ICRU REPORT 58

Dose and Volume Specification for Reporting Interstitial Therapy

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Dose and Volume Specification For Reporting Interstitial Therapy

Issued: 30 December 1997

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Preface

Scope of ICRU Activities

The International Commission on Radiation Units and Measurements (ICRU), since its inception in 1925, has had as its principal objective the development of internationally acceptable recommendations regarding:

1. Quantities and units of radiation and radioactivity,
2. Procedures suitable for the measurement and application of these quantities in clinical radiology and radiobiology and
3. Physical data needed in the application of these procedures, the use of which tends to assure uniformity in reporting.

The Commission also considers and makes similar types of recommendations for the radiation protection field. In this connection, its work is carried out in close cooperation with the International Commission on Radiological Protection (ICRP).

Policy

The ICRU endeavors to collect and evaluate the latest data and information pertinent to the problems of radiation measurement and dosimetry and to recommend the most acceptable values and techniques for current use.

The Commission's recommendations are kept under continual review in order to keep abreast of the rapidly expanding uses of radiation.

The ICRU feels that it is the responsibility of national organizations to introduce their own detailed technical procedures for the development and maintenance of standards. However, it urges that all countries adhere as closely as possible to the internationally recommended basic concepts of radiation quantities and units.

The Commission feels that its responsibility lies in developing a system of quantities and units having the widest possible range of applicability. Situations may arise from time to time when an expedient solution of a current problem may seem advisable. Generally speaking, however, the Commission feels that action based on expediency is inadvisable from a long-term viewpoint; it endeavors to base its decision on the long-range advantages to be expected.

The ICRU invites and welcomes constructive comments and suggestions regarding its recommendations and reports. These may be transmitted to the chairman.

Current Program

The Commission has divided its field of interest into 12 technical areas and has assigned one or more members of the Commission the responsibility for identification of potential topics for new ICRU activities in each area. Each area is reviewed periodically by its sponsors. Recommendations for new reports are then reviewed by the Commission and a priority assigned. The technical areas are:

Radiation Therapy
Diagnostic Radiology
Nuclear Medicine
Radiobiology
Radioactivity
Radiation Physics— X Rays, Gamma Rays and Electrons
Radiation Physics— Neutrons and Heavy Particles
Radiation Protection
Radiation Chemistry
Critical Data
Theoretical Aspects
Quantities and Units

The actual preparation of ICRU reports is carried out by ICRU report committees. One or more Commission members serve as sponsors to each committee and provide close liaison with the Commission. The currently active report committees are:

Absorbed Dose Standards for Photon Irradiation and Their Dissemination
Assessment of Image Quality in Nuclear Medicine
Beta Rays for Therapeutic Applications
Bone Densitometry
Chest Radiography — Assessment of Image Quality
Clinical Proton Dosimetry — Part II: Dose Specification for Reporting, Treatment Planning and Radiation Quality
Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology
Dose Specification in Nuclear Medicine
Dosimetric Procedures in Diagnostic Radiology
Fundamental Quantities and Units
In vivo Determination of Body Contents of Radionuclides.
Mammography — Assessment of Image Quality
Measurement of Operational Quantities for Neutrons
Nuclear Data for Neutron and Proton Radiotherapy and for Radiation Protection
Prescribing, Recording and Reporting Electron Beam Therapy
Proton Therapy
Requirements for Radioecological Sampling
Retrospective Assessment of Exposure to Ionizing Radiation
ROC Analysis
Stopping Power for Heavy Ions
Tissue Substitutes, Characteristics of Biological Tissue and Phantoms for Ultrasound

ICRU's Relationships with Other Organizations

In addition to its close relationship with the ICRP, the ICRU has developed relationships with other organizations interested in the problems of radiation quantities, units and measurements. Since 1955, the ICRU has had an official relationship with the World Health Organization (WHO), whereby the ICRU is

looked to for primary guidance in matters of radiation units and measurements and, in turn, the WHO assists in the world-wide dissemination of the Commission's recommendations. In 1960, the ICRU entered into consultative status with the International Atomic Energy Agency. The Commission has a formal relationship with the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), whereby ICRU observers are invited to attend UNSCEAR meetings. The Commission and the International Organization for Standardization (ISO) informally exchange notifications of meetings, and the ICRU is formally designated for liaison with two of the ISO technical committees. The ICRU also corresponds and exchanges final reports with the following organizations:

Bureau International de Métrologie Légale
Bureau International des Poids et Mesures
Commission of the European Communities
Council for International Organizations of Medical Sciences
Food and Agriculture Organization of the United Nations
International Council of Scientific Unions
International Electrotechnical Commission
International Labor Office
International Organization for Medical Physics
International Radiation Protection Association
International Union of Pure and Applied Physics
United Nations Educational, Scientific and Cultural Organization

The Commission has found its relationship with all of these organizations fruitful and of substantial benefit to the ICRU program. Relations with these other international bodies do not affect the basic affiliation of the ICRU with the International Society of Radiology.

Operating Funds

In the early days of its existence, the ICRU operated essentially on a voluntary basis, with the travel and operating costs being borne by the parent organization of the participants. (Only token assistance was originally available from the International Society of Radiology.) Recognizing the impractibility of continuing this mode of operation on an indefinite basis, operating funds were sought from various sources.

During the last 10 years, financial support has been received from the following organizations:

American Society for Therapeutic Radiology and Oncology
Atomic Energy Control Board
Bayer AG
Central Electricity Generating Board
Commissariat à l'Énergie Atomique
Commission of the European Communities
Dutch Society for Radiodiagnostics
Eastman Kodak Company
Ebara Corporation
Électricité de France
Fuji Medical Systems
General Electric Company
Hitachi, Ltd.
International Atomic Energy Agency
International Radiation Protection Association
International Society of Radiology
Italian Radiological Association
Japan Industries Association of Radiation Apparatus
Konica Corporation
National Cancer Institute of the U.S. Department of Health and Human Services
National Electrical Manufacturers Association
Philips Medical Systems, Incorporated
Radiation Research Society
Scanditronix AB
Siemens Aktiengesellschaft
Sumitomo Heavy Industries, Ltd.
Theratronics
Toshiba Corporation
University Hospital, Lund, Sweden
World Health Organization

In addition to the direct monetary support provided by these organizations, many organizations provide indirect support for the Commission's program. This support is provided in many forms, including, among others, subsidies for (1) the time of individuals participating in ICRU activities, (2) travel costs involved in ICRU meetings and (3) meeting facilities and services.

In recognition of the fact that its work is made possible by the generous support provided by all of the organizations supporting its program, the Commission expresses its deep appreciation.

André Allisy
Chairman, ICRU

Sèvres, France
5 July 1997

Contents

Dose and Volume Specification For Reporting Interstitial Therapy

1. Introduction

The ICRU has previously published reports dealing with *Dose Specification for Reporting External Beam Therapy with Photons and Electrons* (ICRU Report 29, ICRU, 1978), *Dose Specification for Reporting External Beam Therapy* (ICRU Report 50, ICRU, 1993) and *Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology* (ICRU Report 38, ICRU, 1985). The present report addresses the problem of absorbed dose[1] specification for reporting interstitial therapy. Although specific to interstitial therapy, many of the concepts developed in this report are also applicable to certain other kinds of brachytherapy applications. In particular, special cases of intraluminal brachytherapy and plesiobrachytherapy via surface molds employing x or gamma emitters are addressed in this report.

It is not the intention of this report to encourage users to depart from their normal practice of brachytherapy and dose prescription. The aim is to develop a common language which is based on existing concepts. It should be usable to describe what has been done in a way that can be more closely related to the outcome of treatment and one that is generally understood.

In order to retain as much consistency as possible with dose and volume specification for external beam radiotherapy, it is desirable to use the same terms and concepts wherever possible. The definitions of the particular volumes (see Section 2.5) used in the two techniques are therefore the same.

For external beam treatment, the ICRU reference point for dosimetry is located firstly, in the central part of the clinical target volume, and secondly, in or near the intersection of the beam axes. For brachytherapy, there are high dose gradients within the clinical target volume and the use of a single reference point is not, therefore, useful. It is, however, appropriate to consider the dose at points where plateaux of dose occur in the center of the clinical target volume where the bulk of the target is (see Sections 2.5 and 2.6.5).

In order to achieve the desired clinical effect, the whole of the clinical target volume must receive a certain minimum dose. It is therefore also recommended that the minimum dose at the periphery of the clinical target volume (see Section 2.6.4) be recorded.

Several classical systems of brachytherapy have developed historically. Best known and most widely used, with or without modification, are the Manchester, Quimby and Paris systems (Meredith, 1967, Quimby and Castro, 1953, Pierquin *et al.*, 1978). The term "system" denotes a set of rules which takes into account the source types and strengths, geometry and method of application to obtain suitable dose distributions over the volume(s) to be treated. The system also provides a means of calculating and specifying dose. It is important to remember that **while an implant may follow the source distribution rules of a system, it does not comply with the system unless the method of dose specification and prescription are also followed.** In addition, if the implant rules are modified, the dose uniformity intended by the system may be compromised.

Over the last two decades, technological developments in brachytherapy have seen the introduction of miniaturized and highly flexible sources which can be used in afterloading devices with radionuclides of different activities that can produce a wide range of dose rates. At the same time, sophisticated 3-D source localization methods have been developed and can be linked to computerized methods of dose calculation and representation of dose distribution. These developments have led many clinicians to depart from the long established implant systems and it is for this reason that a common language is valuable to provide a method of dose specification and reporting which can be used for implants of all types and can be common to all those involved in interstitial brachytherapy.

[1] For brevity, the word "dose" is used instead of "absorbed dose" throughout the text.

2. Definition of Terms and Concepts

2.1 Temporary and Permanent Implants

Interstitial implants fall into two general categories, temporary or permanent. In **temporary implants**, the radioactive sources are removed from the tissue after the treatment is completed. In contrast, in **permanent implants**, the sources remain in the tissues.

In temporary implants, the radioactive sources are generally linear (wires) or arranged in a linear fashion (seed ribbons, etc.), whereas in permanent implants, multiple point sources are not distributed, in general, in linear arrays. The latter type of source pattern is considered separately in this Report.

In planning temporary implants, the total time of implantation depends on the number of sources, their strength and pattern. In contrast, in permanent implants, the number of sources depends on their initial strength.

In temporary implants, in the event of a non-ideal source pattern, there may be the possibility of improving the associated dose distribution through manipulation of the dwell time of some sources in the implant. However, no such possibility exists in the case of permanent implants.

2.2 Source Specification
(see also Appendix A.2.)

The **Reference Air Kerma Rate** of a brachytherapy source is the kerma rate to air, in air, at a reference distance of 1 meter, corrected for air attenuation and scattering. For this purpose, this quantity is expressed in **mGy.h^{-1}** at one meter, or μGy.h^{-1} at one meter.

2.3 Description of Source Patterns (see also Section 3.1.2)

Since essentially all implants irradiate a volume of tissue, the term "volume implant" should not be used to describe a specific implant. A more accurate description of the source pattern is required. Commonly employed source patterns are briefly described as follows:

(i) A single plane implant is defined as an implant containing two or more sources which lie in the same plane. In some instances, the sources lie in a single curved surface.

(ii) A two plane implant contains two planes which are generally parallel to each other.

(iii) Larger implants can often be described according to the number of planes of sources used.

(iv) If the implant is not formed in recognizable planes, then it may be described by the location of the sources relative to a plane passing through the center of the implant or by a specific geometrical configuration (*e.g.*, sphere or cylinder).

2.4 Total Reference Air Kerma

The total reference air kerma (TRAK) is the sum of the products of the reference air kerma rate (see Appendix A.2) and the irradiation time for each source. It is analoguous to mg.h, proportional to the integral dose to the patient, and can also serve as a useful index for radiation protection of personnel.

The simple determination of the total reference air kerma does not, however, allow one to derive, even approximately, the absorbed dose in the immediate vicinity of the sources (*i.e.*, in the tumor or target volume).

2.5 Volumes and Planes

The definitions of gross tumor volume and clinical target volume are entirely based on general oncological principles and, thus, are identical to the definitions given for external beam radiotherapy (see ICRU Report 50, ICRU, 1993).

2.5.1 Gross Tumor Volume

The **gross tumor volume** (GTV) is the gross palpable or visible/demonstrable extent and location of the malignant growth.

According to the above definition, there is no gross tumor volume after complete "gross" surgical resection. There is no gross tumor volume when there are only a few individual cells or "subclinical" involvement (even histologically proven).

2.5.2 Clinical Target Volume

The **clinical target volume** (CTV) is a tissue volume that contains a gross tumor volume and/or subclinical microscopic malignant disease which has to be eliminated. This volume thus has to be treated adequately in order to achieve the aim of therapy: cure or palliation.

The clinical target volume must always be described, independently of the dose distribution, in terms of the patient's anatomy and the tumor volume. The clinical target volume is a tissue volume intended to be irradiated according to a specified dose-time pattern. As a minimum, the physical dimensions of the clinical target volume are described in terms of its maximum dimension (cm) in three orthogonal directions (see Figure 2.1).

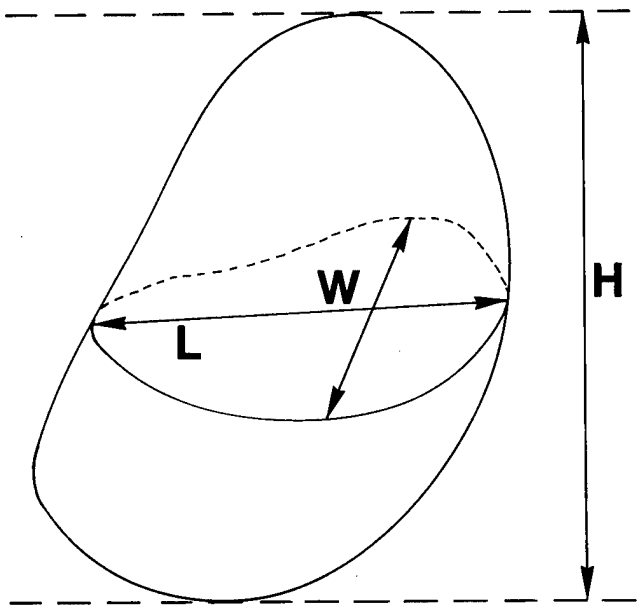


Fig. 2.1. Size of the clinical target volume. The three physical dimensions of the clinical target volume to be reported, are the three maximum diameters measured in orthogonal directions. They are, in general, noted as width **W**, length **L** and height **H**.

In external therapy, the two steps, clinical target volume localization and treatment planning can always be dissociated and therefore checked separately. However, the clinical target volume in interstitial therapy is sometimes decided upon by the clinician at the time of implantation, on the assumption that it is contained within the minimum target isodose (see Section 2.6.4). This procedure is not recommended. The clinical target volume should be clearly described in the patient chart before the implant is planned.

2.5.3 Planning Target Volume

In external therapy, to ensure that all the tissues included in the clinical target volume receive the appropriate dose, it is sometimes necessary to plan the irradiation of a larger volume: the **planning target volume**. In interstitial brachytherapy, the **planning target volume** is, in general, identical to the clinical target volume with very few exceptions. For instance, with some techniques in which there are uncertainties of consistency of source positions (high dose rate, moving sources, fractionated techniques) or alteration of source position (permanent implants) during the application, the planning target volume may be larger than the clinical target volume to take these factors into account.

In this Report, the term clinical target volume is used rather than planning target volume.

2.5.4 Treated Volume

The **treated volume** is that volume of tissue, **based upon the implant as actually achieved,** which is encompassed by an isodose surface selected or specified by the radiation oncologist as being appropriate to achieve the purpose of treatment (*e.g.*, tumor eradication, palliation). The dose value at this isodose surface is the **minimum target dose** (see Section 2.6.4). This isodose surface should, ideally, entirely encompass the clinical target volume.

2.5.5 Central Plane

In source patterns in which the source lines are straight, parallel, of equal length and with centers which lie in a plane perpendicular to the direction of the source lines, this plane is the central plane (see Section 2.6.5 and Figure 2.4).

In an actual implant, all source lines may not necessarily be straight, parallel and of equal length. In such cases, the central plane should be chosen perpendicular to the main direction of the source lines and passing through the estimated center of the implant.

For more complex implants, it may be necessary to subdivide the target volume into two or more subvolumes for dose evaluation. In this event, a central plane may be defined for each of these subvolumes (see Section 2.6.5).

The calculation of dose distributions in multiple planes throughout the target volume shows that a variation of a few millimeters, in the position of the central plane, is not critical.

2.6 Description of Dose Distribution

2.6.1 General Concepts

In brachytherapy, the dose distribution is nonhomogenous and includes steep dose gradients and regions of high dose surrounding each source. However, within the volume of the implant, there are regions where the dose gradient approximates a plateau (see Figure 2.2).

(i) In an interstitial implant, the regions of plateau dose are equidistant between adjacent neighbouring sources, for sources of identical linear activity. They are regions of local minimum doses.

(ii) Variations in the dose between the different plateau doses can be used to describe the dose uniformity of an implant.

(iii) A region of plateau dose is the place where the dose can be calculated most reproducibly and compared easily by different departments.

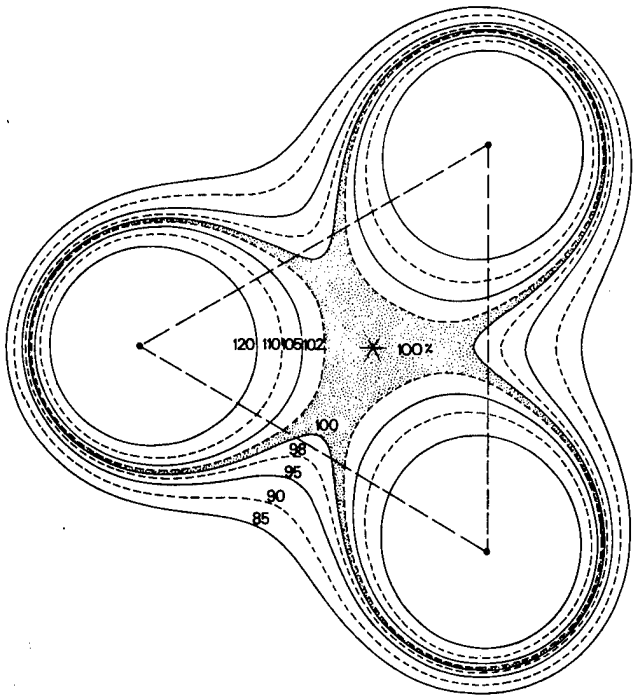


Fig. 2.2. Plateau dose region between radioactive sources. The dose distribution in a plane perpendicular to linear and parallel sources, shows a plateau dose region of low dose gradient. In this example of three sources 6 cm long and with 1.5 cm spacing, the dose varies by less than 2% in the gray region between the sources. (After Dutreix et al., 1982).

2.6.2 Dose Distributions in One or More Planes through the Implant

Although, in modern computer systems, the 3-D dose distribution can be computed and presented as isodose surfaces, these facilities are not yet available in many departments.

In order to provide the minimum of information needed about the dose or dose-rate distribution, the calculation of isodose curves in at least one chosen plane is necessary.

Methods to present dose information, either in tabular form or by graphical presentation have been discussed in ICRU Report 42 (ICRU, 1987).

If only one plane is chosen for isodose calculation, the central plane of the implant (as defined in Section 2.5) should be chosen for this purpose. In order to assess the dose distribution in other areas of the implant, multiple planes for isodose calculation can be chosen, either parallel or perpendicular to the central plane.

2.6.3 Prescribed Dose

For purposes of this Report, the prescribed dose is defined as the dose which the physician intends to give and enters in the patient's treatment chart. Depending on the system used, the approach for dose prescription may be different. It is not the intention of this Report to encourage users to depart from their normal practice of dose prescription.

2.6.4 Minimum Target Dose

The minimum target dose (MTD) is the minimum dose at the periphery of the clinical target volume. It should be equal to the minimum dose decided upon by the clinician as adequate to treat the clinical target volume.

The minimum target isodose is the isodose surface corresponding to the minimum target dose. It defines the treatment volume and should entirely encompass the clinical target volume (see Section 2.4). The MTD is known in some American centers as the minimu peripheral dose. The word peripheral is not recommended as being too vague and leading to confusion with the concept of peripheral dose in external therapy referring to the dose to healthy structures outside of the target volume. The MTD is known as the reference dose in the Paris System. The MTD is equal to about 90% of the prescibed dose in the Manchester system for interstitial therapy.

2.6.5 Mean Central Dose

In the field of brachytherapy, the mean central dose (**MCD**) is taken to be the arithmetic mean of the local minimum doses between sources, in the central plane, or in the central planes if there are more than one.

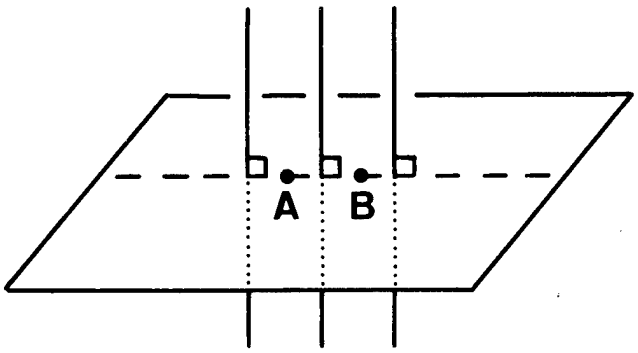
In the case of a single plane implant, the mean central dose is, in the central plane, the arithmetic mean of the doses at mid distance between each pair of adjacent source lines, taking into account the dose contribution at that point from all sources in the pattern (see Figures 2.3a and 2.3c).

In the case of implants with line sources in more than one plane, the mean central dose is the arithmetic mean of the local minimum doses between each set of three adjacent source lines within the source pattern (Figures 2.3.b and 2.4). The minimum dose lies at the intersection of perpendicular bisectors of the sides of the triangles [geometric center] formed by these source lines. This point is equidistant from all three source lines (see Figure 2.2).

In some complex implants, a single central plane may not bisect or even include all the sources. In these cases, a mean central dose based on one plane can be misleading and it is advisable to subdivide the volume and to choose a separate central plane for each subvolume (see Figure 2.4)

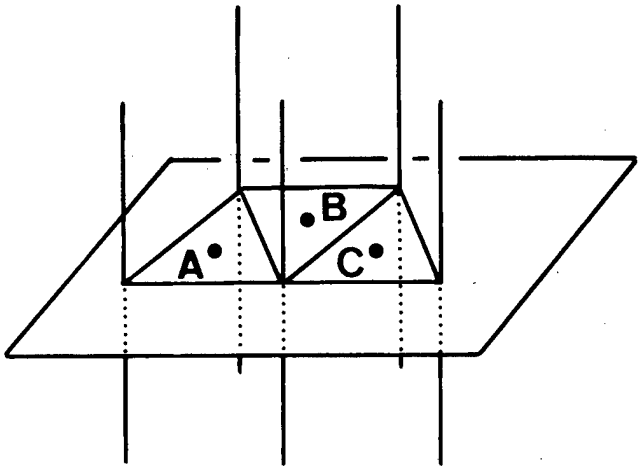
Three practical methods are acceptable for determining mean central dose. These include the following:

(i) In the case of implants with parallel lines, identify triangles consisting of three adjacent



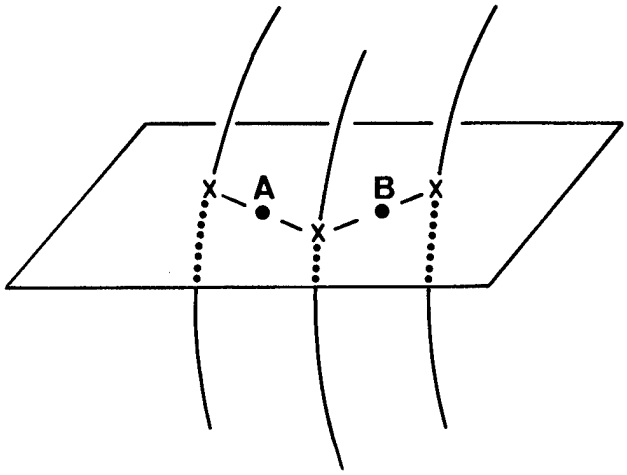
$$D_m = \frac{D_A + D_B}{2}$$

(a)



$$D_m = \frac{D_A + D_B + D_C}{3}$$

(b)



(c)

Fig. 2.3. Central plane. In an implant where the source lines are rectilinear, parallel and of equal length, the central plane is perpendicular to the direction of the source lines and passes through their centers. The mean central dose D_m is the arithmetic mean of the local minimum doses D_I (I = A, B . . .) in the plateau dose regions. a) a planar implant. b) a two plane implant. c) an actual single plane implant where sources are not rectilinear: the central plane can be defined as in (a).

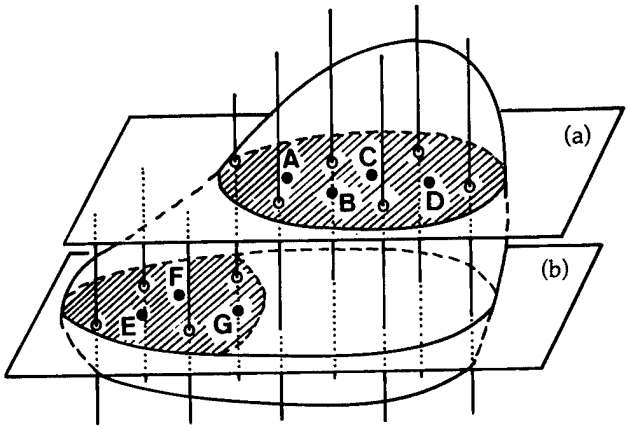
source lines for all the sources, so that the triangles formed constitute as many acute triangles as possible. Determine the intersection points of the perpendicular bisectors of each triangle and calculate the local minimum dose at each of these points. The mean of these local minimum doses is the mean central dose (see Figures 2.3 and 2.4). This method is the most precise one for parallel lines.

(ii) Evaluation of dose profiles: Calculate dose profiles for one or more axes through the center of the implant expected to pass through as many local minima as possible. Determine, by inspection, the local minimum doses. The mean of these local minimum values is the mean central dose (see Figure 2.5). In a single surface implant performed following a curved surface, a profile may lead to an underestimation of the mean central dose. In a complex implant, it may be difficult to find axes passing through the minima and profiles may lead to an overestimation of the mean central dose. However, examples show that the error lies within acceptable limits. This method is sometimes preferred for seed implants. In a seed implant, such as the one presented in Figure 2.6, the dose should be calculated along several random profiles passing through the implant.

(iii) Inspection of dose distribution: Plot the dose distribution in the central plane. With isodose lines varying by 5% (at most 10%) of the local dose in the central region, the local minima can be determined by inspection. The mean of these local minima is the mean central dose (see Figure 2.7). This method is often preferred for complex implants with line sources.

2.6.6 High Dose Volumes

In order to correlate radiation dose with late damage, the high dose volumes around sources should be assessed.



$$D_{ma} = \frac{D_A + D_B + D_C + D_D}{4} \quad \text{(a)}$$

$$D_{mb} = \frac{D_E + D_F + D_G}{3} \quad \text{(b)}$$

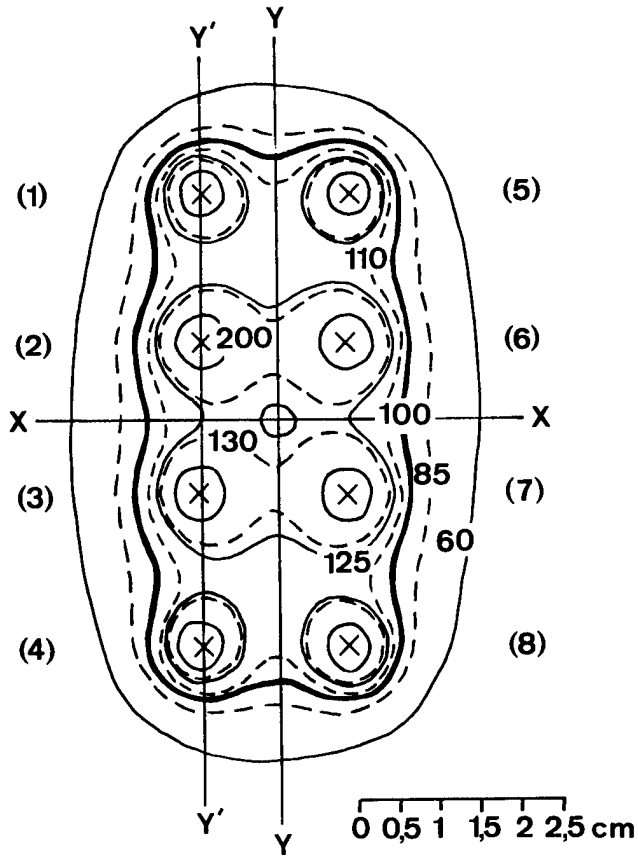
Fig. 2.4. Central planes in a complex implant. It is sometimes necessary to plan the treatment in terms of two or more subvolumes. In the example shown, where all source lines are not of equal length, two central planes are identified: (a) for the longest source lines and (b) for the shortest ones. Two mean central doses are determined in the two sub volumes (a) D_{ma} and (b) D_{mb}. Open circles are the intersections of sources with central plane, and closed circles are the points where the local minimum doses are calculated.

There will inevitably be a high dose zone around each source. Although it is often small and well-tolerated, the exact tolerance dose and volume for interstitial therapy are not known. However, it is necessary, for intercomparison purposes, to agree on a way to describe the high dose volumes. It is suggested that a dose of approximately 100 Gy is likely to be significant in determining late effects. In those patients who receive 50 to 60 Gy as minimum target dose or 60 to 70 Gy as mean central dose, 100 Gy correspond approximately to 150% of the mean cenral dose. It is therefore recommended that the size of the region receiving more than 150% of the mean central dose be reported.

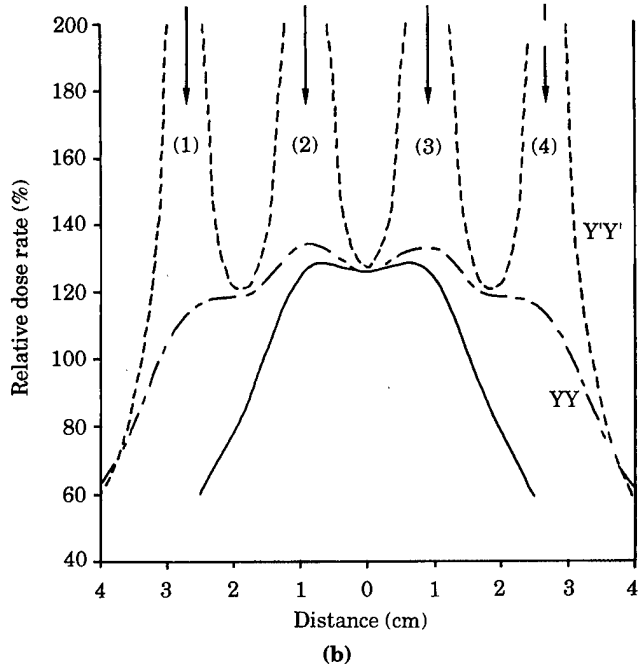
The **high dose volumes** should be defined as the volumes encompassed by the isodose corresponding to 150% of the mean central dose around the sources in any plane parallel to the central plane where a high dose region is suspected. The maximum dimension of the largest region in all planes calculated should be reported (see Figure 2.8).

2.6.7 Low Dose Volumes

A **low dose volume** should be defined as a volume within the clinical target volume, encompassed by an isodose corresponding to 90% of the prescribed



(a)



(b)

Fig. 2.5. Evaluation of dose profiles. Three profiles (b) are drawn along two orthogonal directions through a two plane implant (a) with 8 parallel line sources, 10 cm long, 1.8 cm spacing. The profiles are calculated in percentage of the minimum target dose (thick line) along axes XX, YY and Y'Y' in the central plane. The profile along the axis YY is the most representative to estimate the mean central dose. The mean of the local minimum doses is the mean central dose. The mean central dose is equal to 118% of the peripheral dose.

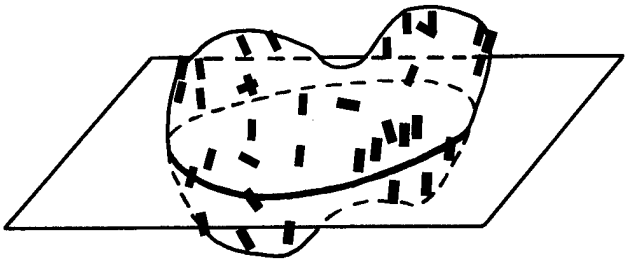


Fig. 2.6. Central plane in a seed implant. The central plane is perpendicular to the main direction of the lines of implantation and passes through the center of the implant.

dose. The maximum dimension of the low dose volume in any plane calculated should be reported.

In implants where the clinical target volume is included within the minimum target isodose, the occurence of a low dose region is exceptional. If the clinical target volume is not covered by the minimum target isodose, there will be low dose regions due to geographical miss.

In order to correlate the local recurrence rate with the dose distribution, it is recommended that low dose volumes be reported.

2.6.8 Dose Uniformity Parameters

Several indices quantifying the homogeneity of the dose distribution have been proposed (see, for example, Paul *et al.*, 1988, Wu *et al.*, 1988, Saw and Suntharalingam, 1991).

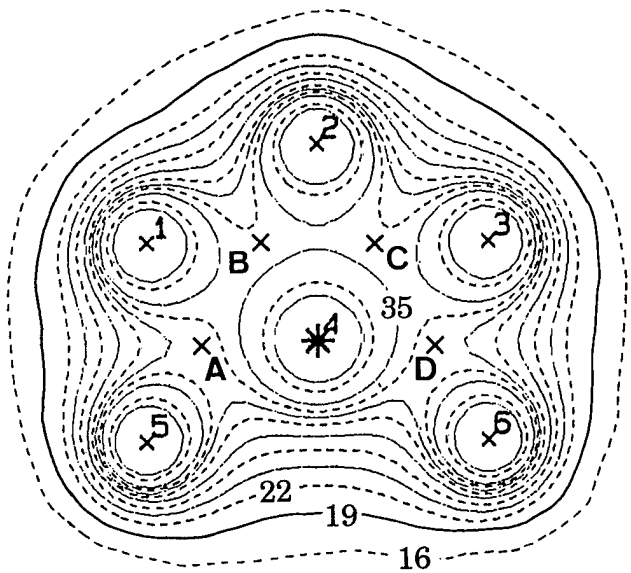


Fig. 2.7. Inspection of dose distribution. Dose distribution in the central plane of an implant with 6 parallel Iridium line sources, 6 cm long, 1.5 cm spacing, reference air kerma-rate 14.5 μGy.h^{-1} at one meter. The dose varies by 5% between plotted isodose lines in the region of interest (A, B, C, D). The isodose values are 16, 19, 22, 24, 26, 28, 30, 31.5, 33, 35, 40 and 45 cGy.h^{-1}. The local minima, A, B, C and D, can be easily estimated by inspection. D_A and D_D approximate 31 cGy.h^{-1}, and D_B and D_C approximate 34 cGy.h^{-1}. The estimated mean central dose is D_m = 32.5 cGy.h^{-1}.

In this Report, two parameters describing dose uniformity for interstitial implants are recommended. They can be derived directly from the concepts of minimum target dose and mean central dose (see Figure 2.9):

(i) The spread in the individual minimum doses used to calculate the mean central dose in the central plane expressed as a percentage of the mean central dose.

(ii) The dose homogeneity index;, defined as the ratio of minimum target dose to the mean central dose.

2.6.9 Additional Representations of the Dose Distribution

In order to obtain a full perception of the dose distribution of an implant, the use of volume-dose calculations has been advocated (see, for example, Neblett *et al.*, 1985, Anderson, 1986, Bridier *et al.*, 1988, McCrae *et al.*, 1987). For this purpose, the clinical target volume (or a larger volume including an additional margin) is subdivided in subvolumes (e.g., voxels) and the dose rate is calculated at the center of each subvolume. The volume receiving at least a specified dose is then defined as the sum of all subvolumes where, at the center at least, that dose is received. Examples of results are shown in Figure 2.10. Because of high dose gradients, significant differences in calculated volumes can be observed, depending upon the size of the elementary subvolumes. The size of the grid and of the elementary subvolumes (voxels) used in dose and volume calculations should be clearly stated. Volume-dose data can also be represented by means of histograms, showing the distribution of fractions of the clinical target volume receiving doses within chosen intervals. The value of these alternative representations of the dose distribution as possible prognostic factors for treatment outcome has still to be established in clinical research.

2.7 Time Dose Factors

2.7.1 General Considerations

Considerable experience has been gained over many years with conventional dose rates. For removable implants, 60-70 Gy has usually been delivered in 4 to 8 days at a dose rate of 30 to 90 centigrays per hour. For permanent implants with iodine-125, doses of 120 to 160 Gy have been delivered with 50% of the dose received in the first two months and the majority of the remainder over the succeeding six months. Even with these conventional treatments, it has been recognized that the dose rates within and

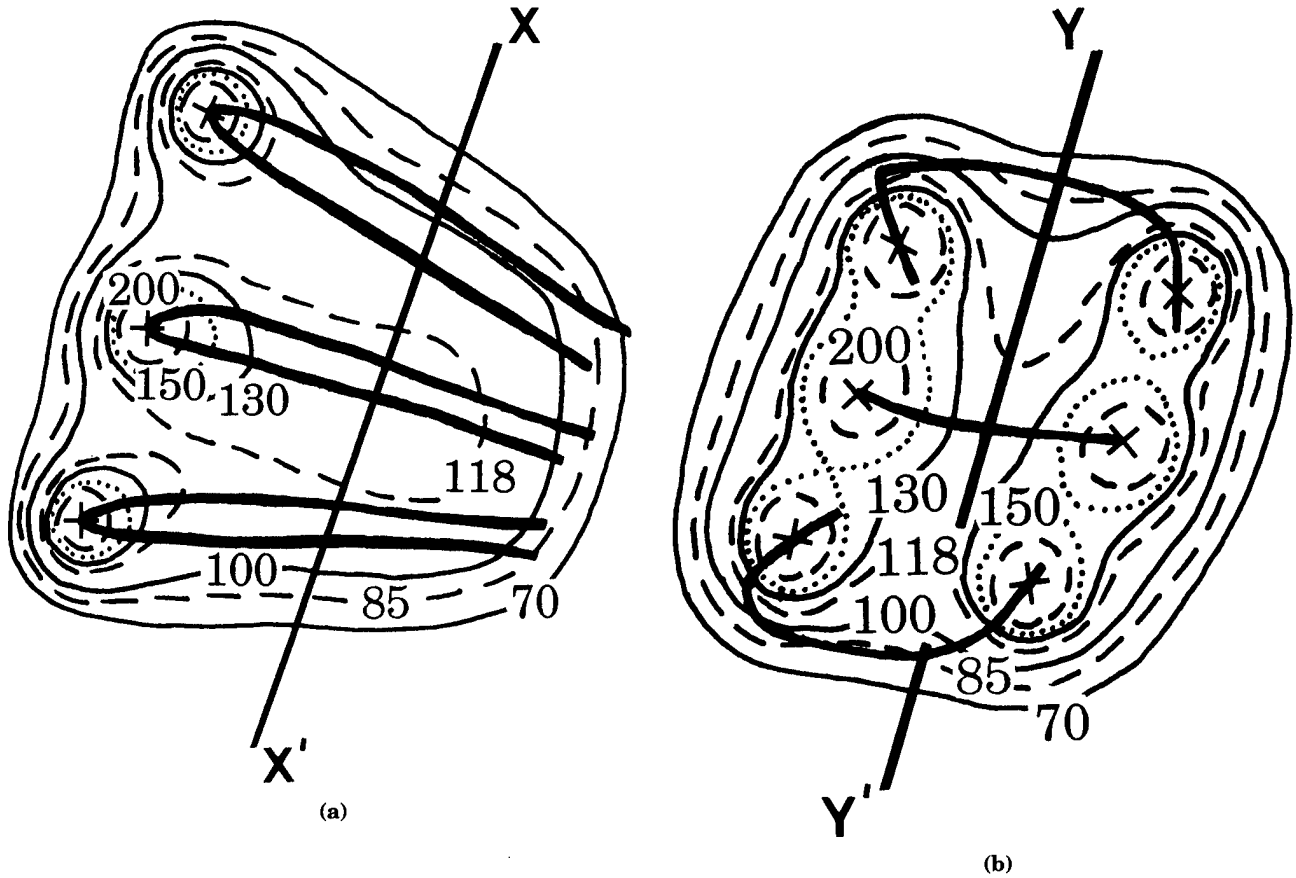


Fig. 2.8. High dose regions. Dose distributions in two planes with three nonparallel loops loaded with seed ribbons. In figure (a), in a plane YY′ parallel to the main direction of the implant, the dose distribution does not display any unexpected high-dose region. In figure (b), in the central plane XX′ of the implant, the maximum dimension of the 150% isodose line (dotted line), varies from 6 mm to 27 mm. In lower perpendicular planes, the dimension of the high dose region increases slowly to 33 mm.

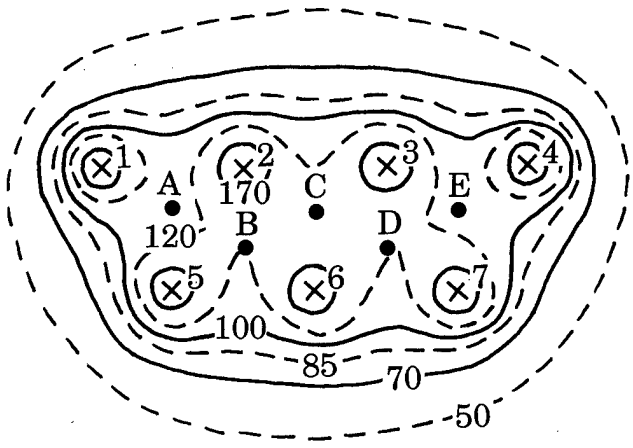


Fig. 2.9. Uniformity parameters. Dose distribution in the central plane of a two plane breast implant, with 7 line sources, 10 cm long, 2 cm spacing, 90 μGy.h^{-1} at one meter. The mean central dose is 70.9 cGy.h^{-1} (the local minima in cGY.h^{-1} are $D_A = D_E = 65.4$, $D_B = D_D = 74.4$ and $D_C = 75.3$). The minimum target dose (100 %) is 58.1 cGy.h^{-1}. The spread in the individual minimum doses is from −8% to +6%. The dose homogeneity index, expressed as the ratio of the minimum target dose and the mean central dose, is 0.82 = 58.1/70.9.

adjacent to the target volume vary considerably as a function of the distance from the sources and that these variations may be significant in determining effects on both tumor and normal tissues.

The development of new afterloading techniques and, in particular, the use of high dose rate introduces new dose time patterns which require evaluation. These include:

- Continuous low dose rate; with short scheduled or unscheduled interruptions.
- Single moving source high dose rate used to treat several channels of an implant over several days to simulate continuous low dose rate (see section 2.7.3: pulsed irradiation).
- High dose rate; in a single fraction.
- Fractionated high dose rate.
- Combinations of external beam radiation with any type of brachytherapy with varying intervals between the two.

The overall treatment time for brachytherapy, and the duration of the interval(s) between treatments can have an important effect on outcome. Therefore, the dose time pattern should be recorded, and it is sometimes necessary to group different patterns for the purpose of analysis of outcome and intercomparisons.

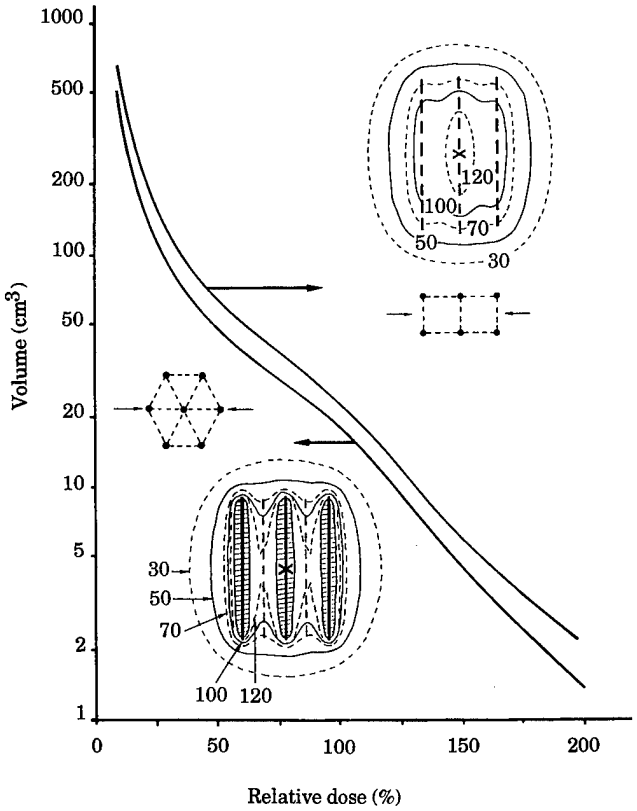


Fig. 2.10. Volume-dose curves. Volume (sum of subvolumes receiving at least a certain dose) versus dose, for two different patterns of parallel source lines: a two plane implant with 6 sources 5 cm long (upper curve), and a cylindrical implant with 7 sources 4 cm long (lower curve). The dose is expressed in percentage of the minimum target dose. The size of the voxel used for calculations is 1 mm³. (Bridier et al., 1988).

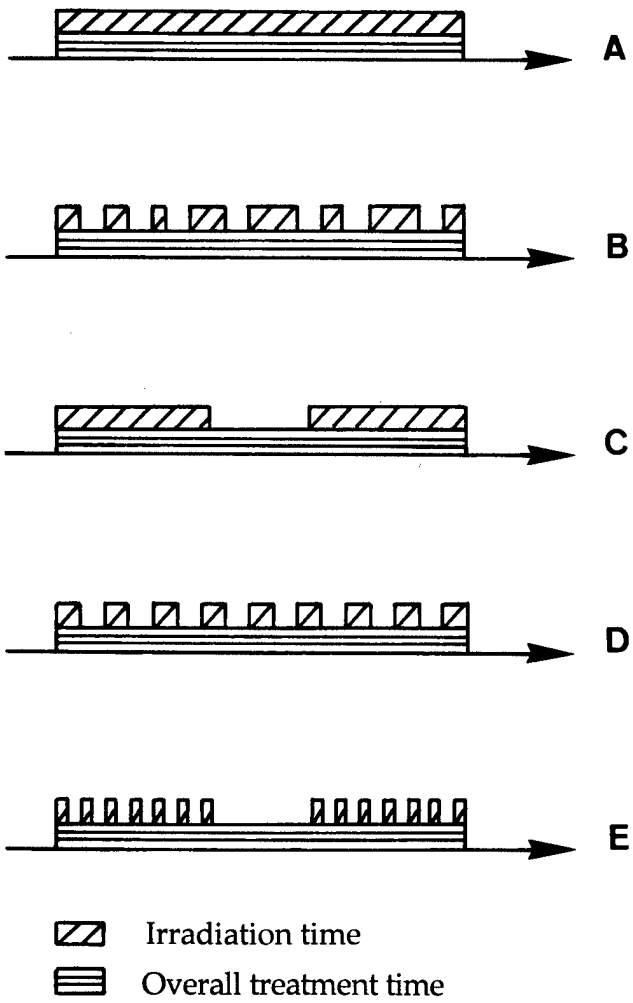


Fig. 2.11. Time-dose pattern. Overall treatment time and irradiation time for different types of treatment.: A, continuous irradiation. B, non-continuous irradiation. C, fractionated irradiation. D, hyperfractionated irradiation. E, pulsed irradiation in two fractions.

2.7.2 Times and Dose Rates for Temporary Implants (see Figure 2.11)

Irradiation time is the time during which a radioactive source is present in the patient.

Overall treatment time is the total time elapsed from the beginning of the first irradiation to the end of the last one.

Instantaneous dose rate is the quotient of the dose and the irradiation time, for a given fraction or pulse.

Average overall treatment dose rate is the quotient of the total dose and the overall treatment time. Average overall treatment dose rate is a concept useful for continuous low dose-rate irradiations with or without short interruptions and for some pulsed irradiations (see Section 2.7.3).

2.7.3 Time Dose Pattern for Temporary Implants (see Figure 2.11)

Continuous irradiation. The overall treatment time does not differ from the irradiation time: only the instantaneous dose rate is considered. When the irradiation times of individual sources are different, the instantaneous dose-rate varies with time and the average overall treatment dose rate is, in general, meaningless.

Non-continuous irradiation. With the advent of remote afterloading, in most instances the overall treatment time is greater than the total irradiation time (which is the sum of the partial irradiation times) due to incidental or planned short interruptions during the treatment. The instantaneous dose rate is greater than the average overall treatment dose rate. In low dose-rate irradiations, when the duration of one given interruption is longer than 10% of the total irradiation time, the irradiation should be considered as fractionated.

Fractionated irradiation. In this type of treatment, irradiation time is subdivided into multiple fractions. In fractionated irradiation, the overall treatment time is much greater than the total irradiation time. For fractionated irradiation, the instantaneous dose rate is the ratio of the dose per fraction

and the irradiation time per fraction, and the average overall treatment dose-rate is, in general, meaningless.

Although the time interval between fractions is usually of the order of magnitude of a day or days, a low dose-rate irradiation is considered as fractionated when one given interruption is longer than 10% of the total irradiation time.

The special case of multiple short irradiations with high dose-rate source(s) is considered in the following paragraph.

Hyperfractionated irradiation. When two or more fractions are given per day, the irradiation is considered as an hyperfractionated irradiation. When the time interval between short high dose-rate irradiations reaches or exceeds four hours, the irradiation should be considered as a hyperfractionated irradiation. It should be considered as fractionated when the time interval is equal to one or several days.

Pulsed irradiation. When a single high dose-rate source is used to give a sequence of short irradiations (pulses) to simulate continuous low dose-rate irradiation, the irradiation should be considered as a pulsed irradiation as long as the time interval is shorter than four hours.

3. Recommendations For Recording and Reporting

It is recommended that adequate information be recorded to give a consistent description of any implant. The guidelines for reporting dose will make it possible to compare results of future brachytherapy practice and to better relate outcome to treatment. In order to report an implant the following should be recorded.

3.1 Parameters Required for Recording and Reporting

3.1.1 Description of Volumes

The description of the volumes should include, as a minimum, the gross tumor volume, the clinical target volume and the treated volume.

3.1.2 Description of Sources (Refer to Appendix B)

The description of the sources employed should include details of:

(i) Radionuclide used, including filtration, if relevant.
(ii) Type of source used, *i.e.*, wire, seeds, seed ribbon, hairpin, needle, etc.
(iii) Length of each source line used.
(iv) Reference air kerma rate of each source or source line.
(v) The distribution of the strength within the source should be described (uniform or differential loading, etc.).

3.1.3 Description of Technique and Source Pattern

If the source distribution rules of a standard system have been followed, this shall be specified; if not, the source pattern should be described as explained in section 2.3.

In addition, the following data should also be recorded:

(i) Number of sources or source lines.
(ii) Separation between source lines and between planes.
(iii) Geometrical pattern formed by the sources with the central plane of the implant (*e.g.* , triangles, squares), where relevant.
(iv) The surfaces in which the implant lies, *i.e.* , planes or curved surfaces.
(v) Whether crossing sources are placed at one or more ends of a group of linear sources.
(vi) The material of the inactive vector used to carry the radioactive sources, if any (*e.g.*, flexible or rigid), whether rigid templates are used at one or both ends.
(vii) Type of remote afterloading if used.

3.1.4 Description of Time Pattern

The description of the time pattern should include the type of irradiation with the necessary data on treatment and irradiation times as described below. The information on dose and time should provide the necessary data to calculate instantaneous and average dose rates.

Continuous irradiation—the overall treatment time should be recorded.

Non-continuous irradiation—both the overall treatment time and the total irradiation time should be recorded, together with information about lengths of gaps.

Fractionated and hyperfractionated irradiation—the irradiation time of each fraction or pulse, the interval between fractions or pulses and the overall treatment time should be recorded.

When the irradiation times of the different sources are not identical, they should be recorded.

Moving sources:

(i) Stepping sources: Step size and dwell time should be recorded if constant. Variation of the dwell times of a stepping source can be used for manipulating the dose distribution. If such a dose optimization is applied, this should be specified (*e.g.*, optimization on dose points defined in the implant or geometrical optimization (Kolkman-Deurloo *et al.*, 1994)). For pulsed irradiation, at least two statements of dose-rate may be necessary. One is the "pulse-average dose-rate," which is the quotient of the pulse dose by the time from beginning to end of the pulse. The other is the maximum local dose rate at 1 cm from the stepping source.
(ii) Oscillating sources: Speed in different sections of the vectors should be recorded.

3.1.5 Total Reference Air Kerma

The Total Reference Air Kerma (TRAK) for the total irradiation time should be recorded (see Section 2.4).

3.1.6 Description of Dose Distribution

The following doses should be recorded:

Prescribed Dose. If the dose is not prescribed at the level of either the minimum target dose or the mean central dose, the method of dose prescription

should be recorded. If, for clinical or technical reasons, the dose received differs from the prescribed dose, it should be noted (Section 2.6.3).

The minimum target dose should be recorded (Section 2.6.4).

The mean central dose should be recorded (Section 2.6.5).

The following additional information, when available, should be recorded:

(i) Dimension of high dose volume(s) (Section 2.6.6)

(ii) Dimension of any low dose volume (Section 2.6.7)

(iii) Any dose uniformity data (Section 2.6.8)

(iv) Additional representation of dose distribution, if any (Section 2.6.9).

3.2 Priority

Three levels of priority are recognized for reporting an interstitial therapy application. They are linked to the different levels of dose computation sophistication needed to fulfill the reporting requirements (Visser, 1989). The wide variation in the availability of treatment planning systems is recognized and taken into account in Tables 4.1 to 4.5.

4. Practical Applications of the Recommendations

It is not the intention of this Report and is not the task of the ICRU to encourage radiation-oncologists to depart from their current practice of dose prescription or technique of application.

Application of the reporting recommendations to existing systems and techniques is developed below.

4.1 Temporary Implants

The recommended hierarchy of dose reporting, for a temporary implant is presented in Table 4.1.

TABLE 4.1—*Levels of priority for reporting temporary interstitial implants*

Parameters for reporting temporary interstitial implants	Priority[a]	Level[b] of computation
Description of Volumes (3.1.1):		
Gross Tumor Volume	1	1
Clinical Target Volume	1	1
Treated Volume (2.6.4)	1	3
Description of Sources and Techniques (3.1.2, 3.1.3):	1	1
Radionuclide, type of source		
Source size and shape, source pattern		
Reference air kerma rate		
Inactive vector (applicator), if any		
Description of Time Pattern (3.1.4)	1	1
Total Reference Air Kerma (3.1.5)	1	1
Description of Doses (3.1.6):		
Prescribed Dose including point or surface of prescription[c]	1	1
Reference Doses in Central Plane		
(a) Mean Central Dose	1	2
(b) Minimum Target Dose	1	2
Description of High and Low Dose volumes (2.6.6, 2.6.7)	2	3
Uniformity Parameters (2.6.8)	3	3
Alternative Representation of Dose Distribution (2.6.9)	3	3
Dose Rates[d] at point or surface of prescription (2.7.2, 2.7.3)	3	1

[a] Priority
1. Concerned with doses in the central plane
2. Requires calculations outside the central plane. If this is not available, then a more detailed description of source pattern under priority 1 is required
3. Additional information mostly of clinical research interest

[b] Level of computation
1. No computer needed
2. Hand calculation and/or computer calculation in central plane
3. 3-D or multiple plane computation needed

[c] Essential to establish consistent reporting and to relate to past experience, necessary for comparison of brachytherapy data and for relating outcome to treatment. If a classical system is used, the system should be identified.

[d] See section 2.7.

4.2 Permanent Implants

The majority of permanent implants are not done with recognizable source lines and it is therefore difficult to identify a central plane or to calculate a mean central dose. The recommended hierarchy of dose reporting for a permanent implant is presented in Table 4.2.

TABLE 4.2—*Levels of priority for reporting permanent interstitial implants*

Parameters for reporting permanent interstitial implants	Priority[a]	Level[b] of computation
Description of Volumes (3.1.1):		
Gross Tumor Volume	1	1
Clinical Target Volume	1	1
Treated Volume (2.6.4)	1	3
Description of Sources and Techniques (3.1.2, 3.1.3):	1	1
Radionuclide, type of source		
Source size and shape, source pattern		
Reference air kerma rate		
Inactive vector (applicator), if any		
Total Reference Air Kerma[c] (3.1.5)	1	1
Description of Doses (3.1.6):		
Prescribed Dose including method of prescription	1	1
Reference Doses in Central Plane		
(a) Mean Central Dose	1	2
(b) Minimum Target Dose	1	2
Description of High and Low Dose volumes (2.6.6, 2.6.7)	2	3
Uniformity Parameters (2.6.8)	3	3
Alternative Representation of Dose Distribution (2.6.9)	3	3

[a] Priority
1. Concerned with doses in the central plane
2. Requires calculations outside the central plane. If this is not available, then a more detailed description of source pattern under priority 1 is required
3. Additional information mostly of clinical research interest

[b] Level of computation
1. No computer needed
2. Hand calculation and/or computer calculation in central plane
3. 3-D computation needed

[c] For permanent implants, the TRAK is calculated as the product of the total reference air kerma rate at the time of implantation and the decay time constant λ, also known as the mean life time ($\lambda = T/\ln 2$, where T is the half life).

4.3 Single Stationary Source Line

The source can be intraluminal or sometimes interstitial: low dose rate or high dose rate techniques can be applied.

The recommended hierarchy of dose reporting, for a single source line, is presented in Table 4.3.

TABLE 4.3—*Levels of priority for reporting implants with a single stationary source line*

Parameters for reporting implants with a single stationary source line	Priority[a]	Level[b] of computation
Description of Volumes (3.1.1):		
Gross Tumor Volume	1	1
Clinical Target Volume	1	1
Treated Volume (2.6.4)	1	3
Description of Source and Technique (3.1.2, 3.1.3):	1	1
Radionuclide		
Length (App. B4),		
Shape (straight/curved)		
Reference air kerma rate		
Strength distribution (uniform linear strength is assumed, if not, distribution must be specified)		
Diameter of inactive vector (applicator)		
Description of Time pattern (3.1.4)	1	1
Total Reference Air Kerma (3.1.5)	1	1
Description of Doses (3.1.6):		
Prescription Dose and Prescription Point (distance from source line and position along the source line)	1	1
Minimum target dose if different from prescribed dose	1	1
Dose at 1 cm from axis of the source line at its center	1	1
Dose at surface of applicator in contact with tissue	3	3
Additional representation of dose distribution (2.6.9)	3	3
Dose rate:		
Average overall treatment dose rate at the point or surface of dose prescription (2.7.2, 2.7.3)	3	1

[a] Priority
1. Concerned with doses in the central plane
2. Requires calculations outside the central plane. If this is not available, then a more detailed description of source pattern under priority 1 is required
3. Additional information mostly of clinical research interest

[b] Level of computation
1. No computer needed
2. Hand calculation and/or computer calculation in central plane
3. 3-D computation needed

4.4 Moving Sources

In addition to simulating a uniform line source, a moving source can be used to modify the dose distribution by changing the dwell time between moves or the speed of movement.

The hierarchy of dose reporting of a moving source takes the form presented in Table 4.4.

TABLE 4.4—*Levels of priority for reporting implants with moving sources*

Parameters for reporting implants with moving sources	Priority[a]	Level[b] of computation
Description of Volumes (3.1.1):		
Gross Tumor Volume	1	1
Clinical Target Volume[c]	1	1
Treated Volume (2.6.4)	1	3
Description of Sources and Technique (3.1.2, 3.1.3):	1	1
Radionuclide, source type and size		
Type of movement[d]		
Range of motion (effective length of source, App.B4.3)		
Applicator—including diameter of inactive vector.		
Number of inactive vectors		
Reference air kerma rate		
Description of Time pattern (2.7.3):	1	1
Intervals between fractions		
Irradiation time per fraction		
Total Reference Air Kerma (3.1.5)	1	1
Description of Doses (3.1.6):		
Prescription Dose	1	1
Minimum target dose	1	2
For single source line or bifurcation, dose at 1 cm	1	2
For complex implant, mean central dose	1	2
Method of dose optimization, if applicable	2	3
Description of high and low dose volumes (2.6.6 and 2.6.7)	2	2
Uniformity		
Additional representation of dose distribution (2.6.9)	3	3
Dose rate (2.7.2, 2.7.3):	3	1
Instantaneous dose-rate		
Average overall treatment dose rate at point or surface of dose prescription and local maximum dose-rate		

[a] Priority
1. Concerned with doses in the central plane
2. Requires calculations outside the central plane. If this is not available, then a more detailed description of source pattern under priority 1 is required
3. Additional information mostly of clinical research interest

[b] Level of computation
1. No computer needed
2. Hand calculation and/or computer calculation in central plane
3. 3-D computation needed

[c] If there is a bifurcation, more than one target volume should be considered.

[d] Continuous/step wise, size of step, unidirectional/oscillating. Uniform motion is assumed, if not, motion must be specified. (see Section 3.1.4)

4.5 Surface Applicators (X or gamma emitters only)

Although surface applicators are not interstitial implants, the physical factors which govern dose distribution from surface applicators are similar.

At present, surface applicators are most commonly used for treating lesions involving skin or mucosal surfaces and the choroidal layer of the eye. When describing treatment by a surface applicator, the recommended hierarchy of reporting for surface applicators is presented in Table 4.5.

TABLE 4.5—*Levels of priority for reporting use of surface applicators*

Parameters for reporting use of surface applicators	Priority[a]	Level[b] of computation
Description of Clinical Target Volume (3.1.1)	1	1
Treated Volume (2.6.4)	1	3
Description of Applicator (3.1.3):	1	1
Shape (flat/curved, round/square, etc.)		
Size		
Description of source(s) (3.1.2)	1	1
Radionuclide and chemical form		
Construction (seeds/tubes/plated)[c]		
Description of Time pattern (3.1.4)	1	1
Total Reference Air Kerma (3.1.5)	1	1
Description of Doses (3.1.6):		
Prescription Dose and point of dose prescription	1	1
Dose at 5 mm in tissue at the center of the applicator[d]	1	2
Minimum target dose[e]	1	2
Description of high dose at tissue surface in contact with applicator, usually near the– *centre of the applicator*	2	2
Uniformity:		
Additional representation of dose distribution (2.6.9)		
Dose rate:		
Average dose rate at the point of dose prescription (2.7.2)	3	2

[a] Priority
1. Concerned with doses in the central plane
2. Requires calculations outside the central plane. If this is not available, then a more detailed description of source pattern under priority 1 is required
3. Additional information mostly of clinical research interest

[b] Level of computation
1. No computer needed
2. Hand calculation and/or computer calculation in central plane
3. 3-D computation needed

[c] Including distance from source(s) to the surface of the applicator.

[d] For eye plaques, 5 mm from the internal sclera.

[e] Dose at distal extent of the clinical target volume.

Appendix A

Quantities and Units

A.1 Basic Quantities and Units

The quantities and units used in brachytherapy are those used in radiation dosimetry in general and, as such, have been discussed in detail in ICRU Report 33 (ICRU, 1980). Definitions of the quantities most relevant for interstitial brachytherapy and their relationships are given here.

A.1.1 Definition of Quantities

(i) The absorbed dose, D, is the quotient of $d\bar{\epsilon}$ by dm, where $d\bar{\epsilon}$ is the mean energy imparted by ionizing radiation to matter of mass dm:

$$D = \frac{d\bar{\epsilon}}{dm}$$

The unit for absorbed dose is J kg^{-1} . The special name for the unit of absorbed dose is gray (Gy):

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

(ii) The kerma (kinetic energy released in material) K, is the quotient of dE_{tr} by dm, where dE_{tr} is the sum of the initial kinetic energies of all the charged ionizing particles liberated by uncharged ionizing particles in a material of mass dm:

$$K = \frac{dE_{tr}}{dm}$$

The unit for kerma is J kg^{-1}. The special name for the unit of kerma is gray (Gy):

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

Notes:

(1) dE_{tr} includes the energy that the liberated charged ionizing particles radiate in bremsstrahlung and also the energies of any charged particles produced in secondary processes, *e.g.*, Auger electrons, occurring within the element dm.

(2) The material in which the kerma is specified (the reference material) may be, but need not be, the same as the ambient medium and one can speak, for example, of the air kerma in free space (the kerma to air in free space), the air kerma in water, the water kerma in free space, etc.

(iii) The activity, A, of an amount of radioactive nuclide in a particular energy state at a given time is the quotient of dN by dt, where dN is the expectation value of the number of spontaneous nuclear transitions from that energy state in the time interval dt:

$$A = \frac{dN}{dt}$$

The unit for activity is s^{-1}. The special name for the unit of activity is becquerel (Bq):

$$1 \text{ Bq} = 1 \text{ s}^{-1}$$

(iv) The air kerma-rate constant, Γ_δ of a radioactive nuclide emitting photons, is defined as the quotient:

$$\Gamma_\delta = \frac{l^2 \cdot \dot{K}_\delta}{A}$$

where $\dot{K}_\delta$ is the air kerma-rate due to photons of energy greater than δ, at a distance, l, from a point source of this nuclide, having an activity A.

The unit for air kerma constant is: J · kg^{-1} · m^2

When the special names gray (Gy) and becquerel (Bq) are used, the unit becomes Gy · s^{-1} · Bq^{-1} · m^2. For practical reasons, in low dose-rate brachytherapy, the air kerma-rate constant is expressed usually in μGy · h^{-1} · MBq^{-1} · m^2.

$$1\ \mu\text{Gy} \cdot \text{h}^{-1} \cdot \text{MBq}^{-1} \cdot \text{m}^2 = 1 \text{ cGy} \cdot \text{MBq}^{-1} \cdot \text{cm}^2$$

$$= \frac{1}{3.6} \cdot 10^{-15} \text{ Gy} \cdot \text{s}^{-1} \cdot \text{Bq}^{-1} \cdot \text{m}^2$$

Note: The photons included in the definition comprise gamma rays, characteristic x rays and internal bremsstrahlung. A lower limit for the photon energy of 20 keV is recommended but may depend on cladding of specific sources.

A.1.2 Relationships Between Quantities

(i) Kerma, K, and energy fluence, Ψ:

$$K = \Psi\left[\frac{\mu_{tr}}{\rho}\right]$$

where μ_{tr}/ρ is the mass energy transfer coefficient.

(ii) Air-kerma and kerma in a reference material:

The kerma, K_m, in a reference material m, is

equal to the product of air kerma and the ratio of the mean mass energy transfer coefficients in the reference material and in air:

$$K_m = K_{air} \left[\frac{\overline{\mu}_{tr}}{\rho}\right]^m_{air}$$

Water has generally been accepted as the reference material for external beam therapy (ICRU, 1976, 1984). Similar considerations apply to interstitial therapy with photon emitters and water is therefore recommended as the standard reference material for dosimetry of these sources.

(iii) Absorbed dose and kerma in a reference material:

Under complete electronic equilibrium conditions in a reference material, the absorbed dose is equal to that part of the kerma for which the charged-particle kinetic energy is subsequently spent in collision interactions:

$$D_m = K_m(1 - g)$$

In this expression g denotes the small part of the kerma which is lost to bremsstrahlung in the medium. In practical situations in radiotherapy, only transient electronic equilibrium can be achieved and D_m may deviate slightly from K_m (1-g). However, for the energies and the maximum scattering conditions encountered in brachytherapy, one may consider the above equation to be valid.

(iv) Absorbed dose in a reference material and air kerma:

$$D_m \simeq K_{air} \left[\frac{\mu_{tr}}{\rho}\right]^m_{air} \cdot (1 - g)$$

The equation is strictly valid only if two conditions are fulfilled:
- —electronic equilibrium is achieved, which is always the case in tissues in brachytherapy;
- —energy photon fluences are the same in material and air, which is never the case in practice.

If one accepts the reasonable approximation that g, the radiative loss in a medium of low Z has a value approximately the same as the radiative loss in air, then this expression can be written as:

$$D_m = K_{air} \left[\frac{\mu_{tr}}{\rho}\right]^m_{air} \cdot (1 - g)$$

The correction factor (1-g) is close to unity (0.997) for 1.25 MeV, the energy of cobalt-60 photons, and is even closer to 1 for lower energies (Boutillon, 1985).

A.2 Reference Air Kerma Rate

A.2.1 Definition of the Reference Air Kerma Rate

It is recommended that radioactive sources for brachytherapy be specified in terms of the quantity, reference air kerma rate. The reference air kerma rate, $\dot{K}_R$, of a source is the kerma rate to air, in air, at a reference distance of 1 meter, after correction for air attenuation and scattering. The quantity reference air kerma rate is expressed in Gy · s^{-1} or a multiple of this unit. For low dose rate brachytherapy applications, it is recommended that μGy · h^{-1} be used.

A.2.2 Specification of Linear Strength

For wires and other line sources, the linear strength of a source is defined as the reference air kerma rate of the line source divided by the equivalent active length (see Appendix B.4.3). This quantity is expressed in Gy · s^{-1} · cm^{-1} or a multiple of this unit. For low dose-rate applications, the multiple μGy · h^{-1} · cm^{-1} is recommended.

A.2.3 Background of Recommendations

When radium sources were the only radioactive sources used in brachytherapy, their strength was specified in terms of the mass of radium, in mg, contained in the source. When, subsequently, other radionuclides became available, the sources were first specified in terms of their activity, in mCi. Due to the influence of self-absorption and attenuation within the source and the encapsulation, the "contained activity" was of little practical interest and the concept of "apparent activity" was introduced (Young and Batho, 1964). The apparent activity of a source was defined as the activity of a point source of the same nuclide which would deliver the same exposure rate in air at the same distance from the center of the actual source. The distance should be chosen large enough so that the actual source could be considered as a "point source."

In order to compare radium substitutes directly with radium itself, specification in terms of mg radium equivalent came into use. The radium equivalent mass, or mg-Ra equivalent, of a source is the mass of ^{226}Ra filtered by 0.5 mm Pt which would produce the same exposure rate as the actual source at the same distance.

At a later stage, it became usual to specify the source strength directly in terms of its emission, namely in exposure rate at a reference distance. This quantity was often expressed in mR/h, at a reference distance of 1 m. This method of source strength specification has the principal advantage of being a specification in terms of directly measurable quantities (NCRP, 1974; Dutreix and Wambersie, 1975).

The adoption of SI units and the replacement of exposure by air kerma has made a revision of this method necessary. Different organizations have, in recent years, issued recommendations to specify brachytherapy sources in terms of air kerma rate (CFMRI, 1983; BCRU, 1984; AAPM, 1987; NCS, 1991; BIR, 1993). The ICRU, in Report 38, *Dose and Volume Specification for Reporting Intracavitary Therapy in Gynecology* (ICRU, 1985), recommended the use of reference air kerma rate. The present Report follows this method of specification.

It may be remarked that a difference in nomenclature and in definition exists regarding the quantity reference air kerma rate with respect to the report published by the AAPM (AAPM, 1987; Nath *et al.*, 1995) concerning specification of brachytherapy sources. In the latter report, the term "air-kerma strength" is used. The word "strength" has been rejected by the ICRU as too vague and because it might represent some ambiguity when translated in other languages. The ICRU has considered that the name of the quantity referene air kerma rate implies that, in the definition, the air kerma rate be measured in reference conditions, *i.e.*, at 1 meter. Therefore, the unit cannot include the square meter and should be the $Gy \cdot s^{-1}$ at 1m, or a multiple like the $\mu Gy \cdot h^{-1}$ at 1m.

Appendix B

Interstitial Brachytherapy Sources

B.1 Definition

An interstitial brachytherapy source is a radioactive source containing a quantity of a radionuclide, enclosed in an inactive outer cladding, small enough to be inserted into tissue.

B.2 Radionuclides Used in Interstitial Brachytherapy

Interstitial implants were initially performed using radium-226 needles for temporary implants and radon-222 seeds for permanent implants. Radium has largely been replaced by other radioisotopes and radon has been completely replaced. Table B.1 lists the radioisotopes in common use today as well as several radioisotopes under development. Appropriate physical and dosimetric parameters are included.

B.3 Source Types

(Dutreix *et al.*, 1982; Nath *et al.*, 1995) (See Figure B.1).

B.3.1 Needle or Tube Source

A needle or a tube source is a source in which the radioactive material is encapsulated in a rigid metal applicator fitted with an eyelet on one end and a sharp point (needle) or blunt end (tube) on the other. The source activity distribution may be:

(i) **Uniform**: The activity is uniformly distributed along the active length of the source.
(ii) **Indian Club**[a]: The linear activity near one end is higher than that in the remainder of the source.
(iii) **Dumbbell**[a]: The linear activity near both ends is higher than that in the central portion of the source.

B.3.2 Wire Source

A source in which the radioactive material is incorporated into a flexible wire. Special forms of wire sources are:

(i) **Hairpins:** The wire is preshaped to form two parallel lines called branches joined by a short U-shaped section at one end. The branches are usually separated by 1 to 1.3 cm (Figure B.1).
(ii) **Single Pin:** A straight wire source with a length of wire curled into an eyelet on one end.
(iii) **Loop:** Wire is passed through a catheter to form two parallel branches connected by a half circle.

B.3.3 Small Source

A short discrete source (< 0.5 cm long) in the shape of a short wire, cylindrical tube or sphere. These sources may be used as:

(i) **Individual seeds:** Implanted directly in tissue (permanent implant) or affixed to surface applicators (temporary application).
(ii) **Seed ribbons:** A series of seeds contained in a flexible plastic tube.
(iii) **Source train:** In some remote afterloading devices the source(s) are made up from a sequence of small sources, some active and some non-active arranged in a fixed or selectable and reproducible configuration.
(iv) **Moving source:** In some remote afterloading systems, a single seed is moved in a continuous or step-wise fashion inside one or more catheters.

Seed ribbons, source trains, and the single movable source can be designed to simulate a uniform line source, or non-uniform distributions to suit special needs. Some units with a single movable source can be programmed to feed multiple catheters in a single implant.

B.3.4 Source Line

For purposes of this document, any needle, group of tubes, seed ribbon, source train, or movable source forming a single line (straight or curved) is called a *source line*. The linear activity of the source line may be either uniform or nonuniform.

B.4 Length of Sources

(see also Figure B.1)

[a] Indian club and Dumbbell sources are described in the Manchester system (Meredith, 1967) for use when crossing needles cannot be placed.

TABLE B.1.—*Physical and dosimetric parameters of radioisotopes in common use today*

Radioisotope	Half life	Effective energy	$(1\text{-}g)_{air}$	$\mu Gy \cdot h^{-1} \cdot MBq^{-1}$ at 1 m	Reference energies for γ and x-ray spectrum
Cobalt 60	5.27 yr	1.25 MeV	0.997	0.30_6	γ 1.17 & 1.31 MeV
Cesium 137	30.7 yr.	662 keV	0.998	0.077_2	γ .662 MeV
Gold 198	2.696 day	412 keV	0.999	0.055_9	γ .412 MeV 28 x rays > .069 MeV
Iridium 192	74.2 day	350 keV	0.999	0.100 to 0.116	42 γ rays 0.11–1.4 MeV γ .0355 MeV
Iodine 125	59.6 day	28 keV	1.000	0.033_7	x .0272–.0318 MeV 15 γ rays
Tantalum 182	115.0 day	670 keV	0.998	0.163_5	0.043–1.453 MeV 49 γ rays
Radium 226	1600 yr	830 keV	0.997	0.233_6–0.197^a	0.047–2.45 MeV 49 γ rays
Radon 222	3.824 day	830 keV	0.997	0.233_6	0.047–2.45 MeV
Under Development					
Paladium 103	16.97 day		1.000	0.034_3	x .020–.023 MeV
Americium 241	432 yr	60 keV	1.000	0.053_4	γ .014–.060 MeV

[a]Filtered by 0.5 mm Pt

B.4.1 Physical Length

The distance from proximal to distal end of the source or source assembly. This measurement has little value in describing an implant. It can, however, be helpful in interpreting the location of the sources in a radiograph.

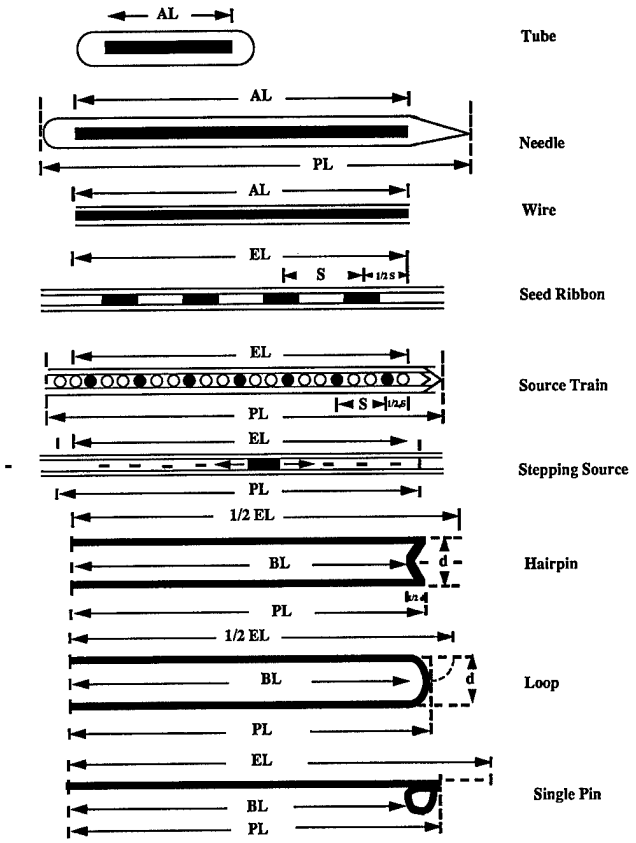


Fig. B.1. Source types. Different types of sources are shown. *AL* is the Active Length. *EL* is the Equivalent Active length. *PL* is the Physical Length. *S* is the separation between small sources. *d* is the branch separation in an hairpin or a loop.

B.4.2 Active Length

Is the distance from the proximal to the distal end of the radioactive material contained in the source line.

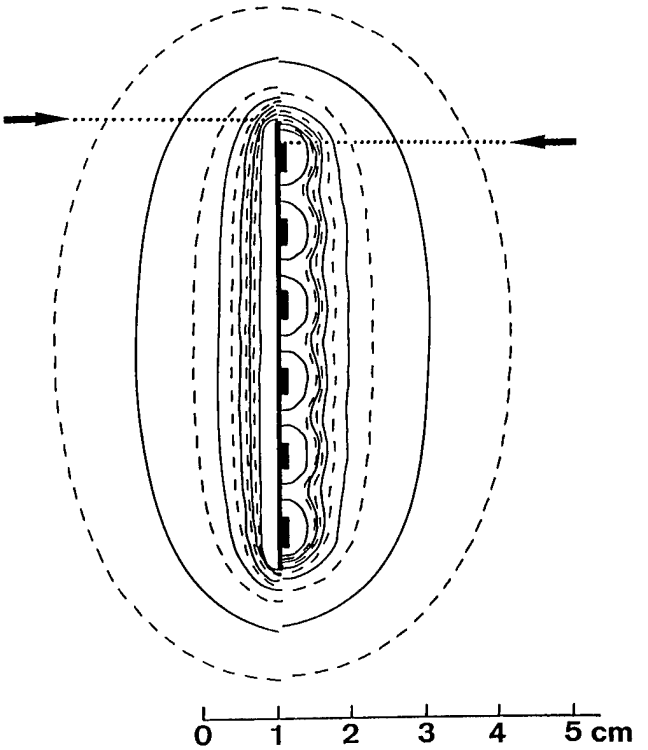


Fig. B.2. Equivalent length. Comparison of dose distributions between a train of 6 seeds of reference air kerma rate K_i spaced by S = 1 cm (right), and a linear source of length $l = 6S = 6$ cm and of total reference air kerma-rate $K = 6K_i$ (left). The doses have been calculated without oblique filtration correction. At a distance of 0.5 cm = S/2 from the sources, the waving of the isodose is negligible, and the diameters of the isodoses around the linear source or the train of seeds are equal. The length of the isodoses is the same for the train of seeds and for the linear source (Bridier et al., 1988).

B.4.3 Equivalent Active Length

The active length of a uniform linear source that yields an isodose distribution in the region of interest equivalent to that from a uniform source line made up of discrete spaced sources is called the equivalent active length of the source line. It has been shown (Dutreix and Wambersie, 1968; p.78 in Dutreix *et al.*, 1982; ICRU, 1985; Bridier *et al.*, 1988; Marinello *et al.*, 1985) that the dose distribution from a seed ribbon or source train most nearly approximates that of a uniform line source whose active length is exactly the number of equal activity seeds times the distance between the source centers. (see Figure B.2).

The equivalent active length of a movable source, moved in a uniform continuous fashion, will be recorded as the total length of travel of the center of the source. This definition is most correct for a point source but is also used for sources of short but finite length.

B.4.4 Height of Hairpin or Loop

The distance from the distal end of the longest branch to the proximal end of the connecting segment is called the branch height. This value, as with physical length, is useful mostly in localization of the source.

B.4.5 Branch Length of Hairpin, Single Pin or Loop

The branch length is the distance from the distal end of the branch to the distal end of the loop for the single pin, the center of curvature of the tube source, and proximal end minus one half of the branch separation for hairpins. This length is important since a wire of this length crossed on one end would generate an equivalent dose distribution (p.147-150 in Dutreix *et al.*, 1982; p. 38–41 in Pierquin *et al.*, 1987).

B.5 Source Construction

The chemical and physical form of the radioisotope, the shape and form of the inert filler material and the material and thickness of the inert cladding all influence the safety and some dosimetric properties of a source. Some calculation algorithms (Shalek and Stovall, 1990) include corrections for attenuation due to self-absorption in the source, but the knowledge of the attenuation coefficient is necessary and, moreover, the **contained activity** should be used rather than the **apparent activity**. The inert filler and cladding have been known to contribute significant characteristic x rays (Ling *et al.*, 1983 and Williamson, 1988) and the effect of encapsulation on the dose distribution is important and has been investigated by a number of authors (Ling *et al.*, 1983; Thomason *et al.*, 1991). This information should be known by the user and is usually available from the manufacturer or from the literature. Needles, tubes and movable sources are typically doubly encapsulated in rigid containers. Wires and seeds are typically coated with thin inert metal cladding.

Appendix C

Determination of Source Parameters, Verificationof Source Strength

The absolute value of the source strength for sources used clinically and the variation among sources in a batch must be assessed. In addition, the linear uniformity of the radiation pattern of each individual source or source line should be assessed.

C.1 Calibration

Figure C.1 shows a diagram of traceability from the National/International Laboratory through a Secondary Standards Laboratory to the user. A clear distinction must be made between "calibration" certificates issued by the manufacturer and official calibration of a source by a Standards Laboratory. The manufacturer's certificate is not considered directly traceable to a Standards Laboratory.

When a national standard is not available for a given isotope, the manufacturer's calibration may need to be accepted; however, the institution should establish a Quality Assurance program to assess each batch of the isotope shipped to assure that the manufacturer's standards do not change with time.

C.2 Recommendations for Calibration

All sources used in brachytherapy should have calibrations traceable to a national or international standard.

The reference distance for reference air kerma rate is one meter; however, the air kerma rate can be measured at any distance large enough for the source to be considered as a point source. In that case, the reference air kerma-rate is the product of the kerma rate and the square of that distance.

Unlike external beam radiation therapy, where the physicist relies on a properly calibrated radiation measuring device (ionization chamber) as a standard, in brachytherapy, the physicist should rely on a properly calibrated standard radioactive source and, to a lesser extent, upon a calibrated radiation measuring device. Sources used clinically should be calibrated by comparison with a standard source. Relying exclusively on the source manufacturer's calibration is not recommended.

Each institution should maintain at least one standard calibrated source of each long half-life isotope used. Sources should be compared to this at the time of purchase and periodically thereafter. For sources with a short half-life (^{192}Ir, ^{125}I, etc.), a standard calibrated source should be obtained and a detector (well ionization chamber) calibrated against it (Goetsch *et al.*, 1991). The stability of the chamber can be tracked by a long half-life source long after the calibrated source has decayed beyond a useful level.

For applications where only a few short half-life seeds are used, the calibration of all seeds should be verified. For an application where a large number of seeds are used, verification of a random sample may suffice (Kutcher *et al.*, 1994).

C.3 Uniformity of Source Strength within A Batch of Sources

Nominally identical sources from any given manufacturing run have some inherent spread in their strength. In the clinical environment, these sources are usually considered to be equal and the average strength used in calculations. This applies equally as well to remote afterloading devices which utilize a number of sources.

Sources whose strength deviates from the average by more than 5% should be considered unacceptable for clinical use. For implants using a large number of seeds, where seed averaging may compensate for variations in individual seed source strengths, these requirements may be relaxed.

C.4 Linear Uniformity

The uniformity of the activity of each source should be verified. Autoradiographs are useful for tubes, needles, wires and seed ribbons.

More elaborate methods are available to verify uniform linear activity of wires and seed ribbons (Bernard *et al.*, 1975, Ling and Gromadzki, 1981).

C.5 Uniformity of Low Energy Sources

A specific problem is raised by iodine-125 seeds. Some sources are known to be anisotropic with large asymmetry about the axis of the seed (radial asymmetry) as well as longitudinally. Anisotropy should be investigated for low energy sources where self absorption is significant.

C.6 Calibration of High Intensity Afterloading Systems

The calibration of high intensity sources (particularly iridium-192) used in afterloading devices re-

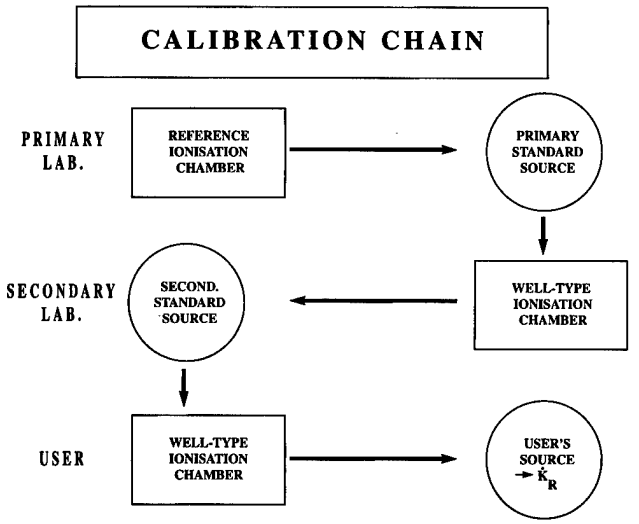


Fig. C.1. Calibration Chain. Traceability of the source calibration at the user's laboratory to the Primary Standard Laboratory. (After Cance and Simoen, 1983). $\dot{K}_R$ is the reference air kerma-rate.

quire special consideration. There is no generally accepted protocol for calibration of these sources. However, work is being done to establish a protocol (Williamson *et al.*, 1982; AAPM, 1993; Venselaar *et al.*, 1994). The following points need to be considered in any such calibration protocol.

Well ionization chambers:

The dose rate is high so ion recombination can be significant. A chamber designed specifically for these sources has been developed (Goetsch *et al.*, 1991).

Thimble chamber, measurement of air kerma at a distance:

National/international standards are not generally available for thimble chambers at ^{192}Ir energies. An interpolation procedure between ^{137}Cs (or ^{60}Co) and orthovoltage energies has to be applied (Cance and Simoen, 1983; Goetsch *et al.*, 1991).

Position is critical, and the contribution from scatter is non-negligible. A technique to minimize these effects has been reported (Goetsch *et al.*, 1991).

Thimble chamber, measurement in a solid phantom:

The use of a solid phantom has the advantage that positioning uncertainty is decreased. In order to determine the air kerma rate at the point of measurement, it is, however, necessary to take into account the replacement of the phantom material by the ionization chamber (Steggerda and Mijnheer, 1994). It has the disadvantage that the measurement includes attenuation and scatter at the point of measurement, and cannot be considered as a source calibration.

Appendix D

Practical Examples

D.1 Single Plane Implant: Manchester System

D.1.1 Volumes

The gross tumor volume is a planar area of 2.0 cm × 2.0 cm with a depth of 2 mm. The clinical target volume is a square area of 3.0 cm × 3.0 cm with a thickness of 5 mm.

D.1.2 Sources

The implant consists of 7 cesium needles, needle 1 through 5 approximately parallel and needle 6 and 7 serving as crossing needles. The geometry of the implant is illustrated in two demagnified projections (Lateral and Anterior-Posterior), see Figure D.1.

The source strength and length specification are as follows:

Needle number	Active length	Total length	Ref. air kerma rate $\mu Gy \cdot h^{-1}$
1 and 5 (outer needles)	30.0 mm	42.0 mm	16.0
2, 3, and 4 (inner needles)	30.0 mm	42.0 mm	8.0
6 and 7 (crossing needles)	22.5 mm	34.5 mm	12.0

The Total Reference Air Kerma rate is 2 × 12 (crossing needles) + 2 × 16 (outer needles) + 3 × 8 (inner needles) = 80 $\mu Gy\ h^{-1}$ at 1m.

D.1.3 Time Pattern

Continuous irradiation:

Following the rules of the Manchester System, the duration for a prescribed dose of 65 Gy was determined to be 173 h. This was determined using an area of 3.9 × 3.6 = 14 cm^2 and using the Manchester System tables for h = 0.5 cm.

D.1.4 Total Reference Air Kerma (TRAK)

The Total Reference Air Kerma is equal to:

80 × 173 μGy = 13840 μGy (or 1.38 cGy) at 1m.

D.1.5 Doses

In order to specify the mean central dose, the dose rate in the central plane is calculated at four reference points located midway between the intersections of needles 1 through 5 and the central plane. The dose rate in these 4 reference points (labelled A through D) appears to be:

A: 59.6 cGy/h
B: 44.2 cGy/h
C: 59.4 cGy/h
D: 50.4 cGy/h

The average dose rate is 53.4 cGy/h.

This value could also have been estimated from an isodose plot in the central plane, as illustrated in Figure D.2, or from a dose-rate profile along a line passing through the intersections, as illustrated in Figure D.3.

The minimum target dose is, in this case, equal to the prescribed dose (65 Gy). From the application time of 173 h, the mean central dose can be calculated to be:

$$173\ (h) \times 0.534\ (Gy/h) = 92.4\ Gy.$$

The minimum target dose is thus (65/92.4) × 100% = 70.3% of the mean central dose.

D.1.6 Uniformity Parameters

The spread in the individual minimum doses in the points A–D is in the range −17% to + 11% relative to the mean central dose.

The ratio of the minimum target dose to the mean central dose is (65/92.4) × 100% = 70.3%.

D.1.7 Dose Rate

The dose rate at the level of the surface of prescription is:

$$65\ Gy/173\ h = 0.376\ Gy.h^{-1}\ (37.6\ cGy.h^{-1}).$$

D.2 Two-plane Breast Implant

D.2.1 Volumes

The gross tumor volume is the excisional field region after lumpectomy. The clinical target volume is an area of 6.5 cm × 4.2 cm and a thickness of 2 cm.

D.2.2 Sources

The implant consists of 69 iridium seeds in 8 source lines (5 with 9 seeds and 3 with 8 seeds) in an approximately parallel, two-plane geometry. The geometry of the implant is illustrated in Fig. D.4. The

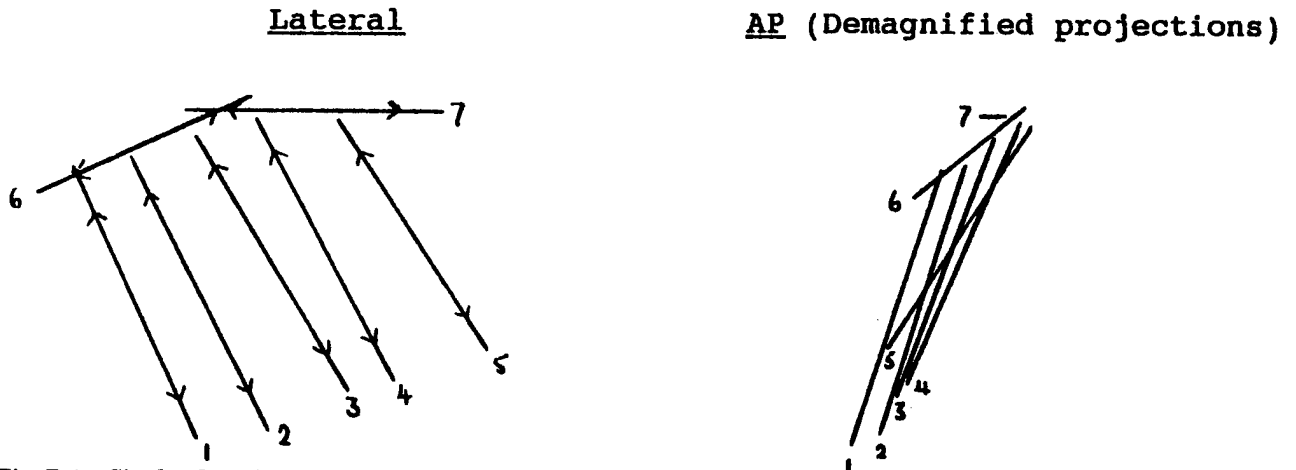


Fig. D.1. Single plane implant: Manchester system. Lateral and AP projections of an implant consisting of 7 cesium needles, needle 1 through 5 approximately parallel and needle 6 and 7 serving as crossing needles. The projections shown in the figure are recalculated from radiographs after demagnification.

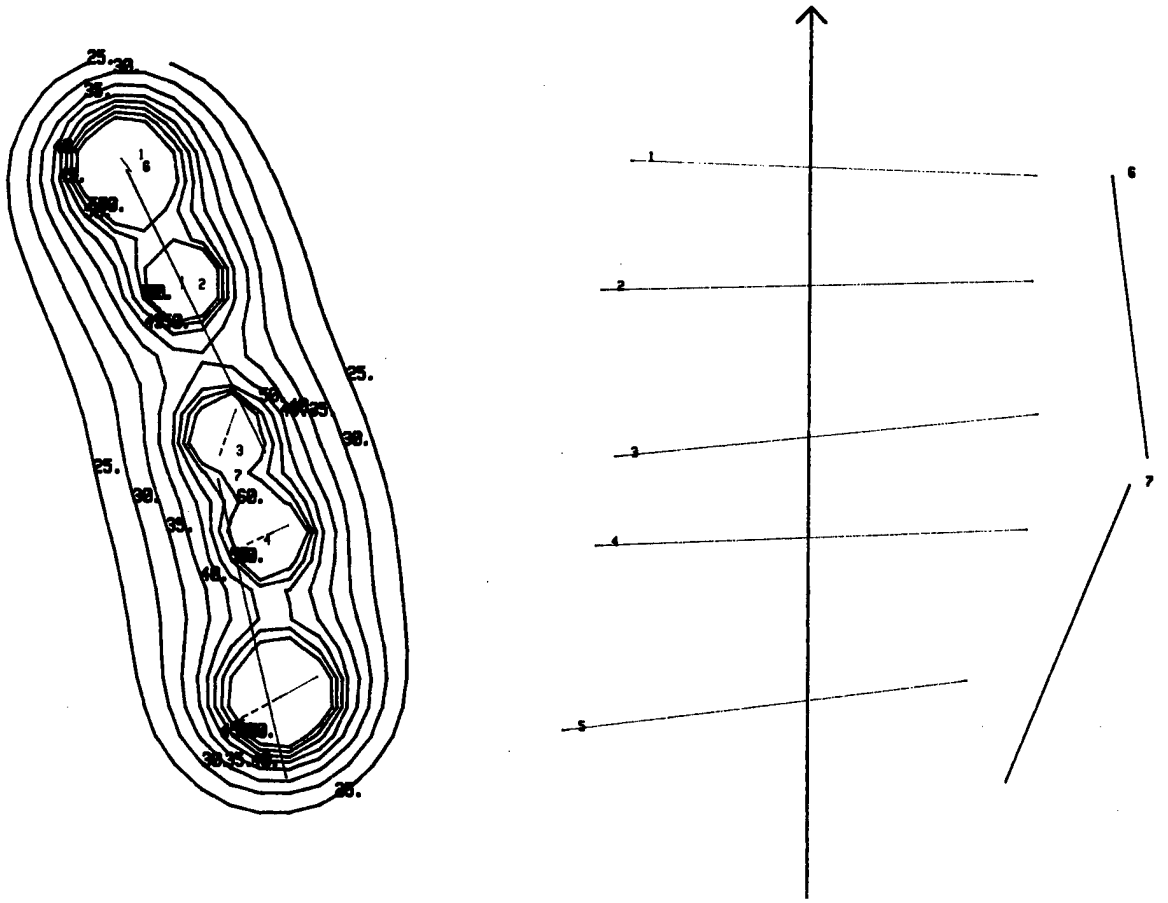


Fig. D.2. Single plane implant: Manchester system. Isodose plot in the central plane of the implant: the isodose lines correspond to doses of 25, 30, 35, 40, 45, 50, 55 and 60 cGy.h^{-1}, respectively. The sketch on the right of the figure is a projection of the implant, the thick line represents the position of the central plane and the direction of the arrow represents the direction for the determination of the profile shown on Fig. D.3.

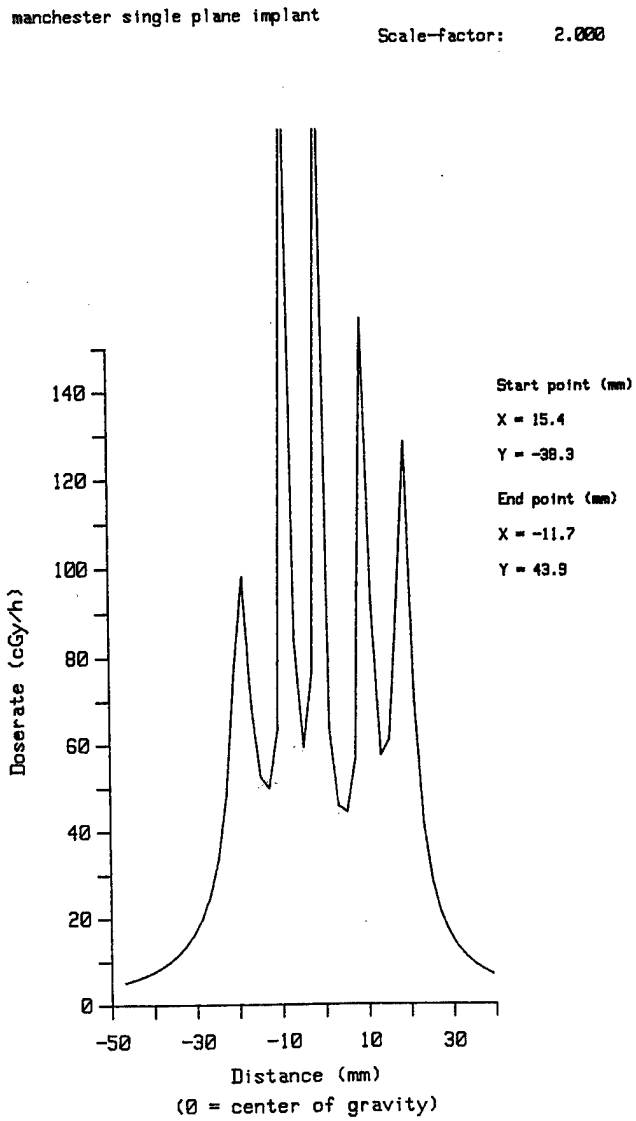


Fig. D.3. Dose profile in a single plane implant. Dose-rate variation along an axis drawn in the central plane approximately in the plane of implant as shown in Fig. D.2. The origin of the co-ordinates is arbitrary. The Mean Central Dose-rate can be calculated from the dose-rate estimated by averaging the four minima on the curve.

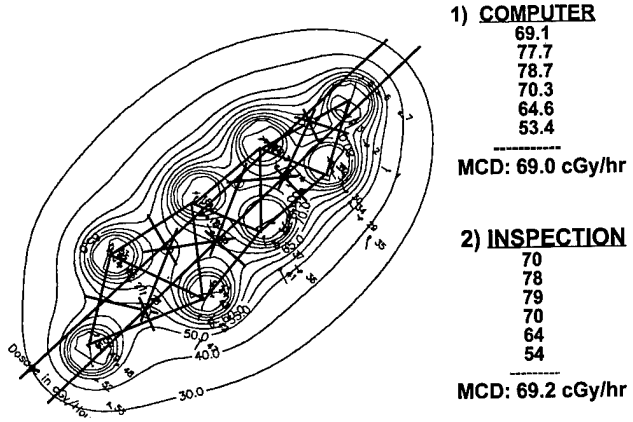


Fig. D.4. Dose distribution in a two-plane breast implant. The implant consists of 69 iridium seeds in 8 source lines (5 with 9 seeds and 3 with 8 seeds) in an approximately parallel, two-plane geometry. The figure illustrates two methods used to derive the Mean Central Dose: either by calculation with the computer planning system of the individual minimum doses in 6 triangles (i.e., the doses on the intersections on the perpendicular bisectors in each triangle) or by inspection of the plotted dose distribution in the central plane. The Mean Central Dose-rates relative to the two methods are 69.0 and 69.2 cGy.h^{-1}, respectively.

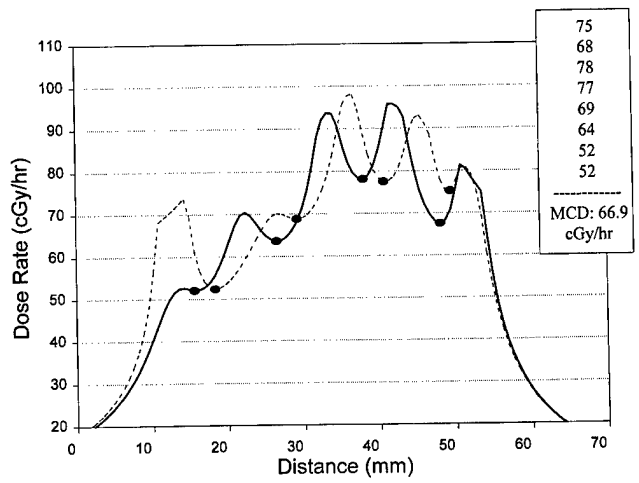


Fig. D.5. Dose profile in a two-plane breast implant. Dose profiles calculated along two axes in the two-plane breast implant shown in Fig. D.4. The two axes pass approximately through the centres of the triangles. The Mean Central Dose-rate, calculated as the arithmetic mean of the 8 minima (4 on each profile) is 66.9 cGy.h^{-1}.

reference air kerma rate of each seed is 1.6 μGy h^{-1} at 1m.

The Total Reference Air Kerma Rate of the implant is 69 × 1.6 = 110 μGy/h at 1m.

D.2.3 Time Pattern

Continuous irradiation.
Application time 50h.

D.2.4 Total Reference Air Kerma

The application time is 50 h. The Total Reference Air Kerma is therefore:

50 × 110 = 5500 μGy (or 0.55 cGy) at 1 m.

D.2.5 Doses

In Figures D.4 and D.5 the three different methods to derive the Mean Central Dose (MCD) are illustrated: a calculation with the computer planning system of the individual minimum doses in 6 triangles (*i.e.*, the doses on the intersections on the perpendicular bisectors in each triangle) gives an average dose rate of 69.0 cGy/h. The method using estimates from the plotted dose distribution in the central plane results in an average dose rate of 69.2 cGy/h, while the average of the local minima in the dose profiles, Figure D.5, yields 66.9 cGy/h.

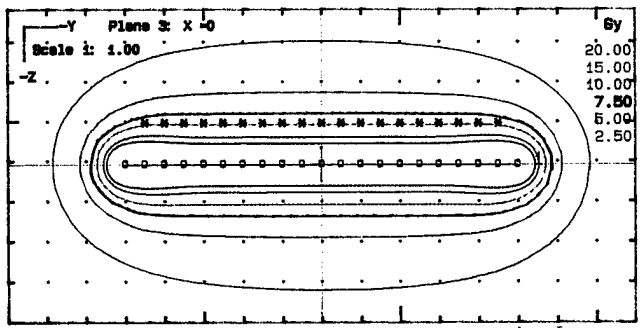


Fig. D.6. Bronchus treatment: moving source. Iridium-192 source, active size = 0.6 mm × 3.5 mm. Step wise movement, step size = 5 mm. Effective length of source = 105 mm. Method of dose optimisation = full dose point optimisation to give 10 Gy at points 1 cm from dwell positions (excluding first and last positions). The position of the points is shown by crosses on the diagram.

The isodose line chosen as reference to prescribe the dose is 50 cGy/h and the prescribed dose is equal to 50 (cGy/h) × 50 (h) = 25 Gy. The minimum target dose is, in this case, identical to the prescribed dose (25 Gy). From the application time of 50 h, the mean central dose can be calculated to be 50 (h) × 0.69 (Gy/h) = 34.5 Gy.

D.2.6 Uniformity Parameters

The spread in the 6 individual minimum doses calculated from the isodose distribution is from −23% to + 13% relative to the mean central dose. The ratio of the minimum target dose to the mean central dose is (25/34.5) × 100% = 72.5%.

D.2.7 Dose Rate

The dose-rate at the level of the surface of prescription is 50 cGy/h.

D.3 Bronchus Treatment: Moving Source

D.3.1 Volumes

The clinical target volume is a cylindrical volume 22 mm in diameter and 100 mm in length.

D.3.2 Sources and Technique

Iridium-192 source, active size = 0.6 mm × 3.5 mm.

Step wise movement, step size = 5 mm.

Effective length of source = 105 mm. Bronchus catheter 1.9 mm diameter. 1 catheter.

Reference air kerma rate = 4×10^{-2} Gy.h^{-1} (4 cGy.h^{-1}) at 1 m.

D.3.3 Time Pattern

Irradiation time per step from 14 sec. to 24.1 sec.

Total irradiation time 337.8 sec.

Total treatment time approximately 6 min.

D.3.4 Total Reference Air Kerma

Total Reference Air kerma = 3.753×10^{-3} Gy (0.375 cGy) at 1m.

D.3.5 Doses

Prescribed dose = 10 Gy.

Dose at 1 cm = 10 Gy.

Method of dose optimisation = full dose point optimisation to give 10 Gy at points 1 cm from dwell positions (excluding first and last positions). See Fig. D.6.

D.3.6 Dose Rate

Average overall treatment dose-rate at 1 cm = 1.67 Gy.min^{-1}.

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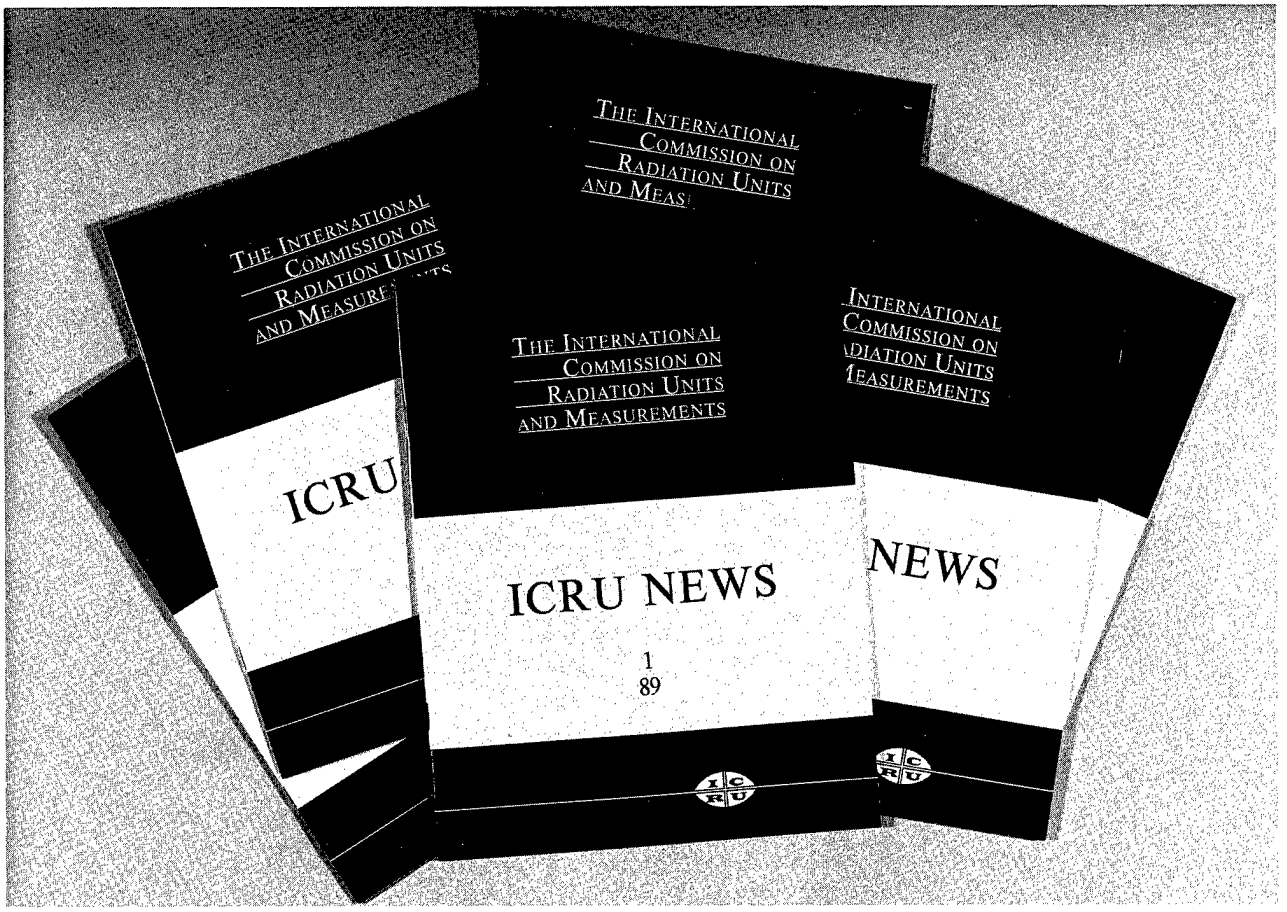

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