Clinicians who prefer the radiobiological effects of LDR can achieve this but with the flexibility of the complex dose distributions achievable by a modern HDR machine. The radiobiology is described in more detail by Brenner and Hall ⁽⁷⁾ and Fowler and Mount ⁽⁸⁾.

1.5 Rationale for afterloading

With minor exceptions, up to the late 1960s all brachytherapy sources and applicators were applied to or inserted into the patient manually, that is directly by the operator. Dr Robert Abbe at St Luke's Hospital in New York performed an early attempt at afterloading in 1905 but that was exceptional and manual placement remained the norm. As concerns grew about the possible effects of radiation on staff, there was increasing effort put into the reduction of radiation doses to operators and the techniques of afterloading were developed. Afterloading involves the initial placement of non-radioactive applicators or carriers in or on the patient followed by the subsequent insertion of the radioactive material.

- ◆ In 'manual afterloading' the sources are applied to the applicators by the operator using appropriate handling tools. This, of course, can only be done for low dose-rate treatments using low activity sources.
- ◆ In 'machine afterloading' or 'remote afterloading' a treatment machine applies the sources, usually under computer control. With appropriate shielded treatment rooms this technique permits high dose-rate treatments using high activity sources although the method is also used for low dose-rate treatments. Table 1.2 shows how various staff groups may benefit from the use of afterloading.

Table 1.2 Staff exposed to possible radiation hazard, showing the benefit obtained with afterloading

	Non afterloading	Manual afterloading	Remote afterloading
Physicists/Technicians	YES	YES	NO
Theatre staff	YES	NO	NO
Clinicians	YES	YES	NO
Radiographers	YES	PERHAPS	NO
Nursing staff	YES	YES	NO
Visitors	YES	YES	NO

1.6 Delivery systems

1.6.1 Manual application

Examples of manual application are the use of radium or caesium tubes for gynaecological treatments and the use of needles for implantation. These commonly use a dosimetry system, such as the Manchester System or the Paterson-Parker Rules and these are described in more detail in Chapter 2. Both of these have now been mainly superseded by afterloading methods.

Prostate implantation using iodine-125 or palladium-103 seeds is an example of a manual (i.e. non-afterloading) insertion method for a permanent implant. Early prostate implants used an open surgery retropubic approach but in the modern method the seeds are contained in needles, which are inserted through the perineum into the prostate. The position of the needles, the depth of insertion and the pattern of seeds in each needle allows a three dimensional arrangement of seeds to be deposited in the prostate. Typically about ninety seeds will be implanted using about twenty-five needles but the precise number depends on the size and shape of the prostate. The intended distribution of seeds in the prostate is determined from an ultrasound study of the prostate in which cross-sectional images 5 mm apart are acquired or, more recently, three dimensional prostate imaging is used. This may be done a few days in advance or, increasingly, at the same session as the implant. The needles are then loaded with the appropriate patterns of seeds, which are deposited in the prostate using ultrasound and fluoroscopic guidance. The low emission energy from the seeds and the ease with which it is shielded means that this technique does not have the same degree of radiation hazard as working with other radionuclides. Also the radiation hazard arising from the patient

after implantation is minimal. An afterloading method is also available for prostate implants; both these techniques are discussed further in Chapter 7.

Beta emitting eye plaques (strontium-90, ruthenium-106) are also applied manually, but the radiation hazard is small provided care is taken to shield the active surface.

1.6.2 Manual afterloading

1.6.2.1 Intracavitary treatments

Systems for manual afterloading for cervix treatments were developed in the 1960s and are still current. Typically hollow carrier tubes (without the sources) are placed in the uterine canal and vagina in a configuration that is similar to the Manchester System and then their positions are checked by radiographs. Each source holder or train consists of low activity caesium-137 sources contained in a spring holder, which is attached to a labelled applicator handle. There will be a series of these source holders containing different numbers and activities of source. The source activities and their arrangement are chosen to match the activities required for the uterine and vaginal component of the (say) Manchester System. At commencement of treatment the source trains are withdrawn from the shielded storage container and inserted into the applicators; they are subsequently manually removed from the applicators at the end of treatment. Often the source holders are mechanically coded to the applicators to prevent incorrect loading of, for example, a train intended for the uterine canal into a vaginal position.

1.6.2.2 Interstitial treatments

Another common manual afterloading method is the use of iridium wire for interstitial treatments. Iridium wires themselves are described in Section 1.3.4. The dosimetry of these using the Paris System is discussed in Chapter 3 but here we will consider the implantation techniques. A pre-implant assessment or 'pre-plan' is usually carried out a week or two before the implant, at which point the approximate wires arrangement is defined and the wire activity calculated in order to give the required dose and dose-rate. The wire can then be ordered from the supplier for delivery a day or two before the scheduled implant date. The activity of the wire is checked before use.

The 'flexible tube technique' involves the insertion of plastic carrier tubing (the so-called 'outer tubing') through the site to be treated. The clinician implants these tubes through the tissue in the planned arrangement. The ends are loosely held by lead discs or clips, often with a nylon ball spacer to keep the clips away from the skin surface, but these are left loose at this stage. Often non-radioactive marker wires are placed in the tubing so that localization

imaging can be done before the active wires are inserted. Meanwhile, the active wires are prepared. The appropriate lengths are cut from the coil and encapsulated into 'inner tubing' which is similar to but of smaller diameter than the outer tubing and a seal is placed in the tubing at each end of the wire to keep the latter in place. Commercial loading devices to assist with this process are available. As the wires are prepared they are placed in a shielded container and are individually identified, as in practice not all wires will be the same length. Following any imaging that may be required, the active wires are inserted into the outer tubing with forceps and using shielding when practicable. The clips are crimped to hold everything in place (Fig. 1.6). The expected removal time is determined from a Paris or other calculation based on a reconstruction of the imaging. When the wires are to be removed it is important that the tubing is cut between the nylon ball and the lead disc so that the active wires remain intact. If it is cut close to the skin there is a risk that the wire might be cut with a consequent risk of loss of radioactive material or its remaining in the patient. Also a radiation monitor must be used to check for complete removal of the sources from the patient. The operation of the monitor must be checked before removal of wires to ensure it is working. Untoward events have been reported by *Arnott et al.* ⁽⁹⁾.

One disadvantage of the flexible technique is that the wires are rarely straight and evenly spaced. This can be avoided by using templates and rigid needles instead of the flexible outer tubes. These are particularly suited to implants of the breast and perineum. For the breast a pair of templates can be used at each end of the needles to support them at the correct separation. In the perineum only one end of the implant is accessible, so a single thick template is used. Once the templates and needles are in place the prepared iridium wires are inserted into the needles, which are closed with screw caps. Localization imaging is often

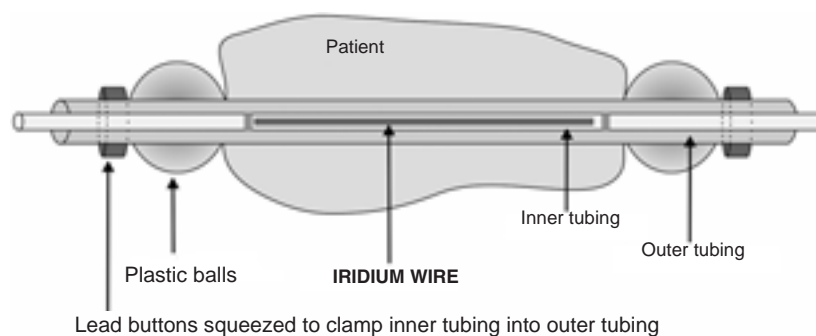


Fig. 1.6 Iridium wire encapsulation and fixing discs.

unnecessary for template implants as the implant geometry is known and fixed, and the dosimetry is predictable. The preferred removal method is to remove the needles and template intact so that the active wires can be recovered under shielded conditions in the preparation laboratory.

1.6.3 Machine (remote) afterloading

In this section afterloading machines from specific manufacturers will be referred to, for ease of description, but the reader should be aware that similar machines are manufactured by other suppliers. Reference to a particular machine does not imply endorsement of equipment from a particular supplier.

1.6.3.1 LDR/MDR afterloading

LDR and MDR afterloading will be discussed together as the equipment principles are the same, the only difference being in the source activities. One example is the Curietron (made by CIS), which was designed for the treatment of the uterine cervix, but is now almost obsolete. It used flexible preloaded trains of caesium-137 sources stored in a shielded safe.

The use of preloaded source pencils severely limits the use of this type of machine. The source configurations have to be decided at the time of purchase and cannot be changed until the sources are replaced. The Selectron (Nucletron), introduced in 1979 and still in use in many hospitals, overcame this difficulty by permitting source trains to be composed as required for each treatment. It is used predominantly for gynaecological treatments and it is available in both three and six channel versions. Each channel can be individually timed. The safe of a Selectron contains, in separate compartments, up to forty-eight caesium-137 sources and a large number of spacers. Sources and spacers are all spheres of 2.5 mm diameter. When the source loadings needed for a patient are known, the details are programmed into the machine and the trains are made up by pneumatically selecting sources and spacers in the correct order and loading them into channels in an intermediate safe. To start the treatment the source trains are driven pneumatically through transfer tubes into the applicators. The machine has fail-safe systems incorporated to ensure, for example, that the source trains cannot be driven out unless applicators are connected and to ensure that source position is correct within ± 1 mm. The machine can be controlled from outside the patient's room to minimize radiation exposure to staff and, of course, can be interrupted for nursing procedures. During interruptions the source trains are returned to the intermediate safe. At the end of the treatment, the source trains are dismantled and sorted automatically, with the sources and spacers being returned to the

main safe. LDR and MDR versions of the machine were identical except for the sources activity. LDR versions had a nominal source activity of 740 MBq (20 mCi) and gave about $0.8 \text{ Gy}\cdot\text{hr}^{-1}$ at the Manchester Point A and MDR versions had a nominal source activity of 1480 MBq (40 mCi) and gave about $1.6 \text{ Gy}\cdot\text{hr}^{-1}$ to the Manchester Point A.

The microSelectron-LDR (Nucletron) was introduced for interstitial therapy. This machine could remotely afterload up to eighteen iridium-192 ribbons (later strings of miniature caesium-137 sources were available). However, it suffered from the disadvantage that the iridium sources needed frequent replacement and the caesium version had the problem of restricted source combinations. It is now no longer available.

1.6.3.2 HDR afterloading

High dose-rate afterloading units came into use in the late 1960s. The advantage of high dose-rate treatments is the shorter treatment times (a few minutes rather than days), although the treatments have to be fractionated so overall treatment time is not necessarily shortened. However, particularly for cervix treatments, the short treatment times permit the use of rigid rectal retractors, which are likely to be more effective at reducing rectal dose. High dose-rate afterloading machines need to be housed in substantial shielded treatment rooms with appropriate interlocks, warning signs, patient monitoring equipment, etc. The first type to be installed in the UK was the Cathetron (made by TEM engineering which later became part of Varian), in Leeds, Charing Cross, Cardiff, and other hospitals in about 1968^(10,11).

As with the Curietron, the use of pre-loaded source pencils meant that source configurations were limited to those decided upon when the sources were installed, and were not likely to be changed for the five year working life of the sources.

A high dose-rate version of the Selectron (Nucletron) was introduced in the mid-1980s. The late 1980s saw the introduction of a new generation of afterloading machines using a single high activity iridium-192 source. The availability of small iridium-192 sources which contain typically an activity of 370 to 740 GBq (10 to 20 Ci) led to the development of HDR afterloading machines in which a single source is sequentially stepped through a series of dwell positions in all the treatment applicators in turn, thereby removing the need for several sources or source trains to be present in the machine. Such machines include the microSelectron-HDR (Nucletron) and its variant the microSelectron-PDR, the Gammamed and its PDR version (Isotopen-Technik Dr Sauerein and later MDS-Nordion), the Varisource (Varian) and others. These machines have a (usually) PC based control station outside the shielded

treatment room. Here we will describe the microSelectron-HDR but the others operate on a broadly similar principle.

A single iridium source is contained in a tungsten-shielded safe in the head of the machine. The source capsule (Fig. 1.4) is laser welded to a long drive cable, which is connected to a stepper motor. The safe also contains a check cable assembly, which is identical in appearance to the source cable (but not radioactive) and is connected to a separate stepper motor. When the appropriate stepper motor rotates, the source or check cable is advanced into the treatment channel and can be positioned with an accuracy of ± 1 mm. Within each treatment channel the source can occupy up to 48 dwell positions with a spacing of either 2.5 mm or 5 mm, thereby treating a maximum length of 235 mm. The exposure time at each of these dwell positions is variable and, in theory, could be different at each position. The front face of the machine, termed the 'indexer', has a series of numbered output ports to which the transfer tubes and applicators can be connected. The microSelectron has eighteen such ports but other machines may vary. This means that up to eighteen applicators can be connected simultaneously. When a treatment starts the check cable is driven in and out of the first channel to check connectivity and for obstructions. The source is then driven into the first channel and the programmed dwell positions and times are exposed. The source retracts back to the safe, the indexer advances one position (internally) and the check cable and then the source can now be driven out into the next channel, and so on until all the required channels and dwell positions have been exposed as programmed.

There are two principal advantages of these 'stepping source' machines over the older machines based on caesium or cobalt source trains. Firstly, the high specific activity of iridium-192 permits the source, and therefore the applicators, to have a small diameter. Typically the source has a diameter of 0.5 mm and the applicators have an external diameter of 2 mm. This means applicators are thin and flexible and can therefore be used in body sites not otherwise conveniently accessible to afterloading such as the bronchus and bile duct. Secondly, complex dose distributions can be produced from the large combination of dwell positions and times. Treatment planning systems are needed to plan these complex dose patterns; nowadays these can often be networked to the treatment unit so that the plan data can be transferred automatically, reducing the risk of transcription errors in entering the details into the treatment unit. Some machines combine the functions of treatment unit and planning system into one computer.

1.6.3.3 PDR afterloading

Afterloading machines designed for PDR use are physically similar to HDR machines. The main difference is in the operating software (and treatment

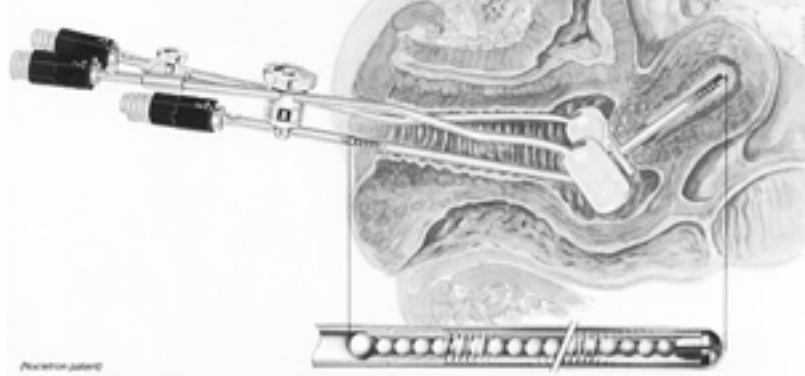


Fig. 1.7 Selectron applicators (cervix insertion), showing sources and spacers. Picture courtesy Nucletron.

planning software), which permits the programming of the treatment pulse duration, interval, and overall treatment time. Usually the iridium-192 source has a smaller activity than that used for HDR (typically 37 GBq) to avoid short dwell times which otherwise cannot be timed with sufficient accuracy.

1.7 Application of remote afterloading

In this section, we will briefly describe how remote afterloading may be applied in different ways to treat lesions in various clinical sites.

1.7.1 Intracavitary treatments

Most of the early afterloading machines were designed specifically around treatment of the uterine cervix. The applicator systems were based on the Manchester System ⁽¹²⁾ or the similar Fletcher System ⁽¹³⁾, consisting of an intrauterine tube and two vaginal source carriers (Fig. 1.7). Similar applicators were developed for the iridium-192 stepping source units, though these had a smaller diameter. For HDR machines the applicators often incorporated a rigid rectal retractor, which could be tolerated for the shorter treatment times and was considered to be more effective at reducing the rectal dose. Recently CT/MR compatible cervix applicators made from plastic materials have become available. Endometrial applicators are also available.

1.7.2 Interstitial treatments

The treatment of implants by remote afterloading was not feasible until miniature sources became available. The microSelectron-LDR, which uses iridium

wires or caesium sources (described in Section 1.6.3.1), was one of the first such machines. The stepping source HDR machines made remote afterloading for interstitial treatments more attractive, provided that dose and fractionation modification required to change from LDR To HDR was accounted for. The small size of the source, dwell time flexibility, and large number of output channels makes them eminently suitable for multiple needle or flexible tube implants. The applicators are similar to the traditional manual treatments, that is flexible tubes or needles held in place by templates. Connectors link the needles or flexible tubes to the transfer tubes, enabling the source to be sent down, each in turn servicing the dwell positions as required by the treatment plan. The Paris System can be adhered to, but increasingly treatments are being modified by taking advantage of the dwell time and position flexibility of the afterloading source. Hospitals with appropriate operating theatre facilities can treat intraoperatively by which applicators are inserted into the tumour at operation and then subsequently connected to the afterloader.

1.7.3 Intraluminal treatments

Treatment of the oesophagus was possible with the Selectron-LDR ⁽¹⁴⁾, but other sites were not easily accessible due to the large diameter of the sources and applicator. However this is not the case with stepping source machines, and sites such as the bronchus ⁽¹⁵⁾, bile duct ⁽¹⁶⁾, and the larger diameter vascular system (such as the femoral artery) ⁽¹⁷⁾ could be treated. The applicators used for intraluminal applications are typically 2 mm in diameter and up to 1500 mm in length (Fig. 1.8). They can therefore be inserted through



Fig. 1.8 MicroSelectron-HDR showing indexer and intraluminal applicator. Picture courtesy Nucletron.

the instrument channel of a suitable endoscope. The technique varies with site, but usually the treatment length and position is identified by taking radiographs with a marker in the applicator

1.8 Surface moulds

A surface mould is a custom-made device, which is attached to the patient in order to support an arrangement of radioactive sources at a known fixed distance, typically between 5 mm and 20 mm, from the surface to be treated. They are usually made to treat skin lesions but treatment of lesions at other sites such as intra-oral and intra-vaginal are also possible. Early moulds used radium-226 sources and later radon-222 seeds, gold-198 grains, caesium-137 tubes, and iridium-192 wires were used. Dosimetry systems such as the Paterson–Parker rules (see Chapter 2) allowed the calculation of the activity and arrangement of radium required to treat a given area to a prescribed dose. The dose to the treated area was often non-uniform due to the fact that the sources are discrete and the number of sources available was limited. A dose variation of $\pm 10\%$ of the prescribed dose was regarded as being acceptable. Surface moulds played a large part in early brachytherapy but they often contained substantial amounts of radioactive material and the radiation risk in their preparation, application, and removal from the patient led to a reduction in use. Most skin lesions were instead treated by superficial X-rays or electrons. However the advent of afterloading led to a reappraisal of surface moulds and many workers have used them through this method; this has been reviewed recently by Joslin and Flynn ⁽¹⁸⁾.

Later the method was adapted for the microSelectron, and various workers have treated surface moulds at HDR ⁽²⁰⁾ and PDR ⁽²¹⁾.

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