PHYSICS OF BRACHYTHERAPY

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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.

Introduction

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 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)

Types of brachytherapy Techniques

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.

classification with 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.

classification with type of source loading

Hot loading

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

Afterloading

- 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)

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

Remote afterloading

- To minimize radiation exposure to medical and support staff several computer driven remote afterloading systems have been developed.

Advantages over manual procedures

- Increased patient treatment capacity.
- Consistent and reproducible treatment delivery.
- Reduced radiation exposure to staff

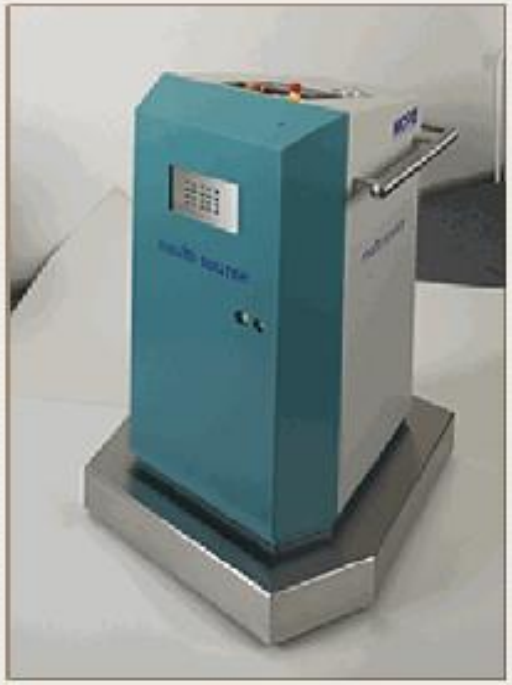
Remote After loading Units

Remote afterloading

1970-
Cobalt RALSTON
Diameter 3 mm

1990-
Ir-192 RALS
Diameter 1.1 mm

2000-
Cobalt RALS
Diameter 1.1 mm



MODERN HDR TREATMENT UNITS

MicroSelectron HDR unit
(Courtesy Nucletron)

Ir-192

Varisource system.
(Courtesy Varian)

Ir-192

Multisource HDR unit
(Courtesy BEBIG)

Co-60 or Ir-192 sources

Gamma Med Plus HDR unit at SSCHRC

GammaMed Plus system.
(Courtesy Varian)

Ir-192 source

Max 12 Ci
0.9 mm Diameter
0.6 mm Active Dia
4.5 mm Length
3.5 mm Active Length
24 Channels

Classification with 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

Pulse Dose Rate - “Dose pulses” of the order of 30 minutes separated by 1 to several hours (Simulation of LDR)

Characteristics of Brachytherapy sources

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

- Contains the radioactivity.
- Provides source rigidity. (70% Iridium & 30% Platinum)
- Absorbs alpha and beta radiation produced through source decay.

Characteristics of brachytherapy sources

- Photon energy
- Half-life
- Half-value layer in shielding materials
- Specific activity
- Source strength
- Inverse-square dose fall-off

Photon source characteristics

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	-	-

PHOTON SOURCE CHARACTERISTICS

Mechanical characteristics of brachytherapy sources

Brachytherapy photon sources are available in various forms, such as:

- Needles (Caesium-137).
- Tubes (Caesium-137).
- Pellets (Cobalt-60 and Caesium-137).
- Seeds (Iodine-125, Paladium-103, Iridium-192, Gold-198).
- Wires (Iridium-192).

Source Specification

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 $(\dot{K}_{air}(d))_{air}$

Source Specification

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 μGy/h).

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

Source Specification

Specification of gamma ray sources (cont.):

2. Air kerma strength S_K, defined by the AAPM as

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

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

AAPM TG 43 recommends a shorthand notation with U

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

Source Specification

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

Source Specification

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 $(\mu Gy \cdot m^2)/(GBq \cdot h)$

d is the distance from the source in m

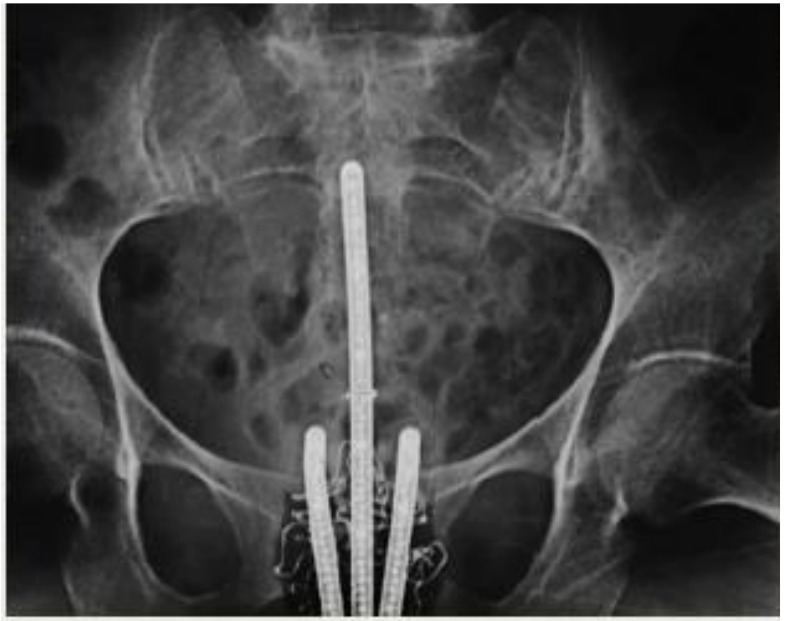
Specification of beta ray sources

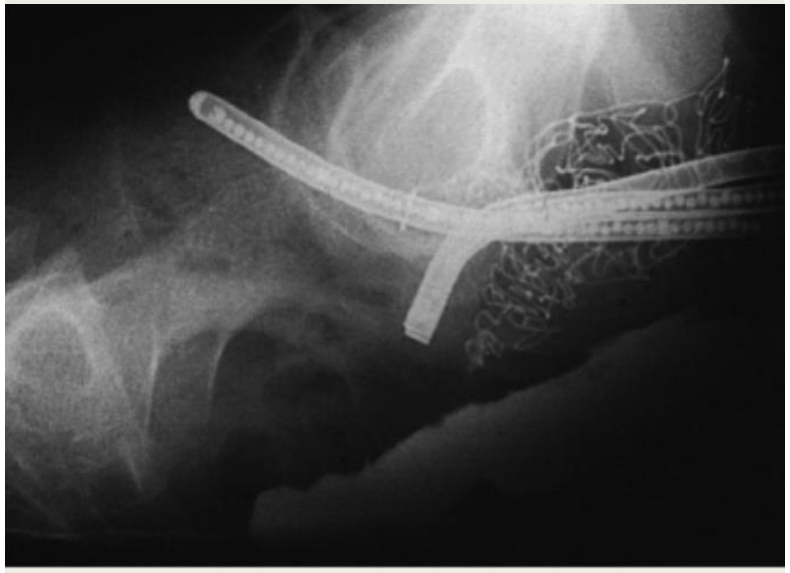
- Beta ray sources are specified as reference absorbed dose rate in water at a reference distance from the source.

- Reference distance differs from one type of source to another and is generally between 0.5 mm and 2 mm from the source.

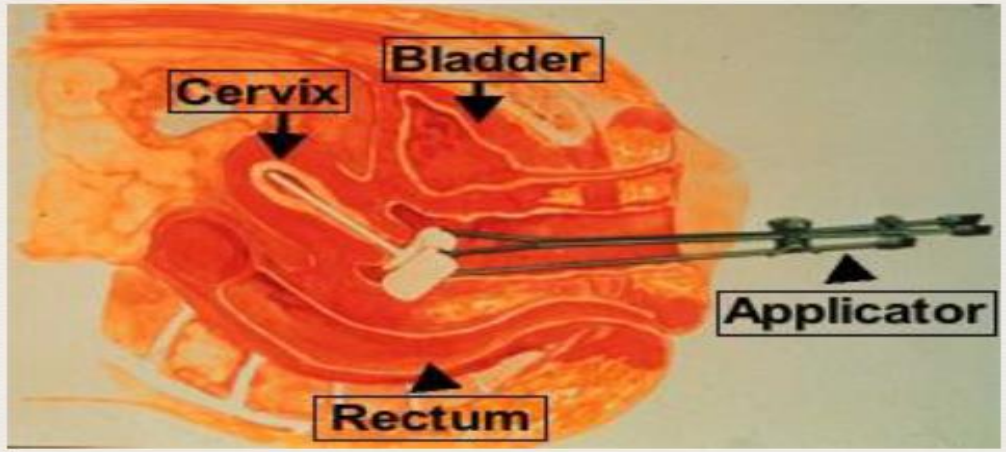
Gynaecology Dosimetry Systems

- Intracavitary brachytherapy 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
- 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.



Sources used for Gynaecology application

- The most widely used source for treatment of gynaecological cancers is Caesium-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.
- Recently HDR units with Cobalt-60 sources (2Ci) available

Gynaecology dosimetry systems

- Cancer of the uterus was first treated with radium in 1908.
- 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:

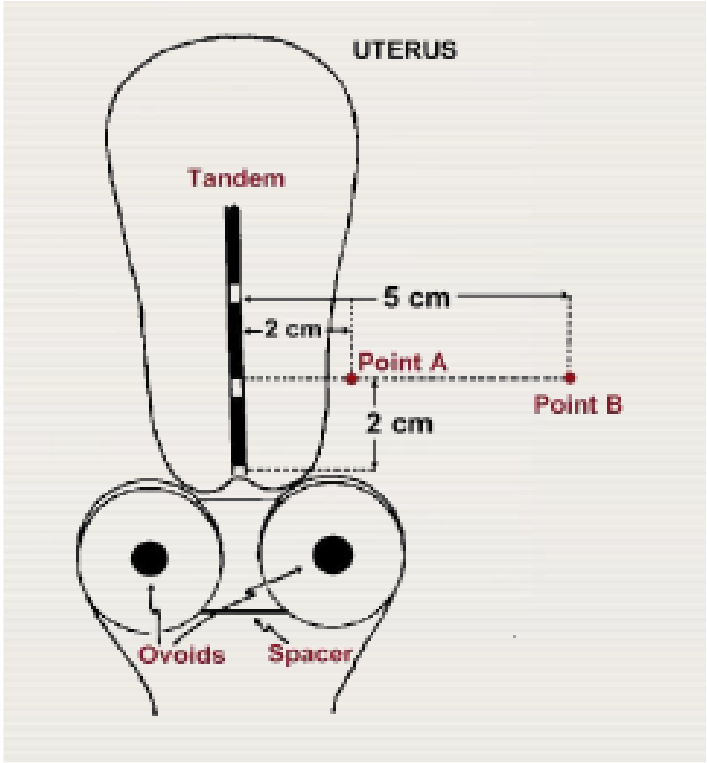
- Manchester system
- ICRU system

Manchester system

Manchester system is characterized by doses to four points: point A, point B, bladder point, and rectum point.

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.

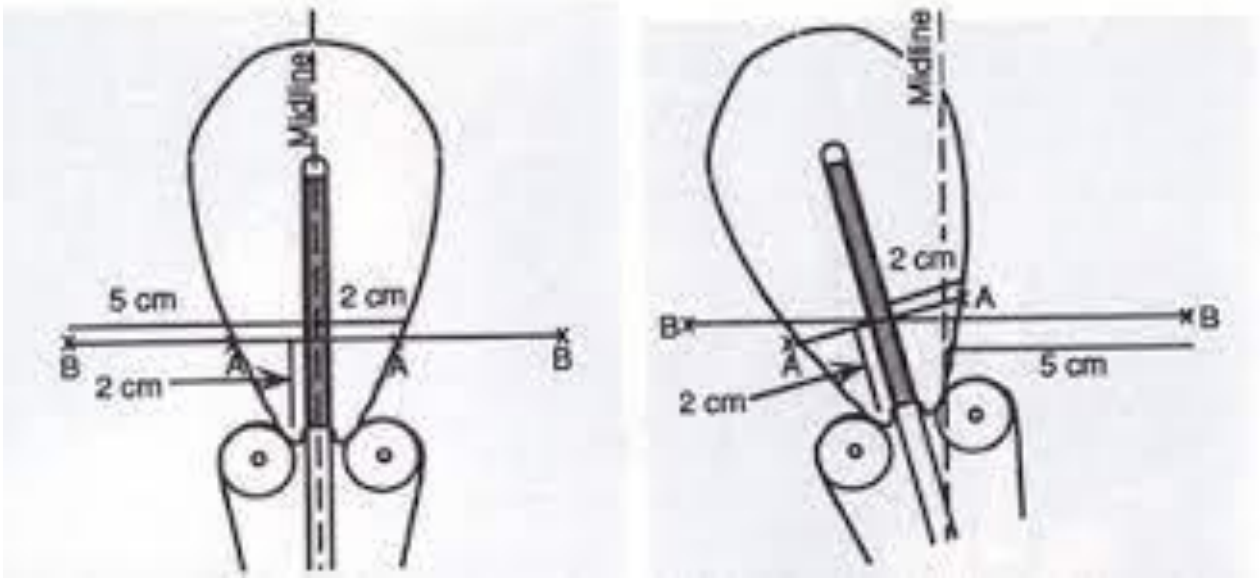
Point B is defined 3 cm laterally to point A when the central canal is not displaced.



Manchester system

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.

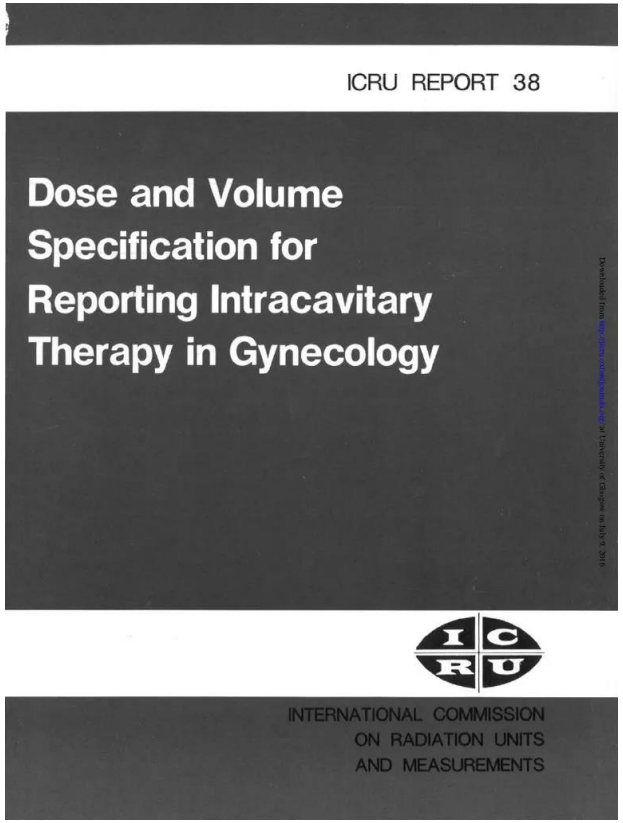
If the tandem displaces the central canal, point A moves with the canal, but point B remains fixed at 5 cm from the midline.



ICRU system

Gyneacological dosimetry system relates the dose distribution to the target volume rather than to a specific point.

- 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



Intracaitary applicators

- 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

GYNAECOLOGY APPLICATORS

Rectal and bladder dose monitoring

- Complication 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.
- Surgical gauze is used to displace the sensitive structures away from the applicator.
- 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.

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.

Interstitial Brachytherapy

Sources used are in the form of needles, wires, or seeds.

Interstitial afterloading techniques consist of two steps:

- First step consists of inserting unloaded, stainless-steel needles (1-2 cm apart) into the tumour.
- Second step consists of afterloading the unloaded needles with radioactive seeds or connecting the needles to an afterloading machine for remotely-controlled source insertion.

Systems of Interstitial Brachytherapy

Manual methods

- Manchester/Paterson-Parker system
- Quimby system
- Memorial nomographs
- Paris system

Computer methods

Manchester/P-P system

- Peripheral sources define the target region
- Goal is to optimize dose uniformity
- Radium dosage system to deliver uniform dose(within +/-10%) to a plane or volume
- Planning relies on pre-calculated tables of the cumulative source strength per unit dose (in mgh per 1000 cGy)
- To obtain the total source strength, table value is multiplied by the desired dose

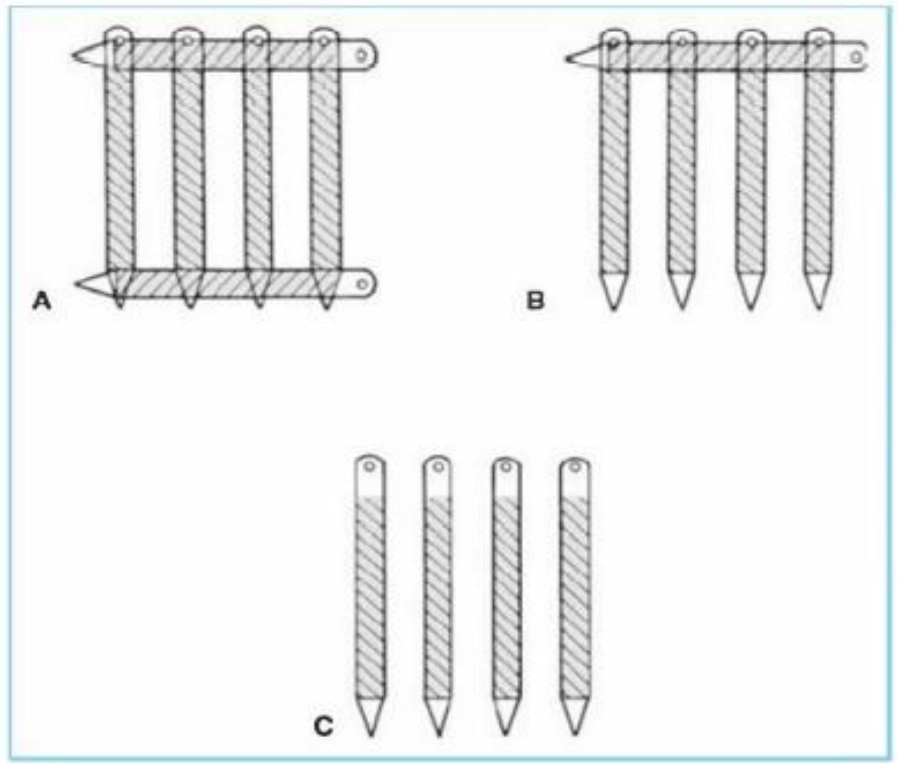
Planar Implant

- Reference dose plane is 0.5cm from source plane
- Single plane implant effectively irradiates tissues of 1cm thickness (0.5 cm on either side)
- Dose at 0.5 cm is the minimum dose throughout the 1cm thick slab

Area	Fraction of activity on	
(cm2)	Periphery	Area
< 25	2/3	1/3
25-100	1/2	1/2
> 100	1/3	2/3

Arrangement of needles for planar implants

- The spacing between needles should not exceed 1 cm
- For each uncrossed end, effective area to be reduced by 10%



Examples of three planar implants
A: Both ends crossed
B: One end uncrossed
C: Both ends uncrossed

Paterson-Parker Tables for Planar implant

Treating distance in cm

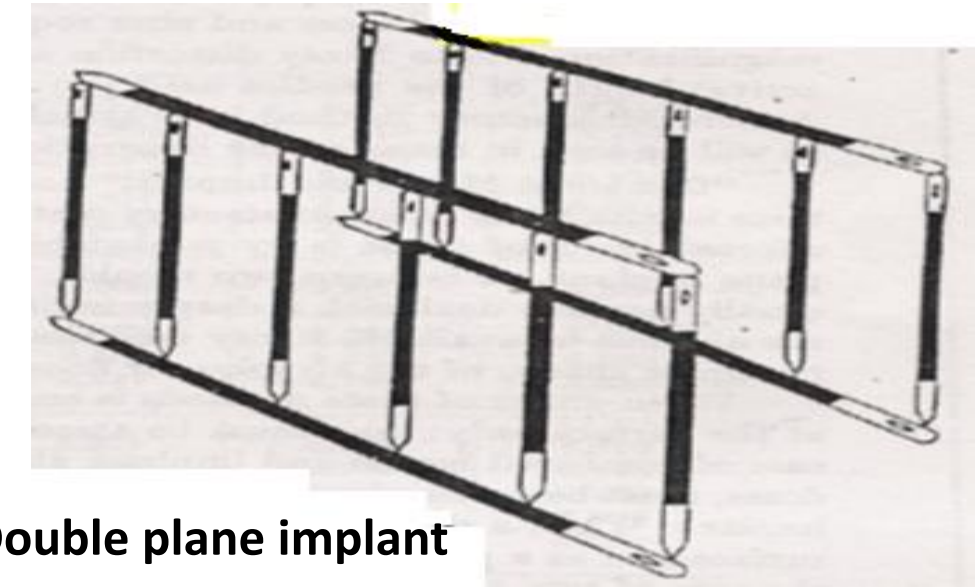
4 x 4 implant

Area Sq.cm	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	5.0
0	32	127	285	506	792	1139	1551	2026	3166
2	103	227	399	632	920	1274	1697	2172	3349
4	150	296	492	743	1032	1388	1823	2307	3450
6	188	354	570	832	1134	1495	1938	2432	3575
8	219	409	637	910	1229	1596	2047	2548	3694
10	250	461	697	982	1314	1692	2149	2660	3809
12	278	511	755	1053	1396	1780	2247	2769	3917
14	306	557	813	1120	1475	1865	2341	2870	4027
16	335	602	866	1184	1553	1947	2429	2968	4131
18	364	644	918	1245	1622	2027	2514	3063	4240
20	392	682	968	1303	1690	2106	2601	3155	4341
24	444	752	1072	1420	1821	2252	2764	3326	4540
28	496	816	1170	1530	1943	2398	2917	3484	4730
32	546	876	1261	1635	2060	2532	3073	3639	4915
36	594	935	1349	1743	2179	2662	3215	3787	5089
40	642	994	1432	1843	2290	2787	3351	3931	5258
50	750	1141	1619	2083	2556	3082	3676	4275	5668
60	851	1283	1790	2319	2815	3362	3974	4605	6054
70	947	1426	1944	2532	3059	3628	4257	4913	6419
80	1044	1567	2092	2726	3301	3891	4532	5213	6756

Mg-hrs for different implant areas

Multiple planes

- Planes should be parallel to each other
- A two plane implant can satisfactorily treat block of tissue upto 2.0 or 2.5cm



Double plane implant

Volume implant

- When lesion to be treated is more than 2.5 cm thick
- Volume implant may be in the form of a sphere, cube or cylinder
- Total amount of radium is divided into 8 equal parts and distributed as follows:

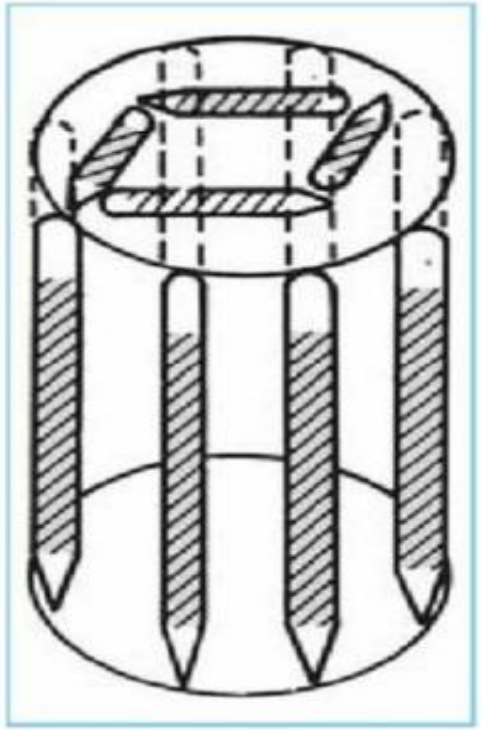
  Sphere: Shell-6 parts, core-2 parts

  Cylinder: Belt-4 parts, core- 2parts, each end- 1 part

  Cuboid: Each side 1 part, core – 2 parts

Volume implant (contd)

- Sources should be spaced evenly
- Separation between two needles should not be more than 1.0 to 1.5 cm.
- In cylindrical implants the belt should consist of atleast 8 needles and core of atleast 4.
- Volume determined by the belt must be reduced by 7.5% for each open end.



Quimby System

- Uses sources of uniform linear activity
- Sources distributed uniformly over the area or volume
- Result is non-uniform dose distribution, higher in the central region
- Planar implants-Quimby tables give the mg.hrs required to deliver 1000R at the centre of treatment plane, upto 3 cm from implant plane
- For Planar implants, stated dose is the maximum dose in the plane of treatment
- For Volume implants, stated dose is the minimum dose in the plane of treatment

Memorial System

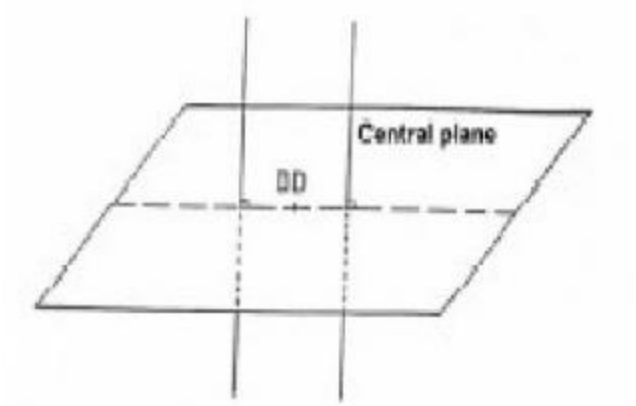
- The Memorial system is an extension of Quimby system
- Based on computer generated dose distributions, tables were constructed that gave mg-hrs to deliver 1000 at designated points
- These tables use proper exposure rate constants and include effects of oblique filteration and tissue attenuation
- The Memorial Nomogram was used for manual intra-operative planning of I-125 implantation

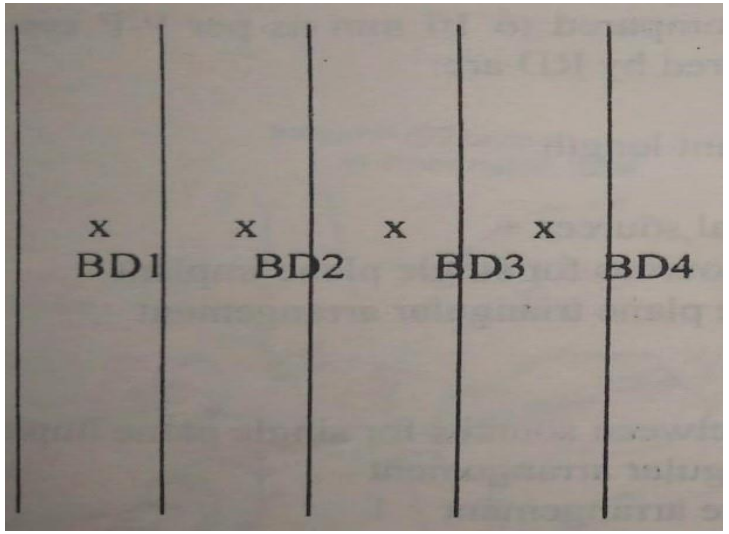
Paris System

- Developed based on experience with Ir-192 interstitial implants by afterloading techniques
- Better suited to the characteristics of flexible wire implants than the previous dosage systems
  - Sources should be parallel and straight
  - Sources should be of equal length and equally spaced
  - Lines must be equidistant
  - Linear activity must be identical for all the lines
- BASAL DOSE (BD) forms the basis for dosimetry
- BD – arithmetic mean of the minimal dose rates in the central region of the implant
- Reference dose rate (RD) equal to 85% of BD and it is the dose rate used for dose prescription

Reference Dose Rate = 0.85 x BD

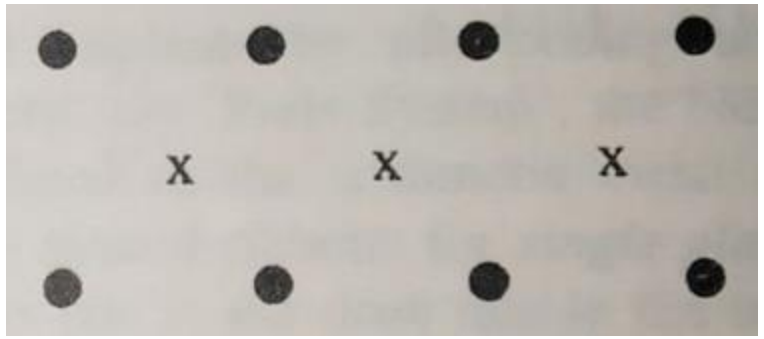
Each basal dose rate should be within ± 10 % of the mean basal dose rate for a satisfactory implant

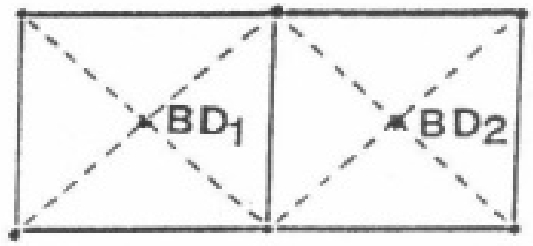




BD = (BD1+BD2+BD3+BD4)/4

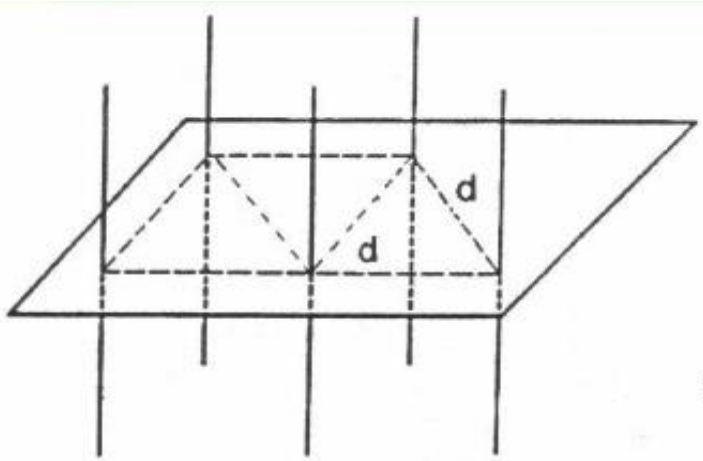
Calculation of basal dose rate in planar implants

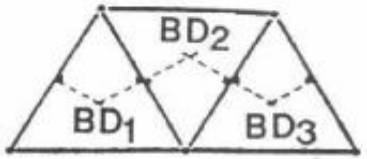




$$BD = \frac{BD1+BD2}{2}$$

(A)





$$BD = \frac{BD1+BD2+BD3}{3}$$

(B)

Calculation of basal dose rate in Squares (A) and triangles (B)

Computer System

- Similar to Paris and Quimby techniques
- Uniform strength sources placed uniformly (about 1.0 to 1.5 cm, larger spacing for larger implants) covering the entire tumour volume
- Dose inhomogeinity is accepted in the central part of target
- Dose specified by isodose surface that just covers the target or impant volume
- Crossing needles not used; Active length of sources 30-40% larger than target length

Remote afterloading systems

Remote afterloading machines are used in both interstitial and intracavitary clinical applications.

Essential components of remote afterloading machines are:

- 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.

Remote afterloading systems

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.

Remote afterloading systems

Advantages of HDR machines are:

- Optimization of dose distribution.
- Treatment on outpatient basis.
- Elimination of staff radiation exposure.

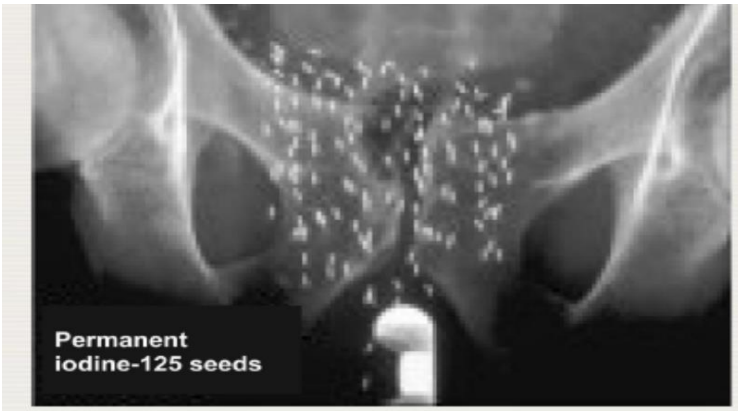
Disadvantages of HDR systems are:

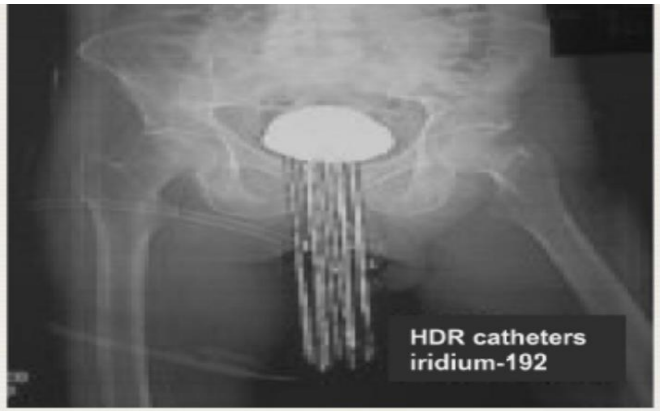
- Uncertainty in biological effectiveness.
- Potential for accidental high exposures.
- Potential for serious errors.
- Increased staff commitment.

Permanent prostate implants

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 .(30kev)
- As a boost to external beam treatments delivered in the form of fractionated or single session treatment using an HDR machine.





Permanent prostate implants

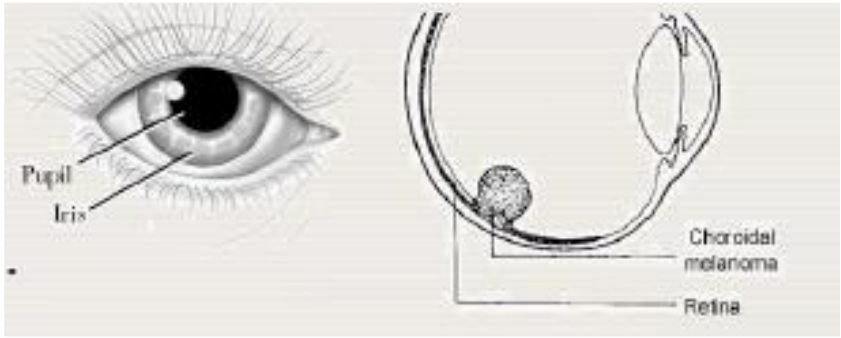
Choice of radionuclide for prostate implant

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.
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

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.

Permanent prostate implants

Brachytherapy treatment

Eye plaque loaded with radioactive 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.

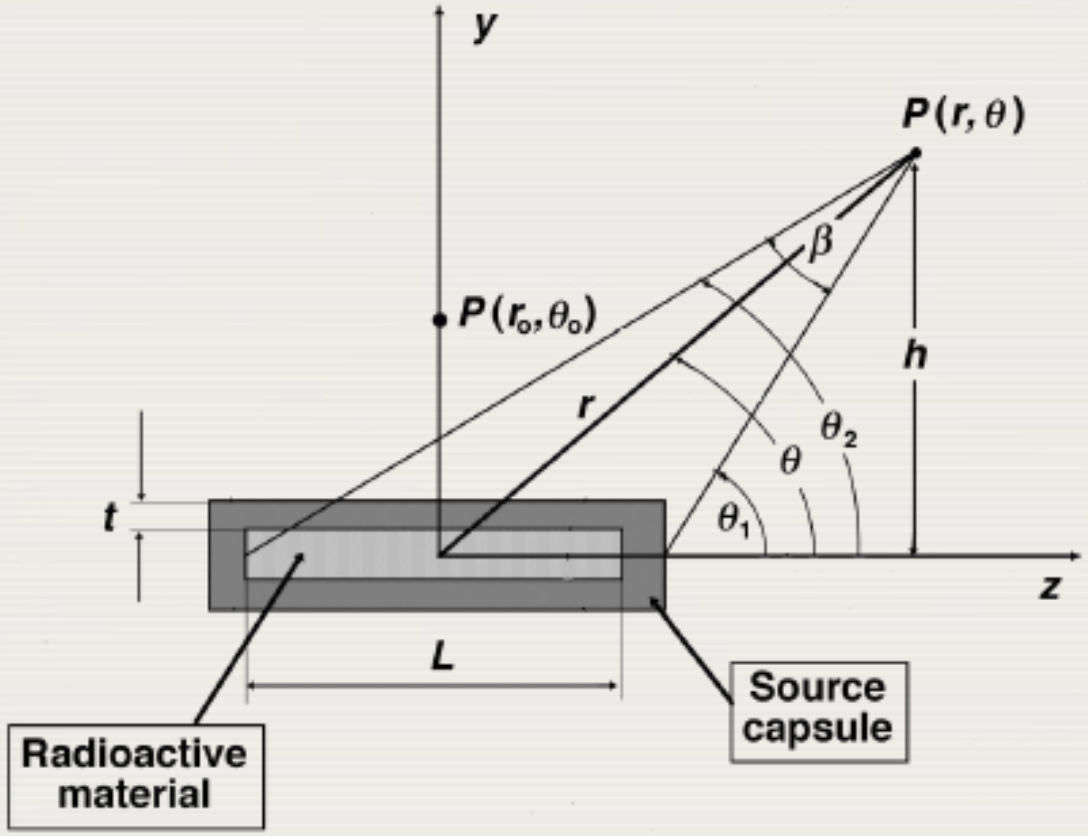
Intravascular brachytherapy

- Application of radiation (temporary or permanent implant) proved to prevent restenosis after treatment of arterial stenosis with angioplasty and stent

- Sealed sources or liquid–filled ballons as temporary implants and radioactive stents as permanent implants are used

DOSE DISTRIBUTIONS AROUND SOURCES
AAPM TG 43 algorithm

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 $(r_0 = 1\,\text{cm}$ and $\theta_0 = \pi/2)$.

Dose distributions around sources

AAPM TG 43 algorithm

Dose rate at point-of-interest P(r,θ) 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 ($\mu Gy \cdot m^2 \cdot h^{-1}$)
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

Dosimetric Parameters

- Air Kerma Strength S_K is specified in terms of air kerma rate at a point along the transverse axis of the source in free space.
- The dose rate Constant is defined as the dose rate to the water at a distance of 1 cm on the transverse axis of a unit air kerma strength source in a water phantom.
- Geometry factor accounts for the variation of relative dose due to the spatial distribution of activity within the source, ignoring the photon absorption and scattering in the source structure
- The radial dose function g(r) accounts for the effects of absorption and scatter in water along the transverse axis of the source ($\theta = \pi/2$)
- Anisotrophy factor $F(r,\theta)$ accounts for the anisotropy of dose distribution around the source including the effects of self absorption

Dose calculation procedures
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, (linear array, tandem and ovoids, vaginal Cylinder) pre-calculated dose distributions (atlases) may be used with appropriate scaling of source strength (activity).

Source localization

Source localization can be established by the use of several radiographic methods:

- Two orthogonal films.
- Two stereo-shift films.
- Computerized tomography (CT) scanning.

Computerized treatment planning

- 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.

Optimization of dose distribution

- Optimization of dose distribution is 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.

Commissioning of brachytherapy TPS

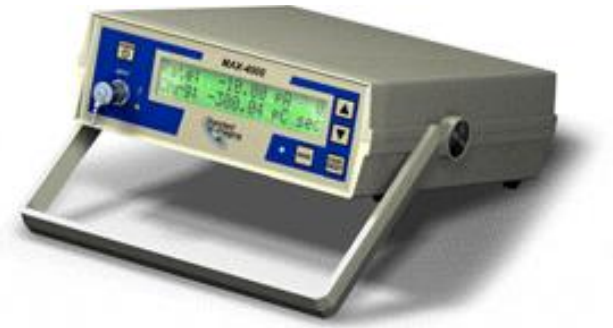
Major sources of errors in brachytherapy are:

- 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).

COMMISSIONING OF BRACHYTHERAPY TPSs
Calibration chain

- 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



Quality Assurance in Brachytherapy

Regular checks of sources and applicators

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.

Quality Assurance in Brachytherapy

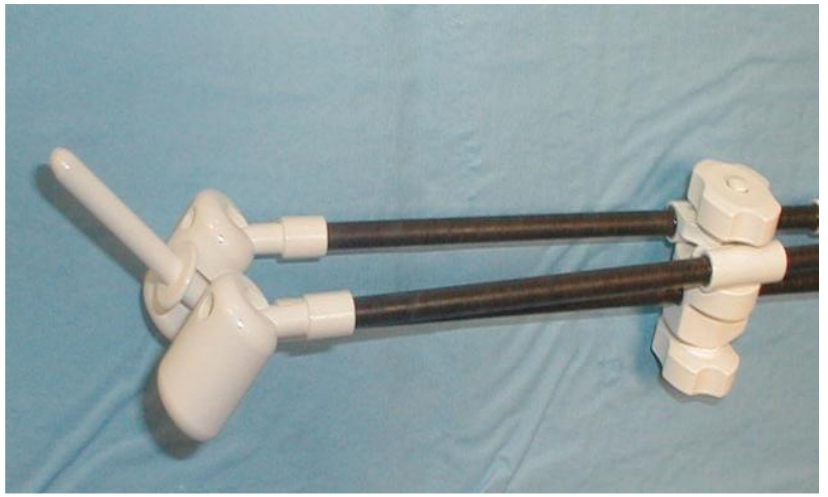
Regular checks of sources and applicators

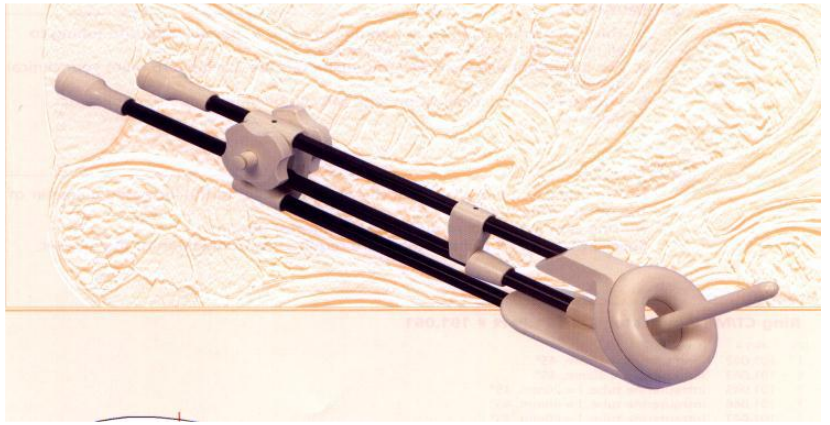
For short half-life sources, activity to be measured at the time of receipt and compared with manufacturer's quoted value

For long half-life sources, activity to be checked at reasonable frequency

For applicators it is necessary to check that:

- Assembly is structurally sound.
- All clamps, screws and retaining devices are functioning properly.





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 to assist in maintaining minimum exposure to hospital staff and visitors

QUALITY ASSURANCE IN BRACHYTHERAPY
Radiation monitoring around patients

• 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 discharge 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.

Conclusion

• About 10 – 20 % of radiation oncology patients are treated with brachytherapy; 80 – 90 % are treated with external beam techniques

- 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.

THANK YOU