## Contents

<table>
<thead>
<tr>
<th>Contributors</th>
<th>v</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>viii</td>
</tr>
<tr>
<td><strong>PART I</strong></td>
<td><strong>THE PHYSICS OF BRACHYTHERAPY</strong></td>
</tr>
<tr>
<td>1</td>
<td>Sources in brachytherapy  Edwin Aird</td>
</tr>
<tr>
<td>2</td>
<td>Source specification and dosimetry  J.M. Wilkinson</td>
</tr>
<tr>
<td>3</td>
<td>Calibration of sources  Colin H. Jones</td>
</tr>
<tr>
<td>4</td>
<td>Systems of dosimetry  Anne Welsh and Karen D'Amico</td>
</tr>
<tr>
<td>5</td>
<td>Computers in brachytherapy dosimetry  Robert van der Laarse and Robert W. Luthmann</td>
</tr>
<tr>
<td>6</td>
<td>Dose specification and reporting: the ICRU recommendations  André Wambersie and Jan J. Battermann</td>
</tr>
<tr>
<td>7</td>
<td>Afterloading systems  A. Flynn</td>
</tr>
<tr>
<td>8</td>
<td>Quality assurance in low dose-rate afterloading  Eric D. Slessinger</td>
</tr>
<tr>
<td>9</td>
<td>Quality assurance in high dose-rate afterloading  Colin H. Jones</td>
</tr>
<tr>
<td>10</td>
<td>Radiation protection in brachytherapy  A.M. Bidmead</td>
</tr>
<tr>
<td><strong>PART II</strong></td>
<td><strong>THE RADIOBIOLOGY OF BRACHYTHERAPY</strong></td>
</tr>
<tr>
<td>11</td>
<td>The radiobiology of low dose-rate and fractionated irradiation  Joel S. Bedford</td>
</tr>
<tr>
<td>12</td>
<td>Dose-rate effects with human cells  G. Gordon Steel and John H. Peacock</td>
</tr>
<tr>
<td>13</td>
<td>Radiobiology of high dose-rate, low dose-rate, and pulsed dose-rate brachytherapy  David J. Brenner, Roger Dale, Colin Orton, and Jack Fowler</td>
</tr>
<tr>
<td>14</td>
<td>Predictive assays for radiation oncology  John A. Cook and James B. Mitchell</td>
</tr>
<tr>
<td>15</td>
<td>Principles of the dose-rate effect derived from clinical data  Eric J. Hall and David J. Brenner</td>
</tr>
<tr>
<td><strong>PART III</strong></td>
<td><strong>CLINICAL PRACTICE</strong></td>
</tr>
<tr>
<td>16</td>
<td>Endobronchial brachytherapy in the treatment of lung cancer  Burton L. Speiser</td>
</tr>
<tr>
<td>17</td>
<td>Brachytherapy in cancer of the esophagus  A.D. Flores</td>
</tr>
<tr>
<td>18</td>
<td>High dose-rate afterloading brachytherapy for prostate cancer  P.J. Hoskin</td>
</tr>
<tr>
<td>19</td>
<td>Low dose-rate brachytherapy for breast cancer  Julia R. White and J. Frank Wilson</td>
</tr>
<tr>
<td>20</td>
<td>Brachytherapy in the treatment of head and neck cancer  A. Gerbaulet and M. Maher</td>
</tr>
</tbody>
</table>

**PART I** THE PHYSICS OF BRACHYTHERAPY

1 Sources in brachytherapy  Edwin Aird

2 Source specification and dosimetry  J.M. Wilkinson

3 Calibration of sources  Colin H. Jones

4 Systems of dosimetry  Anne Welsh and Karen D'Amico

5 Computers in brachytherapy dosimetry  Robert van der Laarse and Robert W. Luthmann

6 Dose specification and reporting: the ICRU recommendations  André Wambersie and Jan J. Battermann

7 Afterloading systems  A. Flynn

8 Quality assurance in low dose-rate afterloading  Eric D. Slessinger

9 Quality assurance in high dose-rate afterloading  Colin H. Jones

10 Radiation protection in brachytherapy  A.M. Bidmead

**PART II** THE RADIOBIOLOGY OF BRACHYTHERAPY

11 The radiobiology of low dose-rate and fractionated irradiation  Joel S. Bedford

12 Dose-rate effects with human cells  G. Gordon Steel and John H. Peacock

13 Radiobiology of high dose-rate, low dose-rate, and pulsed dose-rate brachytherapy  David J. Brenner, Roger Dale, Colin Orton, and Jack Fowler

14 Predictive assays for radiation oncology  John A. Cook and James B. Mitchell

15 Principles of the dose-rate effect derived from clinical data  Eric J. Hall and David J. Brenner

**PART III** CLINICAL PRACTICE

16 Endobronchial brachytherapy in the treatment of lung cancer  Burton L. Speiser

17 Brachytherapy in cancer of the esophagus  A.D. Flores

18 High dose-rate afterloading brachytherapy for prostate cancer  P.J. Hoskin

19 Low dose-rate brachytherapy for breast cancer  Julia R. White and J. Frank Wilson

20 Brachytherapy in the treatment of head and neck cancer  A. Gerbaulet and M. Maher
21 High dose-rate interstitial and endocavitary brachytherapy in cancer of the head and neck
   Peter Levendag, Connie de Pan, Dick Sipkema, Andries Visser, Inger-Karine Kolkman, and Peter Jansen 296

22 Brachytherapy in the treatment of pancreas and bile duct cancer
   Dattatreyudu Nori, Suhrid Parikh, Srinath Sundarakraman, and Margot Heffernan 317

23 Brachytherapy for treating endometrial cancer
   H.A. Ladner, A. Pfeiderer, S. Ladner, and U. Karck 333

24 Low dose-rate brachytherapy for treating cervix cancer: changing dose rate
   R.D. Hunter and S.E. Davidson 343

25 High dose-rate brachytherapy for treating cervix cancer
   C.A Joslin 354

26 Brachytherapy for brain tumors
   Maarten C.C.M. Hulshof and Jan J. Battermann 373

27 Interstitial brachytherapy in the treatment of carcinoma of the cervix
   A.M. Nisar Syed and Ajmel A. Puthawala 379

28 Interstitial brachytherapy in the treatment of carcinoma of the anorectum
   Ajmel A. Puthawala and A.M. Nisar Syed 387

29 High dose-rate brachytherapy in the treatment of skin tumors
   C.A. Joslin and A. Flynn 393

30 Hyperthermia and brachytherapy
   Peter M. Corry, Elwood P. Armour, David B. Gersten, Michael J. Borrelli, and Alvaro Martinez 400

31 The costs of brachytherapy
   Graham Read 410

32 Quality management: clinical aspects
   C.A. Joslin 423

33 Safe practice and prevention of accidents in afterloading brachytherapy
   A. Flynn, S.E. Griffiths, and C.A. Joslin 433

34 Pulsed low dose-rate brachytherapy in clinical practice
   Patrick S. Swift 443

Index 451
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Brachytherapy was for many years in a state of decline, principally because of the radiation hazards to users and those associated with the management of patients. The introduction of afterloading machines in the 1960s provided the means to control the movement and position of individual radioactive sources and greatly reduced the radiation exposure to staff. As a result, brachytherapy underwent a renaissance and provided the necessary stimulus to promote the development of afterloading brachytherapy techniques. These developments have been further supported by the availability of nuclides, particularly cobalt-60, cesium-137, and iridium-192 and, more recently, radioactive seeds of iodine-125 and palladium-105. In parallel with the technological advances in afterloading machines, there have been major developments in imaging techniques and computerized planning.

Cancer management generally has undergone major advances since the 1960s and brachytherapy has played an increasingly important role. The optimal management of cancer patients requires expert teams who specialize in certain cancer sites within which brachytherapy may have a specific place. Much of this work is now being provided on an outpatient or day-care basis and prolonged hospital stay is proving to be unnecessary.

Clinical training is largely obtained by observation of and training from one's peers and also from supervised hands-on experience. In parallel with the development of clinical experience, an understanding of the principles of radiobiology and physics is of great importance. It is also prudent that clinical radiation oncologists continue to update their state of knowledge with respect to current practice.

The purpose of this book is not only to present to the trainee clinical oncologist the scientific background and principles of brachytherapy afterloading techniques, but also to update those who specialize in brachytherapy. The book is presented in three sections: physics, radiobiology, and clinical treatment. The sections attempt to cover the scientific principles, technical procedures, and clinical applications of 'afterloaded' brachytherapy.

The editors have aimed at a consistent presentation for the various chapters without attempting to interfere with the different styles of the individual authors. Some chapters will be found to be more extensive than others, which is mainly a reflection of the widespread application of brachytherapy techniques within the subject of those chapters.

We hope that readers of this textbook will find the contents helpful in their work.

The editors would like to express their appreciation to all authors for their well-prepared manuscripts and for their tolerance during the book's production.

C.A. Joslin, A. Flynn, and Eric J. Hall
PART I

The physics of brachytherapy

1 Sources in brachytherapy 3
2 Source specification and dosimetry 11
3 Calibration of sources 19
4 Systems of dosimetry 35
5 Computers in brachytherapy dosimetry 49
6 Dose specification and reporting: the ICRU recommendations 81
7 Afterloading systems 103
8 Quality assurance in low dose-rate afterloading 112
9 Quality assurance in high dose-rate afterloading 133
10 Radiation protection in brachytherapy 147
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Sources in brachytherapy

EDWIN AIRD

| Introduction | 3 |
| Production of radionuclides | 4 |
| Brachytherapy sources used in afterloading systems | 5 |
| References | 10 |

1.1 INTRODUCTION

1.1.1 Radium

Radium was discovered by Marie Curie in 1898. Within 3 years of this discovery the first patients were treated with radium implanted into their tumors.

In the UK, St Bartholomew's Hospital received its first radium for clinical use in 1906. Early clinical experience with these sources led to radiation necrosis and it became clear that this was due, in part, to the intense beta-ray dose from the radium. It was not until 1920 that successful filtration of the beta-rays was achieved.

Radium was then used extensively throughout the world. Physicists in the major clinical centers developed dosimetry systems for interstitial and intracavity brachytherapy. The Manchester and Paris systems are probably still the most widely used for interstitial therapy. However, in general radium has been replaced by other radionuclides because, although it has a long half-life, it has several disadvantages:

- Radium and several of its daughter products, including radon, are alpha emitters. Radon is a noble gas which is soluble in tissue. This gas could escape through a hairline crack – not easily detected by a visual check – in the radium capsule. If an implanted radium source were to be ruptured within the patient's body, radium and its daughter products may become deposited more or less permanently in the bone.
- There is also the possibility of damage – by incineration or mechanical means – when the sources are lost or while they are being processed, with the subsequent release of toxic radioactivity to the environment.

- The gamma radiation from a radium source is of higher energy than is necessary for brachytherapy. Radiation protection for these sources requires large thicknesses of lead, which can cause problems when it comes to:
  transporting sources in heavy containers
  using very heavy protective screens around the patient
  the need for a heavy rectal shield in applicators used for gynecological treatment.
- The practical maximum activity concentration (the specific activity) of radium salt is low (approximately 50 MBq mm$^{-3}$ of active volume). Sources of higher activity are therefore bulky and not suitable for afterloading systems.

1.1.2 Radium substitutes

This was the phrase used to describe the first set of new (artificial) radionuclides which were found useful for brachytherapy from about 1950 onwards, though it is only very recently that most radiotherapy centers have stopped using radium. It was found that there were very few radionuclides with the appropriate properties of the ideal brachytherapy source. These properties are as follows:

(A full discussion of these points may be found in the British Journal of Radiology Supplement 21 (1987); an abbreviated set is stated here.)

- Photon energy should be low to medium (0.03–0.5 MeV) to minimize radiation protection problems (with the proviso that low-energy radionuclides should not be used near bone because of the enhanced dose to bone at these energies).
- For permanent stock, a long half-life is desirable such that the radioactive decay within the practical lifetime
of the source and its container (typically 10 years) is small.

- For permanent implantation, a fairly short half-life is essential in order to minimize the time over which special precautions, towards relatives of a radioactive patient and members of the public, need to be in place.
- The nuclide should be available at high specific activity.
- There should be no gaseous disintegration product.
- The nuclide should be available in a form which does not powder or otherwise disperse if the source is damaged or incinerated.

The first sources to be used as alternatives to radium were cobalt-60, gold-198, cesium-137 and iridium-192. These are all described briefly below. The most commonly used sources at this time are cesium-137 and iridium-192, both of which are used in after-loading systems. Iridium-192 has the possibility of high specific activity, which allows it to be used as a high dose-rate (HDR) source.

### 1.1.3 New sources

The newer sources are not known as radium substitutes, mainly because they have very different properties from radium, namely very much higher specific activity (for example the HDR iridium-192 source) and very different energy. The only new source that has been accepted into routine clinical use in certain centers throughout the world is iodine-125. Palladium-103 is also now available as a standard commercial source.

The other sources that are still at the research stage of development, to find out whether they can be of use clinically, are samarium-145, americium-241, and ytterbium-169.

### 1.2 PRODUCTION OF RADIONUCLIDES

The most common method of producing the radionuclides used in brachytherapy, apart from cesium-137 (which is a fission product), is by neutron bombardment in a nuclear reactor. The reaction is that of neutron capture, normally in the stable isotope of the element required (except for iodine-125, see below). Thus, for iridium the reaction is:

\[
^{191}_{77}\text{Ir} (n, \gamma) ^{192}_{78}\text{Ir}
\]

For cobalt-60 the reaction is:

\[
^{59}_{27}\text{Co} (n, \gamma) ^{60}_{27}\text{Co}
\]

This method of production has the disadvantage that the radioactive isotope cannot be separated from the stable isotope and limits the specific activity possible. However, for iodine-125, the reaction proceeds in two stages, with xenon as the initial target element:

\[
^{124}_{54}\text{Xe} (n, \gamma) ^{125}_{54}\text{Xe}
\]

The radioactive xenon decays by beta emission, with a half-life of 8 days, to the required \(^{125}_{53}\text{I}\), which can then be chemically extracted as a pure radioisotope.

To estimate the yield of a given radionuclide, it is possible to use the simple form (for short irradiation time and low fluxes) of the yield equation given in *The Radiochemical Manual* [1]:

\[
\text{Activity} = \sigma \varphi n_0 (1 - e^{-\lambda t})
\]

where \(\sigma\) is the reaction cross-section; \(\varphi\) is the neutron flux; \(n_0\) is number of atoms in target (\(=N_w q/A\), where \(w\) is target mass, \(q\) is the isotopic abundance of the nuclide of interest in the target element, and \(A\) is the atomic mass of the target element, \(N_w = \text{Avogadro's number}\); \(\lambda = \text{bombardment time}; t = \text{bombardment time}\).

The specific activity, \(S\), of the target nuclide may be approximated to:

\[
S = \frac{0.6\sigma \varphi}{A} \left[1 - e^{-\lambda t}\right] \text{Bq g}^{-1}
\]

For long irradiation times:

\[\left[1 - e^{-\lambda t}\right] \rightarrow \text{unity}\]

and \(S \rightarrow S_{\text{sat}}\), the maximum activity possible for a given neutron flux.

**Example.** For iridium-191, the neutron capture cross-section is 910 barns. (This is very high, compared with cobalt-60, for example, which has a cross-section of 43 barns.) If the neutron flux is high (typically \(10^{14} \text{n.cm}^{-2}\text{s}^{-1}\)), using the above equations, it is possible to show that the maximum theoretical specific activity for iridium-192 is about 29 TBq g\(^{-1}\), which equates to about 2.5 TBq for an HDR source of 0.086 g.

In practice, although the neutron flux is probably higher:

\[(10^{14} - 10^{15} \text{n.cm}^{-2}\text{s}^{-1})\]

The irradiation times are shorter, so that only a fraction of \(S_{\text{sat}}\) is reached. The typical specific activity produced for HDR sources is 4.3 TBq g\(^{-1}\) (for a 370 GBq source).

It is interesting to compare the specific activities (in terms of activity per unit length) available for the different radionuclides used now in brachytherapy with those in the older sources.

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (TBq mm(^{-1}))</th>
<th>Actual Source Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iridium wire</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td>Iridium HDR source</td>
<td>74</td>
<td></td>
</tr>
</tbody>
</table>
Cesium miniature cylindrical
Cobalt-60 beads
Compared with radium

13.1 Cesium-137 (Table 1.1)

FORMS FOR MANUAL AFTERLOADING

Miniature cylindrical sources (Figure 1.1) contain cesium-137 glass beads encapsulated in stainless steel. They are used in source trains in machine and manual afterloading systems for gynecological brachytherapy.

AMERSHAM MANUAL AFTERLOADING SYSTEM

In the Amersham Manual Afterloading System (Figure 1.2) a source train consists of a flexible stainless-steel holder containing miniature cylindrical sources separated by spherical steel spacers 1.8 mm in diameter. The
sources and spacers are retained in the holder by a steel spring, secured by a screwed-in end plug. They are designed to locate in the Amersham manual afterloading plastic applicators. The standard set of 11 source trains is suitable for the Manchester System of Gynecological tube dosage. Some examples are given in Table 1.2.

**WALSTAM-TYPE SOURCES** [3]

These are short, cylindrical sources with hemispherical ends. They consist of cesium-137 in a ceramic matrix contained in a welded stainless-steel capsule. They are used in dome or cylindrical gynecological applicators. The sources approximate a point source of activity higher than that used in the Amersham (Manchester) System (Table 1.3).

**Table 1.3  Walstam-type sources**

<table>
<thead>
<tr>
<th>Nominal activity (range)</th>
<th>Nominal output (range of air kerma rate at 1 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37–74 GBq</td>
<td>28.5–570.0 mGy h⁻¹</td>
</tr>
</tbody>
</table>

**REMOTE AFTERLOADING CESIUM-137 SOURCES**

**Spherical Sources**

Spherical sources are used in the Selectron (Nucletron BV) afterloading system (Figure 1.3). The cesium-137 is incorporated into a glass bead and encapsulated in stainless-steel ball bearings (referred to as ‘beads’ or ‘pellets’) which, together with inactive spacer beads, can be pneumatically loaded from the intermediate safe into a patient applicator along a plastic tube (nominal activity 1.48 GBq per bead, air kerma rate 112 μGy h⁻¹m⁻¹).

**CESIUM-137 SOURCES FOR BUCHLER* AFTERLOADING**

These are cylindrical sources used in the fixed ovoids of the Buchler Gynaecological System. The sources vary from 10.1 GBq with active dimensions 2 mm x 3.5 mm to fit applicators 6 mm diameter for low dose rates (LDRs), to 148 GBq with active dimensions 4.1 mm x 11.5 mm to fit applicators 8 mm diameter for HDRs.

**CESIUM-137 SOURCES FOR CURIEotron**

These are cylindrical sources that are very similar to those of the Amersham Manual Afterloading System, but for use in a remote afterloading system in which the source trains are attached to a cable drive.

1.3.2  Cobalt-60 (Table 1.4)

**FORM OF SOURCE**

Although used in various forms in the past, the most common form in recent years is in ‘bead’ form, with a design very similar to that used for cesium-137 beads in the Selectron unit. However, the activity of cobalt-60 beads is higher and they are used for HDR brachytherapy.

**Table 1.4  Properties of cobalt-60**

<table>
<thead>
<tr>
<th>Production</th>
<th>By neutron activation of the stable isotope cobalt-59</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>5.27 years</td>
</tr>
<tr>
<td>Decay scheme</td>
<td>α Co → β Ni⁺, e + γ</td>
</tr>
<tr>
<td>Beta energies</td>
<td>Emission probability – beta 0.318 MeV</td>
</tr>
<tr>
<td></td>
<td>99.9%</td>
</tr>
<tr>
<td>Photon energies</td>
<td>Emission probability – photon 1.17 MeV</td>
</tr>
<tr>
<td></td>
<td>99.9%</td>
</tr>
<tr>
<td></td>
<td>Emission probability – photon 1.33 MeV</td>
</tr>
<tr>
<td></td>
<td>100.0%*</td>
</tr>
<tr>
<td>Beta filtration</td>
<td>Typical source wall thickness</td>
</tr>
<tr>
<td>Half value layer in lead</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

* Data from The Radiochemical Manual [1].

1.3.3  Iridium-192 (Table 1.5)

**FORMS OF IRIDIUM-192**

**Wire**

In Europe, platinum-covered iridium-192 wire is supplied in 500 mm length coils. The wire consists of an active iridio-platinum core, 0.1 mm thick, encased in a sheath of platinum, 0.1 mm thick.

* Buchler GmbH, Braunschweig, Germany.