UNIVERSITY of MARYLAND
SCHOOL OF MEDICINE

Brachytherapy

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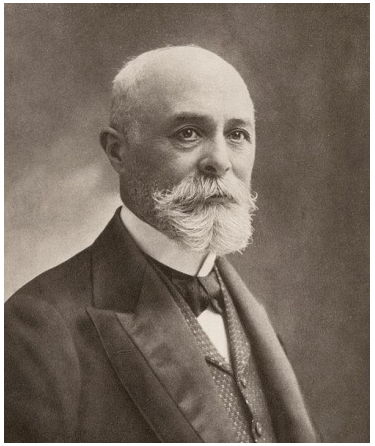
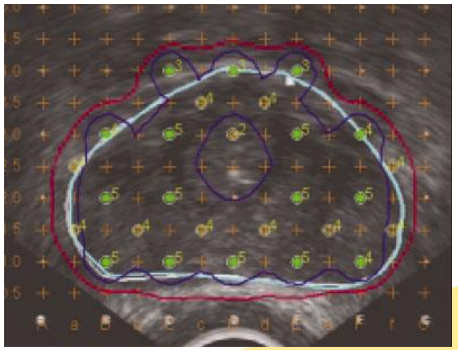
History



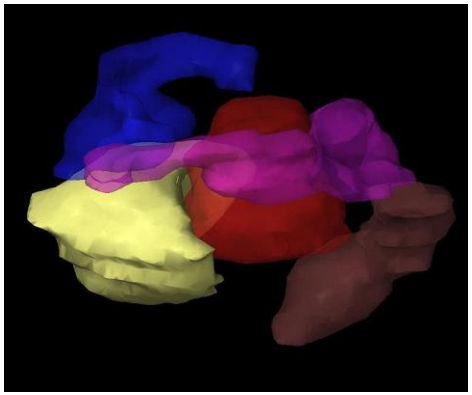
1896: Radioactivity Discovered by Henri Becquerel

1901: First use of Brachytherapy by Pierre Curie

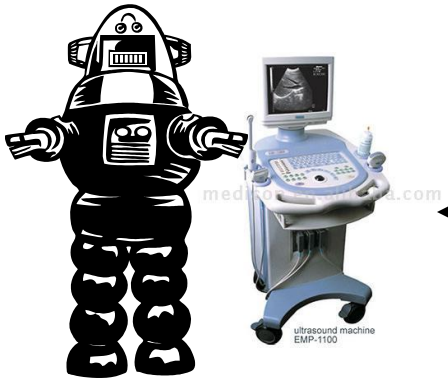
1970's: Remote afterloader was introduced



1990's: 3D imaging Brachytherapy



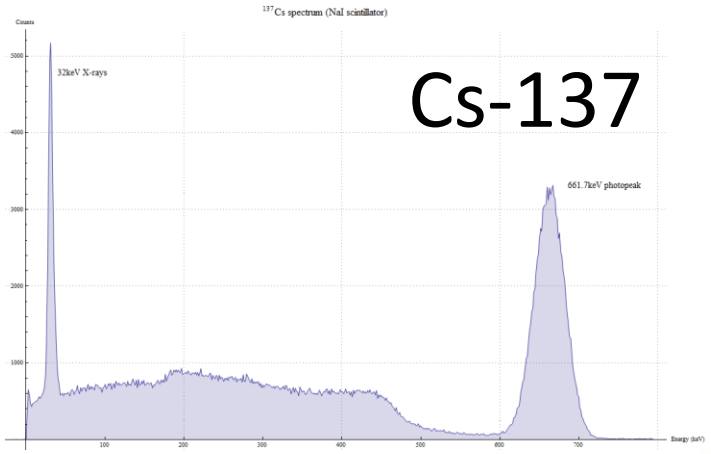
2000's: Virtual treatment planning introduced

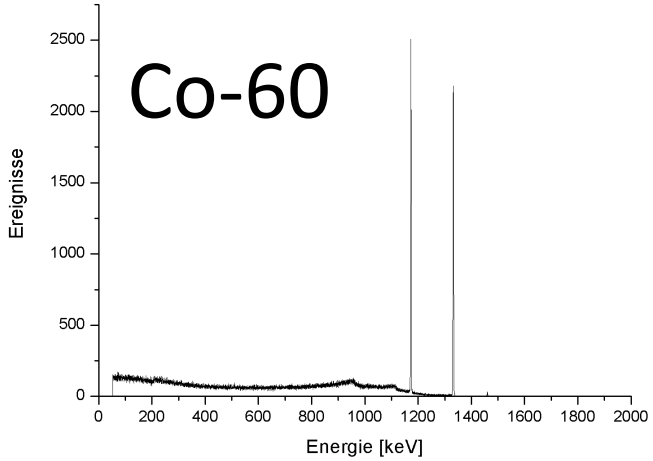


2005: Robot assisted prostate implant

Physical Concepts: Energy

- **Unit: keV or MeV**
- **Range: ~20 keV to 1 MeV (Co-60 → 1.17 MeV and 1.33 MeV)**
- **Mostly continuous energy distribution (except Co-60 is dual energy)**

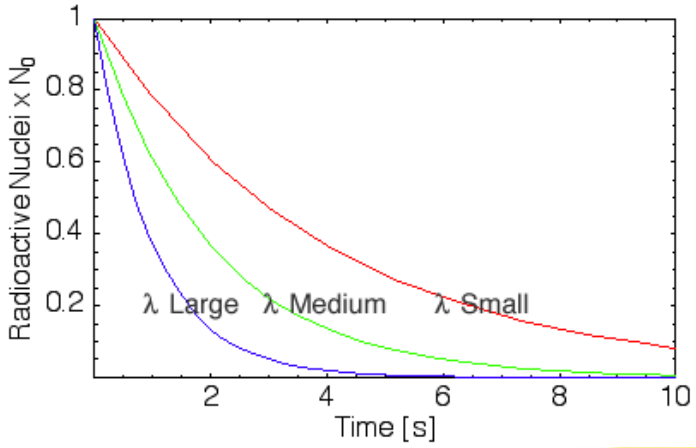


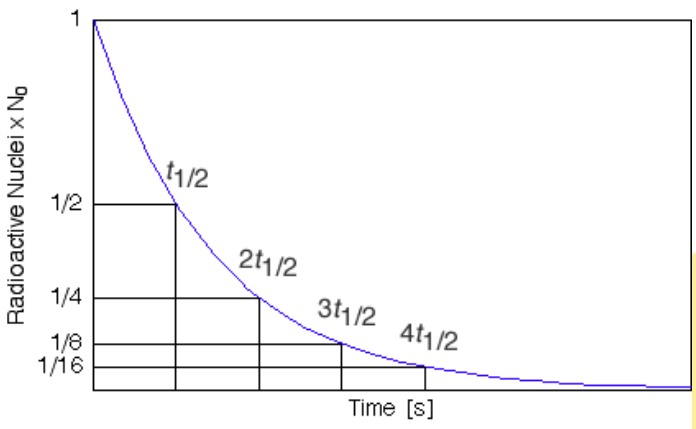


Physical Concepts: Half-Life ($t_{1/2}$) and Decay Constant (λ)

- **Half-Life ($t_{1/2}$): Time required for a quantity (either activity or number of radioactive nucli) of the source to fall to half of its original quantity.**
- **Decay Constant (λ): Rate which the radioactive nucli decays.**

$$t_{1/2} = \frac{\ln 2}{\lambda}$$





Physical Concepts: Radioactive Decay

- **Process by which a nucleus of an unstable atom loses energy by emitting particles of ionizing radiation.**
- **Can be described using decay constant value and/or half-life**

$$N = N_0 e^{-\lambda t}$$

$$\lambda N = \lambda N_0 e^{-\lambda t}$$

$$A = A_0 e^{-\lambda t} = A_0 2^{-t/t_{1/2}}$$

Physical Concepts: Half-Value Layer (HVL)

- The thickness of a specific material which attenuates the beam of radiation to half of its original intensity.
- Unit: physical distance
- ↑Energy = ↑ HVL
- For a given energy, ↑ Density = ↓ HVL

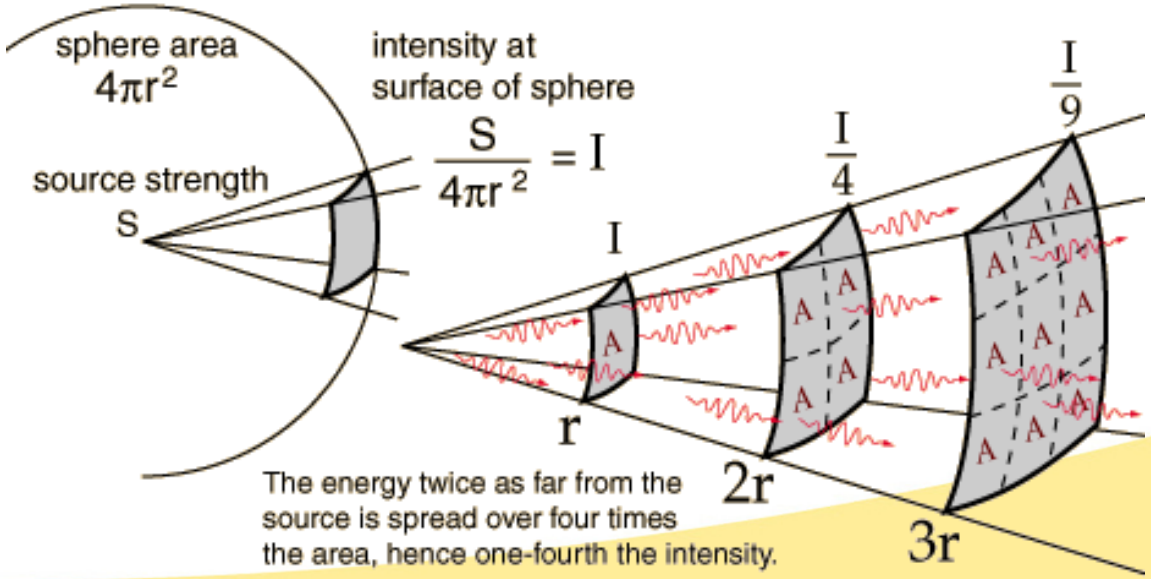
Radioactive Nuclide	Energy (MeV)	HVL		
		Lead	Steel	Concrete
Co-60	1.17, 1.33	0.47”	0.83”	2.6”
Cs-137	0.662	0.28”	0.63”	1.9”

Physical Concepts: Source Strength

- **Activity (Ci):** Number of decays per unit time
- **Air-Kerma (S_K):** quantity which quantify the kinetic energy transferred to electron in air at a distance.
  - Unit: μGym^2h^{-1}
  - 1 U = 1 $\mu Gy \cdot m^2 \cdot h^{-1}$ = 1 $cGy \cdot cm^2 \cdot h^{-1}$
  - Preferred source strength description
- Exposure Rate at a distance
- Equivalent Mass of Radium
- Apparent Activity: The activity of a bare point source at 1 meter.

Physical Concepts: Inverse Square Fall-Off

- **The intensity of the radiation coming out from the radioactive source decreases by inversely proportional to the square of the distance from the source.**
- **Biggest effect on dose distribution**

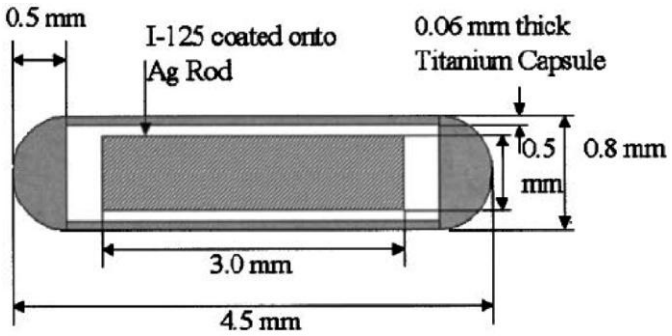


Typical Brachtherapy Source Types and Characteristics

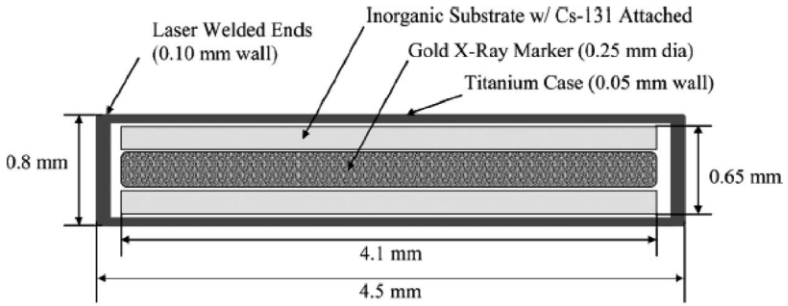
	Radionuclide	Half-Life	Photon Energy (MeV)	Half-Value Layer (mm lead)	Exposure Rate Constant ($Rcm^2/mCi\text{-}hr$)
High Energy (Temporary Implant)	^{226}Ra	1600 yr	0.047-2.45 (0.83 avg)	12.0	8.25 ($Rcm^2/mg\text{-}h$)
	^{222}Rn	3.83 days	0.047-2.45 (0.83 avg)	12.0	10.15
	^{60}Co	5.26 yr	1.17, 1.33	11.0	1307
	^{137}Cs	30.0 yr	0.662	5.5	3.26
	^{192}Ir	73.8 days	0.136 – 1.06 (0.38 avg)	2.5	4.69
Low Energy (Permanent Implant)	^{198}Au	2.7 days	0.412	2.5	2.38
	^{125}I	59.4 days	0.028 avg	0.025	1.46
	^{103}Pd	17.0 days	0.021 avg	0.008	1.48

Source Constructions

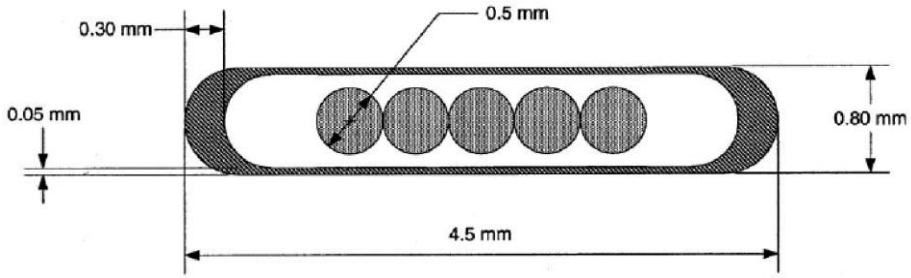
- **Usually double encapsulated and serve multiple purpose**
  - **Contains the radioactivity**
  - **Provides source rigidity**
  - **Absorbs alpha and beta**



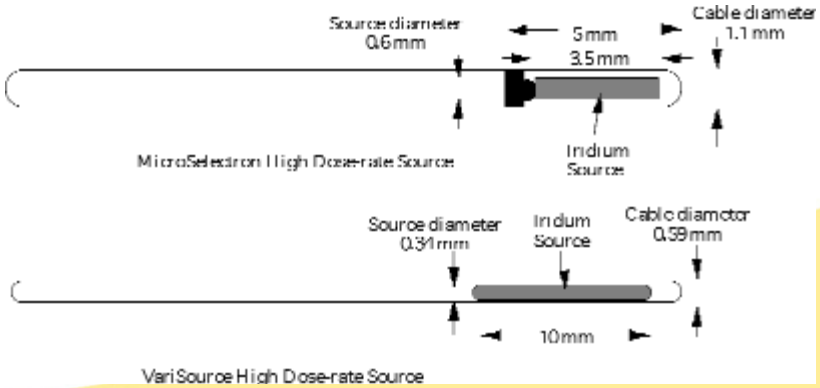
I-125



Cs-131



Pd-103



Ir-192

Brachytherapy Classification

Dose Rate	Dose Rate Range	Implant Type
Low Dose Rate (LDR)	0.4 – 2 Gy/hr	Permanent
Medium Dose Rate (MDR)	2 – 12 Gy/hr	
High Dose Rate (HDR)	> 12 Gy	Temporary

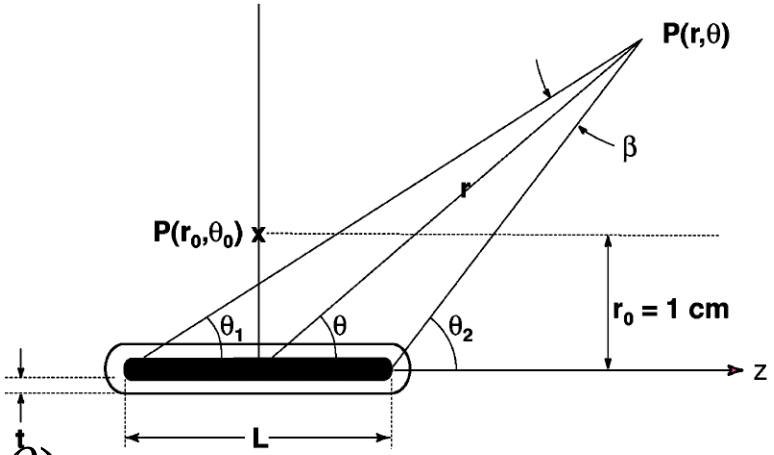
Source Calibration

- **Source calibration is a process of measuring (Well Chamber) the strength of the sources and validating that the stated source strength by the manufacturer is within a clinically acceptable level.**
  - **AAPM TG-40: within 3% of batch mean and maximum 5% deviation from mean.**
  - **Institution is responsible for verification of manufacturer calibration using ADCL calibrated instrumentation**

Source Calibration

- **LDR:**
  - **User's well chamber is calibrated by ADCL based on a specific source type (e.g., I-125) and model (BEST model 2301)**
  - **All the sources for calibration are NIST traceable.**
- **HDR (Ir-192):**
  - **User's well chamber is calibrated by ADCL using one of two Ir-192 source models (Nucletron or Varian)**

TG-43 Dose Calculation Formalism (2D)



$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_o,\theta_o)} \cdot g_L(r) \cdot F(r,\theta)$$

$\dot{D}(r,\theta)$ = *Dose rate to water at point P(r,θ)*

S_K = *Air Kerma Strength (1U = 1 μGy m² h⁻¹ = 1 cGy cm² h⁻¹)*

Λ = *Dose-rate constant (Ratio of dose rate @ reference position in water and air kerma)*

G_L = *Geometry function (inverse square fall off)*

g_L = *Radial dose function (accounts for scattering and attenuation)*

$F(r,\theta)$ = *2D anisotropy function*

NO heterogeneity correction exist within the dose calculation formalism.

TG-43 Dose Calculation Formalism (2D): Geometry Function

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_o,\theta_o)} \cdot g_L(r) \cdot F(r,\theta)$$

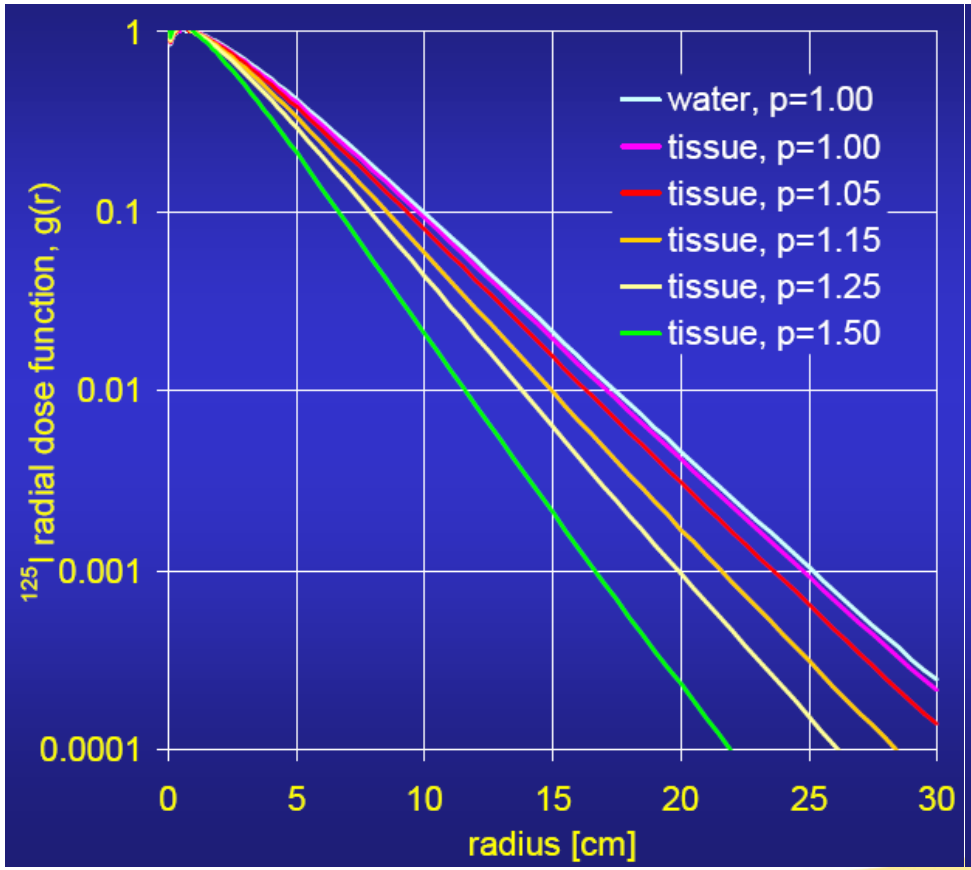
$$G_L(r,\theta) = \begin{cases} \dfrac{\beta}{Lr\sin\theta} & \text{If } \theta \neq 0^o \\ \dfrac{1}{r^2 - \dfrac{L^2}{4}} & \text{If } \theta = 0^o \end{cases}$$

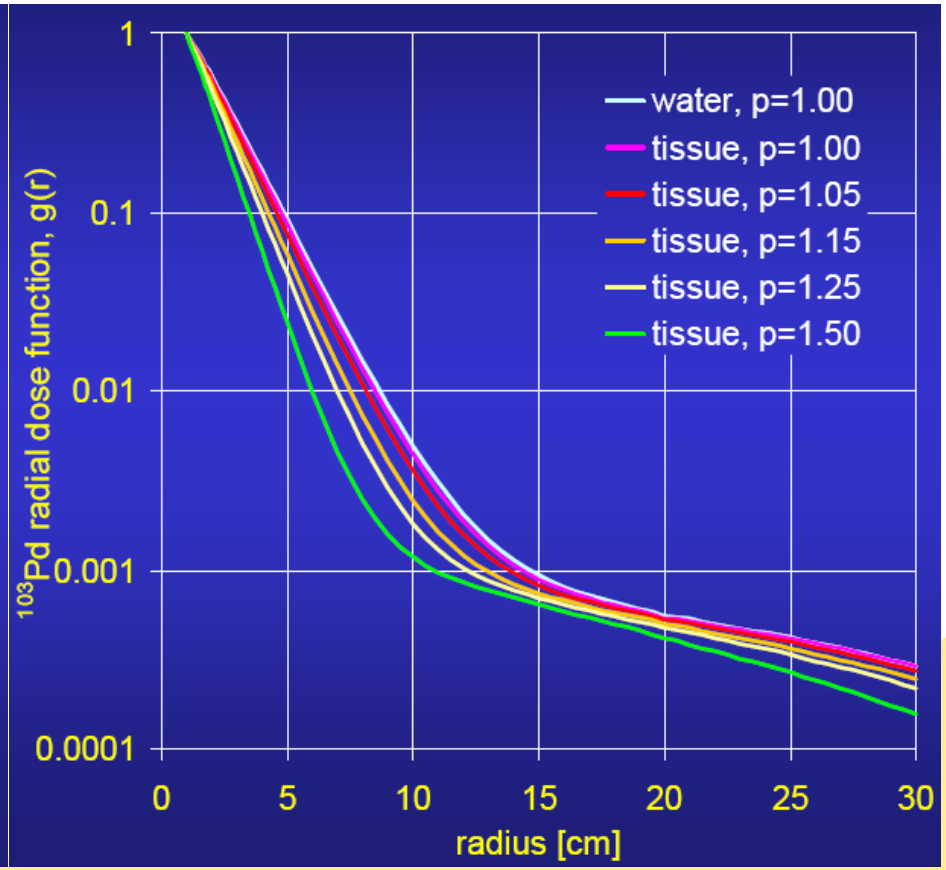
r_o = 1 cm

θ_o = 90°

TG-43 Dose Calculation Formalism (2D): Geometry Function

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_o,\theta_o)} \cdot g_L(r) \cdot F(r,\theta)$$

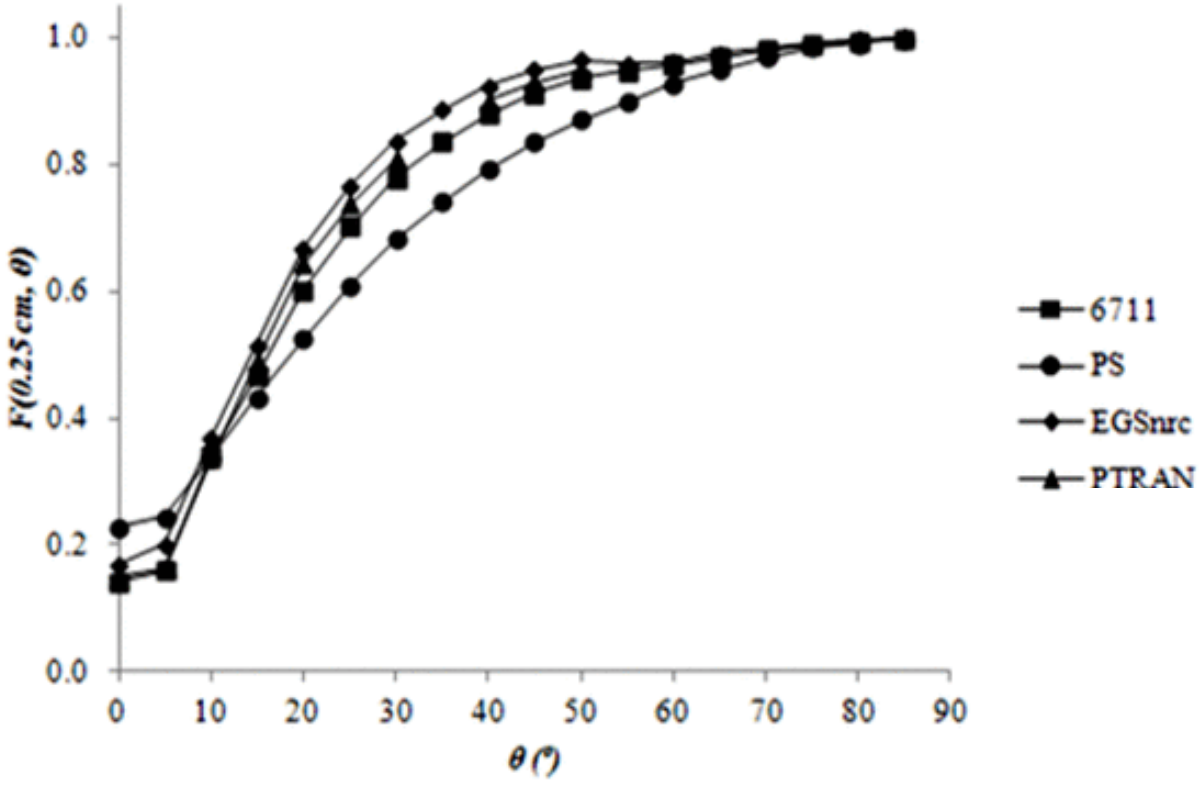


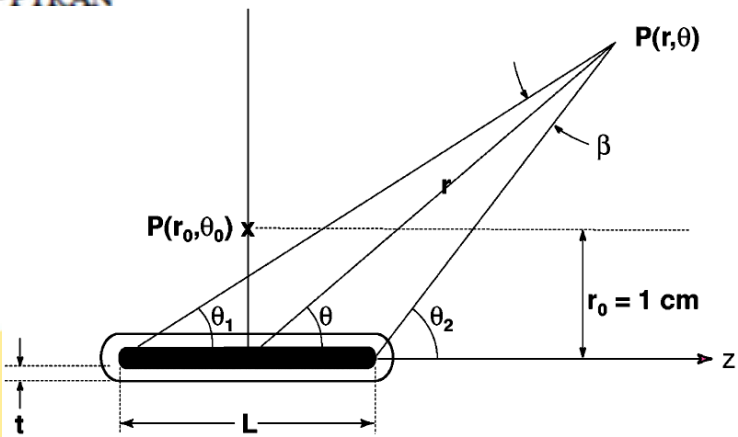


Mark Rivard et al., 2004 TG43 update presentation.

TG-43 Dose Calculation Formalism (2D): Geometry Function

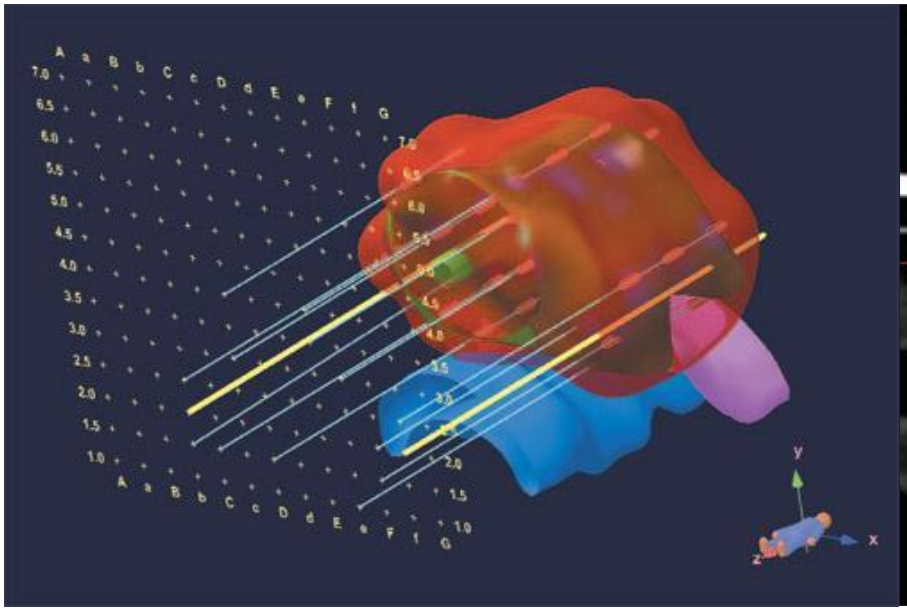
$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(r_o,\theta_o)} \cdot g_L(r) \cdot F(r,\theta)$$



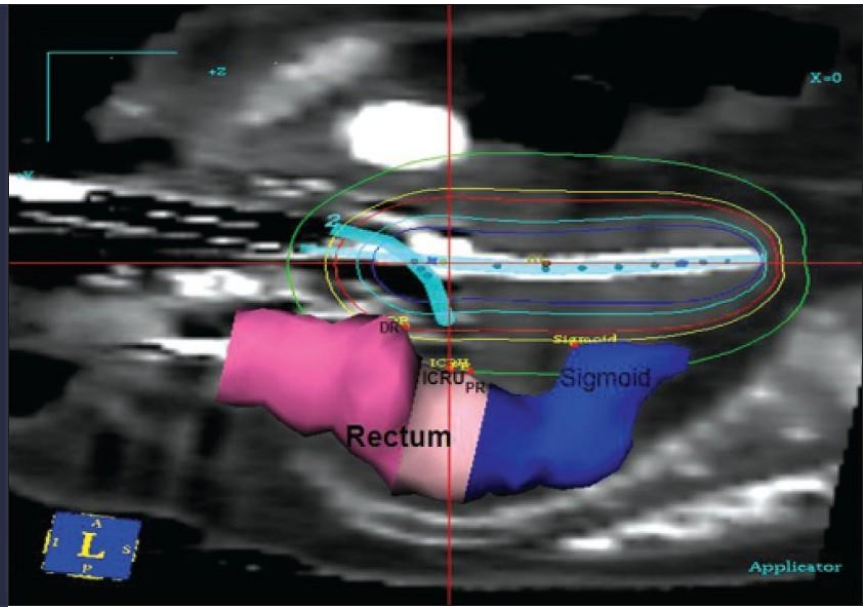


Paixao et al, Monte Carlo study of a new I-125 brachytherapy prototype seed with a ceramic radionuclide carrier and radiographic marker, JACMP, Vol, No 3 (2012)

Implantation Techniques



Interstitial



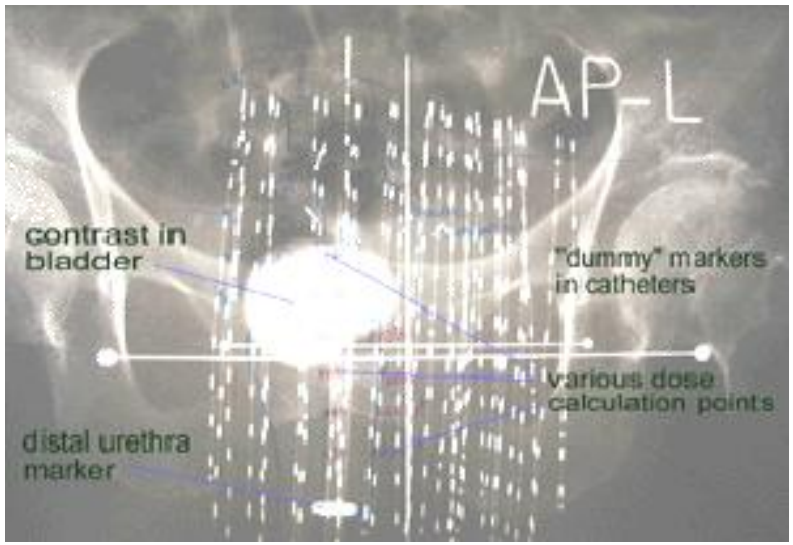
Intracavitary

Implantation Techniques: Interstitial

- Radioactive sources are fabricated in the form of needles, wires, or seeds, which can be inserted directly into the tissue.
- Two types
  - Temporary: Sources removed after the desired dose has been delivered (GYN, H&N, Breast, and etc)
  - Permanent: Sources are left in the tissue (Prostate)

Interstitial Implant

- **Major improvements with remote afterloader.**
  - **Eliminates exposures to the staffs and to the public**
  - **“Dummy” sources are used for radiographic localization and dosimetry.**



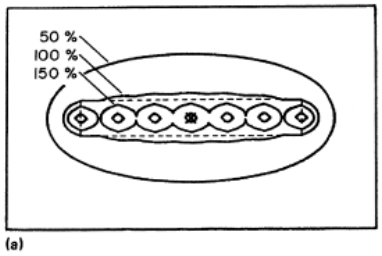
Early Practice of Interstitial Brachytherapy

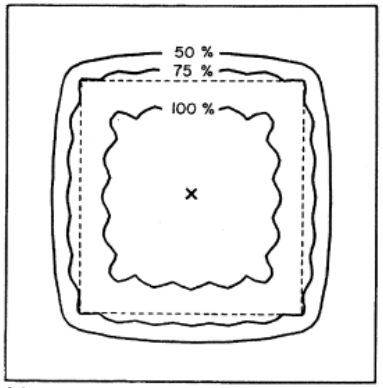
- **Quimby system (1932):** a uniform source distribution to produce a non-uniform dose distribution
- **Manchester system (1934):** a.k.a Paterson and Parker system is arranged in a non-uniform patter to obtain a uniform dose distribution.
- **Paris system (1960):** Modification from Manchester system which variable source placement to obtain a uniform dose distribution
- **These systems are guide to radiation oncologist. If the sources were arranged according to the rules of the system, then the oncologist had a good sense of the resultant dose distribution and could provide consistency in patient care.**

Quimby System

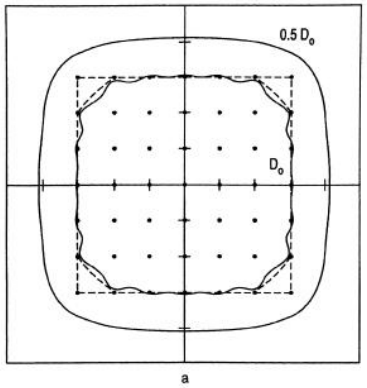
- **Assumes equally spaced array of uniform Radium-226 source activities and shows the exposure rates at various distance from the source plane.**

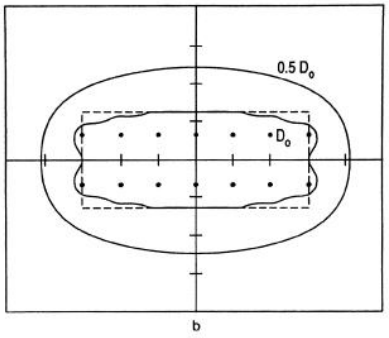
Planar Dose Distribution





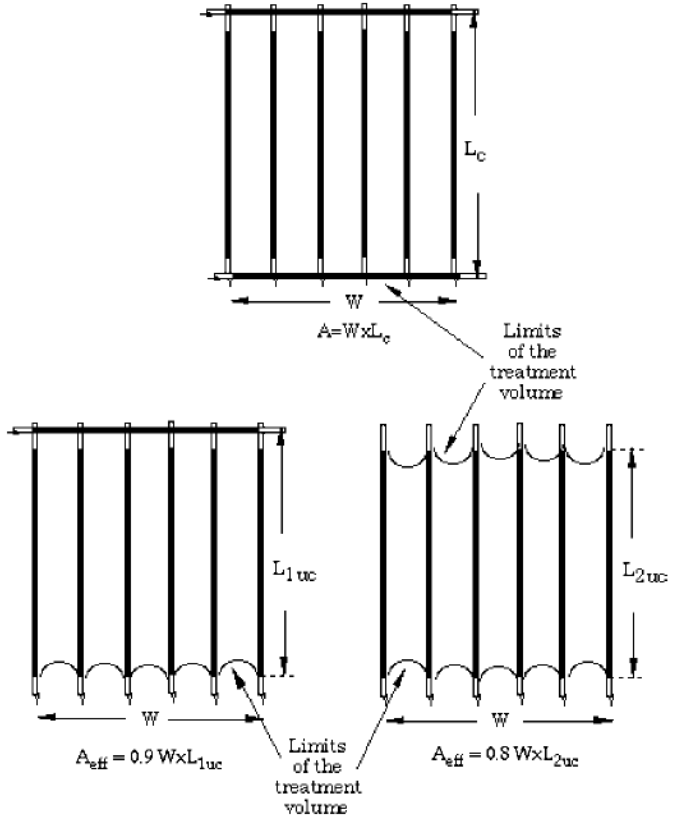
Volume Dose Distribution





Manchester System

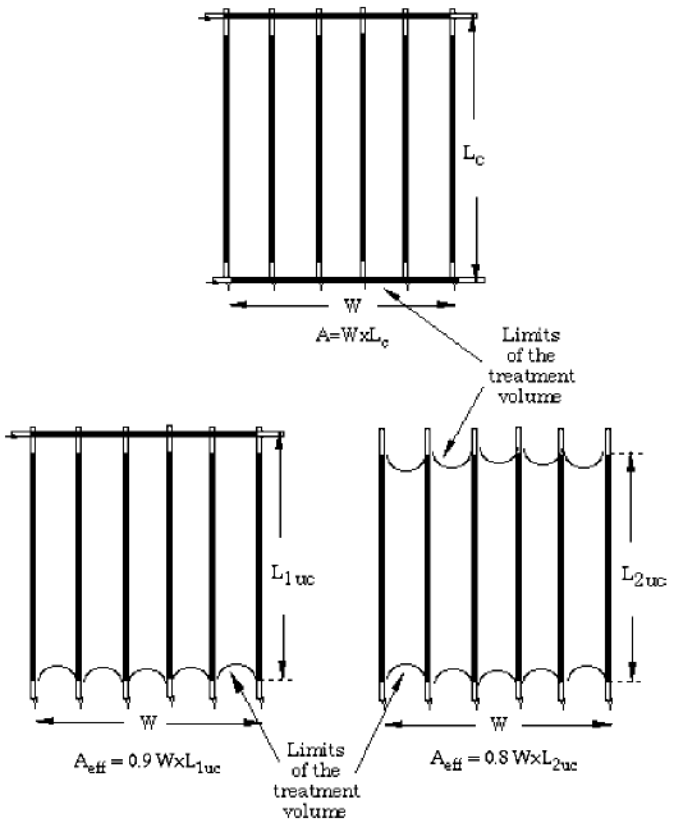
- **Strict rules developed for distribution of activity in implant using Ra-226**
- **Dose rate was uniform (+/-10%) when rules were followed**
- **Rx based on tx area at a distance**
- **Dose rate determined from table when rules were followed.**



Implant Area

Manchester System

- Planar Implant rules
  - Sources place in a plane a certain amount of activity on the periphery and the rest evenly distributed in the center
  - Needles should be in parallel rows spaced around 1 cm
  - Crossing needles are permitted and they should be placed across the active ends if possible, but not more than 1 cm from the active ends.
  - If the ends of the implant cannot be across, 10% of the are is deducted from each uncrossed end
  - For implants, which use seeds or short sources, the distance between the active ends should not exceed 1 cm.
  - If two planes are used, the separate planes should be arranged as for a single implant, parallel to each other. If they differ in area, then the area used to determine the amount of activity is the average area and the activity is divided between the planes in a ratio of the areas of the planes. Generally, 2 cm separation between two planes



Manchester System

- **Distribution of Activity**
  - **More activity is placed in the center as the area of the implantation increases**

Area	Relative Proportion of Activity	
	Periphery	Center
$< 25\ cm^2$	2/3	1/3
$> 25\ cm^2$ and $< 100\ cm^2$	1/2	1/2
$> 100\ cm^2$	1/3	2/3

Paris System

- Developed in Paris using Iridium-192 wire implants in 1960's and 1970's.
- Uniform distribution of activity
- Rx based on the basal dose (minimum dose rate in the central plane) and the reference dose (85% of the average basal dose)
- Treatment volume is the volume enclosed by the reference dose.

Paris System

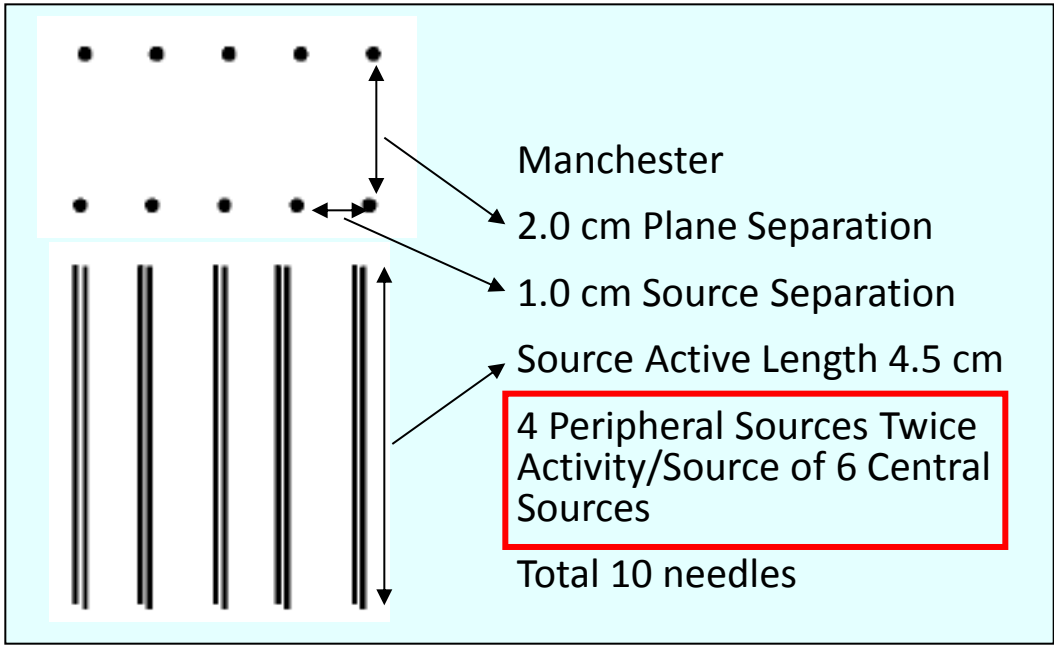
- **Implant Rules**
  - **Each wire is uniform activity**
  - **All wires should be same length and activity**
  - **All wires should be straight and parallel to each other**
  - **Separation between the seeds should be 1.5 times the active length of the seeds (e.g., if active length is 3 mm, the separation is 4.5 mm)**

Table 5. Predictive Relationships in the Paris System for Rectilinear Sources Equal in Length

Patterns	Ratio of Treated Length to Active Length	Ratio of Treated Thickness to Spacing	Ratio of Lateral Margin to Spacing	Ratio of Safety Margin to Spacing
2 Lines	0.7	0.5	0.37	—
N lines in 1 plane	0.7	0.6	0.33	—
N lines in squares	0.7	1.55–1.60	—	0.27
N lines in triangles	0.7	1.3	—	0.20

Manchester vs. Paris

Consider 2.5 cm x 3.5 cm x 2.5 cm target volume



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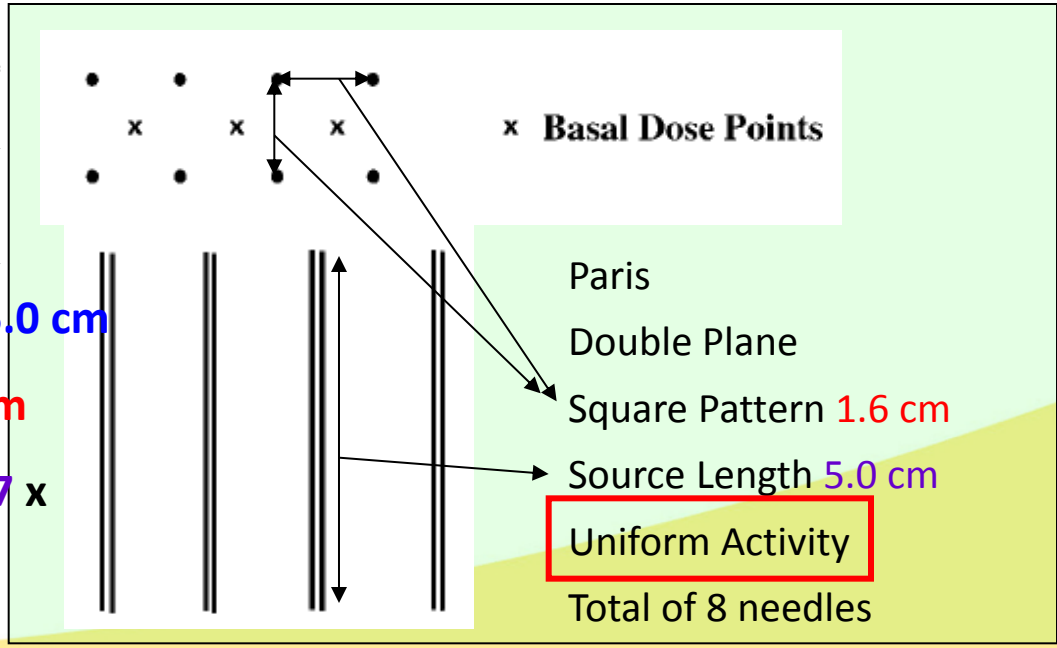
N lines in squares	0.7	1.5–1.60	—	0.27
N lines in triangles	0.7	1.3	—	0.20

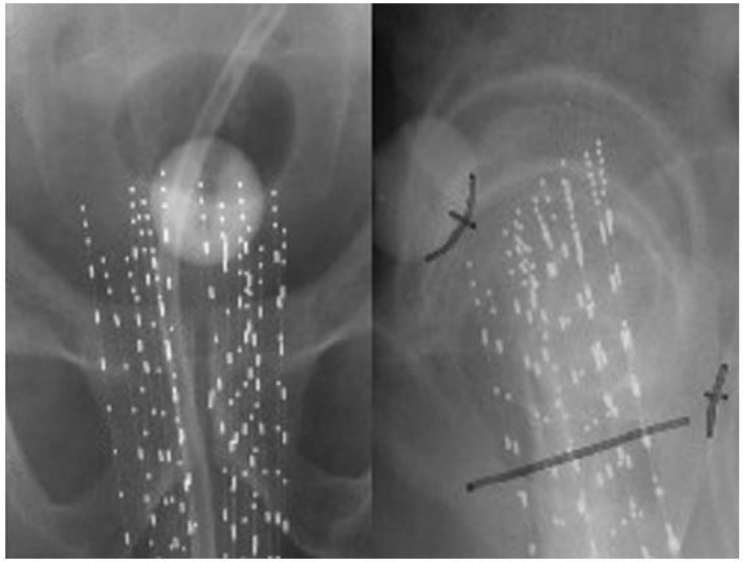
Active Length = Tx Length/0.7 = 3.5/0.7 = 5.0 cm

Source Space= Tx Thick/1.6=2.5/1.6= 1.6 cm

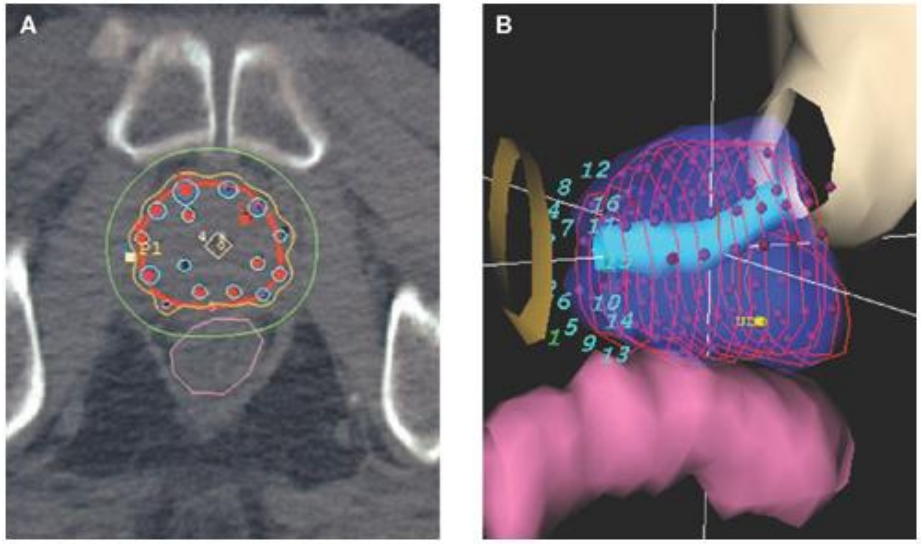
Safety Margin = 0.27 to source space = 0.27 x 1.6 = 0.4 cm



Current Practice of Interstitial Brachytherapy



Orthogonal pair image with dummy ribbons

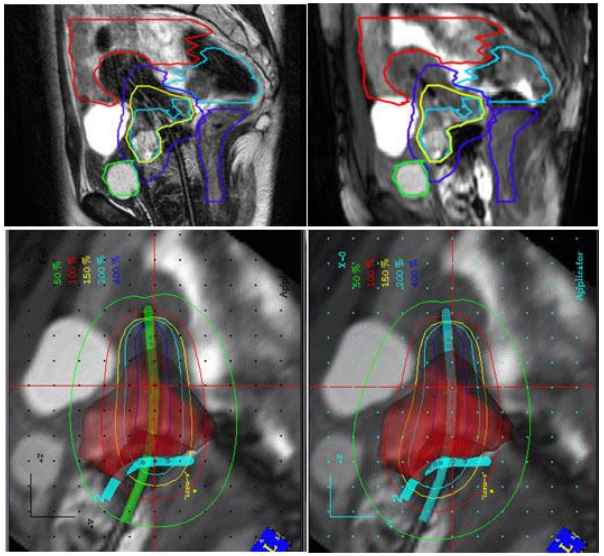


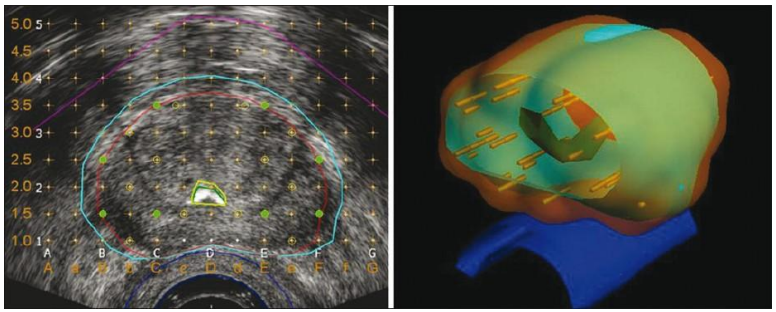
3D Image-based computer treatment planning system

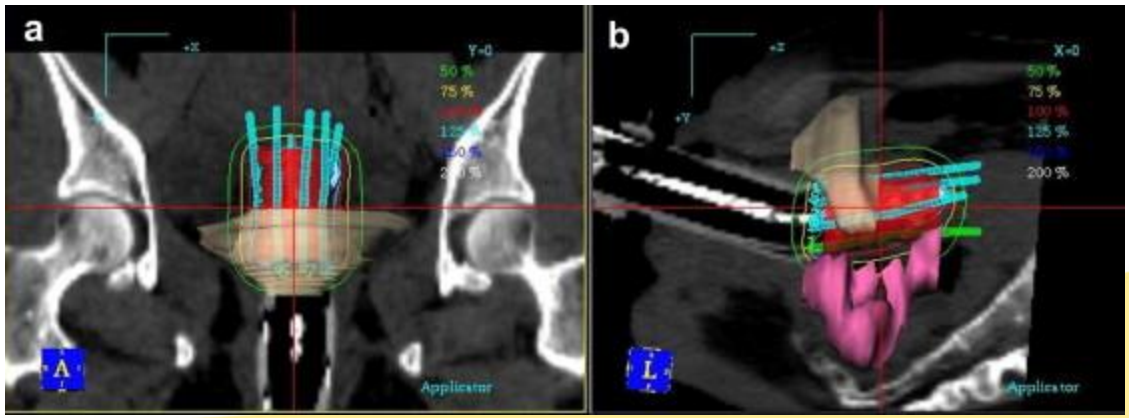
- 3D Image-based computer treatment planning system
  - CT, MR, Ultrasound, and PET
  - Use TG-43 formalism and some may have Monte Carlo calc
  - Provide information about dose to anatomy and catheter position
  - Source positions and/or dwell time can be adjusted based on dose to anatomy
  - Each organs can be evaluated using DVH

Brachytherapy Treatment Planning Systems

- **Forward Planning: Treatment parameters are first chosen and then the resulting dose distribution is calculated and evaluated.**
- **Inverse Planning: Starts with the desired dose distribution or objects and then determines the treatment parameters what will fulfill it.**



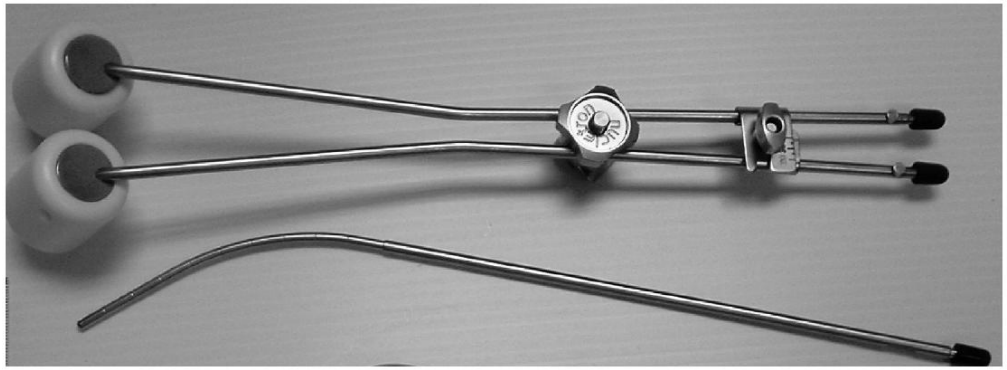


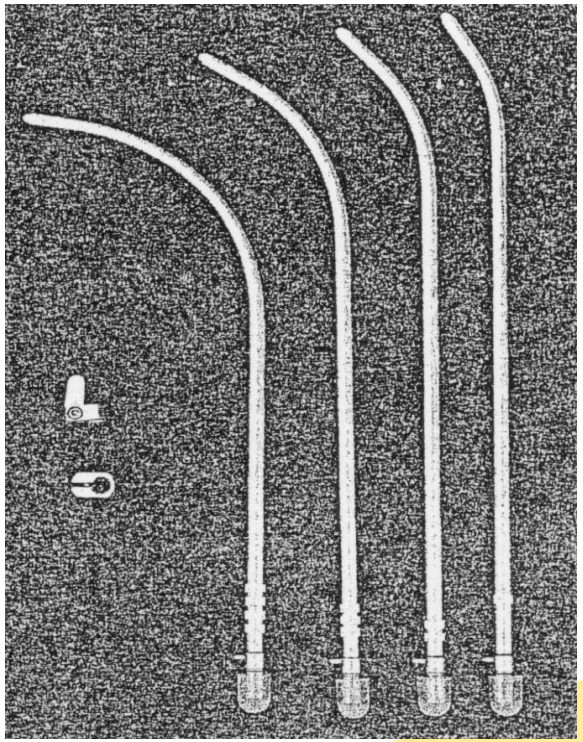


Implantation Techniques: Intracavitary

- Radioactive sources are placed inside the body in a natural cavity or in the cavity left after a surgical resection using an applicator.
- Most common site: GYN
- Temporary Implant
- LDR, HDR and PDR

Applicator Design: Tandem and Ovoid

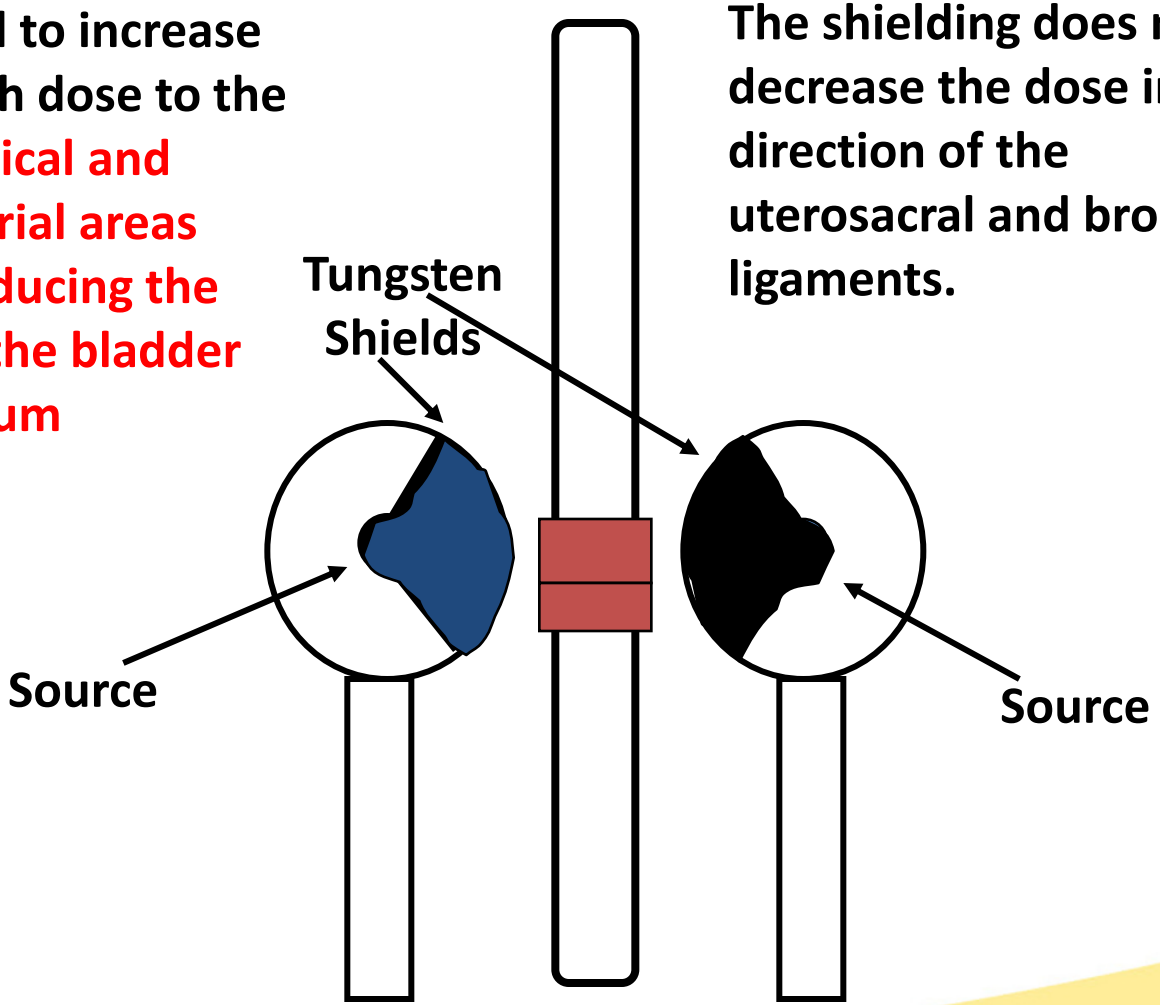




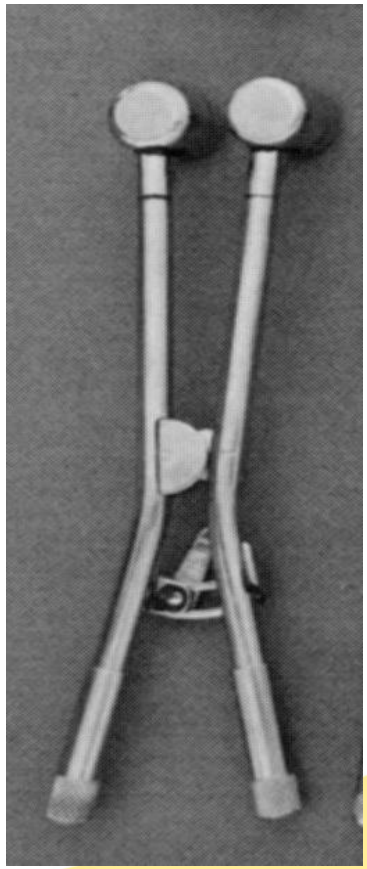
- Tandem
  - Majority of dose to uterus
  - Separate from the ovoids.
  - Made of stainless steel.
  - Hollow inside.
  - Inserted into the uterus through the cervix.
  - Available in 4 different curvatures.
  - Sources are loaded from the inferior end.

Applicator Design: Ovoid

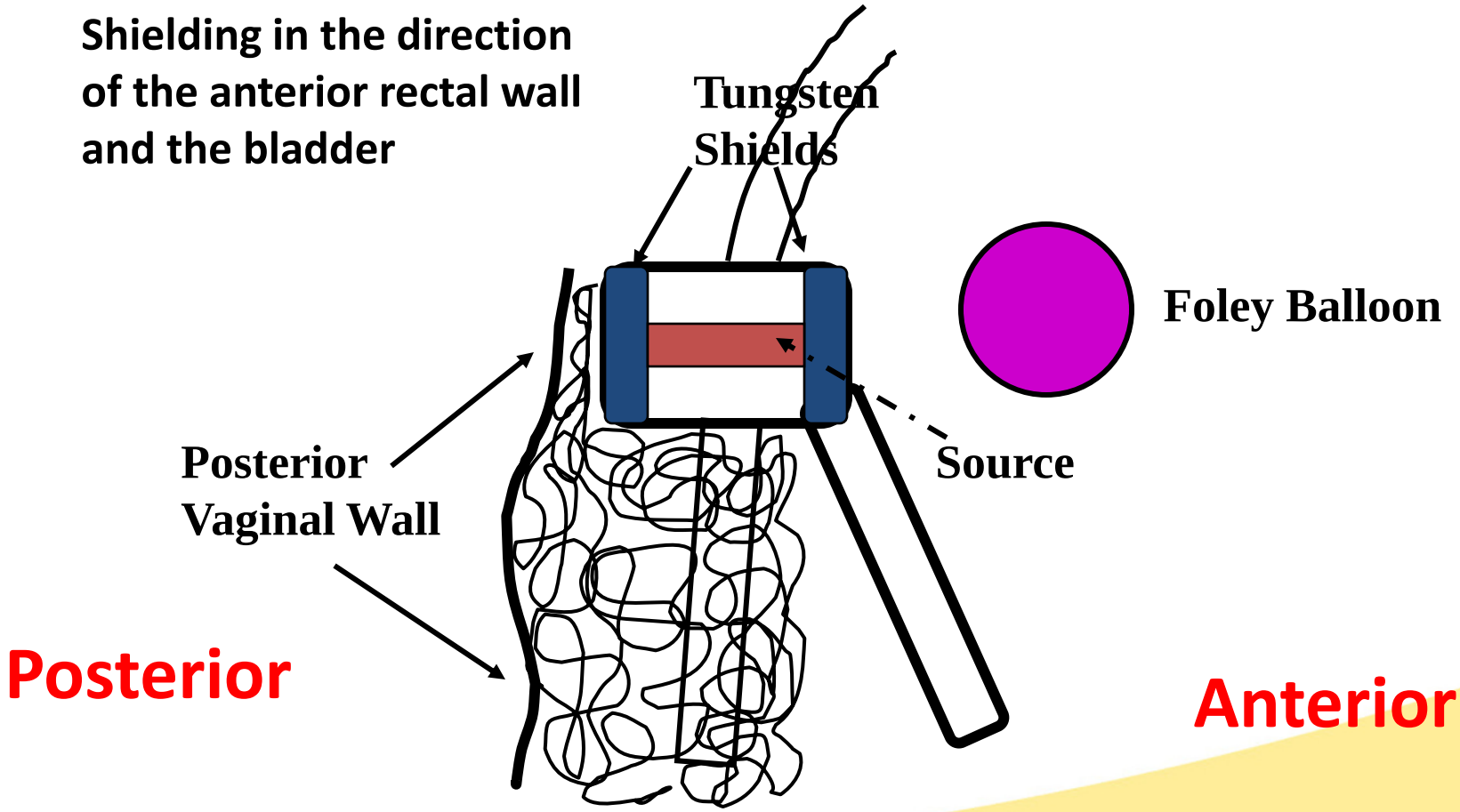
The ovoid was designed to increase the depth dose to the paracervical and parametrial areas while reducing the dose to the bladder and rectum



The shielding does not decrease the dose in the direction of the uterosacral and broad ligaments.



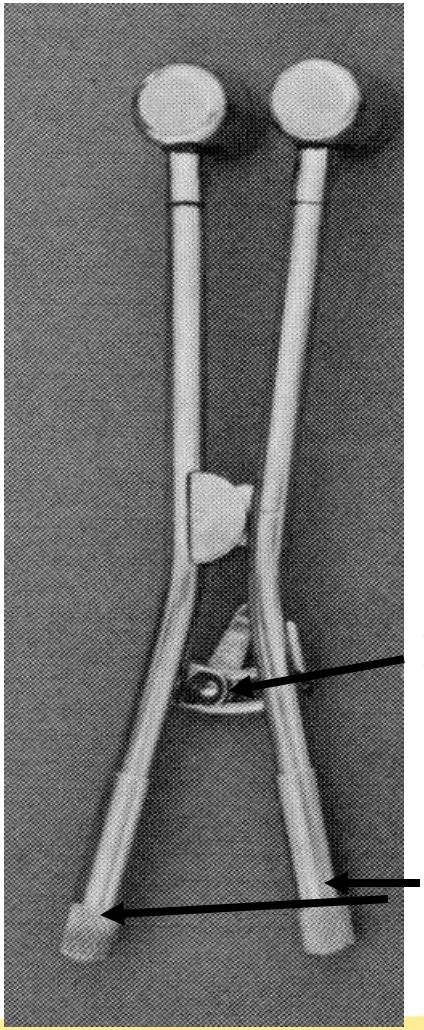
Applicator Design: Ovoid



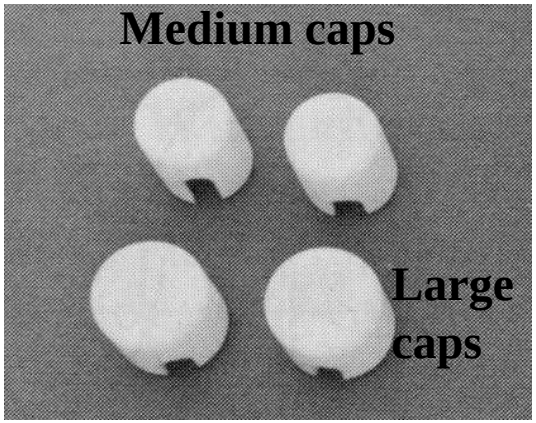
Applicator Design: Ovoid Shielding

- The reduction in the bladder and rectal dose is enhanced by the addition of tungsten shields at both poles of the applicator.
- The rectal shield is half disc.
- The bladder shield is a 150 degree sector.

Applicator Design: Small Ovoid

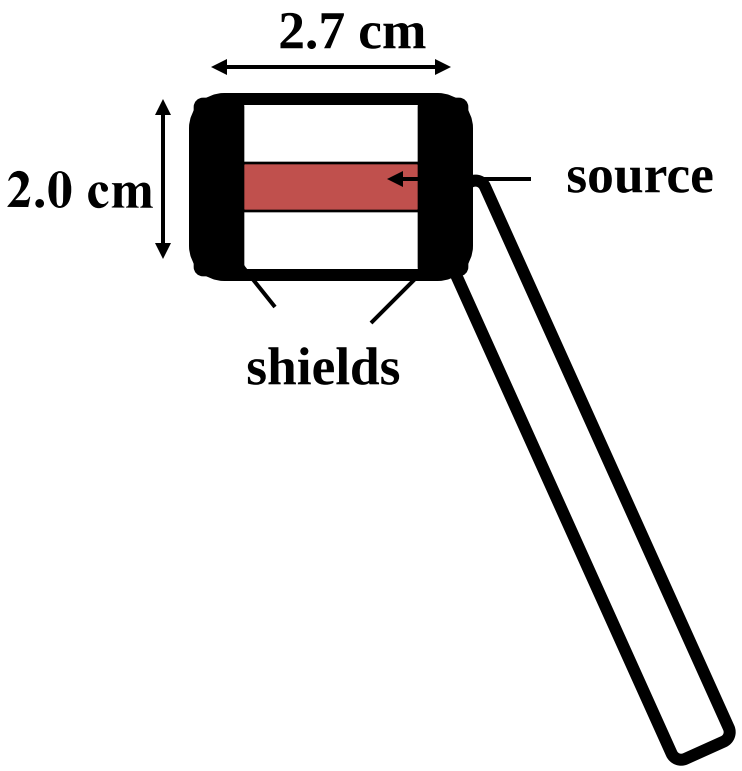


The manual small ovoid is made of stainless steel.



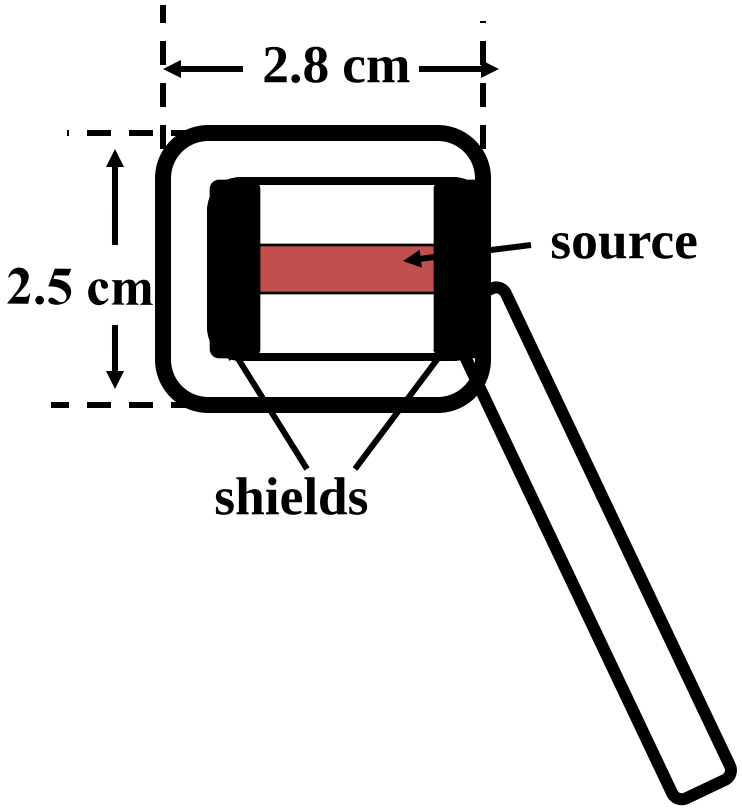
Caps can be added to the small ovoid to increase the size of the ovoid.

Applicator Design: Small Ovoid



Tungsten shielding is placed in the direction of the anterior rectal wall and the bladder.

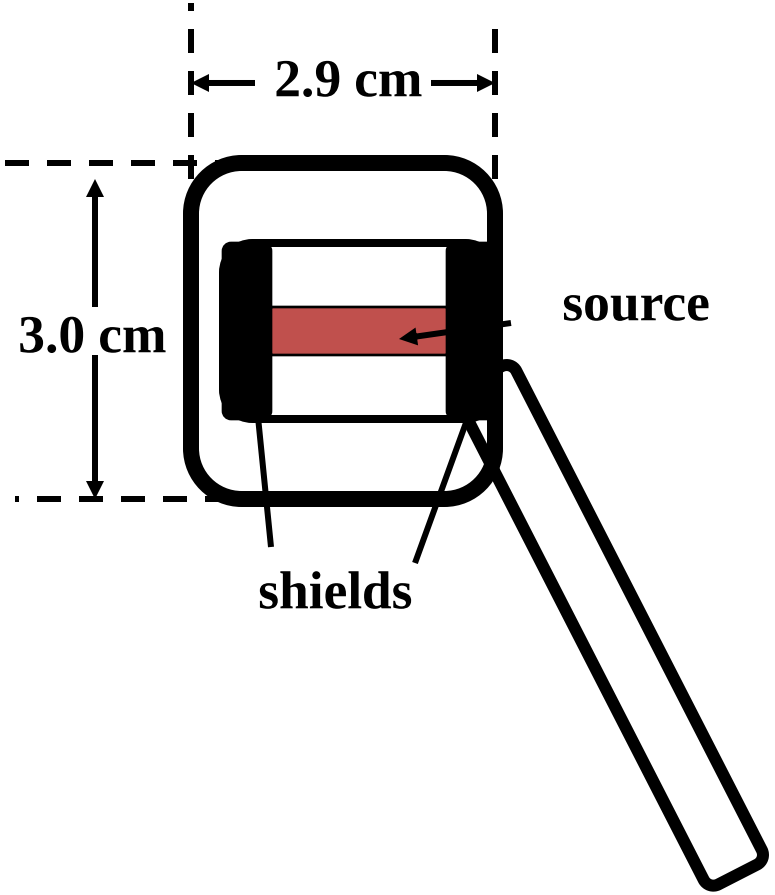
Applicator Design: Medium Ovoid



The medium ovoid is a small ovoid with a teflon cap placed on the ovoid.

The medium cap increases the width of the ovoid 0.25 cm superiorly and inferiorly, and increases the length by 0.1 cm in the posterior (non handle) direction.

Applicator Design: Large Ovoid

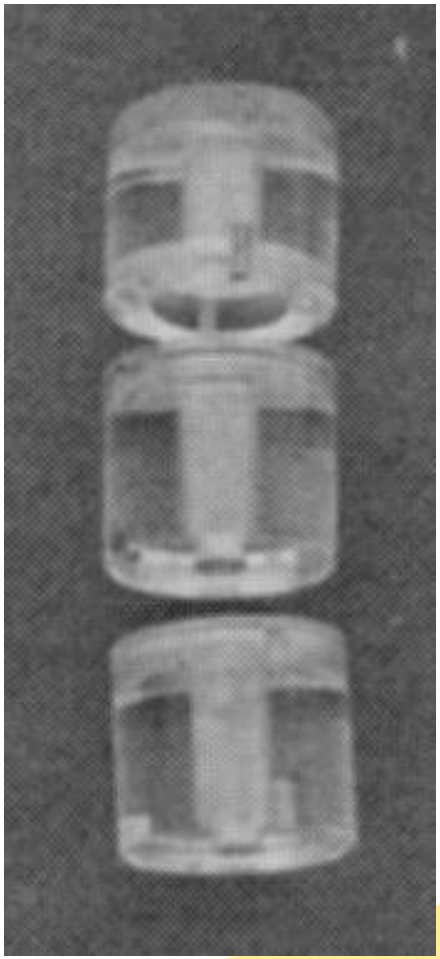


The large ovoid is a small ovoid with a teflon cap placed on the ovoid.

The large cap increases the width of the ovoid 0.50 cm superiorly and inferiorly, and increases the length by 0.2 cm in the posterior (non handle) direction.

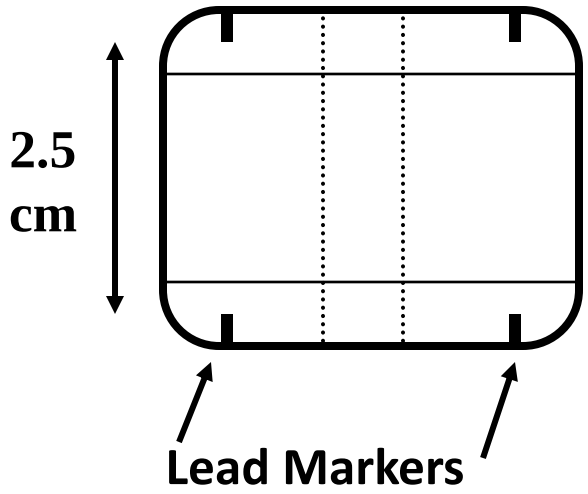
Applicator Design: Vaginal Cylinders

- Vaginal cylinders are used to treat the vagina when the tumor extends from the cervix down along the vaginal wall.
- Vaginal cylinders are used to hold a vaginal source when the vagina is too narrow to accommodate ovoids.



Applicator Design: Vaginal Cylinders

Diameters of 2.0 cm to 5.0 cm in 0.5 cm increments.



Vaginal cylinders are made of lucite.

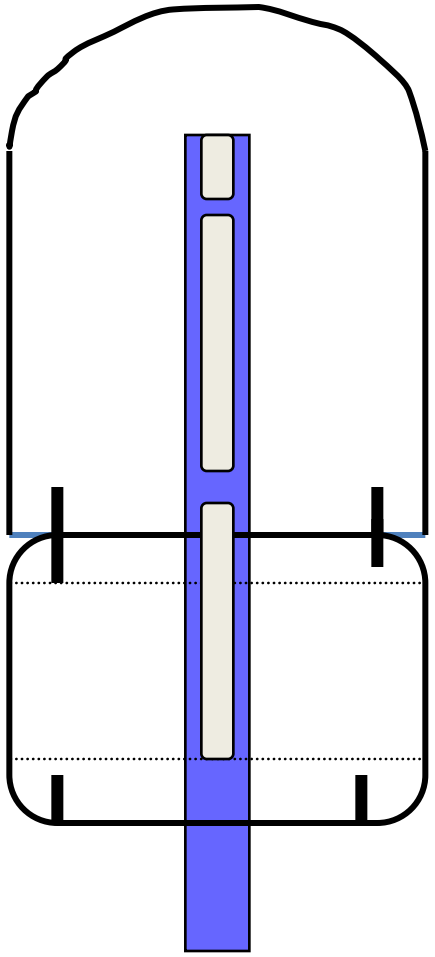
These cylinders have no shielding.

Vaginal cylinders are radiopaque and have lead markers in the top and bottom to aid in identification on film.

These cylinders can be placed on the tandem, inferior to the flange, or on the stem of a dome cylinder.

Applicator Design: Dome Cylinders

- **Designed to deliver a homogenous dose to the vaginal cuff alone or to areas of the vagina in patients who have had a hysterectomy (there is no uterus to insert a tandem into).**



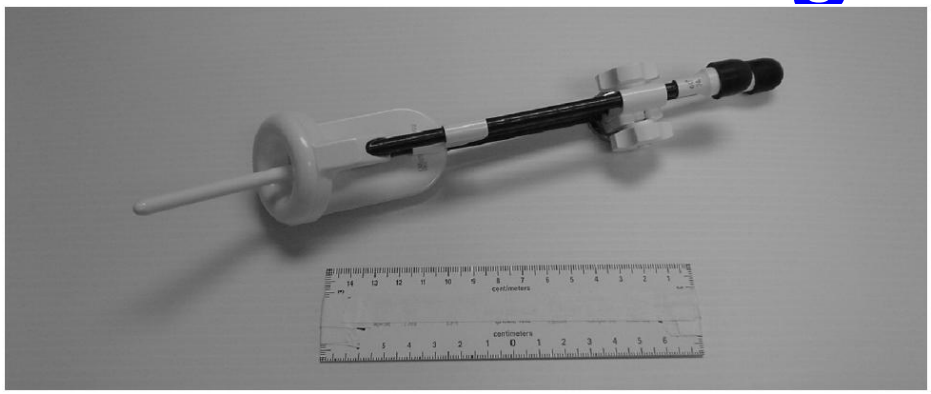
Manual dome cylinders are made of lucite.

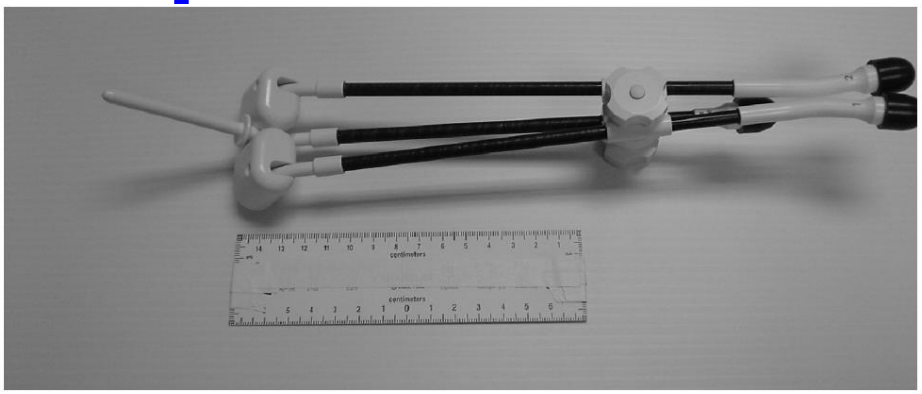
Available in diameters of 2.0 cm to 5.0 cm in 0.5 cm increments.

The 2.0 cm and 2.5 cm domes have a length of 3.5 cm.

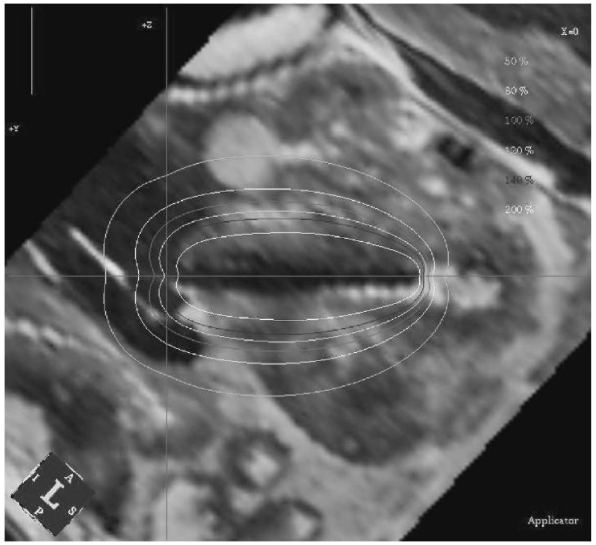
The remaining diameters have a length of 4.0 cm. The stem of the dome is stainless steel and hollow.
Vaginal cylinders can be placed on the dome stem when needed.

Applicator Design: Image-Based Planning Compatible

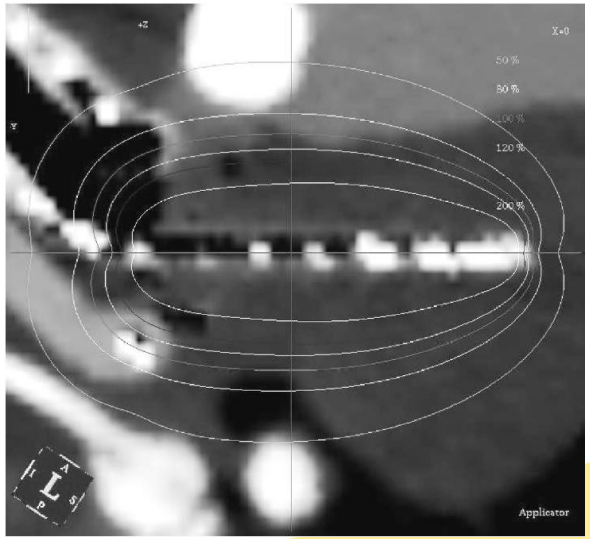




CT/MR compatible tandem and ring and tandem and ovoid applicator



MR recon image of CT/MR compatible tandem and ring

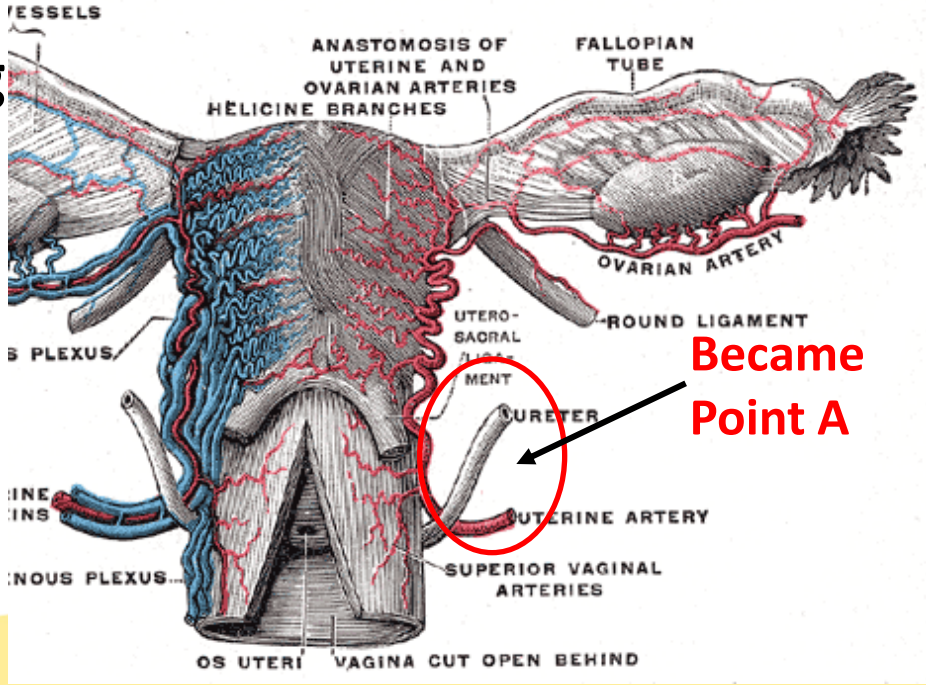


MR recon image of CT/MR compatible tandem and ring

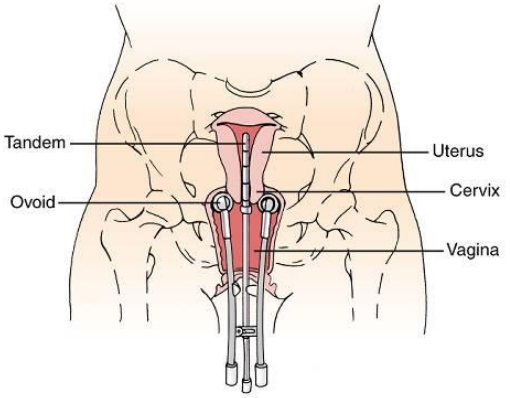
Manchester System for Cervical CA Intracavity Brachytherapy

- First described by Tod and Meredith in 1938
- Wanted to find a anatomical points that were meaningful and reproducible/consistent
- Target points (e.g., external os) not chosen due to high dose gradient

Concluded that the dose limiting structures were not the critical structures (bladder and rectum) but to the medial edge of the broad ligament where the uterine vessels cross the ureter (paracervical triangle).

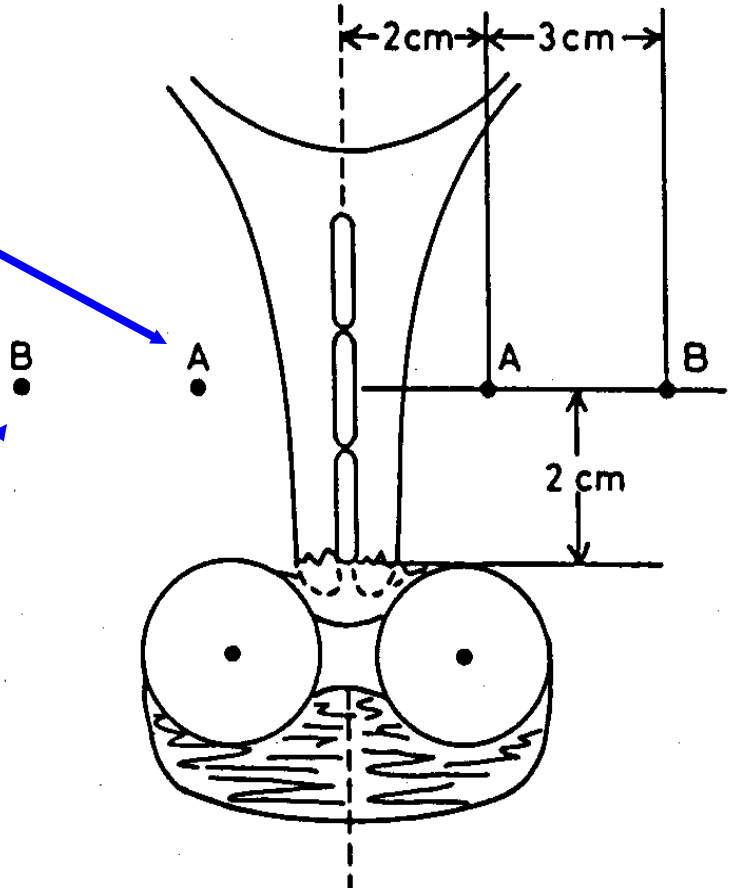


Definition of Points A and B



Point A - 2 cm superior to the vaginal fornix & 2 cm lateral from the center of the uterine canal

Point A where the uterine vessels cross the ureter

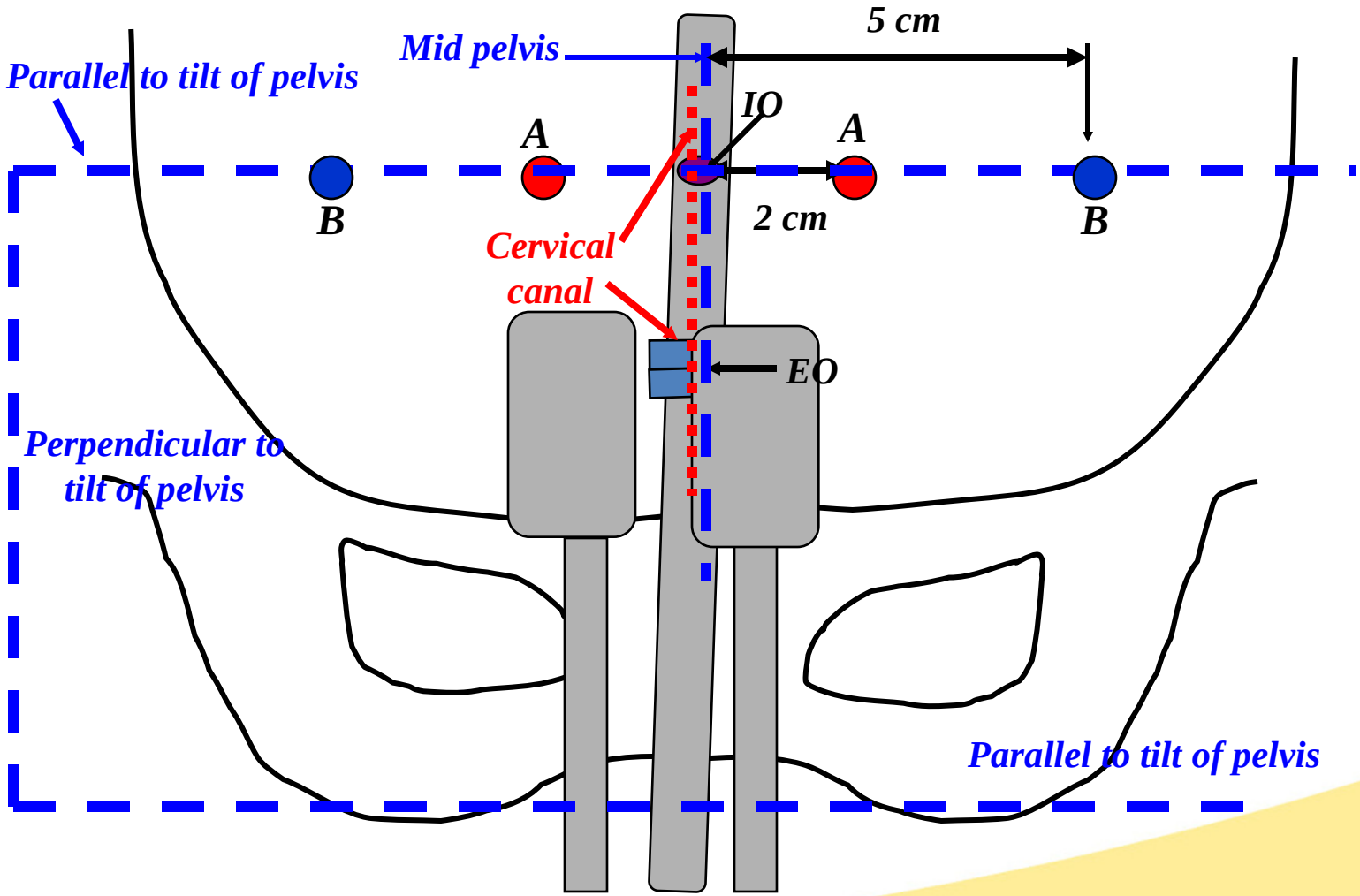


Point B location of the obturator nodes

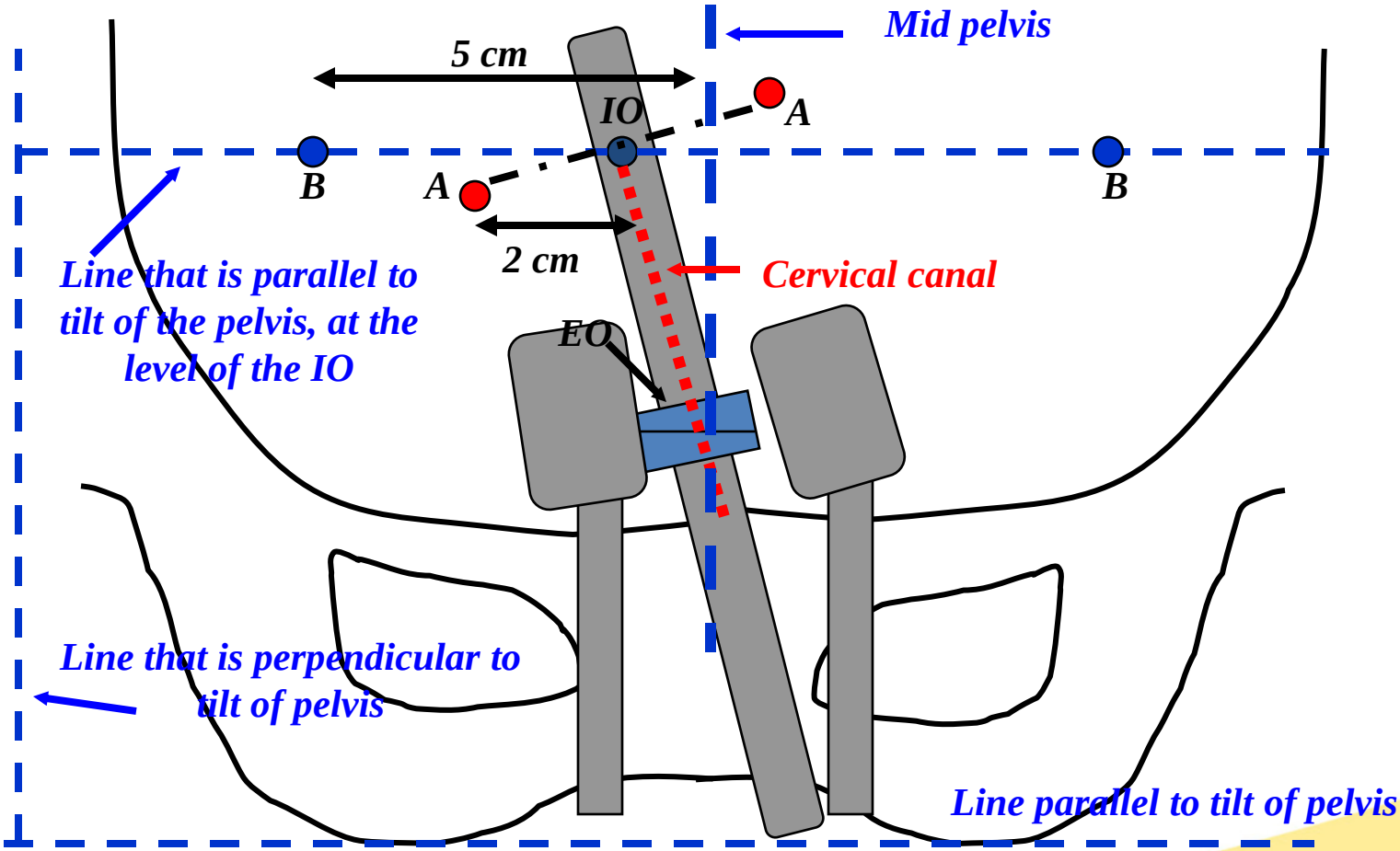
Point B – 3 cm lateral to point A

Whether the plan is based on orthogonal films or image based, these point system still applies.

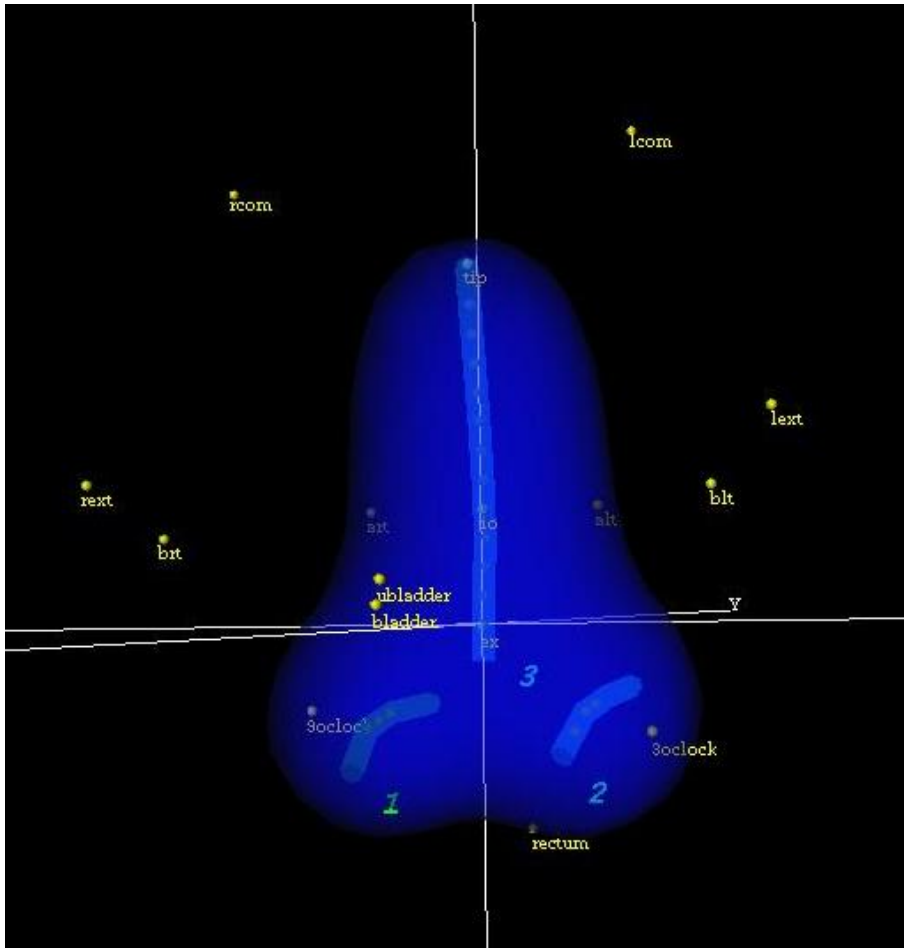
Location of Points A and B when Uterus/Cervical Canal is Straight

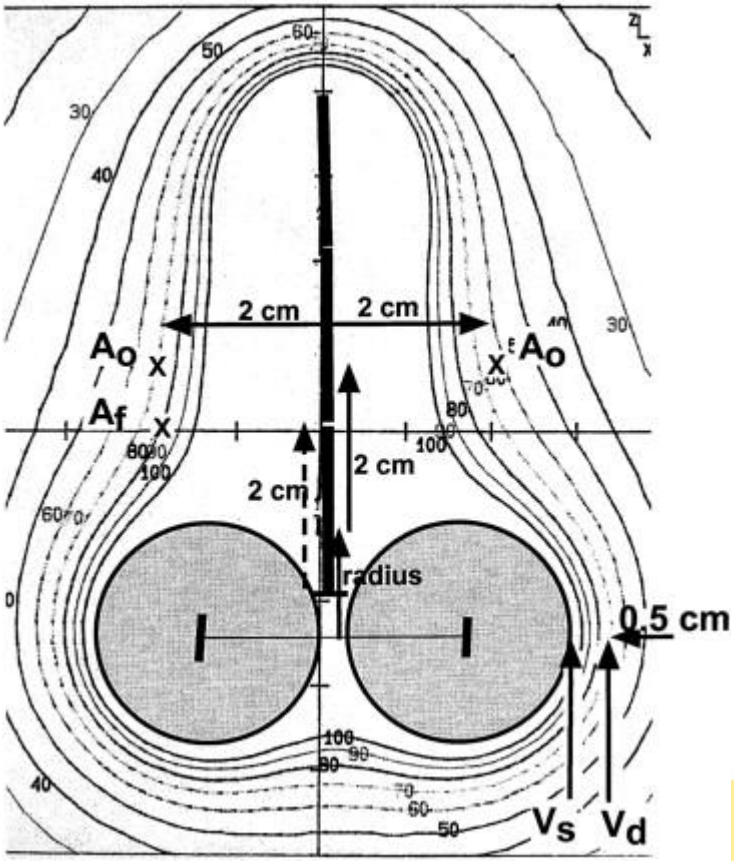


Location of Points A and B When Uterus is Pulled to One Side



Typical Tandem and Ovoid Dose Distribution

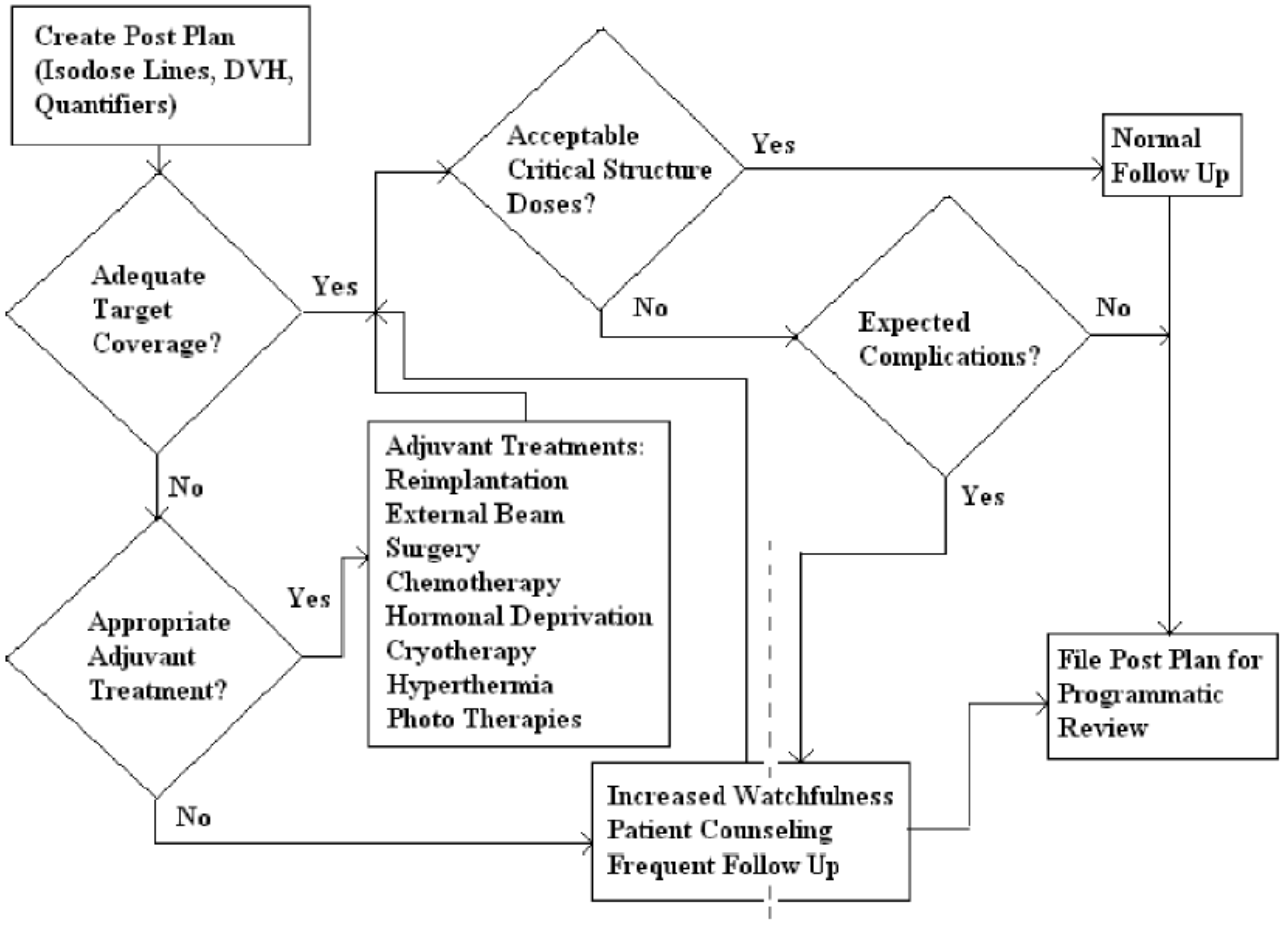




Post-Implant Evaluation

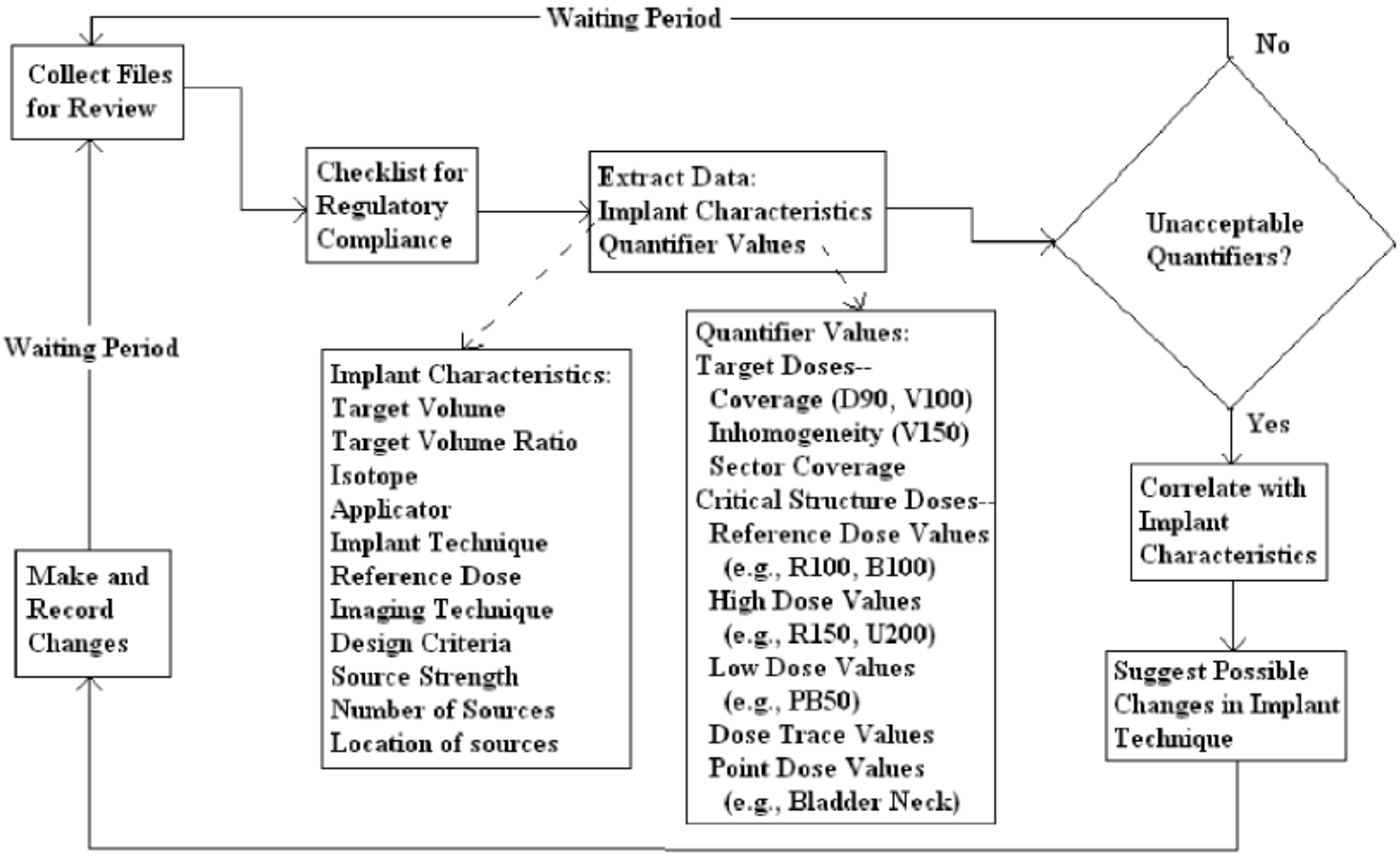
- **Purpose:**
  - **Determine whether the individual implant meets the desired goals**
  - **Evaluating the performance of the implant team**
- **Post-Plan Evaluation:**
  - **Provides immediate quantitative feedback about the implant, indicative of clinical success and a measure of procedural success.**

Post-Implant Evaluation



Paradigm that may be used to evaluate an individual implant

Post-Implant Evaluation



Paradigm that may be used to evaluate a series of implant

References

- The Physics of Radiation Therapy by F. Khan
- AAPM Monograph No. 31, Brachytherapy Physics, 2nd Edition
- AAPM Task Group #40
- AAPM Task Group #43U

Thanks


University of Maryland Medical Center
Named U.S. Hospital of the Decade for patient safety and quality