

# Physical aspects and principles of Brachytherapy



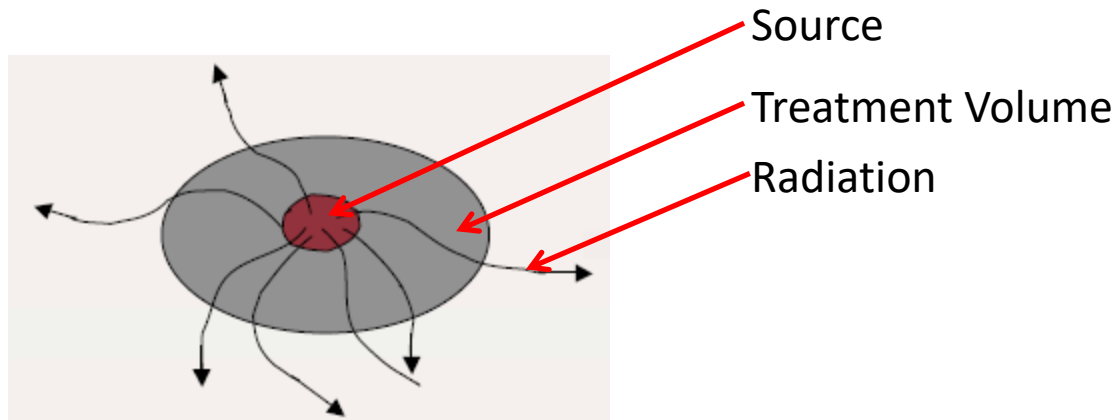
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# Brachytherapy

- Brachus (Greek word “βραχυσ”) - Short
- 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.



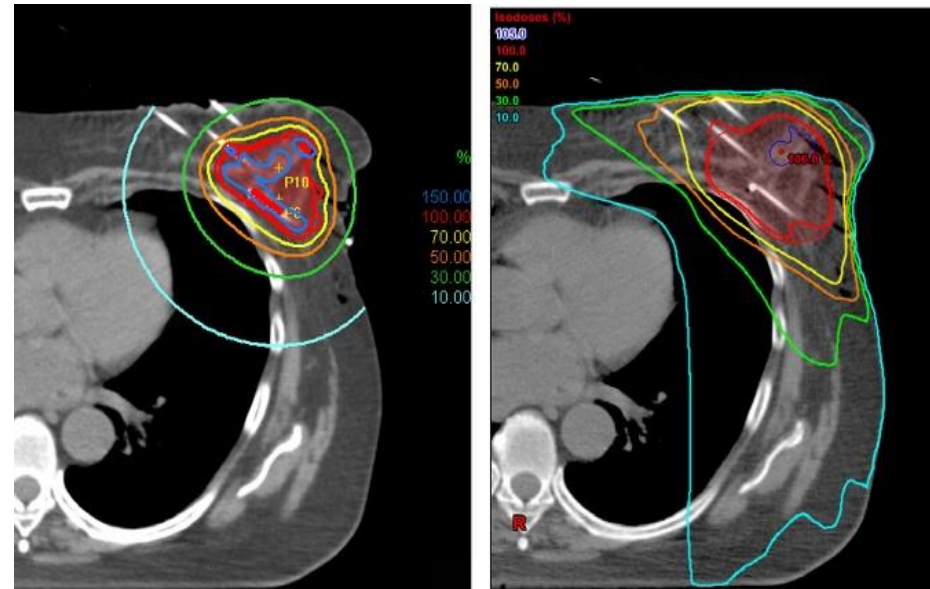
# Brachytherapy

## Advantages

- Improved localized dose delivery to the target
- Sharp dose fall-off outside the target volume
  - Less integral dose
- Better conformal therapy
- Excellent cosmetic and functional outcomes

## Disadvantages

- Only good for well localized tumors
- Only good for small lesions
- Very labor intensive



# Ideal (desirable) Source characteristics for Brachytherapy

- Pure gamma emitter
  - betas or alphas are too short in range and result in very high doses to small volumes around the source
- Optimum gamma energy : 0.2 - 0.4 MeV (mono-energetic)
  - high enough to treat the target with homogenous dose
  - low enough to avoid normal tissues and reduce shielding requirements
- High specific activity
  - To minimize the physical size of the sources
  - suitable also for high dose rate applications

# Ideal (desirable) Source characteristics for Brachytherapy

- No gaseous disintegration product
- Half life
  - longer half life is desirable for temporary implants
    - allows economical re-use of sources
    - minimal decay correction during treatment
  - Short half life is desirable for permanent implants
- Non-toxic and insoluble form and should not powder or disperse, if damaged.
- Different sizes and shapes
- Cost: Economical
- Availability: Local

# Available Sources for brachytherapy

Radionuclide	Half-life	Photon Energy (MeV)	Half-value Layer (mm lead)
<sup>226</sup> Ra	1600 years	0.047 - 2.45 (0.83 ave)	8.0
<sup>222</sup> Rn	3.83 days	0.047 - 2.45 (0.83 ave)	8.0
<sup>60</sup> Co	5.26 years	1.17, 1.33	11.0
<sup>137</sup> Cs	30.0 years	0.662	5.5
<sup>192</sup> Ir	74.2 days	0.136 - 1.06 (0.38 ave)	2.5
<sup>198</sup> Au	2.7 days	0.412	2.5
<sup>125</sup> I	60.2 days	0.028 ave	0.025
<sup>103</sup> Pd	17.0 days	0.021 ave	0.008

# Mechanical characteristics

- Brachytherapy sources are commonly 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.

# Classification: Dose Rate

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

but usually in the region of 2.5 Gy/min



# Pulsed dose rate (PDR)

- Treatment is simulated by a series of short duration “dose pulses” of the order of 30 minutes separated by intervals of 1 hour to several hours of no dose given.
- The technique is referred to as pulsed dose rate (PDR) brachytherapy.

# Techniques

- *Intracavitary:* Sources are placed into a body cavity.
- *Interstitial:* Sources are implanted into the tumor volume.
- *Surface mould:* 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 intra-vascularly into a lesion or near a lesion.

# Loading systems

- Pre loading
  - The applicator is pre-loaded and contains radioactive sources at time of placement into the patient.
- After loading:
  - 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)



# Remote LDR Brachytherapy

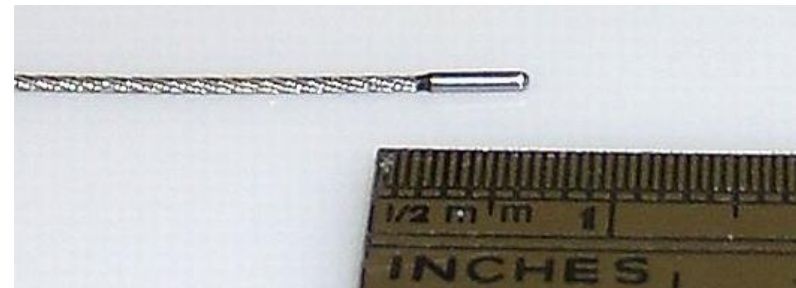
- Duration of irradiation ~ several hours or even days
- Continuous radiation delivery over a period of time
- Repair of sub-lethal damage during the treatment

- $^{137}\text{Cs}$  source pellets: 2.5 mm dia.
- Max activity/ pellet: 40 mCi
- Active pellets: 36
- No. of Channels: 6
- 2 Patients can be treated at a time
- Source drive: pneumatic



# Remote HDR Brachytherapy

- Most popular source: Ir-192
- High Specific activity - small size.
- Maximum activity loaded ~ 10 - 12 Ci
- Treatment time: 1 - 5 minutes
- More throughput
- Out patient treatment
- Miniature source and applicator
- More patient comfort
- Less patient trauma
- Allow wider applications



# Source Strength Specification

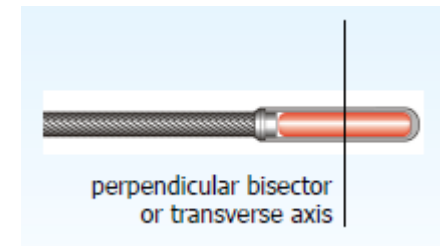
- Historically the quantity 'Activity' with special unit 'Curie' was introduced for source strength specification. And defined as quantity of Rn 226 equilibrium with 1 gm of Radium. (Curie,  $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$ ).
- The major problem with this quantity is that, for a given radionuclide, the dose rate at a given point outside the source depends not only on the amount of radioactivity inside the source but also on the attenuation, scattering and filtration of the emitted radiation in the source material and capsule (often called self-absorption).

# Source Strength Specification

Reference air kerma rate (RAKR) ( $\mu\text{Gy h}^{-1}$  at 1 m):

(ICRU 38 and ICRU 58):

“The kerma rate to air, in air, at a reference distance of one meter along the perpendicular bisector of long axis of the source, corrected for air attenuation and scattering.”



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

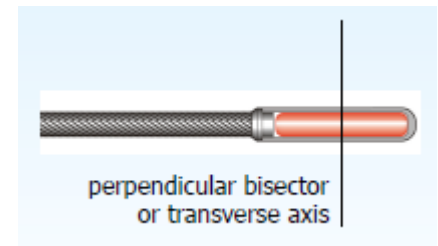
# Source Strength Specification

Air kerma Strength (AKS) ( $\mu\text{Gy h}^{-1} \text{m}^2$ ):

[Defined by the American Association of Physicists in Medicine (AAPM)]

“The product of air kerma rate in free space and the square of the distance of the calibration point from the source center along the perpendicular bisector of long axis of the source.”

RAKR and ASK yield the same  
numerical value





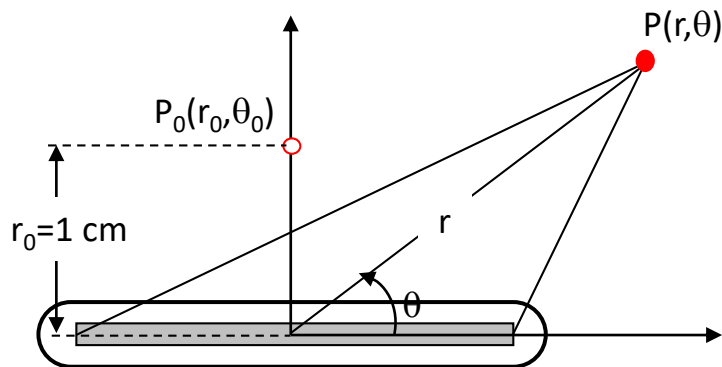
# Dose distributions around sources

The dose calculations around radioactive sources in brachytherapy treatments are divided into following categories:

- The AAPM TG 43 formalism is being used in present treatment planning system (TPS).
- Model based dose calculation algorithms
  - Accuros (Linear Boltzmann transport equation) in Eclipse TPS
  - Advanced Collapsed Cone algorithm in Oncentra TPS

# Dose distributions around sources: TG-43 Algorithm

- 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  $P(r, \theta)$

$\theta$  is the angle with respect to the long axis of the source

Point  $P(r_0, \theta_0)$  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  $\theta_0 = \pi / 2$ )

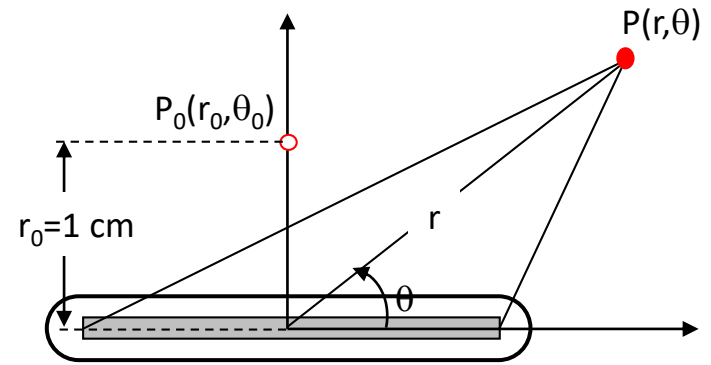
# Dose distributions around sources: TG 43 Algorithm

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

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

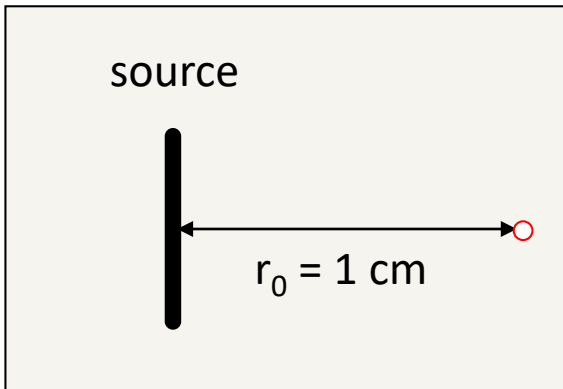
- $r$  is the distance (in cm) from the origin to the point-of-interest P
- $\theta$  is the angle between direction of radius vector  $r$  and the long axis of the source
- $\theta_0$  defines the source transverse plane and is equal to  $\pi/2$  radians
- $S_k$  is the air-kerma strength of the source ( $\mu\text{Gy} \cdot \text{m}^2 \cdot \text{h}^{-1}$ )
- $\Lambda$  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

# TG 43 Algorithm



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

## The “Dose Rate Constant” $\Lambda$



The “Dose Rate Constant”  $\Lambda$ , is defined as the **dose rate to water** at a distance of 1 cm on the transverse axis of a unit air kerma strength source in a **water** phantom.

$$\Lambda \equiv \frac{\dot{D}(r_0, \theta_0)}{S_k}$$

‘ $\Lambda$ ’ includes the effects of source geometry, the spatial distribution of radioactivity within the source, encapsulation, and self-filtration within the source and attenuation and scattering in water.

# TG 43

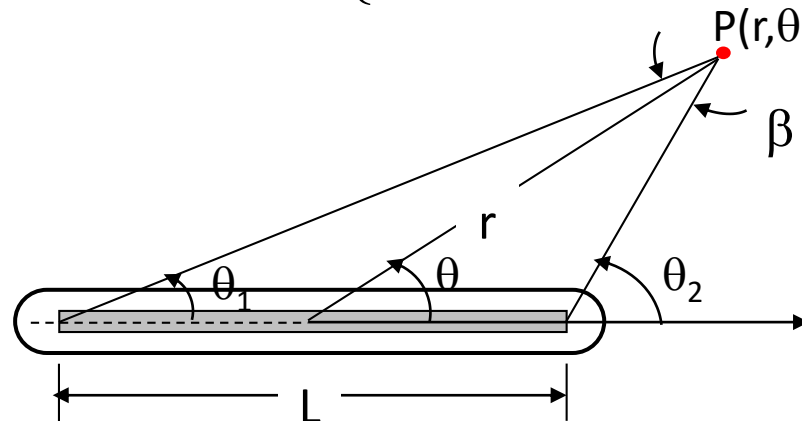
## Algorithm

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

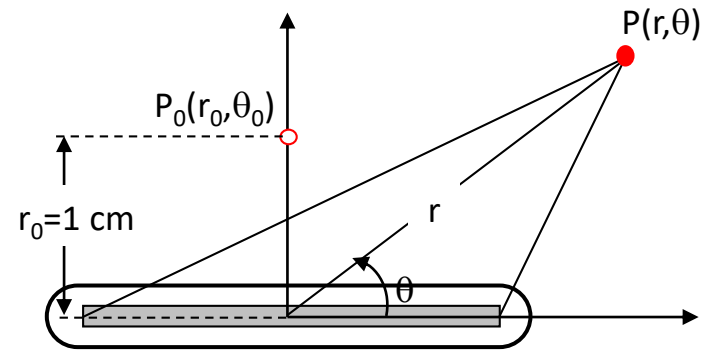
### The “Geometry Factor” $G(r, \theta)$

The “Geometry Factor”  $G(r, \theta)$ , accounts for the variation of relative dose due only to the **spatial distribution of activity within the source**, ignoring photon absorption and scattering in the source structure.

$$G(r, \theta) \equiv \frac{\int_V [\rho(\vec{r}') / |\vec{r} - \vec{r}'|^2] d\vec{r}'}{\int_V \rho(\vec{r}') d\vec{r}'} = \begin{cases} 1/r^2, & \text{for point source} \\ \frac{\beta}{Lr \sin \theta}, & \text{for line source} \end{cases}$$



# TG 43 Algorithm



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

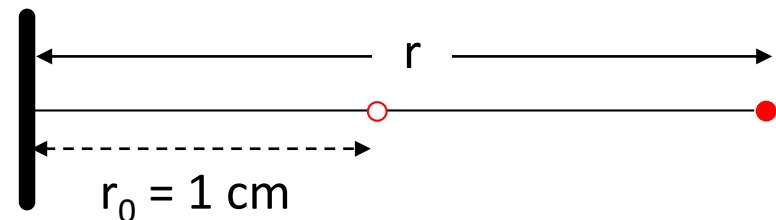
## The “radial dose function” $g(r)$ ,

The “radial dose function”  $g(r)$ , accounts for the effects of **absorption and scatter in the medium** along the **transverse axis** of the source. It depends on the source (photon energies, source design, filtration by the encapsulated material, and the source material).

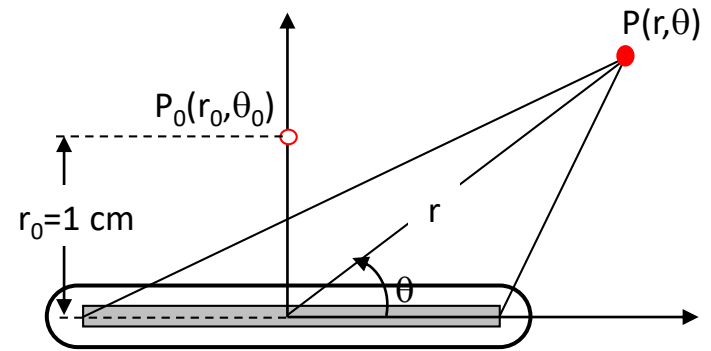
$$g(r) = \frac{\dot{D}(r, \theta_0) / G(r, \theta_0)}{\dot{D}(r_0, \theta_0) / G(r_0, \theta_0)}$$

where  $r_0 = 1 \text{ cm}$ ,  $\theta_0 = \pi/2$

source



# TG 43 Algorithm



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

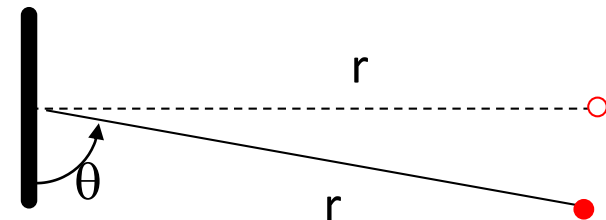
## The “anisotropy function” $F(r, \theta)$

The “anisotropy function”  $F(r, \theta)$ , accounts for the **anisotropy** of dose distribution around the source, including the effects of absorption and scatter in the medium. It gives the angular variation of dose rate at each distance due to oblique filtration through the source.

$$F(r, \theta) = \frac{\dot{D}(r, \theta) / G(r, \theta)}{\dot{D}(r, \theta_0) / G(r, \theta_0)}$$

where  $\theta_0 = \pi/2$

source



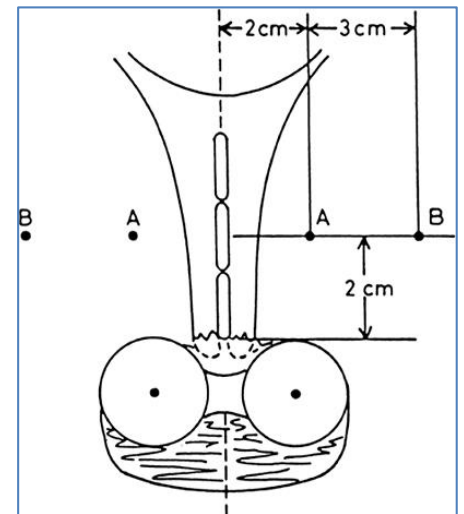
# Dosimetry systems

- The objectives of treatment planning are to determine the distribution and type of radiation sources to provide optimum dose distribution and to provide a complete dose distribution in the irradiated volume.
- It is difficult to define the dose to a point in brachytherapy since the dose varies considerably in proximity to the sources.
- It is also not always possible to accurately deliver the intended treatment because of the difficulty in positioning sources precisely in tissue.
- Therefore dosimetry systems are needed to prescribe the treatment.



# Dosimetry Systems: Intracavitary

- **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.

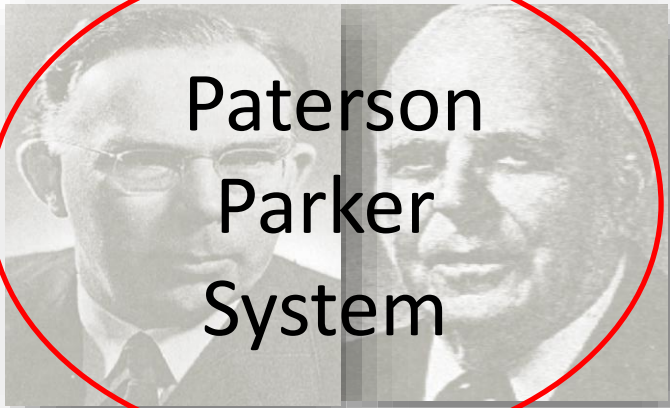


# Dosimetry Systems: Interstitial

## Classical Dosimetry Systems:

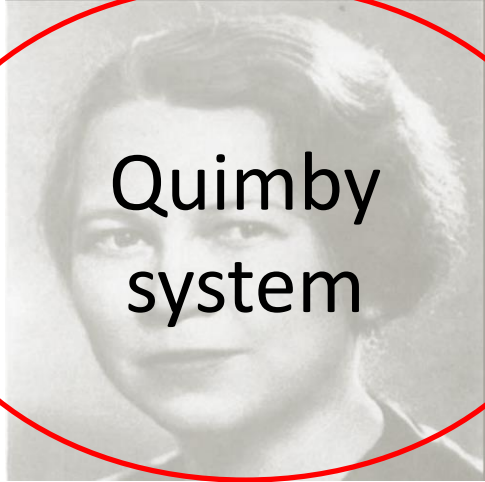
- Various pre-planning dosimetry systems had been developed for clinical use, all based on tables of total dose delivered as a function of area or volume to be treated.
- These system designed during times when computers were not available for routine planning
- Extensive table & elaborate rules of source distribution were devised to facilitate the process of manual treatment planning
- These systems differ in rule of implantation, definition of dose uniformity & method used in reference dose specification

# Classical Dosimetry Systems



## Paterson Parker System

The system specified rules of source distribution to achieve the dose uniformity (within  $\pm 10\%$  of the prescribed dose) and provided dosage tables for these idealized implants



## Quimby system

- Uniform distribution of sources of equal linear activity
- The dose in the centre of the treatment volume is higher than the dose near the periphery
- The dose value obtained from the Quimby tables represents the minimum dose within the target volume



## Paris System

Predictive implantation system was developed for interstitial brachytherapy with Iridium wire sources

# Paris System

Pierquin B, Deutrix A et al, Acta Oncologica 1978, 17:1, 33-48  
Marinello G, Radiotherapy & Brachytherapy 2009, 219-225

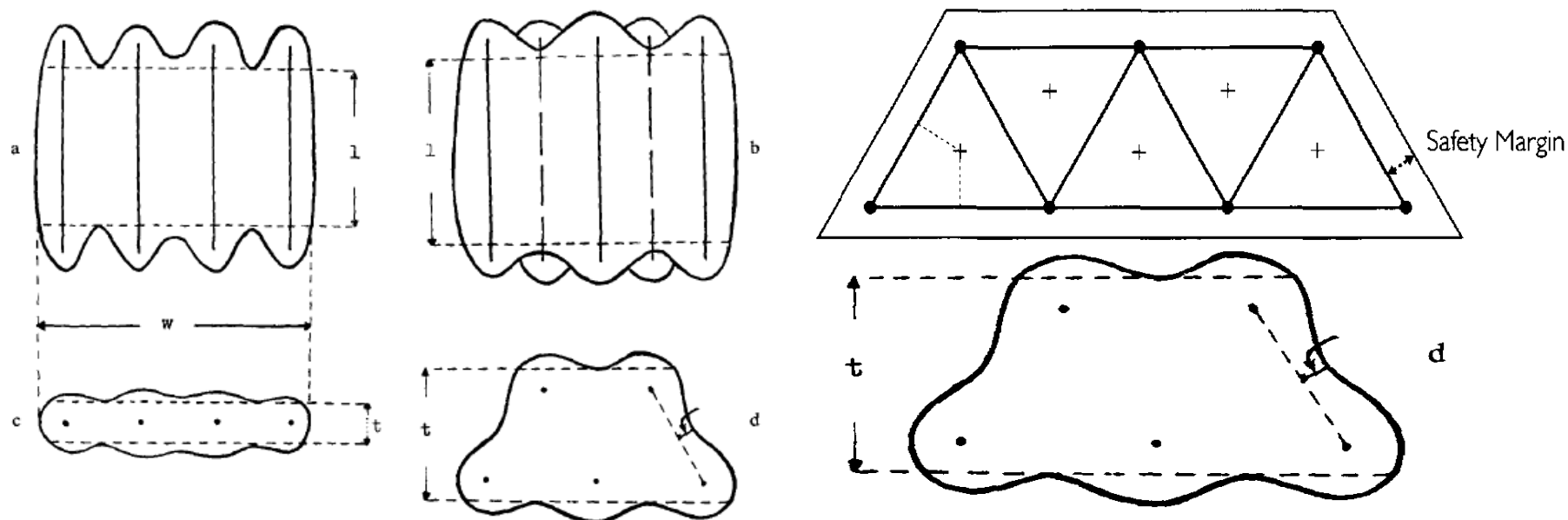
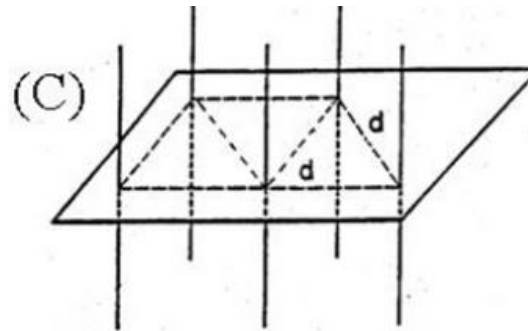
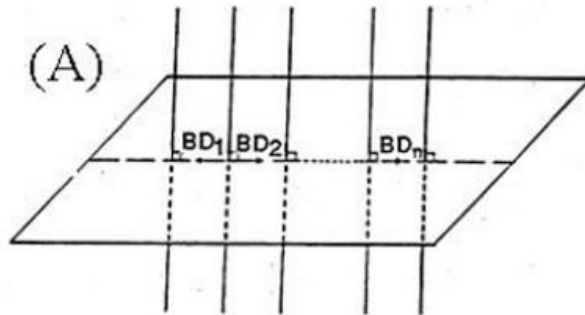


TABLE 1. Predictive relationships for rectilinear sources equal in length.

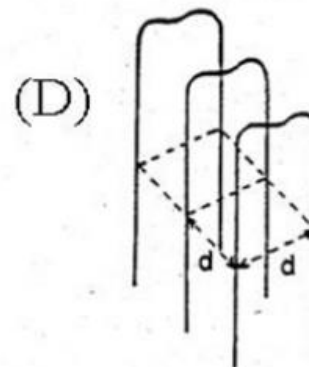
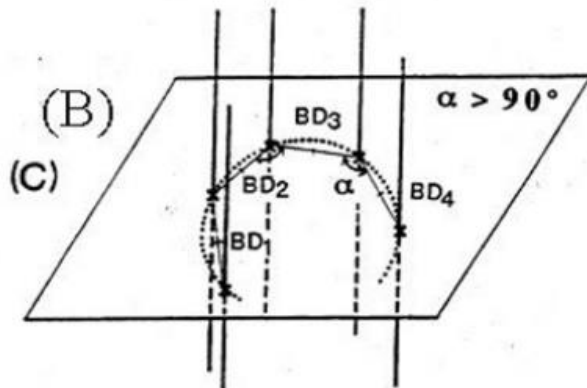
Patterns	Treated length/active length	Treated thickness/spacing	Lateral margin/spacing	Security margin/spacing
Two lines	0.7	0.5	0.37	—
N lines in one	0.7	0.6	0.33	—
N lines in squares	0.7	1.25	—	0.27
N lines in	0.7	1.33	—	0.20

# Paris system rules

- Linear activity of the sources must be uniform along the catheters
- Sources must be straight, parallel and equidistant from each other
- The centers of all the sources are contained on a single plane which perpendicularly bisects the sources



$$BD = \frac{BD_1 + BD_2 + BD_3}{3}$$



$$BD = \frac{BD_1 + BD_2}{2}$$

# Paris system rules

- **Basal dose rate** is the average lowest dose rate
- **Reference Dose Rate** is a dose which encompasses the tumour volume completely.

Defined as being 85% of the basal dose rate and is the dose rate used for calculating the total time of the implant.

- **Treatment volume** is defined as the volume enclosed by the 85% reference isodose.
- **Hyper dose Sleeve** is defined as the volume of the tissue receiving twice the reference dose rate.  
(170% of the basal dose).

# Dosimetry Systems: Computer

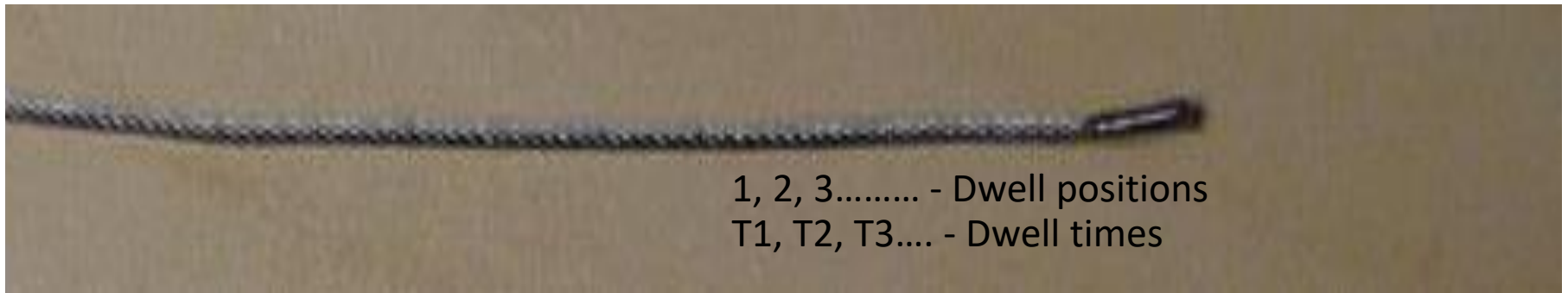
- Development of advanced treatment planning computers
- Flexibility to deviate from established dosimetry systems
- Optimize isodose distributions according to clinical needs
- Compensation for poor implant geometry may possible to some extent by optimization tools

## **Stepping Source Dosimetry System:**

- Evolution of HDR & PDR systems
- High activity, single, miniaturized source

# Stepping source dosimetry system (SSDS)

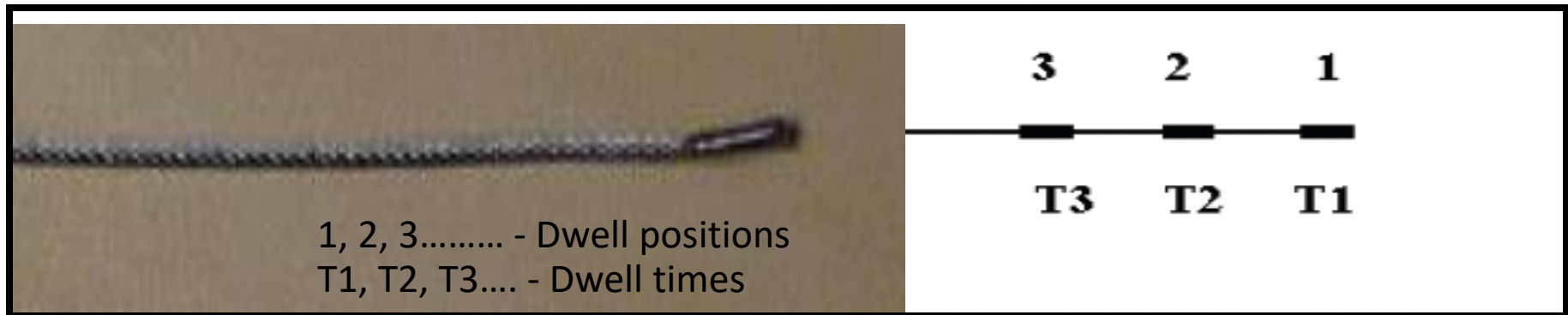
- Used in current Treatment Planning System which is adapted from Paris system for interstitial brachytherapy.
- SSDS uses the same implant rules as the Paris Dosimetry System.





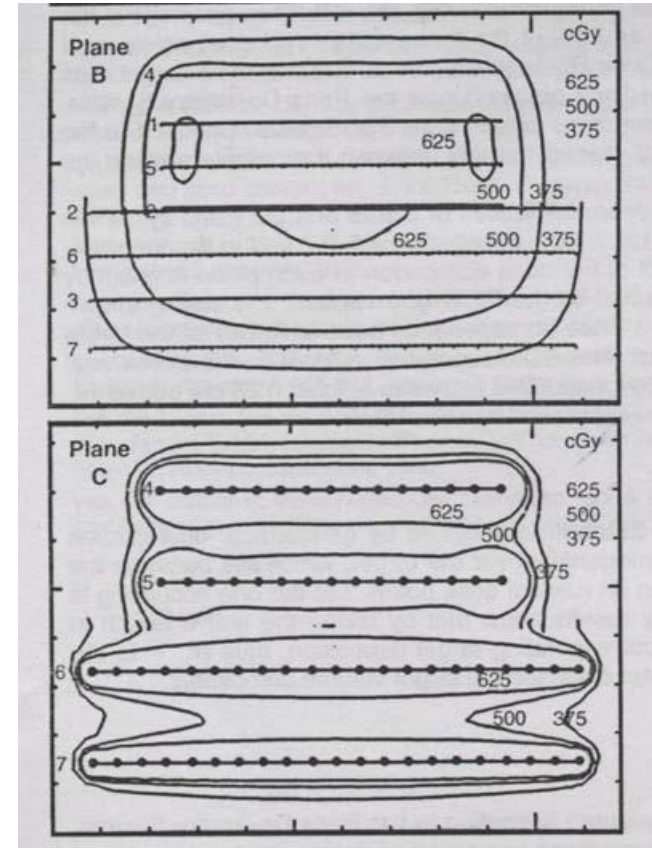
# Stepping source dosimetry system (SSDS)

- Stepping source technology with dwell-time optimization with HDR source
- 3D conformal brachytherapy - Image-based, allow defining the target volume independent of the implant and evaluate the implant dosimetry according to the volume.



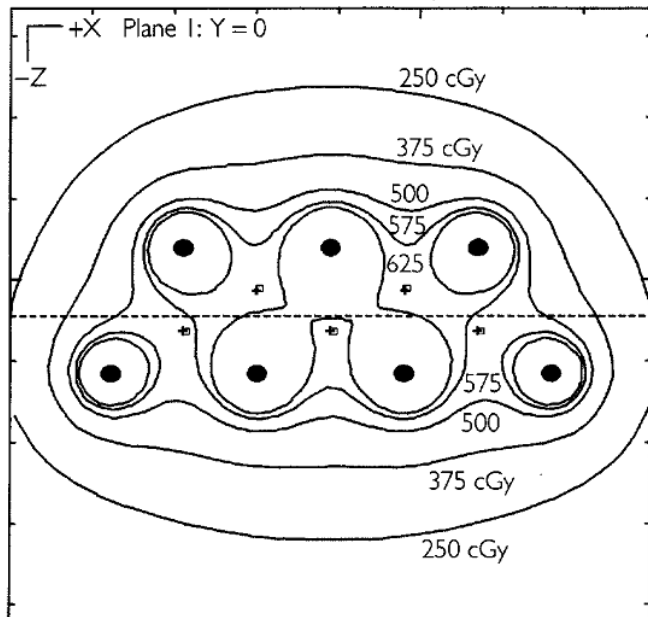
# Paris dosimetry system (PDS) Vs SSDS

- **Active lengths** in PDS outside the Target compensate the dose fall off, whereas increased dwell times at outer ends compensate for the same in SSDS.
- **Homogeneity**: Poor Homogeneity in PDS due to same active lengths, Superior homogeneity due to optimization in SSDS.
- **Reference Dose**: In PDS RD is the mean value of all BD points in central plane, in SSDS RD is the mean dose of all dose points in the implant.

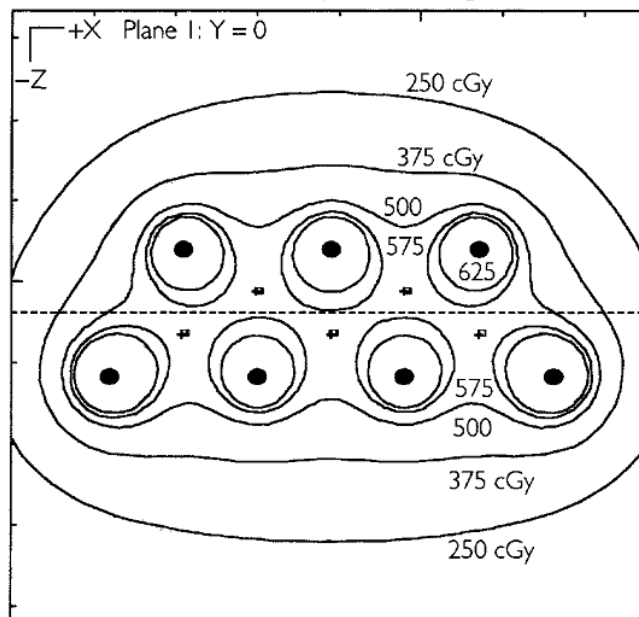


**SSDS vs Paris system**

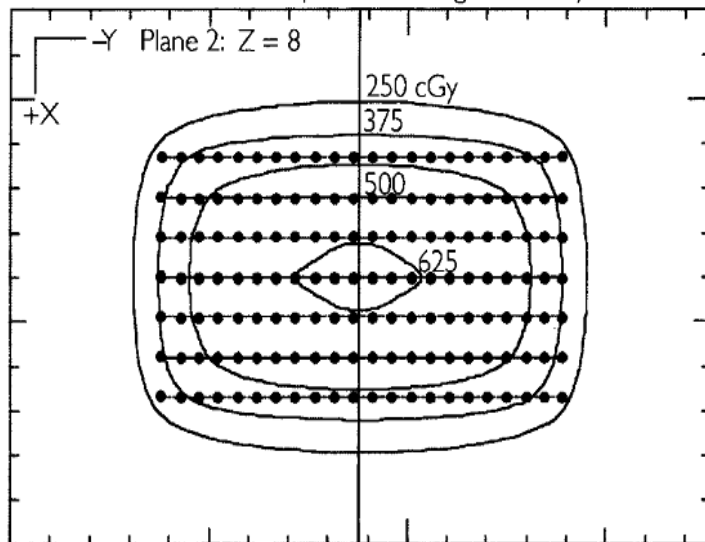
Two-Plane Breast Implant according to Paris System



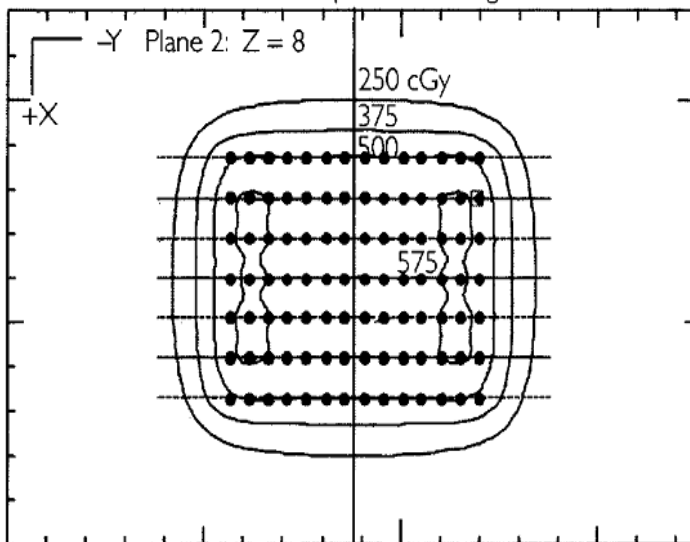
Two-Plane Breast Implant according to SSDS



Two-Plane Breast Implant according to Paris System



Two-Plane Breast Implant according to SSDS



# Optimization in SSDS

- Optimization in high dose rate brahytherapy is the technique in which a uniform dose distribution is achieved by adjusting the dwell time of the stepping source in each dwell position

## Un-optimized plan:

- In this the dwell time of the stepping source in each dwell position is the same

# Dose Optimization objectives

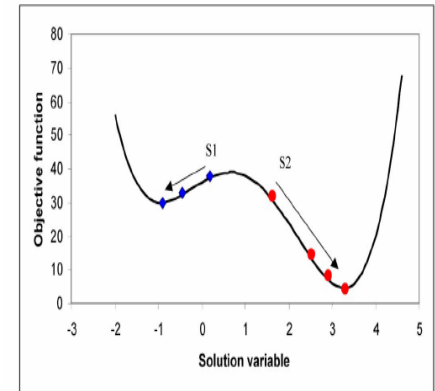
- Reference isodose surface should pass as closely as possible to the assigned dose points (dose conformality)
- Dose midway between the catheters should be as homogeneous as possible, throughout the implant (dose uniformity)
- Hyperdose sleeve as small as possible (less hot spots)
- Active dwell positions confined within the target volume (conformal avoidance)

# Optimization techniques

## ■ Non Stochastic (deterministic/forward):

Fast, but cannot escape from local minima.

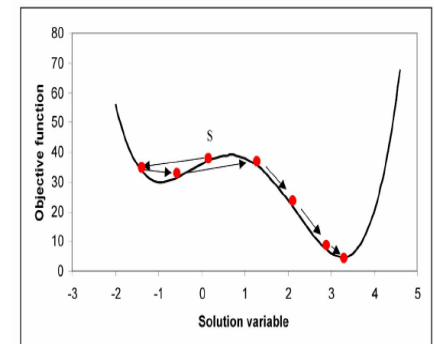
- Dose Point optimisation
- Geometric optimisation
- Manual optimisation
- Graphical optimisation



## ■ Stochastic (probabilistic/inverse):

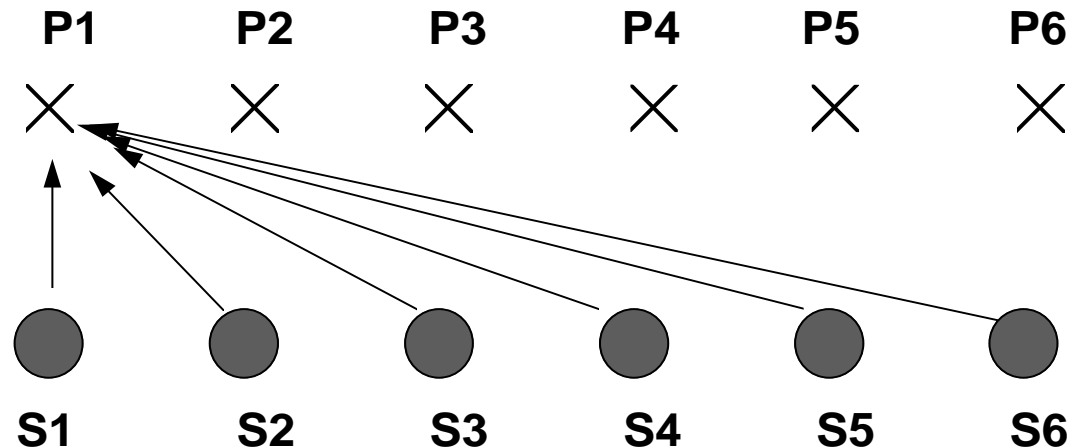
Use randomness in the search process,  
Slower, Can escape from local minima

- IPSA



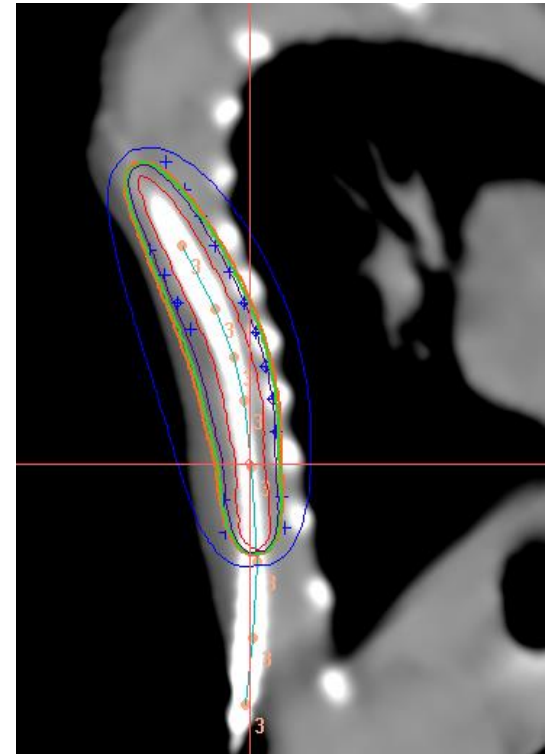
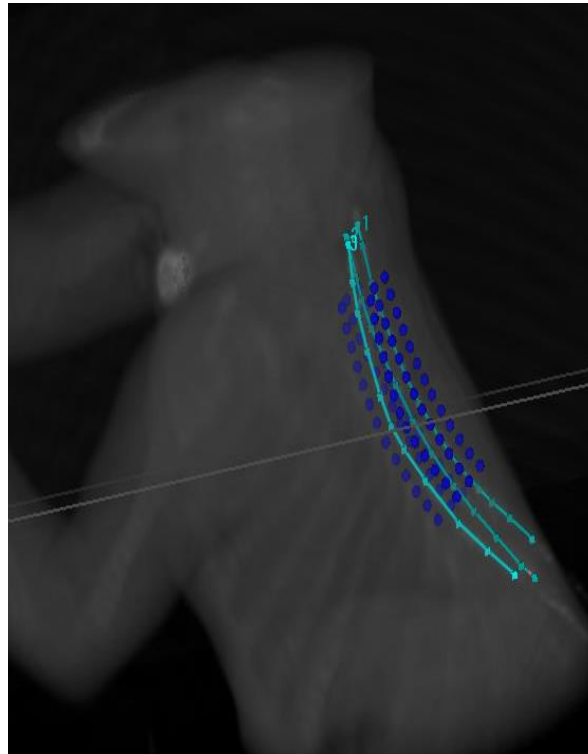
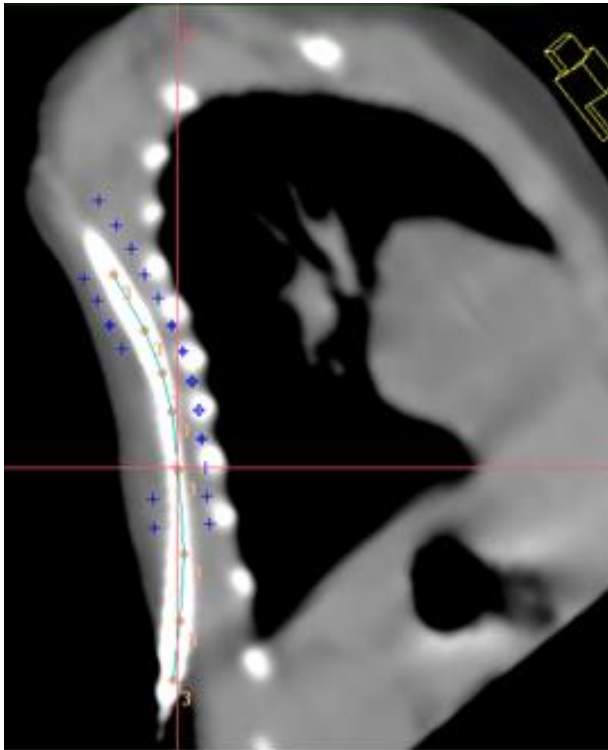
# Dose point optimization

- Number of dose points defined along the axis of catheters at a constant distance from each dwell position
- Done on **single plane implant or surface mould brachytherapy** where an isodose surface required at a given distance from the catheters



# Dose point optimization

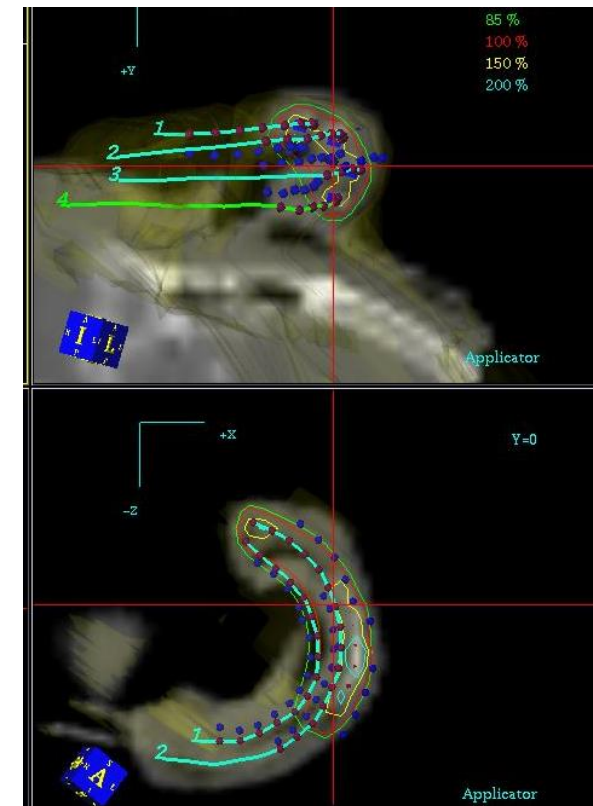
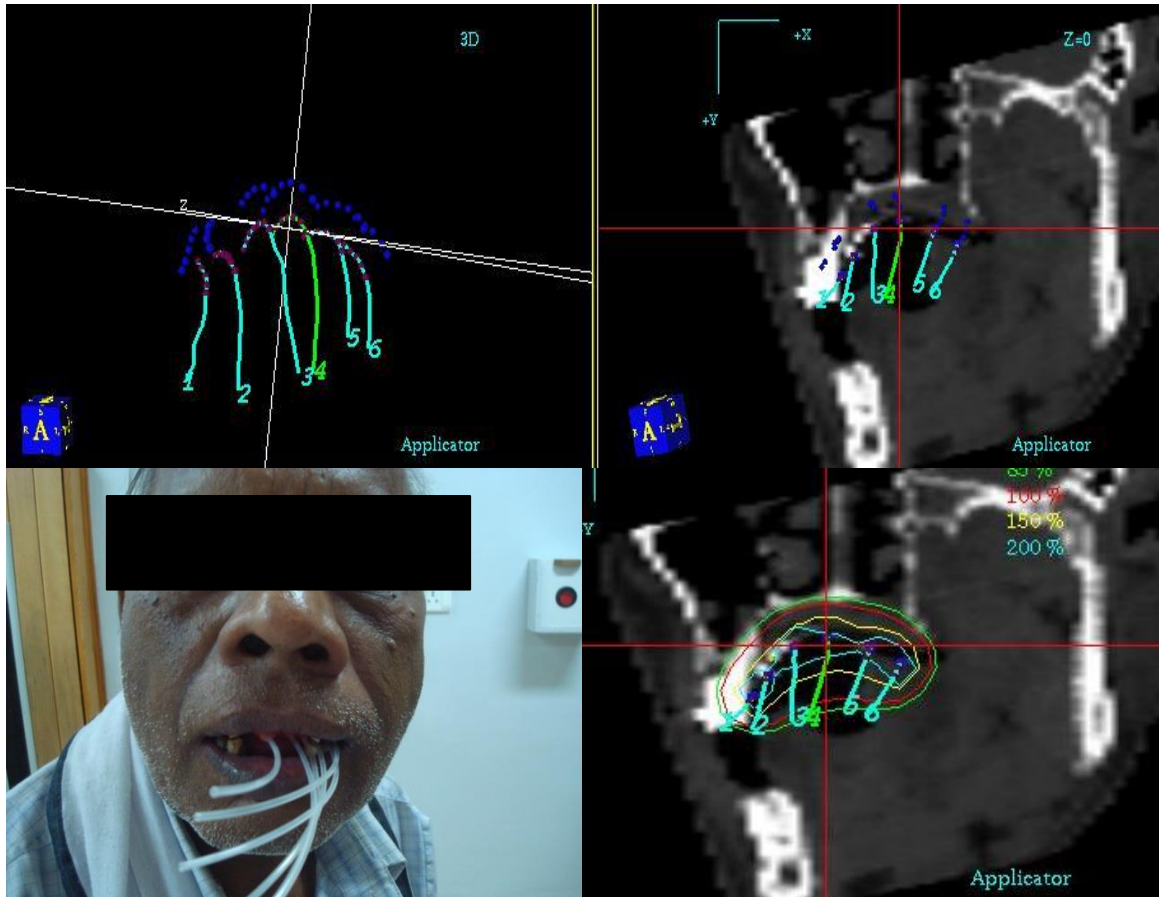
- Soft tissue sarcoma





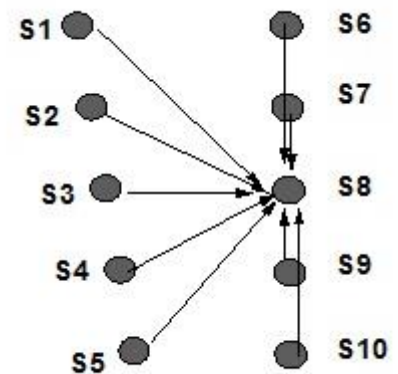
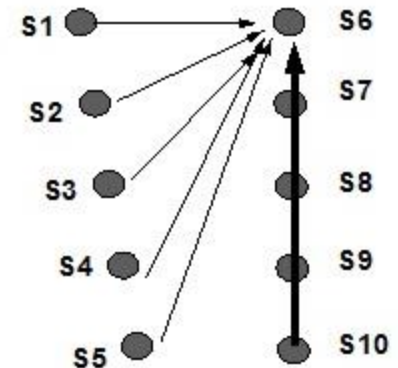
# Dose point optimization

## Surface mould brachytherapy



# Geometric Optimization

- This is a catheter oriented optimization
- It's goal is to homogenize the dose distribution around the catheters.
- Uses dwell positions themselves as dose point so as to give uniform dose in the vicinities around each dwell positions.
- Optimized dwell time in a given dwell position is mainly determined by dose contribution from its nearest neighbors.

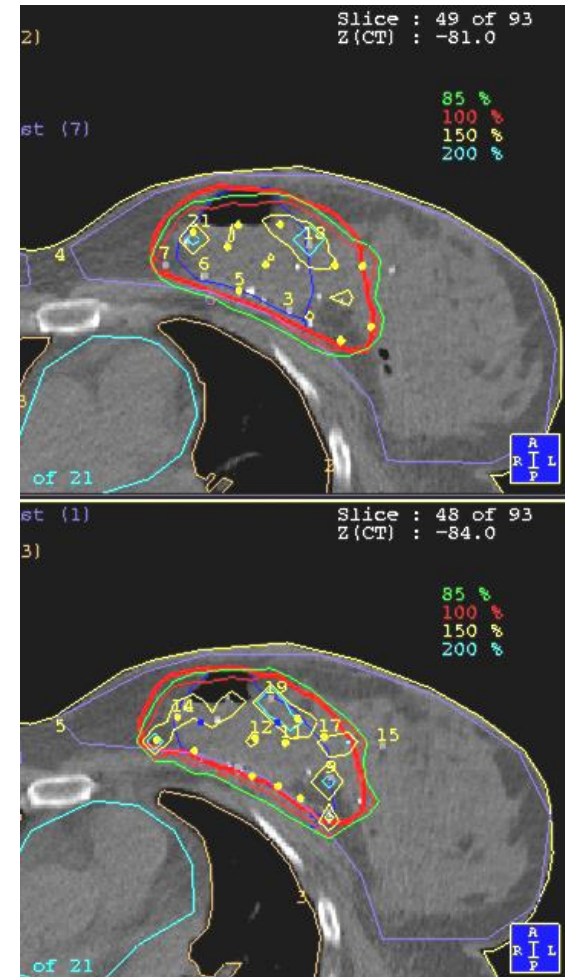


- **Distance optimisation:**
  - **Adjacent dwell positions along same catheter** track can produce greatest effect on dwell weights resulting in isodose surfaces that tend to follow the catheters rather than conform to the shape of implanted volume as a whole.
- **Volume optimisation:**
  - **Neglects dwell positions along same catheter** when calculating dwell weights in a given catheter.
  - Tends to spread the doses along implanted volume
  - Volume mode is used to fill in the gap b/w diverging catheters and Distance mode is used to get a homogenous dose distributions along the catheters

# Graphical Optimization

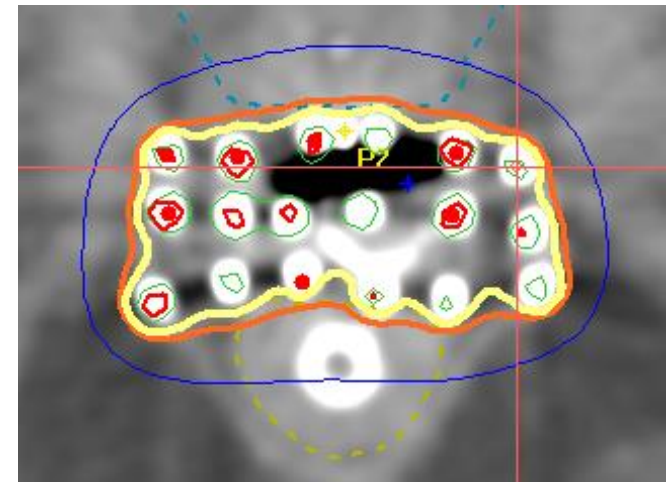
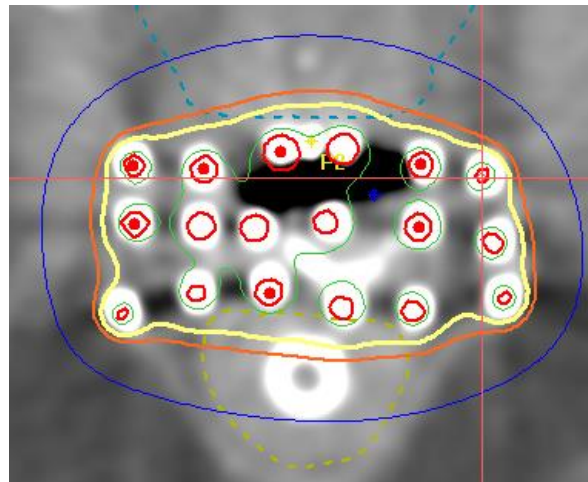
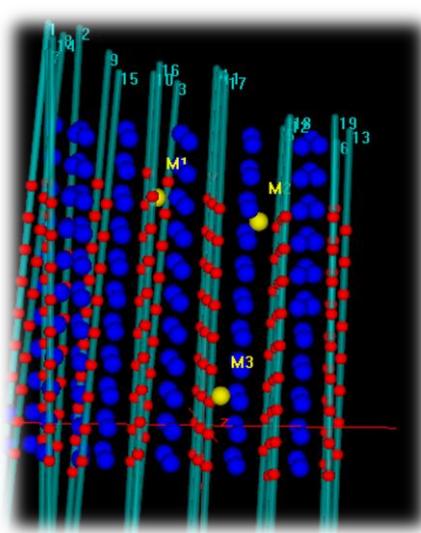
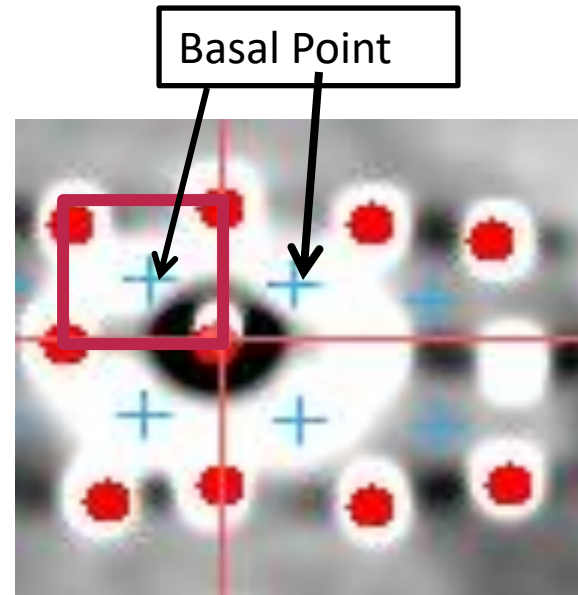
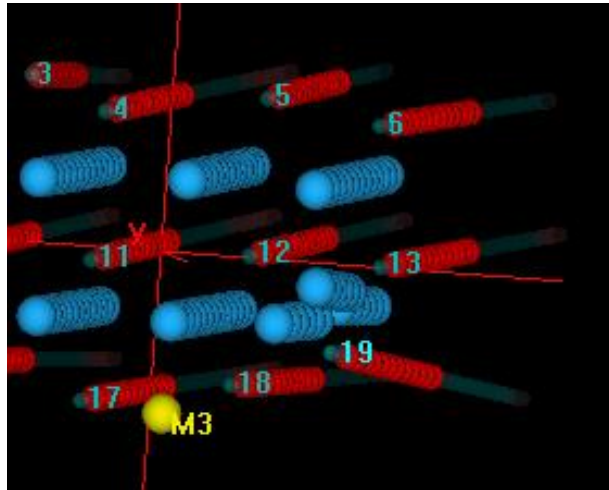
- Allow **interactive changes** in the isodose lines by automatic adjusting the dwell weight/time of the specific dwell positions
- User defines the shift/change of isodose line by dragging isodose line with the mouse.
- The ***Global / Local*** regulator defines the degree of locality for these adjustments. (only very close neighbouring dwell positions or also far neighbouring dwell positions).

**Sharma SD, Budrukkar A, Upreti RR *et al.*. Clin Oncol 2008;20: 46-52**





# No optimization Vs Optimization for MUPIT

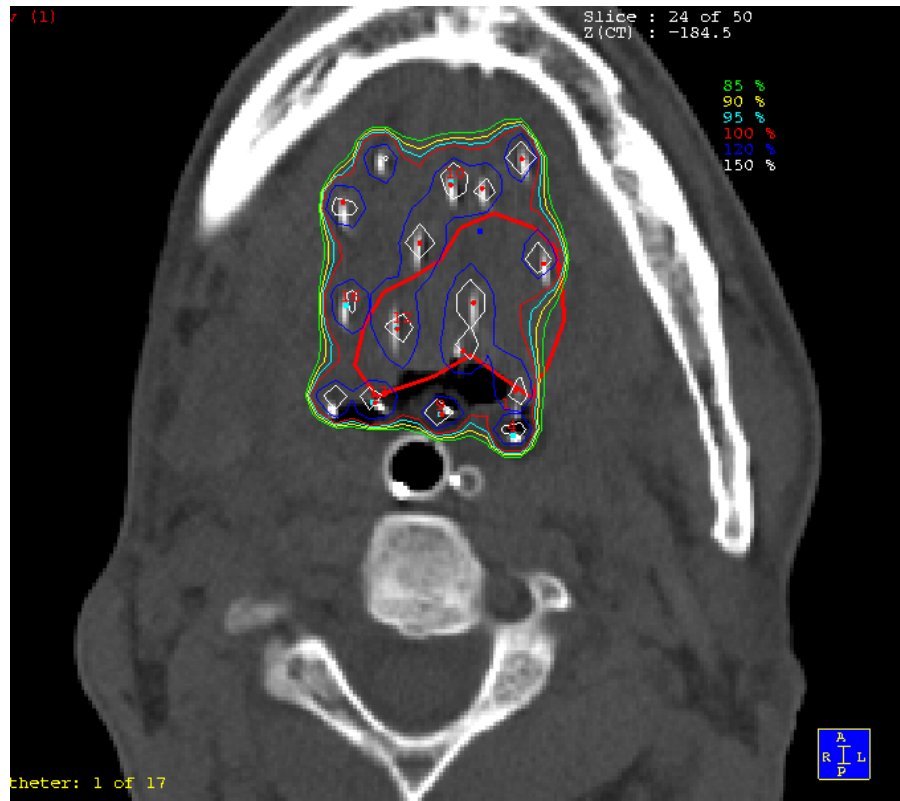


No optimization

With optimization

# Geometrical Vs Graphical optimization

## Geometric optimization



## Graphical optimization



Graphical Optimization should be used with caution

May result in a unacceptable distribution & hot spots

# Brachytherapy Reporting

ICRU REPORT 38

**Dose and Volume  
Specification for  
Reporting Intracavitary  
Therapy in Gynecology**

ICRU REPORT 58

**Dose and Volume  
Specification For  
Reporting  
Interstitial Therapy**

ICRU REPORT No. 89

**PRESCRIBING, RECORDING, AND  
REPORTING BRACHYTHERAPY FOR  
CANCER OF THE CERVIX**



# Quality Assurance in brachytherapy

- QA of HDR unit
  - Source calibration
  - Source positioning
  - Timer accuracy
  - Room and treatment unit surveys
  - Interlock & indicator light checks
  - Audiovisual device checks
- QA of treatment planning system
- QA of patients procedure

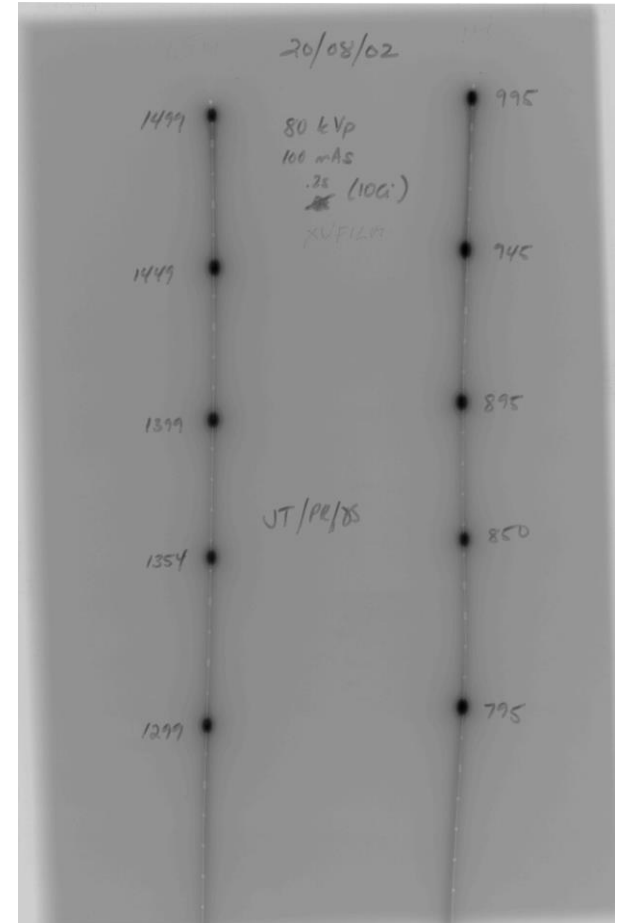
# Source calibration



**Reference Air Kerma Rate**  
**Air Kerma Strength**

# Source positioning

- The position of sources placed within afterloading devices can be determined with autoradiographs.
- The use of appropriate radiographic markers and combination of a radiographic image with an autoradiograph are convenient methods for checking source positioning.



# QA of Brachytherapy TPS

- Input parameters : Source Coordinates, Dose points, etc.
- Reconstruction accuracy
- Manual verification
- Test cases
- Periodic activity checks

# Quality Assurance check list before the HDR brachytherapy treatment

- Proper selection of the patient and verification of all planning parameters
- System checks
- Accuracy of date & time of the system
- Accuracy of source strength & decay correction
- Functionality of Safety interlocks, warning lights, CCTV Camera, Zone monitor etc
- Availability of Emergency procedures
- Availability emergency container

# Summary

- Rapid fall off the dose beyond target volume results in the lesser integral doses and better OAR sparing in brachytherapy compared with external beam radiotherapy
- High specific activity, optimum gamma energy and pure gamma emitter are the desirable characteristics for brachytherapy source
- Source strength is specified in reference air kerma rate in SI units
- Model based dose calculation algorithms are now available for modern brachytherapy TPS

# Summary

- Stepping source technology with dwell-time optimization with HDR source provides various optimization tools in modern brachytherapy TPS.
- Graphical Optimization should be used with caution and may result in an unacceptable distribution & hot spots
- Quality assurance in brachytherapy is essential to prevent any incidence with radioactive sources.
- ICRU reports are the guiding documents for the prescribing, recoding and reporting the intracavitary and interstitial brachytherapy.