Chapter 13: Brachytherapy: Physical and Clinical Aspects

Set of 163 slides based on the chapter authored by
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of the IAEA publication:
Radiation Oncology Physics:
A Handbook for Teachers and Students

Objective:

To familiarize the student with the basic physical and clinical principles of brachytherapy.

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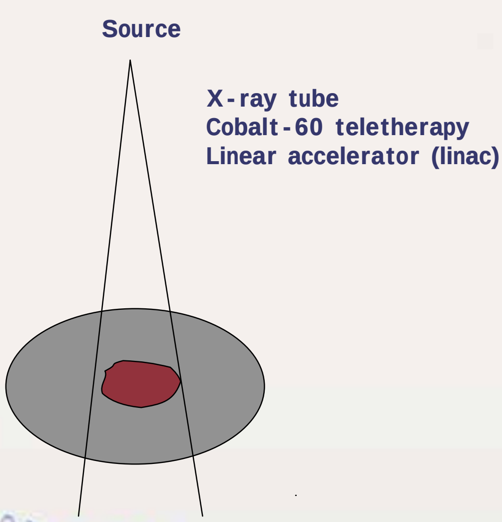
CHAPTER 13. TABLE OF CONTENTS

13.1 INTRODUCTION

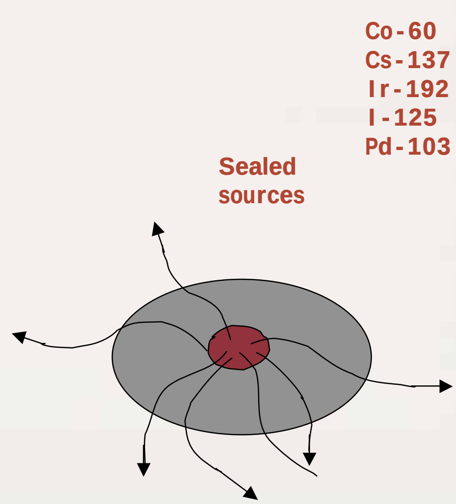
- Brachytherapy (also referred to as Curietherapy) is defined as a short-distance treatment of malignant disease with radiation emanating from small sealed (encapsulated) sources.
- The sources are placed directly into the treatment volume or near the treatment volume.

13.1 INTRODUCTION

External beam radiotherapy
(*external source of radiation*)



Brachytherapy
(*internal source of radiation*)



Brachytherapy compared to external beam therapy:

- Advantages of brachytherapy
  - Improved localized dose delivery to the target
  - Sharp dose fall-off outside the target volume
  - Better conformal therapy
- Disadvantages of brachytherapy
  - Only good for well localized tumors
  - Only good for small lesions
  - Very labor intensive

- Brachytherapy treatment outcome is affected by:
  - The particular model used for source distribution in the target volume.
  - The algorithm used for calculation of dose distribution.
  - The methods used for the determination of the source strength.
  - The dose rate and prescribed dose used in treatment.

13.1 INTRODUCTION

Brachytherapy sources:

- Photon sources

  Emit gamma rays through gamma decay and possibly characteristic x rays through electron capture and internal conversion

  (examples: Co-60, Cs-137, Ir-192, I-125, Pd-103)

- Beta sources

  Emit electrons following beta source decay

  (example: Sr-90/Y-90)

- Neutron sources

  Emit neutrons following spontaneous nuclear fission

  (example: Cf-252)

13.1 INTRODUCTION

The important aspects of any brachytherapy treatment are:

- Use of a suitable dosimetric model for the treatment time and dose distribution calculation.
- Use of calibrated sources with the calibration traceable to a standards laboratory.
- Accurate positioning of sources to prevent geographical misses.

13.1 INTRODUCTION

Types of brachytherapy implants:

- Intracavitary: Sources are placed into a body cavity.
- Interstitial: Sources are implanted into the tumor volume.
- Surface plaque: Sources are loaded into a plaque which is brought into contact with a skin surface lesion.
- Intraluminal: Sources are inserted into a lumen.
- Intraoperative: Sources are brought surgically into or near the tumor. volume.
- Intravascular: Sources are brought intravascularly into a lesion or near a lesion.

13.1 INTRODUCTION

Brachytherapy classification with respect to treatment duration:

- Temporary implant
  - Dose is delivered over a period of time that is short in comparison with the half-life of the sources.
  - Sources are removed when the prescribed dose has been reached.
- Permanent implant
  - Dose is delivered over the lifetime of the sources.
  - The sources undergo complete radioactive decay.

13.1 INTRODUCTION

Brachytherapy classification with respect to source loading:

- Hot loading

  The applicator is pre-loaded and contains radioactive sources at time of placement into the patient.

- Afterloading

  The applicator is placed first into the patient and the radioactive sources are loaded later
  - either by hand (manual afterloading)
  - or by machine (automatic remote afterloading)

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13.1 INTRODUCTION

Manual afterloading

- Generally, the radiation sources are manually afterloaded into applicators or catheters that have been placed within the target volume. At the end of treatment the sources are removed, again manually.

- The manual loading and removal of sources from the applicators or catheters result in some radiation exposure to the medical and support staff.

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13.1 INTRODUCTION

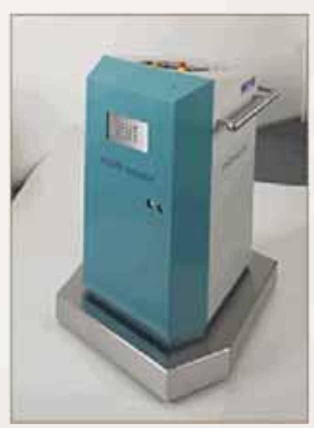
Remote afterloading

- To minimize radiation exposure to medical and support staff several computer driven remote afterloading systems have been developed.
- The use of remote afterloading machines offers several practical advantages over manual procedures, such as:
  - Increased patient treatment capacity.
  - Consistent and reproducible treatment delivery.
  - Reduced radiation exposure to staff.

13.1 INTRODUCTION

Remote afterloading

1970-	1990-	2000-
Cobalt RALSTON	Ir-192 RALS	Cobalt RALS
Diameter 3 mm	Diameter 1.1 mm	Diameter 1.1 mm



13.1 INTRODUCTION

Brachytherapy classification with respect to dose rate:

- Low dose rate (LDR) (0.4 - 2 Gy/h)
- Medium dose rate (MDR) (2 - 12 Gy/h)
- High dose rate (HDR) (> 12 Gy/h)

13.1 INTRODUCTION

Brachytherapy classification with respect to dose rate:

- In addition to LDR, MDR, and HDR brachytherapy techniques, another type of afterloading brachytherapy has been developed in which a continuous low dose rate (LDR) treatment is simulated by a series of short duration “dose pulses” of the order of 30 minutes separated by intervals of 1 to several hours of no dose given.
- The technique is referred to as pulsed dose rate (PDR) brachytherapy.

Brachytherapy sources are usually encapsulated and the capsule serves multiple purposes:

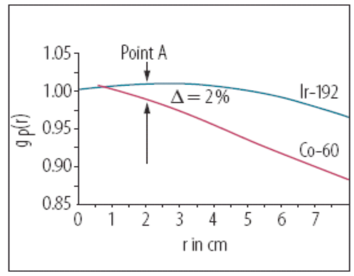
- Contains the radioactivity
- Provides source rigidity
- Absorbs alpha and beta radiation produced through source decay

13.2 PHOTON SOURCE CHARACTERISTICS
13.2.1 Practical considerations

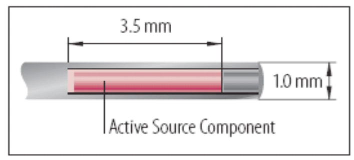
The useful radiation produced in brachytherapy sources:

- Gamma rays resulting from gamma decay.
- Characteristic x rays resulting from electron capture.
- Characteristic x rays resulting from internal conversion.
- Characteristic x rays and bremsstrahlung originating in the source capsule.

- Dosimetric characteristics of brachytherapy sources:
  - Photon energy
  - Half-life
  - Half-value layer in shielding materials
  - Specific activity
  - Source strength
  - Inverse-square dose fall-off



Radial Dose Rate Function



Miniaturised Co-60 Source

- Photon energy of the brachytherapy source influences:
  - Penetration into tissue
  - Radiation protection requirements
- Dose distributions in tissue are not influenced much by photon scattering for photon energies above 300 keV because the attenuation in tissue is compensated for by scatter build up of dose.
- Tissue attenuation is very significant for low photon energies of the order of 30 keV and below.

- Over a dozen radioactive nuclides have a history of use as sealed sources in brachytherapy.
- The common contemporary sources are:
  cobalt-60, cesium-137, iridium-192, iodine-125 and paladium-103
- Less common sources are:
  gold-198, ruthenium-106 and californium-252
- The use of radium-226 and radon-222 was discontinued because of safety concerns.

Characteristics of common radionuclides used in brachytherapy

Nuclide	Average photon energy (MeV)	Half-life	HVL in lead (mm)	Γ_{AKR} $\left(\frac{\mu Gy \cdot m^2}{GBq \cdot h}\right)$	Λ $\left(\frac{cGy \cdot h^{-1}}{cGy \cdot cm^2 \cdot h^{-1}}\right)$
Co-60	1.25	5.26 y	11	309	1.11
Cs-137	0.66	30 y	6.5	77.3	1.11
Au-198	0.41	2.7 d	2.5	56.2	1.13
Ir-192	0.38	73.8 d	3.0	108	1.12
I-125	0.028	60 d	0.02	-	-
Pd-103	0.021	17 d	0.01	-	-

- Brachytherapy photon sources are available in various forms, such as:
  - Needles (cesium-137)
  - Tubes (cesium-137)
  - Pellets (cobalt-60 and cesium-137)
  - Seeds (iodine-125, paladium-103, iridium-192, gold-198)
  - Wires (iridium-192)

13.2 PHOTON SOURCE CHARACTERISTICS
13.2.3 Mechanical characteristics of brachytherapy sources

- The sources are used as sealed sources, usually doubly encapsulated in order to:
  - Provide adequate shielding against alpha and beta radiation emitted from the source.
  - Contain radioactive material.
  - Prevent leakage of the radioactive material.
  - Provide rigidity of the source.

- Specification of gamma ray sources:
  - (1) Reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$
  - (2) Air kerma strength S_K
  - (3) Exposure rate in air $\dot{X}_P$
  - (4) Air kerma rate in air $(\dot{K}_{air}(d))_{air}$

- Specification of gamma ray sources:
  - (1) Reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$,
    defined by the ICRU (reports No. 38 and 58) as the air kerma rate in air at a reference distance d_{ref} of 1 m, corrected for air attenuation and scattering (unit: $1\ \mu$Gy/h).

    The SI unit of the reference air kerma rate is Gy/s, but for the purposes of source specification it is more convenient to use μGy/h for LDR sources and μGy/s for HDR sources.

- Specification of gamma ray sources (cont.):

(2) Air kerma strength S_K, defined by the AAPM as

$$S_K = (\dot{K}_{air}(d_{ref}))_{air} \times d_{ref}^2$$

The unit of air kerma strength is $\mu Gy \cdot m^2 \cdot h^{-1}$.

AAPM TG 43 recommends a shorthand notation with U

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

- Specification of gamma ray sources (cont.):

(3) Exposure rate in air $\dot{X}_P$ at point P in air at a distance d from the source:

$$\dot{X}_P = \frac{A\,\Gamma_X}{d^2}$$

where

A is the source activity in Ci
Γ_X is the exposure rate constant in $R \cdot m^2 \cdot Ci^{-1} \cdot h^{-1}$
d is the distance from the source in m

- Specification of gamma ray sources (*cont*.)

  (4) Air kerma rate in air $(\dot{K}_{air}(d))_{air}$ at point P in air at a distance d from the source:

$$(\dot{K}_{air}(d))_{air} = \frac{A_{app}\Gamma_{AKR}}{d^2}$$

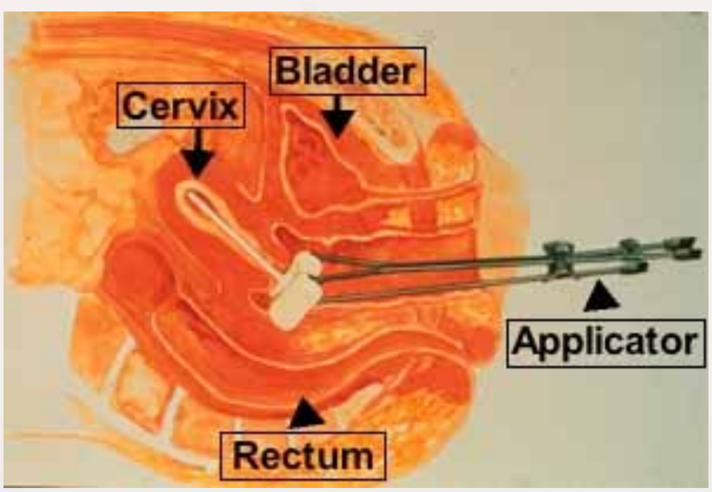
where

A_{app} is the apparent activity of the source in Bq
Γ_{AKR} is the air kerma rate constant given in $(\mu\mathrm{Gy}\cdot\mathrm{m}^2)/(\mathrm{GBq}\cdot\mathrm{h})$
d is the distance from the source in m

- Specification of beta ray sources:
  - The recommended quantity for the specification of beta ray sources is the reference absorbed dose rate in water at a reference distance from the source.
  - The reference distance differs from one type of source to another and is generally between 0.5 mm and 2 mm from the source.

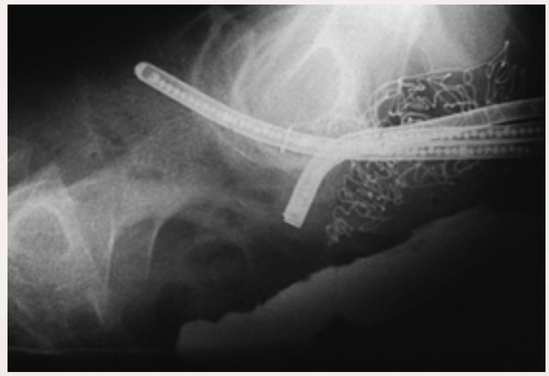
- Intracavitary brachytherapy is mainly used for treatment of the cancer of the cervix, uterine body and vagina.
- Various applicators are in use to hold sources in an appropriate configuration in the tumor volume.
- A cervical applicator consists of a central tube (tandem) and lateral capsules (ovoids or colpostats).

- Female anatomy and placement of an applicator (tandem and two ovoids) for treatment of the cancer of the cervix with remote afterloading machine.



13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

- AP and lateral radiographs of cervix treatment with an applicator (tandem and two ovoids) loaded with a train of "dummy cobalt-60 pellets". The source train for treatment is composed of active (0.5 Ci) and dummy pellets to produce a train of 20 pellets for each of the three channels.



13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

Types of sources:

- The most widely used source for treatment of gynaecological cancers is cesium-137. It is often necessary to use sources of differing strengths in order to achieve the desired dose distribution.

- In modern remote afterloading machines iridium-192 is the commonly used radionuclide.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

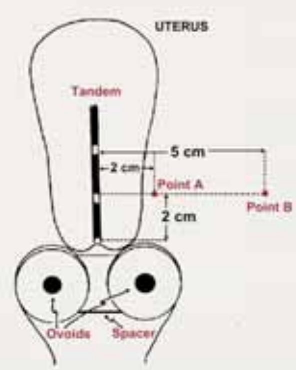
Cancer of the uterus was first treated with radium in 1908. Since then many systems have been designed for dose delivery and specification.

The two most commonly used systems for dose specification in treatment of the cervix are:

- The Manchester system
- The ICRU system

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

- The Manchester system is characterized by doses to four points: point A, point B, bladder point, and rectum point.
- The duration of the irradiation is based on the dose rate at point A, which is located 2 cm superior to the cervical orifice (os) and 2 cm lateral to the cervical canal.
- Point B is defined 3 cm laterally to point A when the central canal is not displaced.



13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

- Since point A relates to the position of the sources rather than to a specific anatomic structure, it may lie inside the tumour or outside the tumour.
- If the tandem displaces the central canal, point A moves with the canal, but point B remains fixed at 5 cm from the midline.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

- The gyneacological dosimetry system recommended by the ICRU (Report 38) relates the dose distribution to the target volume rather than to a specific point.
- The report identifies a dose level of 60 Gy as the appropriate reference dose level for LDR treatments. This results in a requirement to specify the dimensions of the pear-shaped 60 Gy isodose reference volume.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

Gyneacological intracavitary applicators

- Vaginal applicators are used to irradiate tumours that extend downward form the cervix along the vaginal vault.
- The most commonly used applicator in the treatment of cervical cancer is the Fletcher-Suit-Delcos system consisting of a tandem and ovoids. The dose distribution delivered by this rigid applicator system can be optimized by a careful selection and placement of the sources in the tandem and colpostats.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.1 Gynaecology

CT/MR
COMPATIBLE

Rectal and bladder dose monitoring

- The most frequent clinical complication of intracavitary gyneacological radiation treatments result from a high dose delivered to the portions of the rectum and bladder.
- Applicators should be placed so as to keep the dose to these critical structures as low as possible. Often surgical gauze is used to displace the sensitive structures away from the applicator.

Rectal and bladder dose monitoring

- Direct measurement of rectal and bladder dose has been attempted using miniature ionization chambers, scintillation detectors, and MOSFET dosimeters. Measured data give large variability and correlate poorly with calculated values.
- In order to keep the dose to critical structures (rectum and bladder) as low as possible often surgical gauze is used to displace the sensitive structures away from the applicators.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.2. Interstitial brachytherapy

- In interstitial brachytherapy radioactive sources are inserted directly into diseased tissue.
- With regard to treatment time there are two types of interstitial implants:
  - Temporary
  - Permanent
- With regard to source loading there are three types of interstitial implants:
  - Direct loading
  - Manual afterloading
  - Remote afterloading

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.2. Interstitial brachytherapy

- The sources used in direct insertion are fabricated in the form of needles, wires, or seeds.
- The interstitial afterloading techniques consists of two steps:
  - The first step consists of inserting unloaded, stainless-steel needles (1-2 cm apart) into the tumour.
  - The second step consists of afterloading the unloaded needles with radioactive seeds or connecting the needles to an afterloading machine for remotely-controlled source insertion.

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13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.2. Interstitial brachytherapy

Patient treated for carcinoma of the tongue with a HDR remote control afterloading machine.

The HDR afterloading machine uses an iridium-192 source and 18 catheters.

The typical initial source activity is 3.7×10^{10} GBq (10 Ci).

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.2. Interstitial brachytherapy

Patient treated for carcinoma of the lip with a HDR remote control afterloading machine.

The HDR afterloading machine uses an iridium-192 source and 18 catheters.

The typical initial source activity is 3.7×10^{10} GBq (10 Ci).

- Various pre-planning dosimetry systems have been developed for clinical use, all based on tables of total dose delivered as a function of area or volume to be treated.

- The most commonly used systems are:
  - Patterson-Parker (Manchester) system
  - Quimby (Memorial) system
  - Paris system

Patterson-Parker (Manchester) system

- The aim of this system is to deliver a uniform dose (within $\pm 10\%$ of the prescribed dose) throughout the target volume.

- The sources are distributed non-uniformly, following certain rules, with more source strength concentrated in the periphery of the target volume.

- The Patterson-Parker tables give cumulative source strength required to deliver 900 cGy, using current factors and units, as a function of:
  - Area for planar implants
  - Volume for volume implants
- If the sources are close to the patient surface one can determine the size of the implant directly. If not, the size is determined radiographically.

The Patterson-Parker tables

- Single plane: The source arrangement treats a 1 cm thick slab of tissue. The prescribed dose is on a parallel plane 0.5 cm away from the source plane.
- Double plane is used to treat slabs of tissue with thickness between 1 cm and 2.5 cm. The required total source strength is equally divided between the two planes.

Quimby (Memorial) system

- The Quimby system is based on uniform distribution of source strength, accepting a non-uniform delivery of dose in the target volume, with the dose in the target centre exceeding the dose on the periphery.
- The dose value obtained from the Quimby tables represents the minimum dose within the target volume.

Paris system

- The Paris system is used for single and double plane implants.
- The general rules for the Paris system are as follows:
  - Sources must be linear and their placement must be parallel.
  - Centres of all sources must be located in the same (central) plane.
  - Linear source strength (activity) must be uniform and identical for all sources in the implant.
  - Adjacent sources must be equidistant from one another.

- Remote afterloading machines are used in both interstitial and intracavitary clinical applications.
- There are three distinct types of remote afterloading device:
    - LDR (low dose rate)
    - HDR (high dose rate)
    - PDR (pulsed dose rate).

- The essential components of remote afterloading machines:
    - A safe to house the radioactive source
    - Radioactive sources (single or multiple)
    - Remote operating console
    - Source control and drive mechanism
    - Source transfer guide tubes and treatment applicators
    - Treatment planning computer

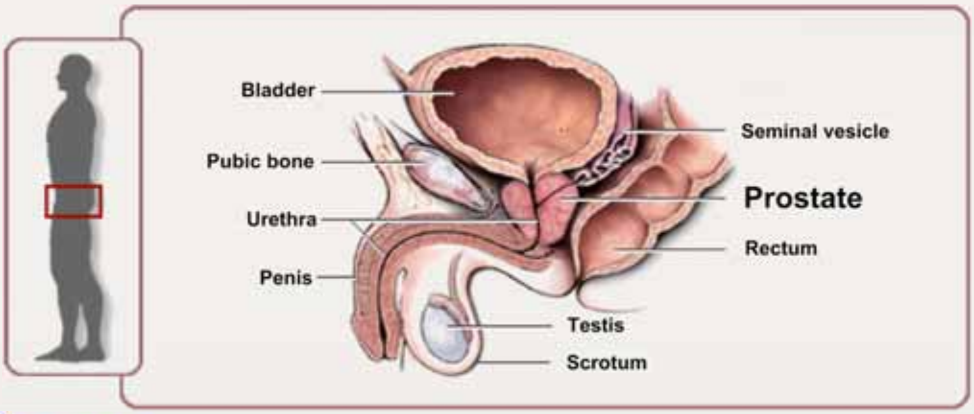
- The three common radionuclide sources used in remote afterloading machines are: Co-60; Cs-137; Ir-192.
- Ir-192 is most widely used because of its medium gamma ray energy(~ 400 keV)and its high specific activity. Its disadvantage is its relatively short half-life (73.8 d).
- LDR and HDR remote afterloading systems are used for intracavitary, interstitial and intraluminal treatments.

- The advantages of HDR machines are:
  - Optimization of dose distribution
  - Treatment on outpatient basis
  - Elimination of staff radiation exposure
- The disadvantages of HDR systems are:
  - Uncertainty in biological effectiveness
  - Potential for accidental high exposures
  - Potential for serious errors
  - Increased staff commitment

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.4 Permanent prostate implants

- Brachytherapy is one of the treatment modalities for early stage prostate cancer in which the disease is confined to the prostate gland.
- The male pelvic anatomy:



13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.4 Permanent prostate implants

- The common modalities for treatment of prostate cancer are:
  - Surgery
  - External beam radiotherapy
  - Brachytherapy

- Brachytherapy is applied in prostate treatment:
  - As primary treatment using permanent implantation of short lived radionuclide sources (such as I-125 or Pd-103) emitting low energy photons ($\leq$ 30 keV) .
  - As a boost to external beam treatments delivered in the form of fractionated or single session treatment using an HDR machine.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.4 Permanent prostate implants

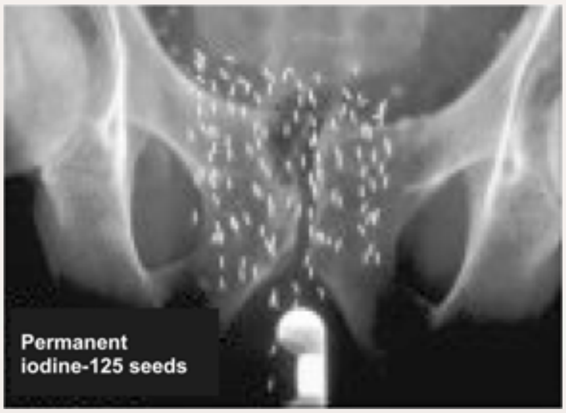
- Brachytherapy applied as primary treatment using permanent implantation of short lived radionuclide sources (such as I-125 or Pd-103) emitting low energy photons.
- Prostate brachytherapy is reserved for treatment of early stage cancer that has not spread outside the prostate gland.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS
13.3.4 Permanent prostate implants

- Brachytherapy applied as a boost to external beam treatments delivered in the form of fractionated or single session treatment using an HDR machine.

Brachytherapy in prostate cancer treatment

- Primary treatment with iodine-125 seeds



- Boost treatment with HDR remote afterloader

Choice of radionuclide for prostate implant

- Introduction of low photon energy emitters iodine-125 and palladium-103 has renewed interest in permanent prostate implants.
- Palladium-103, which has a shorter half-life (17 d) than iodine-125 (60 d) delivers a higher initial dose rate and is thus useful in treating fast growing high grade tumours.

Seed implantation technique

There are two surgical approaches to performing implantation of the prostate with radioactive seeds:

- Retropubic (open)
- Transperineal (closed)

The transperineal approach with ultrasound guidance has become the technique of choice, in part because it is carried out as an outpatient one day procedure.

Selection of patients for treatment with seed implants is based on three parameters used to characterize prostate tumours:

- Stage refers to size of tumour and its extension beyond the prostate capsule. T1a is the smallest; T4 the largest tumour.
- Grade is characterized by the Gleason score. Score 2 represents the most well behaved tumour; score 10 the most aggressive tumour.
- PSA (prostate specific antigen) level represents the quantity of cancer cells present and is usually placed into one of four groups: 0 - 4; 4 - 10; 10 - 20; and greater than 20.

Pre-planning, seed placement and dose distributions

- Pre-planning of the implant is based on either ultrasound or CT cross-sectional (transverse, axial) images.
- The intended treatment volume generally is the whole prostate gland with a small margin of periprostatic tissue. The seeds are placed and spaced so as to minimize the dose to the urethra to decrease complications.
- The number of seeds and their geometric placement in the target volume is determined through optimized computer dose planning or pre-calculated nomograms.

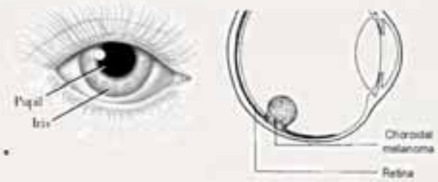
Prescribed dose and post-treatment evaluation

- The recommended total dose to the periphery of the target volume when brachytherapy implant is the sole treatment modality is:
  - 150 - 160 Gy for iodine-125 seed implants
  - 115 - 120 Gy for palladium-103 seed implants
- Post-implant CT imaging:
  - Is usually carried out two to three weeks post-implantation to allow for seed migration and volume reduction resulting from oedema.
  - Dose calculations are performed and compared with pre-implant dose distributions.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.5 Eye plaques

- Intraocular melanoma is the most common primary malignant eye tumour in adults, originating mostly in the choroid (choroidal melanoma).
- Traditional treatment was enucleation (surgical eye removal).



- More recent treatment approaches rely on radiotherapy:
  - External beam radiotherapy with high energy x rays or charged particles.
  - Brachytherapy with temporary implants based on radioactive seeds loaded onto an eye plaque.

13.3 CLINICAL USE AND DOSIMETRY SYSTEMS

13.3.5 Eye plaques

Brachytherapy treatment

- Eye plaque loaded with radio-active seeds is applied externally to the scleral (outer) eye surface over the tumour base.
- Radiation with appropriate dose is intended to eliminate tumour cells without causing anatomical or functional damage to normal ocular tissues.

Brachytherapy treatment with eye plaques

- Most commonly used seeds are iodine-125 seeds with typical activities of the order of 1 mCi.
- The number of seeds per plaque ranges from 7 to 24 for plaque diameters of 12 to 20 mm.
- Typical treatment dose rates are of the order of 1 Gy/h and typical prescription doses are of the order of 100 Gy.

Brachytherapy treatment with eye plaques

- Most commonly used seeds are iodine-125 seeds with typical activities of the order of 1 mCi.
- A less common brachytherapy approach is based on beta emitting sources, such as strontium-90/ittrium-90 and, more recently, ruttenium-106

- Application of radiation (temporary or permanent implant) after treatment of arterial stenosis with angioplasty and stent placement has been proven useful in preventing re-stenosis.
- Restenosis is the formation of scar tissue in an artery within 6 months following angioplasty, occurring in about 40% of angioplasty patients.

- The important characteristics of intravascular treatment are:
  - Type of source: electronic x ray, gamma ray, electron, positron
  - Physical form of radionuclide: wire, seed, pellet, metallic stent
  - Method of radiation delivery:
    - Manual or remote afterloading;
    - Syringe and inflatable balloon;
    - Radioactive stent
  - Radionuclide
    - For use in afterloading: iridium-192; ittrium-90; strontium-90/ittrium-90.
    - For use in inflatable balloon: xenon-133; rhenium-186; rhenium-188
    - For use in radioactive stent: phosphorus-32; vanadium-48

13.4 DOSE SPECIFICATION AND REPORTING

Using standardized and uniform methodology, ICRU reports 38 and 58 recommend the minimum information that must be reported when performing brachytherapy treatments, such as:

- Description of the implant
- Definition of the volume of interest
- Prescription dose
- Delivered dose
- Reference air kerma rate in air in cGy/h at 1 m

13.4 DOSE SPECIFICATION AND REPORTING

13.4.1 Intracavitary treatments

The data recommended in the ICRU report 38 for reporting of gynaecological brachytherapy are:

- Description of technique
- Reference air kerma rate in air in cGy/h at 1 m
- Time/dose pattern
- Description of the reference volume
- Dose at reference points (bladder, rectum, lymphatic trapezoid, pelvic wall)
- Dimensions of the pear shaped 60 Gy isodose reference volume

The data recommended in the ICRU report 58 for reporting of interstitial implant treatments are:

- Description of the clinical target volume
- Sources, technique, and implant time
- Prescription dose
- Reference air kerma rate in air in cGy/h at 1 m
- Description of the dose distribution
- Description of the high and low dose region and dose uniformity indices
- Dose-volume histograms

As far as dose distribution is concerned, four different dose related quantities are to be reported to adequately describe an implant treatment:

- Total reference air kerma
- Mean central dose representing the plateau dose region inside the target volume
- Minimum dose, important for tumour control
- High dose regions exceeding 150% of the mean central dose and low dose regions that are below 90% of the peripheral dose.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

The dose calculations around radioactive sources in brachy-therapy treatments are divided into two categories:

- The AAPM TG 43 formalism is considered the most complete formalism currently available.
- Several historical approaches to dose calculations that may be used for quick checks and verification of treatment plans.
  - Point source calculation based on air kerma in air
  - Linear sources
    - Unfiltered line source in air
    - Filtered line source in air
    - Filtered line source in water

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

- The dose distributions around brachytherapy sources are calculated assuming only photon interactions, and are influenced by:
  - Emitted radiation
  - Surrounding media
- The dose at any point from a single finite source can be considered as a summation of doses from multiple point sources.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

- Point source in free space:
  - When a radioactive point source is in free space, no absorption or scattering effects are present.
  - The air kerma rate in air $(\dot{K}_{air})_{air}$ follows an inverse square law function with radial distance r from the source:

$$(\dot{K}_{air})_{air} \propto \frac{1}{r^2}$$

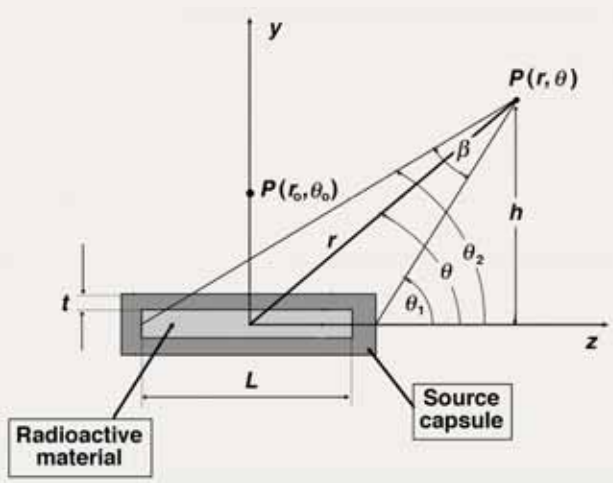
13.5 DOSE DISTRIBUTIONS AROUND SOURCES

- Point source in water or tissue:
  - When the source is placed in water, absorption and scatter of radiation influence the dose rate at any point away from the source surface.
  - Up to a distance of a few centimeters from a point source the dose fall off with distance is essentially governed with inverse square law. This means that effects of beam attenuation and scattering compensate each other.

- In 1995 the AAPM introduced in TG 43 report, a dose calculation formalism to establish the 2-D dose distribution around cylindrically symmetric brachytherapy sources such as palladium-103, iodine-125 and iridium-192.

- The AAPM TG 43 brachytherapy dosimetry protocol introduced new and updated quantities, such as:
  - Air kerma strength
  - Dose rate constant
  - Radial dose function
  - Anisotropy function
  - Anisotropy factor

The dose distribution is described in terms of a polar coordinate system with its origin at the source centre.



r is the distance from the origin to the point of interest P(r,θ)

θ is the angle with respect to the long axis of the source

Point P(r_0,θ_0) is the reference point that lies on the transverse bisector of the source at a distance of 1 cm from the origin ($r_0 = 1$ cm and $\theta_0 = \pi/2$)

The dose rate at point-of-interest $P(r,\theta)$ in water is written as:

$$\dot{D}(r,\theta) = S_K \Lambda \frac{G(r,\theta)}{G(r_0,\theta_0)} g(r) F(r,\theta)$$

- r is the distance (in cm) from the origin to the point-of-interest P
- θ is the angle between direction of radius vector r and the long axis of the source
- θ_0 defines the source transverse plane and is equal to $\pi/2$ radians
- S_K is the air-kerma strength of the source $(\mu\text{Gy} \cdot \text{m}^2 \cdot \text{h}^{-1})$
- Λ is the dose rate constant in water
- $G(r,\theta)$ is the geometry factor
- $g(r)$ is the radial dose function
- $F(r,\theta)$ is the anisotropy function

- The air kerma strength S_K, with units given in $\mu\text{Gy} \cdot \text{m}^2 \cdot \text{h}^{-1}$, is defined in the AAPM TG 43 report as

  $$S_K = (\dot{K}_{air}(d_{ref}))_{air} \times d_{ref}^2$$

  where d_{ref} is the reference distance at which the reference air kerma rate is defined

- A shorthand notation is usually used with U defined as

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

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

- The dose rate constant Λ is defined as the dose rate to water at a distance of 1 cm on the transverse axis (reference point) per unit air kerma strength in water

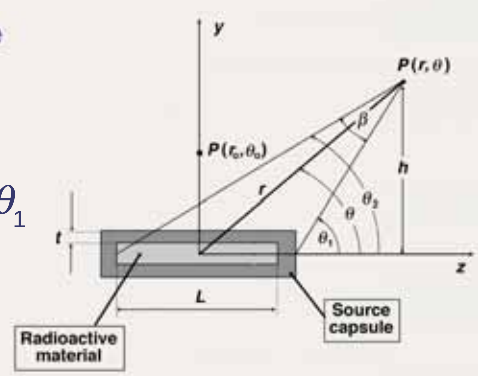
$$\Lambda = \frac{\dot{D}(r_o,\theta_o)}{S_K} \quad \text{with units of} \quad \frac{\text{cGy}\cdot\text{h}^{-1}}{\text{cGy}\cdot\text{cm}^2\cdot\text{h}^{-1}} = \text{cGy}\cdot\text{h}^{-1}\cdot\text{U}^{-1} = \text{cm}^{-2}$$

- The dose rate constant Λ accounts for:
  - effects of source geometry
  - spatial distribution of radioactivity within the source encapsulation
  - self-filtration within the source
  - scattering in water surrounding the source

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

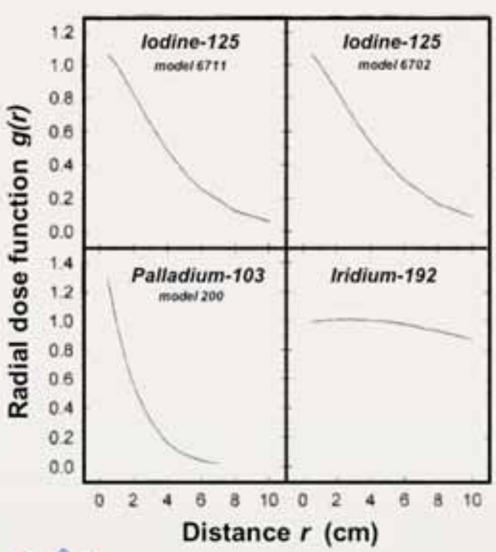
The geometry factor $G(r,\theta)$ accounts for the geometric falloff of the photon fluence with distance r from the source and also depends on the spatial distribution of activity within the source.

- $G(r,\theta)$ reduces to $1/r^2$ **for a point source approximation.**
- $G(r,\theta)$ reduces to $\beta/(Lh)$ for a line source approximation, **where** $\beta = \theta_2 - \theta_1$ **and** $h = r\sin\theta$
- $G(r,\theta)$ reduces to $1/r^2$ for a line source when $r >> L$.



- The radial dose function $g(r)$ accounts for the effects of attenuation and scatter in water on the transverse plane of the source $(\theta = \pi / 2)$, excluding falloff which is included by the geometry function $G(r,\theta)$.
- The radial dose function g(r) may also be influenced by filtration of photons by the encapsulation and source materials.

Radial dose function $g(r)$ for various radionuclide seeds

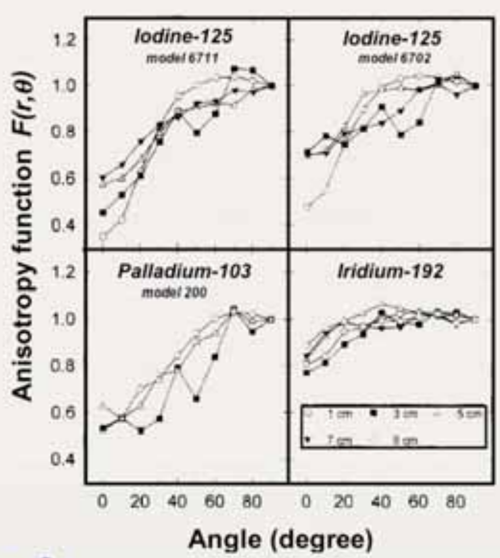


r(cm)	I-125 (6702)	I-125 (6711)	Ir-192
	$g(r)$		
0.5	1.040	1.040	0.994
1	1.000	1.000	1.000
2	0.851	0.831	1.010
3	0.670	0.632	1.020
4	0.510	0.463	1.010
5	0.389	0.344	0.996

From Meli JA, Anderson LL, Weaver KA: *Interstitial Brachytherapy*, Raven, New York 1990

- The anisotropy function $F(r,\theta)$ accounts for the anisotropy of dose distribution around the source, including the effects of absorption and scatter in water.
- $F(r,\theta)$ is defined as unity on the transfer plane.
- $F(r,\theta)$ decreases in directions off the transfer plane
  - As r decreases
  - As θ approaches 0º or 180º
  - As the source encapsulation thickness increases
  - As the photon energy decreases

The anisotropy function $F(r,\theta)$ for various radionuclide seeds



Anisotropy function $F(r,\theta)$
for iodine-125 (model 6702) seeds

r(cm)	0.5	1.0	2.0	5.0
0º	0.45	0.50	0.54	0.63
15º	0.62	0.68	0.70	0.77
30º	0.82	0.87	0.87	0.87
90º	1.00	1.00	1.00	1.00

From Meli JA, Anderson LL, Weaver KA: *Interstitial Brachytherapy*, Raven, New York 1990

- In 2004 the AAPM updated and revised the original TG 43 protocol for calculation of dose rate distributions around photon emitting brachytherapy sources.
- The updated protocol (TG 43U1) includes a revised definition of the air kerma strength S_K which is now defined as the air kerma rate in vacuum $(K_\delta(d))_{vac}$ and is attributed to all photons of energy larger than a cut-off energy δ at a distance d from the source centre.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.1 AAPM TG 43 algorithm

- The distance d can be any distance that is large relative to the maximum dimension of the source and detector.
- The stipulation “*in vacuum*” means that the measurement should be corrected for photon attenuation and scattering in air and the encapsulation material as well as for photon scattering from nearby objects, such as floor, walls and ceiling.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.1 AAPM TG 43 algorithm

- The cut-off energy δ (typically 5 keV) excludes all low energy and contaminating photons that increase without contributing to the dose in tissue at distances exceeding 1 mm.
- The TG 43 protocol represents an accurate method for absorbed dose calculations for general source geometries.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.2 Other calculation methods for point sources

- Calculations based on point source models and air kerma rate in air can be used as convenient methods for checking a treatment plan calculated with the TG 43 protocol.
- With the knowledge of the apparent activity A_{app} and the air kerma rate constant Γ_{AKR}, the air kerma rate in air at a distance d from the point source can be calculated as

$$(\dot{K}_{air}(d))_{air} = \frac{A_{app}\Gamma_{AKR}}{d^2}$$

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.2 Other calculation methods for point sources

- From the knowledge of the air kerma rate in air $(\dot{K}_{air}(d))_{air}$ we calculate the air kerma rate in water $(\dot{K}_{air}(d))_{wat}$ as

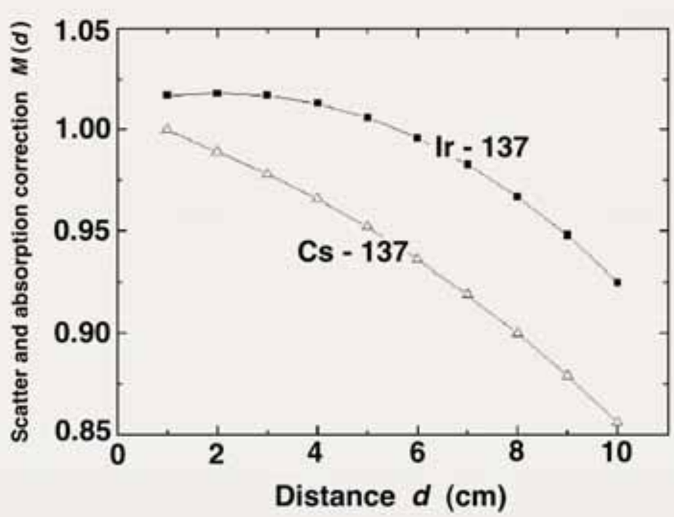
$$(\dot{K}_{air}(d))_{wat} = (\dot{K}_{air}(d))_{air} \times M(d)$$

- For photon emitting sources with energies at or above those of iridium-192 the Meisberger function $M(d)$ which corrects for absorption and scattering in water, is a slowly varying function of the distance d and may be represented quite accurately by a polynomial of third or fourth degree.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.2 Other calculation methods for point sources

Scatter and absorption correction for iridium-192 and cesium-137 against distance from source



The original work by Meisberger assumed that the correction factors are valid at distances between 1 cm and 10 cm. It has been shown that the discrepancy becomes appreciable at distances exceeding 5 cm.

- The water kerma rate in water $(\dot{K}_{wat}(d))_{wat}$ is related to the air kerma rate in water $(\dot{K}_{air}(d))_{wat}$ through the ratio of mass energy transfer coefficients $(\mu_{tr}/\rho)_{air}^{wat}$

$$(\dot{K}_{air}(d))_{wat} = (\dot{K}_{air}(d))_{air} \times (\mu_{tr}/\rho)_{air}^{wat}$$

- For most radionuclides used in brachytherapy with photon energies above 200 keV the ratio $(\mu_{tr}/\rho)_{air}^{wat}$ is essentially constant at 1.11; for iodine-125 and palladium-103 the ratio is 1.01.

- The absorbed dose rate to water $\dot{D}_{wat}(d)$ at a distance d between the point source and the point of interest is calculated from the water kerma rate in water $(\dot{K}_{wat}(d))_{wat}$

$$\dot{D}_{wat}(d) = (\dot{K}_{wat}(d))_{wat} \times (1-\bar{g})$$

- The radiation fraction $\bar{g}$ is generally ignored because of its small magnitude (less than 0.3%) for the radionuclides used in brachytherapy.

- If the source is calibrated in terms of reference air kerma rate in air $(\dot{K}_{air}(d_{ref}))_{air}$, the air kerma rate in air at a distance d is given by

$$(\dot{K}_{air}(d))_{air} = (\dot{K}_{air}(d_{ref}))_{air} \times (d_{ref} / d)^2$$

- The absorbed dose rate to water $\dot{D}_{wat}(d)$ is now given as

$$\dot{D}_{wat}(d) = (\dot{K}_{air}(d_{ref}))_{air} \times M(d) \times (\mu_{tr} / \rho)^{wat}_{air} \times (1 - \bar{g}) \times (d_{ref} / d)^2$$

- The general expression for the dose rate in water is

$$\dot{D}_{wat}(d) = (\dot{K}_{air}(d_{ref}))_{air} \times M(d) \times (\mu_{tr} / \rho)^{wat}_{air} \times (1 - \bar{g}) \times (d_{ref} / d)^2$$

- For an easy and quick check of the dose at a short distance (e.g., 1 cm) from a point source, approximations $\bar{g} \approx 0$ and $M(d) \approx 1$ may be made and the dose rate at 1 cm from the point source is approximated by

$$D_{wat}(d = 1\text{ cm}) \approx (\dot{K}_{air}(d_{ref}))_{air} \times 1.11 \times (1/0.01)^2$$

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear (line) sources

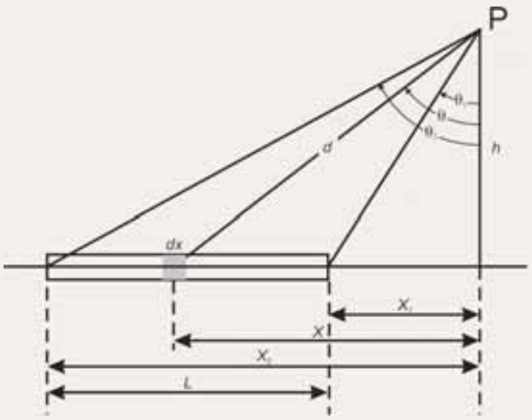
- Dose rate distributions around linear (line) brachytherapy sources can be calculated using the Sievert integral, introduced by Sievert in 1921.
- For purposes of dose distribution calculation, linear sources are assumed to consist of a number of small elementary point sources, each point source contributing to the total dose at the point of interest P.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear (line) sources

- Two possible situations are to be considered:
  - Unfiltered line source
  - Filtered line source
- The dose rate at point of interest P in water is determined from the calculated air kerma rate in air at point P.

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear (line) sources

Air kerma in air for unfiltered line source in air



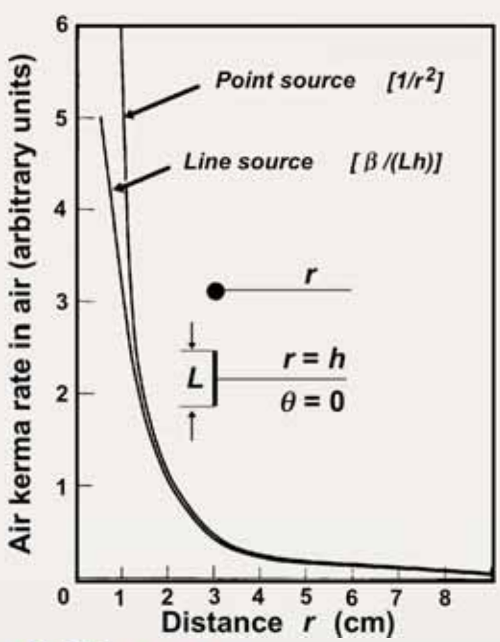
$$d(\dot{K}_{air})_{air} = (A\frac{dx}{L})\frac{\Gamma_{AKR}}{d^2}$$

$$\cos\theta = \frac{h}{d} \qquad \tan\theta = \frac{x}{h}$$

$$dx = \frac{h}{\cos^2\theta}d\theta = \frac{d^2}{h}d\theta$$

$$(\dot{K}_{air})_{air} = \frac{A\Gamma_{AKR}}{L}\int_{x_1}^{x_2}\frac{dx}{d^2} = \frac{A\Gamma_{AKR}}{Lh}\int_{\theta_1}^{\theta_2}d\theta = \frac{A\Gamma_{AKR}}{Lh}(\theta_2-\theta_1) = \frac{A\Gamma_{AKR}\beta}{Lh}$$

13.5 DOSE DISTRIBUTIONS AROUND SOURCES
13.5.3 Linear (line) sources



Air kerma rate in air $(\dot{K}_{air})_{air}$

(1) For point source
$$(\dot{K}_{air})_{air} \propto 1/r^2$$

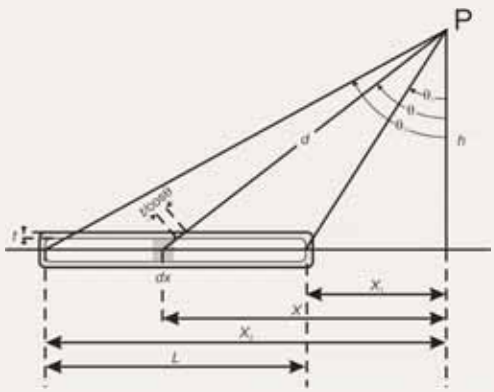
(2) For line source $(\theta = 0;\ r = h)$
$$(\dot{K}_{air})_{air} \propto \beta/(Lh)$$

(3) For line source $(h = r \to \infty)$
$$r \to \infty \Rightarrow \beta \to 0$$
$$\tan\frac{\beta}{2} \approx \frac{\beta}{2} = \frac{L}{2r} \Rightarrow \beta \approx \frac{L}{r}$$
$$(\dot{K}_{air})_{air} \propto \frac{\beta}{Lh} \approx \frac{1}{r^2}$$

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.3 Linear sources

Air kerma in air for filtered line source in air



$$d(\dot{K}_{air})_{air} = (A\frac{dx}{L})\frac{\Gamma_{AKR}}{d^2}e^{-\frac{\mu t}{\cos\theta}}$$

$$\cos\theta = \frac{h}{d} \qquad \tan\theta = \frac{x}{h}$$

$$dx = \frac{h}{\cos^2\theta}d\theta = \frac{d^2}{h}d\theta$$

$$(\dot{K}_{air})_{air} = \frac{A\Gamma_{AKR}}{L}\int_{x_1}^{x_2} e^{-\frac{\mu t}{\cos\theta}}\frac{dx}{d^2} = \frac{A\Gamma_{AKR}}{Lh}\int_{\theta_1}^{\theta_2} e^{-\frac{\mu t}{\cos\theta}}d\theta$$

13.5 DOSE DISTRIBUTIONS AROUND SOURCES

13.5.3 Linear sources

Air kerma in air for filtered line source in air

$$(\dot{K}_{air})_{air} = \frac{A\Gamma_{AKR}}{L}\int_{x_1}^{x_2} e^{-\frac{\mu t}{\cos\theta}}\frac{dx}{d^2} = \frac{A\Gamma_{AKR}}{Lh}\int_{\theta_1}^{\theta_2} e^{-\frac{\mu t}{\cos\theta}}d\theta$$

$$= \frac{A\Gamma_{AKR}}{Lh}\left\{\int_{0}^{\theta_2} e^{-\frac{\mu t}{\cos\theta}}d\theta - \int_{0}^{\theta_1} e^{-\frac{\mu t}{\cos\theta}}d\theta\right\}$$

- t thickness of source capsule wall
- μ attenuation coefficient for photons traversing the capsule

Sievert integral

- The Sievert integral $\int_0^{\theta} e^{-\frac{\mu t}{\cos\theta}} d\theta$ is widely used in computing dose distributions about filtered line sources in brachytherapy.
- The integral is named after Rolf Sievert, a Swedish medical physicist, who developed it in 1921.
- The Sievert integral accounts for photon attenuation in the source capsule of the brachytherapy line source.
- For θ < 0.35 radian (20º) the following approximation holds

$$\int_0^{\theta_2} e^{-\frac{\mu t}{\cos\theta}} d\theta \approx \theta e^{-\mu t}$$

Dose rate in water around filtered line source

$$\dot{D}_{\text{wat}} = \frac{A\Gamma_{\text{AKR}}}{Lh} \left\{ \int_0^{\theta_2} e^{-\frac{\mu t}{\cos\theta}} M(d,\theta) d\theta - \int_0^{\theta_1} e^{-\frac{\mu t}{\cos\theta}} M(d,\theta) d\theta \right\} \left(\frac{\mu_{\text{tr}}}{\rho} \right)_{\text{air}}^{\text{wat}} (1-\bar{g})$$

- $M(d,\theta)$ is the absorption and scatter correction varying over the source length.
- d is the distance between the source segment and the point of interest P.
- $\bar{g}$ is the radiation fraction.

Manual summation of doses

- In the first approximation, each source can be assumed to be a point source if the distance between the dose calculation point (point of interest) and the source centre is at least twice the active length of the source.
  - The total dose at any point is the sum of the doses contributed by each individual source.
  - For most seed sources (active length~ 3 mm) this approximation is within 5% at distances larger than 5 mm.
  - For line sources (active length~ 2 cm) pre-calculated tables should be used for dose estimation close to the implant at distances from 0.5 cm to 5 cm.

13.6 DOSE CALCULATION PROCEDURES
13.6.1 Manual dose calculations

Pre-calculated dose distributions (atlases)

- For some clinical situations, in which the arrangement of sources for the implant follows a standard pattern, such as linear array, tandem and ovoids, vaginal cylinder, pre-calculated dose distributions (atlases) may be used with appropriate scaling of source strength (activity).

Source localization

- The source localization can be established by the use of several radiographic methods:
  - Two orthogonal films
  - Two stereo-shift films
  - Two or three isocentric films
  - Computerized tomography (CT) scanning

Source localization

- It is usually difficult and time consuming to carry out manual matching of sources, especially when large number of seeds or line sources are used.
- Several automatic matching algorithms are now available in most brachytherapy treatment planning systems.

Dose distribution display

- The most common display is a 2-D distribution of dose in a single cross sectional plane that contains or is close to the centres of most sources.
- The dose distribution calculation is carried out for a matrix of points in 3-D. It is then possible to display 2-D distributions in any arbitrary plane.

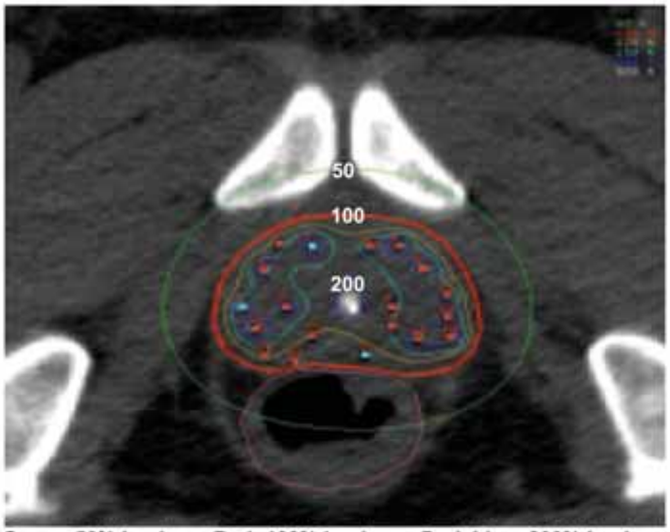
Dose distribution display

- The display usually presents:
  - Isodose rate curves
  - Target of interest
  - Location of the sources
- Three dimensional calculations of dose distributions offer an improved analysis of dose distributions with respect to target volume coverage and the dose delivered to normal tissues.

Dose distribution display (cont.)

- The calculated dose values are used to display isodose surfaces as well as dose-volume histograms.
- Three dimensional displays of dose distributions offer a major advantage in their ability to help visualize dose coverage in 3-D, as seen from any arbitrary orientation.

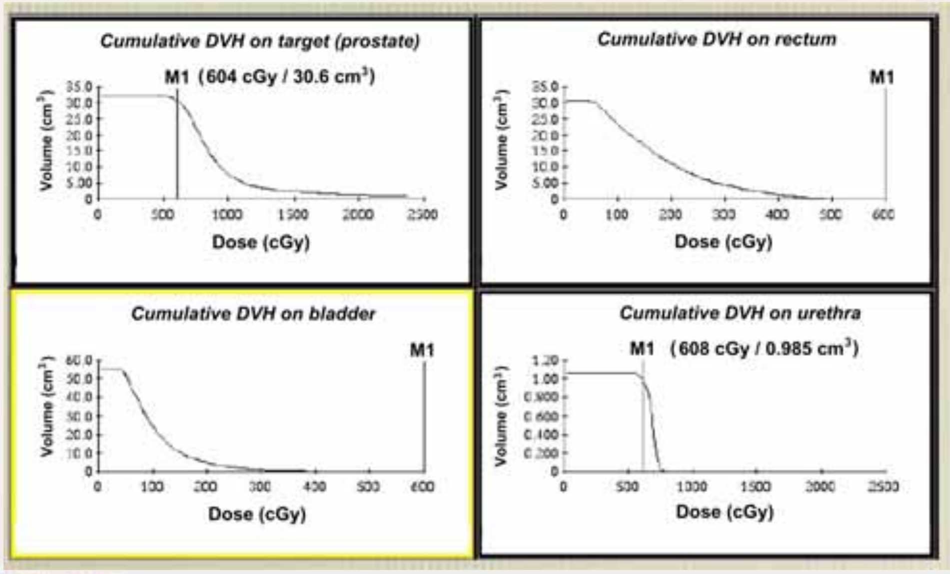
Dose distribution display for typical treatment of the prostate with iodine-125 seeds.



Green: 50% isodose; Red: 100% isodose; Dark blue: 200% isodose

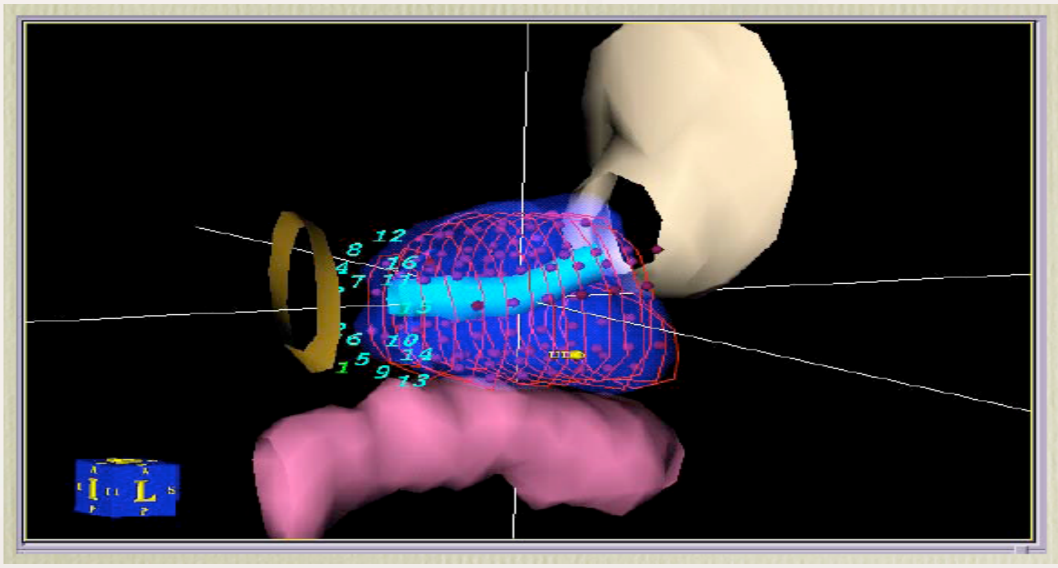
13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

Dose-volume histogram for the prostate and neighbouring sensitive structures (rectum, bladder, and urethra).



13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

Three dimensional organ rendering and position of seeds

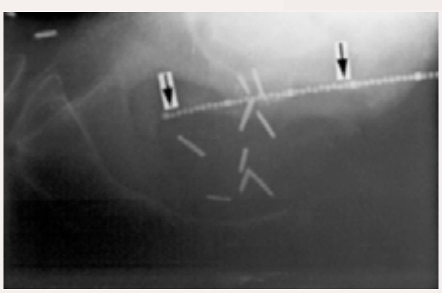


Brachytherapy in treatment of rectal carcinoma

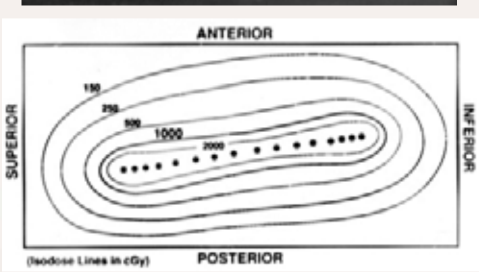
- Brachytherapy is administered with standard tandem applicator (line source) inserted into a tissue equivalent cylinder of appropriate diameter which in turn is inserted into the rectum.

- Consequences of cylinder diameter choice:
  - As the cylinder diameter increases, the dose rate on cylinder surface decreases.
  - As the distance from the line source increases, the dose gradient decreases producing a more uniform dose distribution for tumours of the same thickness.

Brachytherapy in treatment of rectal carcinoma



- Lateral radiograph taken with barium and applicator (loaded with train of “dummy seeds”) in place. Arrows indicate position of proximal and distal active seeds.



- Isodose distribution for a line source composed of 16 active cobalt-60 (0.5 Ci each) pellets. The isodose curves are shown in units of cGy.

Brachytherapy in treatment of rectal carcinoma

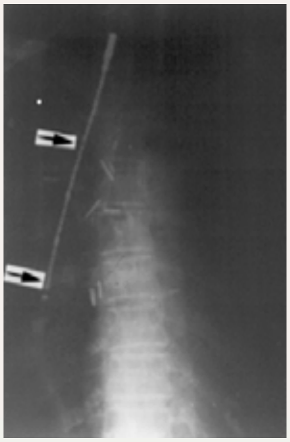
- Typical dose prescription: 5 fractions of 8 - 10 Gy each.
- Prescription depth: 1 - 3 cm from the central axis of the source train.
- Fractionated treatment time: of the order of 30 minutes
- Time for entire fractionated procedure: about 30 minutes.
- Unlike in gyneacological brachytherapy treatments in which the patient is given an epidural unaesthetic, the patients undergoing rectal treatments are awake and mobile.

Brachytherapy in treatment of oesophageal cancer

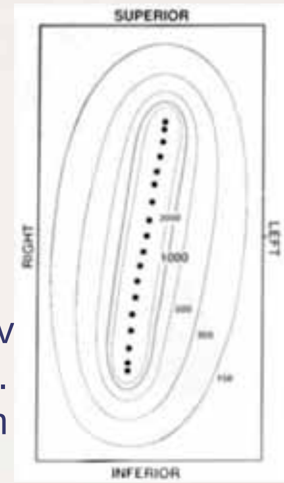
- Brachytherapy is administered with a special applicator made of transparent, semi-rigid plastic with a length of about 60 cm. The applicator is positioned with the help of a gastroscope and the position of active sources is determined using a line of “dummy seeds” and verification radiographs.
- Typical dose prescription: 6 - 10 Gy
- Treatment depth from central axis of line source: 0.8 - 1 cm
- Treatment time: of the order of 2 minutes

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

Brachytherapy in treatment of oesophageal cancer



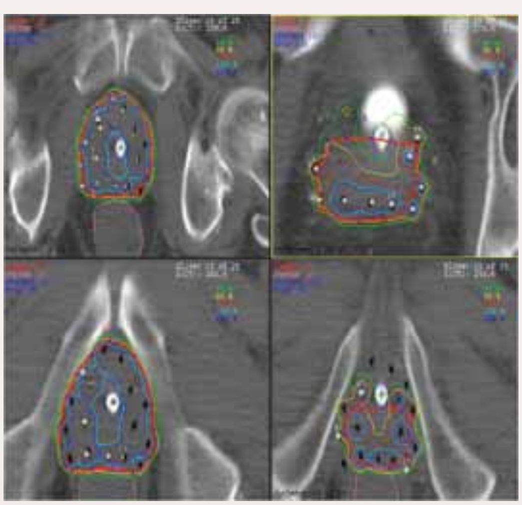
- Typical AP chest radiograph showing the applicator loaded with “dummy seeds”. Arrows indicate positions of proximal and distal active seeds.
- Isodose distribution for a line source configured with 16 activ cobalt-60 pellets (0.5 Ci each). The isodose curves are shown in units of cGy.



IAEA

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

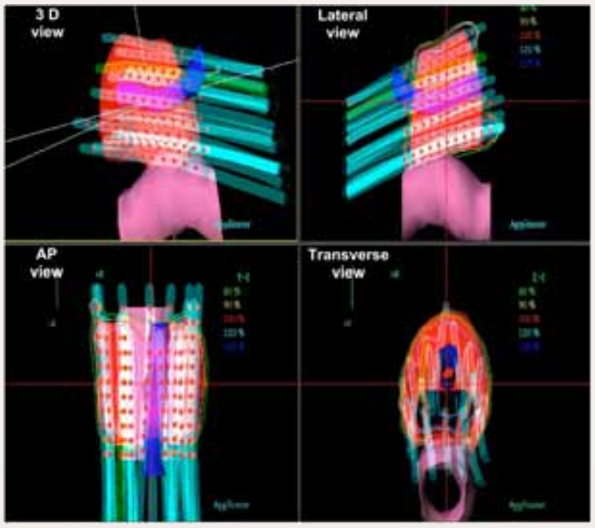
Prostate treatment with HDR brachytherapy boost to external beam therapy. Four transverse CT slices are shown.



- The white dots represent the 17 catheters used in the treatment; the blue dots represent the dose matrix calculation points.
- Isodose contours 80, 90, 100, 120, 125% are shown in green, yellow, red, light blue, dark blue, respectively.
- The target (prostate) is delineated with the heavy red contour; dose of 10 Gy is prescribed to the 100% isodose line.

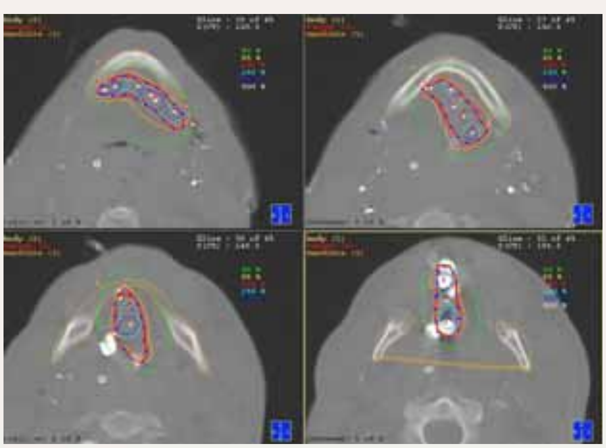
IAEA

Prostate treatment with HDR brachytherapy boost to external beam therapy (cont). Four different projections are shown.



- Catheters are shown green; active source positions red.
- The target (prostate) is delineated in dark red; urethra in blue; rectum in pink.
- An iridium-192 HDR machine is used for treatment. The source activity is 10 Ci (370 GBq) and the treatment time to deliver 10 Gy to the 100% isodose surface is of the order of 10 minutes.

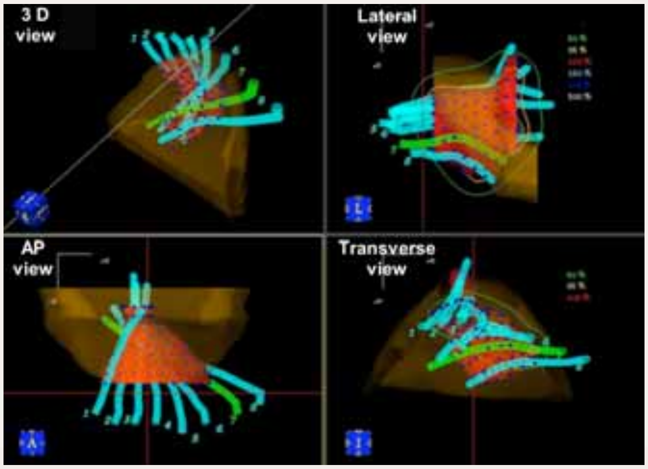
A tumour of the tongue treated with HDR brachytherapy. Four transverse CT slices are shown.



- The white dots represent the 8 catheters (channels) used in the treatment.
- Isodose contours 50%, 95%, 100%, 150%, 200%, and 500% (white) are shown.
- The target volume is delineated with heavy red contour; mandible is a critical structure delineated in yellow.

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

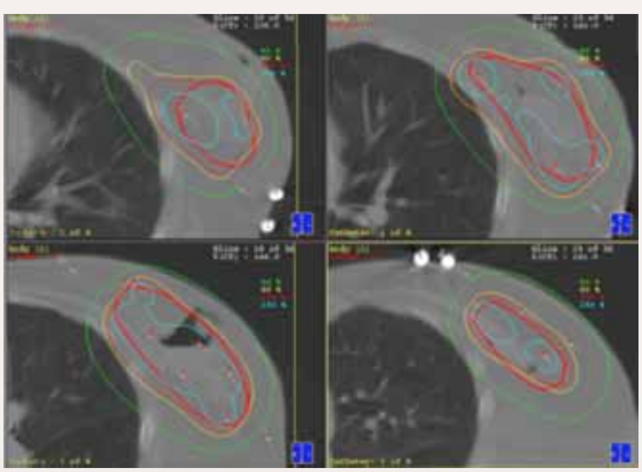
ENT tumour treated with HDR brachytherapy (cont).
Four different projections are shown.



- Typical dose prescription is 25 Gy given in 10 fractions.
- The dose is prescribed to the 100% isodose surface.
- The target volume is shown in red-orange color.
- An iridium-192 HDR machine is used in treatment. Typical source activity is 10 Ci (370 GBq).

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

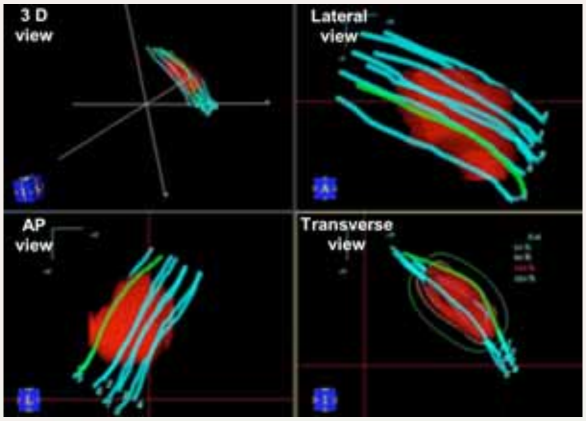
Breast treatment with HDR brachytherapy boost to tumour bed.
Four transverse CT slices (thickness 5 mm) are shown.



- Eight catheters (channels) are used in treatment.
- The target volume is delineated with the heavy red contour.
- Isodose lines 50%, 90%, 100% and 150% are shown.
- Target dose of 24 Gy is delivered in 8 fractions and prescribed to the 100% isodose surface.

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

Breast treatment with HDR brachytherapy boost to tumour bed. Four different projections are shown.



- An iridium-192 HDR machine is used in treatment. Typical source activity is 10 Ci (370 GBq).
- The target volume is shown in red; the catheters are shown in green.
- In the transverse view isodose lines 50%, 90%, 100% and 150% are shown.

13.6 DOSE CALCULATION PROCEDURES
13.6.2 Computerized treatment planning

Optimization of dose distribution

- In brachytherapy optimization of dose distribution is usually achieved by establishing the relative spatial or temporal distribution of the sources and by weighting the strength of the individual sources.
- When computer algorithms are not available, optimization is usually carried out by trial and adjustment.

Optimization of dose distribution

- The current optimization approaches fall into one of the following categories:
  - Source distribution rules
  - Geometry
  - Specified dose points
  - Trial and adjustment

Optimization of dose distributions (cont.)

- Optimization in HDR and PDR treatment planning for a single stepping source involves manipulation of the source dwell positions and the relative dwell times to produce the desired dose distribution.

- Most current optimization methods are analytic. Other approaches use random search techniques in which the performance of the system is made to improve through the use of an objective function.

Calculation of treatment time

- The original Patterson-Parker (Manchester system) tables for planar and volume implants relate the treatment time required to deliver a certain dose with the area or volume of the implant.
- The area or volume of the implant must be established from orthogonal radiographs.

Calculation of treatment time (cont.)

- Corrections must be made for uncrossed ends in determining the treatment volume.
- The treatment time is calculated from the total activity used in the implant and the cumulative strength (total reference air kerma) required to deliver the prescribed dose.

Choice of reference points

- The choice of the reference points for the calculation of treatment dose rates and delivered dose should follow the ICRU recommendations stated in ICRU Reports 38 and 58.
- In general, the reference points are representative of the target volume and other tissues of interest.
- The dose prescription point is usually representative of the periphery of the target volume.

- In calculating the total dose delivered during the implant one must consider the exponential decay of the source strength (activity).
- The cumulative dose D_{cum} delivered during time t is

$$D_{cum} = \dot{D}_0 \int_0^t e^{-\lambda t} dt = \frac{\dot{D}_0}{\lambda}\left\{1 - e^{-\lambda t}\right\} = 1.44 t_{1/2} \dot{D}_0 \left\{1 - e^{-\frac{t \ln 2}{t_{1/2}}}\right\}$$

$\dot{D}_0$ initial dose rate
λ decay constant
$t_{1/2}$ half-life of the radioactive source

For short treatment times compared to source half-life

- The cumulative dose is in general given by

$$D_{cum} = \dot{D}_0 \int_0^t e^{-\lambda t} dt = \frac{\dot{D}_0}{\lambda}\left\{1 - e^{-\lambda t}\right\} = 1.44 t_{1/2} \dot{D}_0 \left\{1 - e^{-\frac{t \ln 2}{t_{1/2}}}\right\}$$

- If the treatment time t is very short in comparison with the half-life $t_{1/2}$ of the source, i.e., $t \ll t_{1/2}$ then

$$e^{-\frac{t \ln 2}{t_{1/2}}} \approx 1 - \frac{t \ln 2}{t_{1/2}} \quad \text{and} \quad D_{cum} = \dot{D}_0 t$$

Permanent implants

- The cumulative dose is in general given by

$$D_{cum} = \dot{D}_0 \int_0^t e^{-\lambda t} dt = \frac{\dot{D}_0}{\lambda}\left\{1 - e^{-\lambda t}\right\} = 1.44 t_{1/2} \dot{D}_0 \left\{1 - e^{-\frac{t \ln 2}{t_{1/2}}}\right\}$$

- For permanent implants $t = \infty$ and the following relationship is used to determine the cumulative dose to complete source decay

$$D_{cum} = \frac{\dot{D}_0}{\lambda} = 1.44 t_{1/2} \dot{D}_0$$

13.7 COMMISSIONING OF BRACHYTHERAPY TPSs

13.7.1 Check of the reconstruction procedure

- The major hardware devices of brachytherapy treatment planning systems (TPSs) are:
  - Computer
  - Digitizer
  - Plotter
- The accuracy of the devices and the planning process should be checked routinely with simple test cases for a small number of sources placed in a known geometry as seen on two orthogonal radiographs.
- The verification test should include translation from film to Cartesian coordinates, rotations, and corrections for magnification.

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13.7 COMMISSIONING OF BRACHYTHERAPY TPSs

13.7.2 Check of consistency between quantities and units

- The major sources of errors in brachytherapy are:
  - Incorrect source calibration
  - Incorrect use of dosimetric quantities and units in the calculation algorithms.
- It is essential to verify correct labeling of the input and output quantities and units used in the dose calculation software.
- Special care must be taken with regard to the specification of source strength (activity).

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13.7.3 Computer vs. manual dose calculation

- The computer-calculated dose distribution around a line source should be compared with:
  - Published dose rate values for a similar source
  - Sievert integral values obtained for the same source
- Additional tests should verify the validity of:
  - The inverse square law for point sources
  - Summation of the dose for multiple sources
  - Scaling of the dose rate with source strength
  - Scaling of the dose with time

13.7.4 Check of the decay corrections

- For temporary implants, the accuracy of the computer-calculated dose rate at specific times within the duration of the implant should be verified with manual calculations.
- For permanent implants, the accuracy of the computer-calculated dose to complete source decay should be verified.
- For both types of implants (temporary and permanent) the choice of units for the source strength, dose rate, and total dose should be verified.

13.8 COMMISSIONING OF RADIOACTIVE SOURCES
13.8.1 Wipe tests

Shipment package

- A package containing shipment of a radionuclide must be monitored immediately upon receipt for any physical damage and excessive radiation levels.
- The package surface should be investigated with wipe tests for any possible radioactive contamination.
- Radiation levels should be measured and recorded both for the surface of the package and for several points at a distance of 1 m from the package.

13.8 COMMISSIONING OF RADIOACTIVE SOURCES
13.8.1 Wipe tests

Individual encapsulated sources

- Individual encapsulated sources should be wipe-tested for possible radioactive leakage and contamination.
  - All new sources should be tested at time of receipt.
  - Sources kept in permanent inventory should be tested at intervals of 6 months.
- The measurement of contamination is usually carried out with a sensitive scintillation well counter.
- A source is considered to be leaking if ~200 Bq (~5 nCi) of removable contamination is measured.

13.8 COMMISSIONING OF SOURCES

13.8.2 Autoradiography and uniformity check of activity

- Radiography and autoradiography using a single film exposure with a simulator can be used to check the uniformity of activity.
- The developed film is scanned with a densitometer to determine isodensity and isodose profiles.
- Autoradiographs are useful for checking a batch of seeds or ribbons with seeds to establish:
  - Uniformity of activity within each seed
  - Presence of any inadvertent cold (non-radioactive) seeds

13.8 COMMISSIONING OF SOURCES

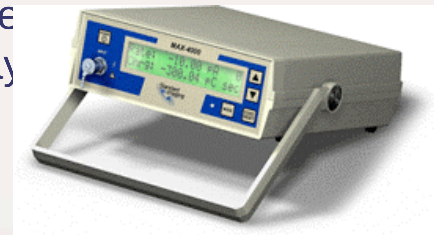
13.8.3 Calibration chain

- Brachytherapy sources should have their source strength calibration traceable to a national standards laboratory.
- In some instances it may be necessary to establish a second level of traceability by comparison with a calibrated source of the same type.
- Comparison calibrations are best done in well type (re-entrant) ionization chambers which are suitable for calibration of both high and low strength (activity) sources.

13.8 COMMISSIONING OF SOURCES
13.8.3 Calibration chain

- The well type (re-entrant) chambers must have a calibration coefficient traceable to a standards laboratory, i.e., they must have been calibrated at a national standards laboratory or at a secondary standards laboratory.

- For high strength sources, the source strength (activity) measurements may also be carried out with calibrated stem type ionization chambers.



13.8 COMMISSIONING OF SOURCES
13.8.3 Calibration chain

- Most standards laboratories will calibrate stem type ionization chambers for different quality radiations, and an interpolation or extrapolation method is then used to obtain the calibration coefficient for a given radionuclide source.

- The activity of all sources should be measured upon receipt with a calibrated local dosimeter and the result should be compared with manufacturer’s certificate of source strength.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.1 Constancy check of a calibrated dosimeter

- The constancy of the response of a calibrated dosimetry system may be checked by periodic response measurement with a long half-life source, such as:
  - Cesium-137 brachytherapy source for well-type (re-entrant) ionization chambers.
  - Cobalt-60 teletherapy machine in the case of a stem-type ionization chamber.
  - Commercial strontium-90/ittrium-90 calibration source in the case of a stem-type ionization chamber

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.1 Constancy check of a calibrated dosimeter

- The periodic constancy check measurement also provides a good quality assurance check for the entire measuring system.
- Appropriate calibration coefficients for the entire dosimetric system must be obtained from a standards laboratory on a regular basis, typically every two years.

Mechanical properties

- The mechanical integrity of a source must be checked at regular intervals by:
  - Visual inspection
  - Leak testing
  - Activity measurement
- Visual inspection and radiographic evaluation of all applicators should be carried out periodically.

Mechanical properties

- For gyneacological applicators it is necessary to check that:
  - The assembly is structurally sound.
  - All clamps, screws and retaining devices are functioning properly.
  - Source insert carriers seat correctly in the colpostats.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.2 Regular checks of sources and applicators

Source strength (activity)

- Long half-life sources maintained within a permanent inventory should be checked at reasonable frequency for change with time in source strength (activity).
- Short half-life sources, used either for temporary or permanent implants, should have their activity measured at the time of receipt and the result should be compared with the value stated on the manufacturer's certificate.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.2 Regular checks of sources and applicators

Source strength (activity)

- Any discrepancy between the locally-determined and manufacturer's stated value exceeding 10% should be investigated and the patient should not be treated until the discrepancy is explained and understood.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY

13.9.3 Check of source positioning with afterloading devices

- The use of appropriate radiographic markers and combination of a radiographic image with an autoradiograph are convenient methods for checking source positioning.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY

13.9.4 Radiation monitoring around patients

- After a permanent or temporary implantation of radioactive sources in a patient, a radiation survey must be carried out in areas within and around the patient and the patient's room.
- Radiation levels should be measured and recorded so as to assist in maintaining minimum exposure to hospital staff and visitors.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.4 Radiation monitoring around patients

- The radiation levels in adjoining patients' rooms should be low so that no individual will be exposed to an equivalent dose exceeding 0.2 mSv in any one hour.
- Prior to release of an implant patient from hospital the patient and the patient's room must be surveyed.
- For patients with temporary implants a survey must be done upon removal of the sources to confirm complete removal of all sources.

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13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.4 Radiation monitoring around patients

- Patients with permanent implants may be discharged from the hospital if at the time of discharge the radiation level at 1 m from the implant is less than 0.5 mSv/h.
- Patient discharged from the hospital with permanent implants should be instructed to keep a distance from children and pregnant women for a reasonable amount of time after the implant.

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13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.5 Quality management programme

- All facilities performing brachytherapy procedures should have in place some form of a quality management programme.
- The objectives of the programme should be well defined to ensure compliance with standard good practices.
- The programme should include written procedures for prescribing, recording and documenting each treatment.
- The brachytherapy procedures manual should also include written policies on reporting and recording treatment errors.

13.9 QUALITY ASSURANCE IN BRACHYTHERAPY
13.9.5 Quality management programme..

The main objectives of a quality management programme are:

- The preparation of a physician's written directive before administration of treatment.
- Clear identification of the patient.
- Documentation of treatment and related calculations.
- Compliance of each treatment with written directive.
- The identification and evaluation of any unintended deviation from the prescription.

13.10 BRACHYTHERAPY VS. EXTERNAL BEAM THERAPY

- Brachytherapy is an important modality in the treatment of malignant disease.
- It allows conformal treatment without heavy technological involvement and cost.
- It generally involves invasive procedures (interstitial brachytherapy) except for the special case of intracavitary brachytherapy.

13.10 BRACHYTHERAPY VS. EXTERNAL BEAM THERAPY

- About 10 - 20% of radiation oncology patients are treated with brachytherapy; 80 - 90% are treated with external beam techniques.
- The basic principles of brachytherapy have not changed much during the past 100 years of radiotherapy.
- In comparison to manual loading, remote afterloading has made brachytherapy much more efficient for the patient and safer for staff from the radiation protection point of view.

13.10 BRACHYTHERAPY VS. EXTERNAL BEAM THERAPY

- Nearly every malignant disease in the human body has been treated with brachytherapy, some with great success, others with complete failure.
- Gyneacological cancer treatments provide the greatest success and permanent implants in treatment of prostate cancer are becoming increasingly common.