QA Review of Brachytherapy Treatment Plans

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Purpose

- Discuss goals, process, and elements of brachytherapy treatment plan QA review
- Review tools of independent calculation check of brachytherapy plans

Outline

- Purposes of Brachytherapy Treatment Planning
- Review of Treatment Prescription
- Review of Imaging for Treatment Planning
- Treatment of Plan Technical Parameters
- Plan Quality Evaluation
- Independent Plan Calculation Check
- Summary

Purposes of Brachytherapy Treatment Planning

- To determine *optimal* source strengths/dwell times and source distribution and loading patterns
  - LDR and HDR pre-implant plans
- To document isodose distribution, target and critical organ doses
- To serve as guidance to future patient management
  - Post-implant prostate dosimetry plans, multi-fractionated LDR and HDR treatment plans, plans of brachytherapy treatments followed by external beam treatments, tumor recurrences and/or future re-treatments

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Review of Treatment Prescription

- **Prescription must be appropriate for the goals of the treatment**
  - **Prescription dose, isotope, prescription points and/or isoodse lines, and fractionation scheme should be reviewed to assure that they are appropriate for the patient's disease site and stage**
    - » **Seeds-alone vs. boost prostate implants**
    - » **Prescription points for vaginal cylinder, T&O, esophagus, endobronchial, and bile duct treatments**
    - » **Review of patient's surgery, pathology, and imaging study reports is often necessary**
  - **When external beam treatment is planned, the brachytherapy treatment prescription needs to be reviewed together with the external beam treatment prescription**
    - » **GYN treatments**
    - » **Later stage prostate treatments**
    - » **H&N and other interstitial brachytherapy treatments**

Review of Treatment Prescription

- **Prescription should comply with institutional treatment policies**

Table 1. Mallinckrodt Institute of Radiology Treatment Policy for Cervical Cancer

Treatment scheme	Indication	External beam treatment (Gy)		Intracavitary treatment		Total: smallest to largest insertion		
		Whole pelvis	Split field	Target mgRaEq-h	Maximum vaginal dose (Gy)	Point A dose (Gy)	Point P dose (Gy)	mgRaEq-h
A	IB < 2 cm	0 Gy	45 Gy	7000	150	70–80	56–60	5580–7980
B	IB 2–4 cm	10	40	7500	150	80–85	61–66	5580–8550
C	IB/IIA/IIB/IIIA bulky (>4 cm), limited parametrial extension	20	30	8000	150	84–90	61–67	5600–9100
D	IIB/IIB bulky, extensive parametrial extension	20	40	8000	150	84–90	71–77	5600–9100
E	IIB, IIIB, IV, poor anatomy, poor regression	40	20	6500	150	92–94	69–74	4610–7410

Williamson, in *Principles and Practice of Radiation Oncology, Perez et al. ed., Lippincott, 2004*

Review of Treatment Prescription

- **Prescription should comply with national guidelines**

Table 1. Brachytherapy as sole treatment for oral cavity cancers

Author (ref)	EBRT	Fx Size (Gy)	# fx	Equiv. dose* (Gy)	# Pts.	L.C.
Dixit *et al.* (8)	0	3	20	65	3	–
Lau *et al.* (11)	0	6.5	7	63	27	53%
Inoue *et al.* (10)	0	6	10	80	14	100%
Donath *et al.* (9)	0	4.5–5	10	54–63	13	90%
Leung *et al.* (12)	0	5.5–6	10	71–80	13	100%

Abbreviations: Fx = fractions; equiv. = equivalent; Pts. = patients; L.C. = local control. EBRT = external beam radiation therapy.
* Equivalent dose for tumor effects as if given at 2 Gy/day using the linear quadratic model with an α/β ratio of 10 (25). See appendix.

Nag *et al*, IJROBP, 50(5), 2001

Review of Treatment Prescription

- **Prescription must be complete and free of errors**
  - **Treatment site, disease, prescribed doses, isodose line/prescription points, isotopes, applicators used, if applicable**
  - **Prescription, if serving as *written directive,* must comply to regulatory requirements**
    - » **HDR: Patient name, treatment site, isotope, dose per fraction, # fractions, and total dose**
    - » **LDR before implant: Patient name, treatment site, isotope, dose**
    - » **LDR after implant: Treatment site, isotope, # sources, total source strength and exposure time (or dose)**
    - » **Authorized user signature and date**

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Review of Patient Images

- **Review that correct patient images are used for treatment planning**
  - **Wrong patient?**
  - **Wrong study?**
  - **Wrong imaging parameters?**
  - **Patient positioning correct?**
  - **Images optimal and free of artifacts for source and point of interest localization?**
  - **Contrast, markers, skin wires available for target and critical organ identification?**
  - **Target and critical organs correctly segmented?**
  - **Applicator insertion adequate?**
  - **Dummy markers identifiable?**

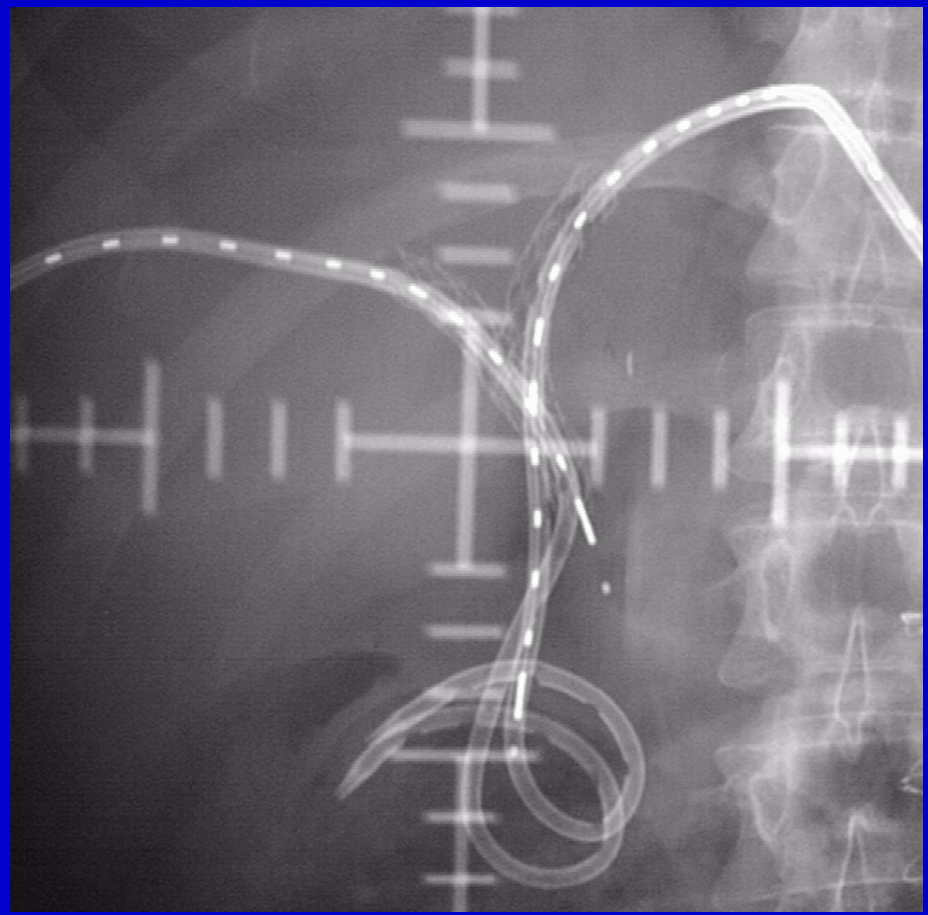
Review of Patient Images

- **Wrong patient and/or study datasets**
  - **When several patients are to be planned in the same day, such as in the case of prostate or brachytherapy partial breast irradiation.**
  - **Multiple imaging studies may be available, for example, multiple sets of prostate ultrasound images may be available for a given patient**
- **Imaging protocols should be determined for each treatment site**
  - **CT scan volume, FOV, gantry angle, table pitch, and slice thickness**
- **Patient positioning should be consistent from applicator insertion to imaging to treatment**
  - **Arm position for brachytherapy partial breast irradiation**

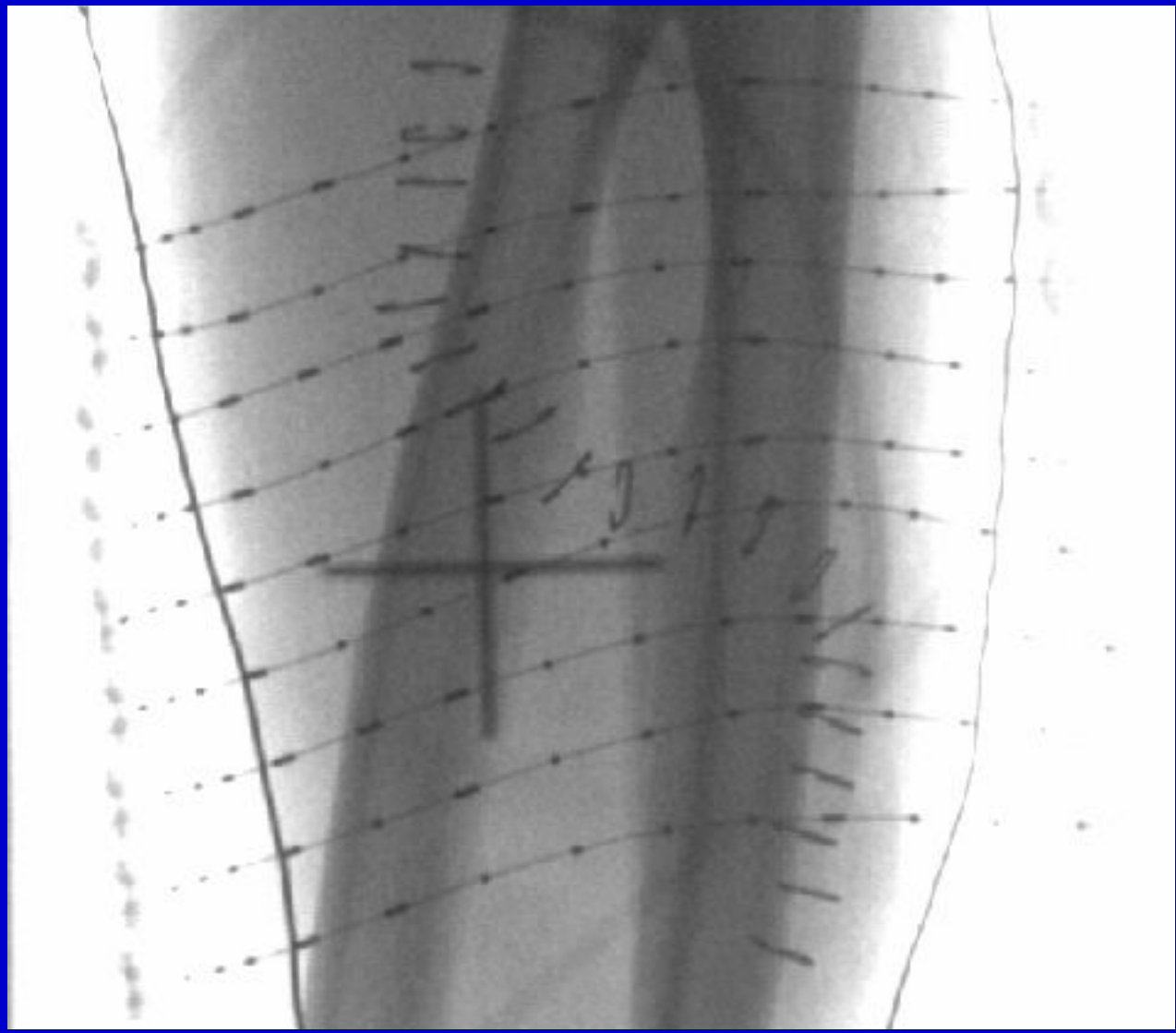
Review of Patient Images

- **Image quality and imaging artifacts**
  - **Isocenter of X-ray simulation films should be near center of implant**
    - » **Orthogonal film reconstruction assigns a single magnification factor for all sources while in reality sources closer than isocenter to source will have larger magnification factor and vice versa**
  - **Patient breathing motion should be well controlled.**
    - » **Ask patient to perform shallow breathing during imaging or hold breath if possible for lung, breast, and abdominal implants**
  - **Contrast, surgical markers, and skin wires adequate**
    - » **Contrast and surgical markers often used to identify post-lumpectomy cavity in breast cancer**
    - » **Surgical markers and skin wires help identify tumor resection margin and critical organs, such as nerves**

Breathing Motion Artifact

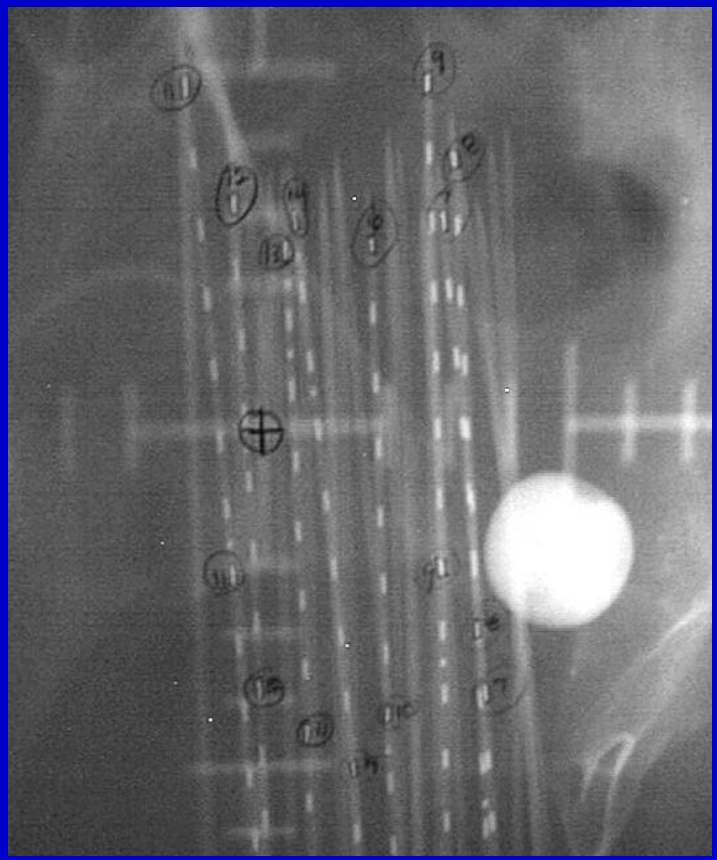


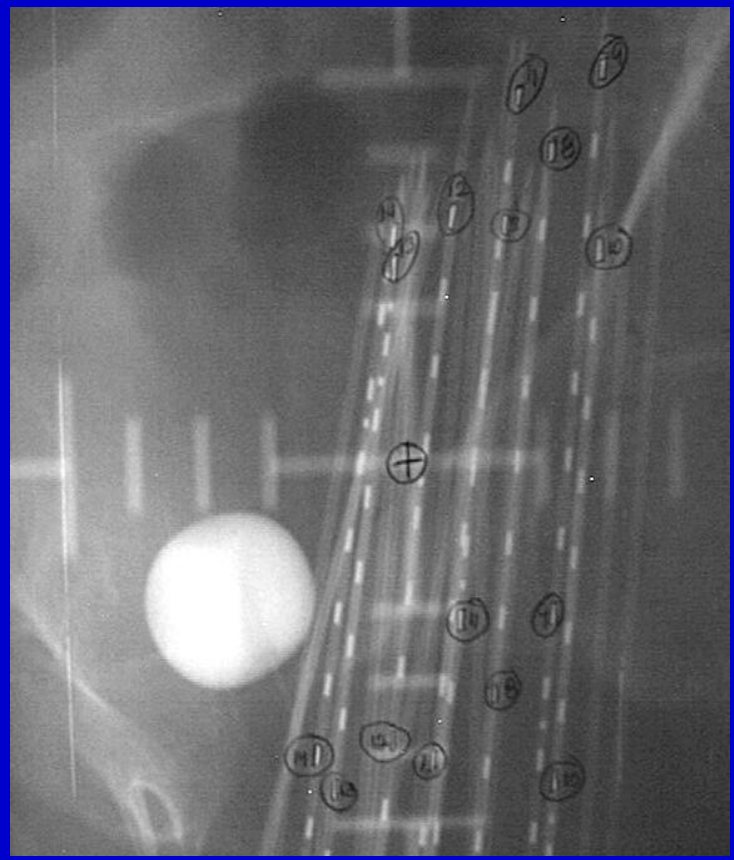
Use of Skin Wires and Surgical Markers



Dummy Markers Identifiable

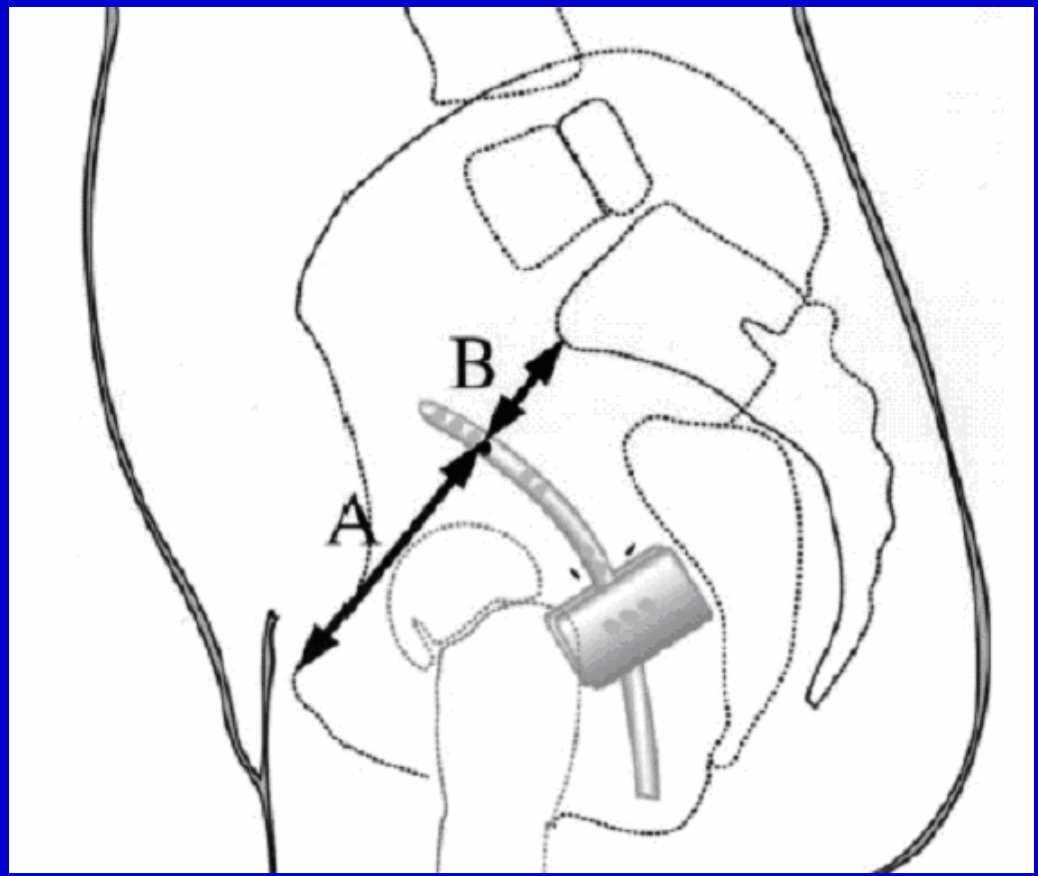
- **Multiple sets of X-ray simulation films may be necessary, with dummy markers in limited number of catheters (even vs. odds)**





Applicator Placement

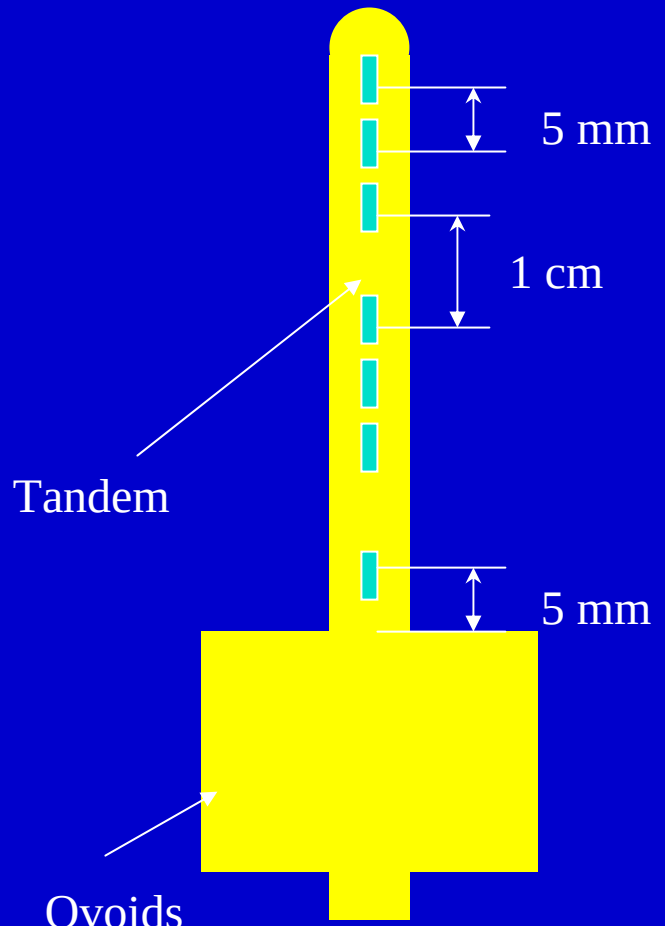
- **T&O placement: Tandem symmetric to ovoids on both AP and lateral films, with good distance away from pubic symphysis and sacrum**
  - **Tandem pointing towards sacrum may indicate perforated uterus**
  - **Large distance between tandem flange and cervical markers may indicate slipped tandem**

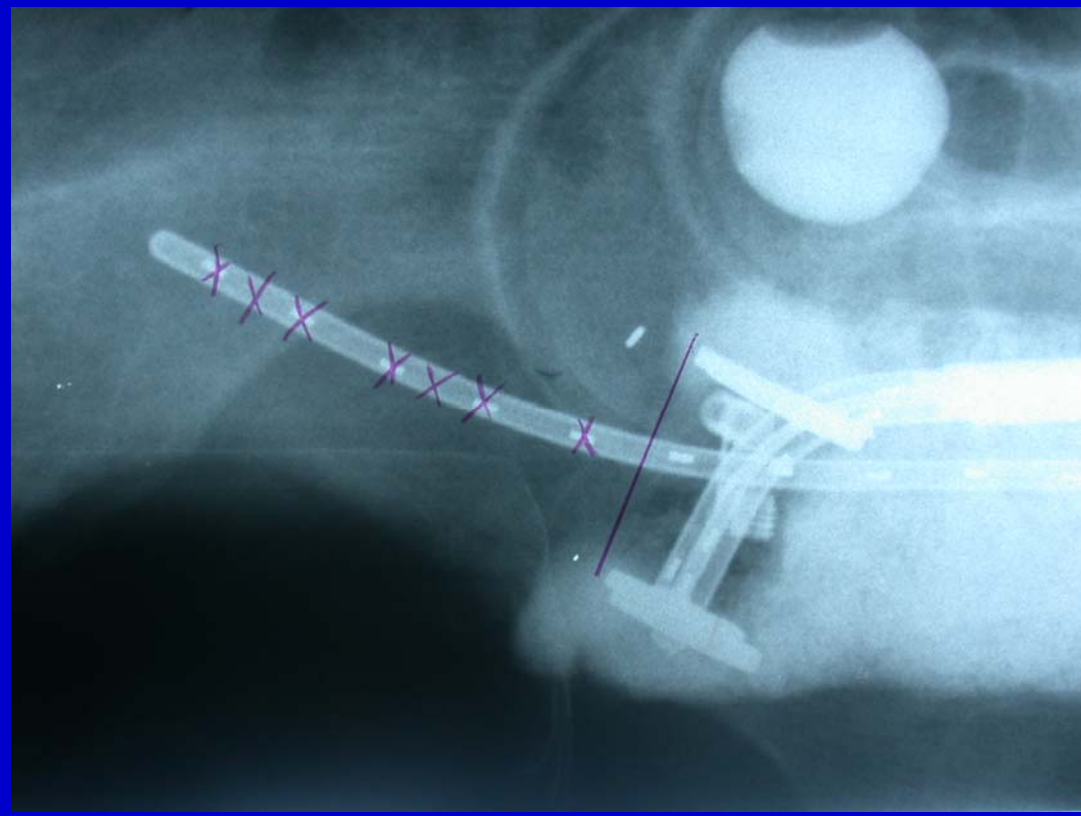


Katz and Eifel, IJROBP, 48(5), 2000

Target Definition on X-ray Films

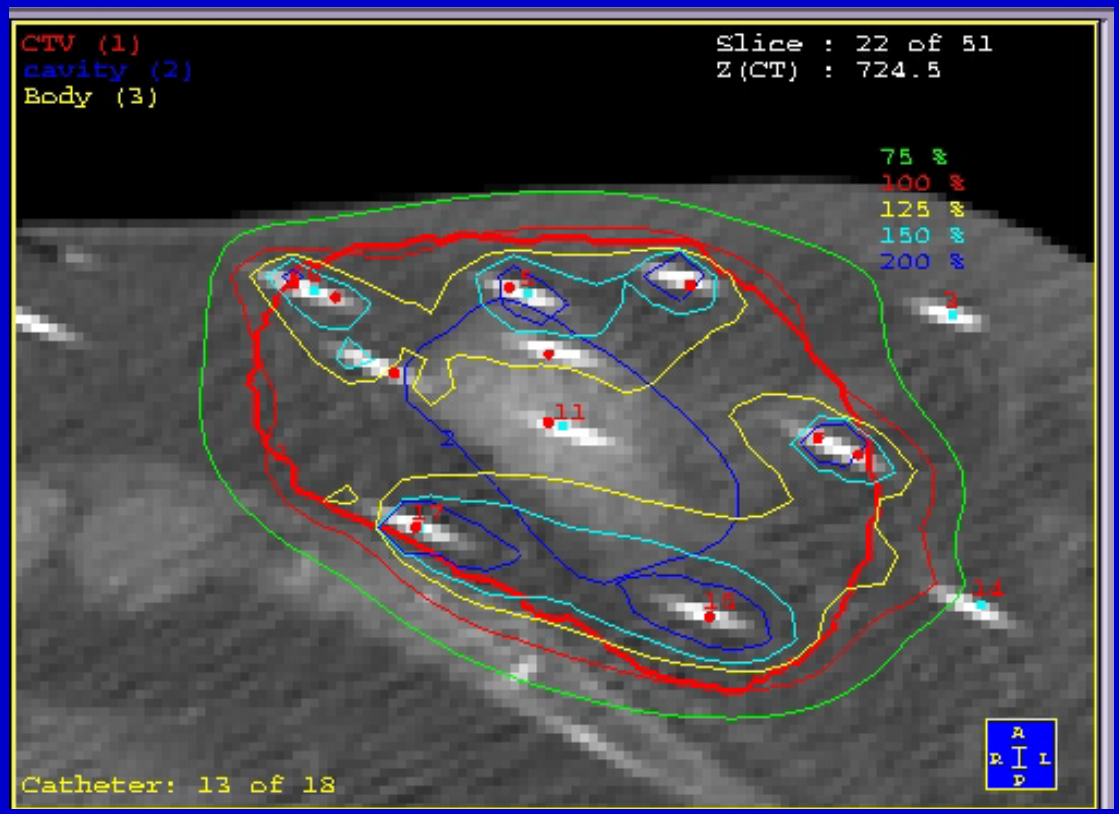
- **Source loading pattern and/or target definition for T&O implants at Washington University**





Target and Critical Organ Segmentation on Volumetric Images

- **Segmentation of target and critical organs should be reviewed for consistency**
  - **Inadequate catheter placement should be discussed with treating physician at earliest possible time**



Know Your Limits

- **Applicator placement may violate machine limits**

Nucletron V2 HDR Unit Characteristics

Parameter	Nominal Values	Comment
Maximum Treatable Distance (from indexer faceplate)	1500 mm	4 mm additional catheter length for check cable test
Minimum Treatable Distance (from indexer faceplate)	725 mm	
Maximum number of dwell positions	48	# of dwell positions multiplied by step size must be between min. and max. treatable distance
Step sizes	2.5 mm, 5 mm, 10 mm	
Gynecological transfer tube	1200 mm	
Flexible catheter transfer tube	1000 mm	
Stainless steel needle transfer tube	1200 mm	

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Review of Input Parameters

- Applicator/catheter geometry parameters
- Applicator/catheter localization
- Points of interest localization
- Source characteristics
- Plan optimization method

Applicator/Catheter Geometry Parameters

- **Length of catheters and transfer tubes used vs. HDR indexer length settings**
  - **Nucletron Classic vs. V2 units have maximum indexer lengths of 995 mm and 1500 mm respectively**
  - **A treatment planned for V2 unit and treated on Classic unit may have an error of up to 50 cm in indexer length**
  - **Stainless steel needles/transfer tubes vs. flexible needles/transfer tubes have typically 30 cm difference in maximum indexer length**
- **Catheter numbering in interstitial implants**
  - **Compare with digital photos and/or drawings**

Applicator/Catheter Geometry Parameters

- Ovoid diameters not identifiable on radiographs
  - 2.5 cm and 3 cm diameter ovoids have Nylon caps and are visually indistinguishable from 2 cm ovoids on radiographs
  - Must rely on documentation in O.R.
- Vaginal cylinder diameters are readily measurable on radiographs and should be verified by measurement on film
- Use of spacers
  - Determination of spacer lengths relative to target and/or critical organs, as well as their documentation

Points of Interest/Critical Organ Localization

- **Localization of point A and B for T&O implants should be per institution protocol**
  - **Classic point A defined at 2 cm superior to vaginal fornices and 2 cm lateral from uterine canal**
  - **Modified point A definition at 2 cm superior to cervical os leads to significant variations in delivered dose between patients**
  - **Dose error up to 15% per mm error in localization of point A**
- **Rectum and bladder localization should be per ICRU Report #38**
  - **Rectum: 5 mm posterior to posterior vaginal wall (as identified by vaginal packing) and bisecting ovoids superior-inferiorly**
  - **Bladder: Posterior-most point of 7 cc Foley balloon on lateral film and bisecting balloon on AP film**

Points of Interest/Critical Organ Localization

- Surgical markers denoting critical organs (such as nerves and vessels in sarcoma treatments) should be digitized for dose calculation
- MammoSite balloon diameter and center location
- Automatically placed dose points for intraluminal and interstitial implants should be reviewed for appropriateness and adequacy
- Reference points (Basal Dose Points) placement

Review of Source Characteristics

- TPS commissioning should include verification of source dimensions and dosimetry parameters
- Plan QA review limited to
  - Correct source model
  - Correct decayed source strength
  - Correct identification of applicators/sources where multiple source strengths are used
  - Correct number of sources

Review of Plan Optimization Method

- Protocols should be developed for selection of plan optimization method specific to treatment site
  - Dose point optimization
  - Geometric optimization
  - Manual optimization
  - Inverse planning/DVH based optimization
- Plan QA review limited to
  - Correct selection of optimization method
  - Correct placement of optimization points relative to applicators/catheters and/or target

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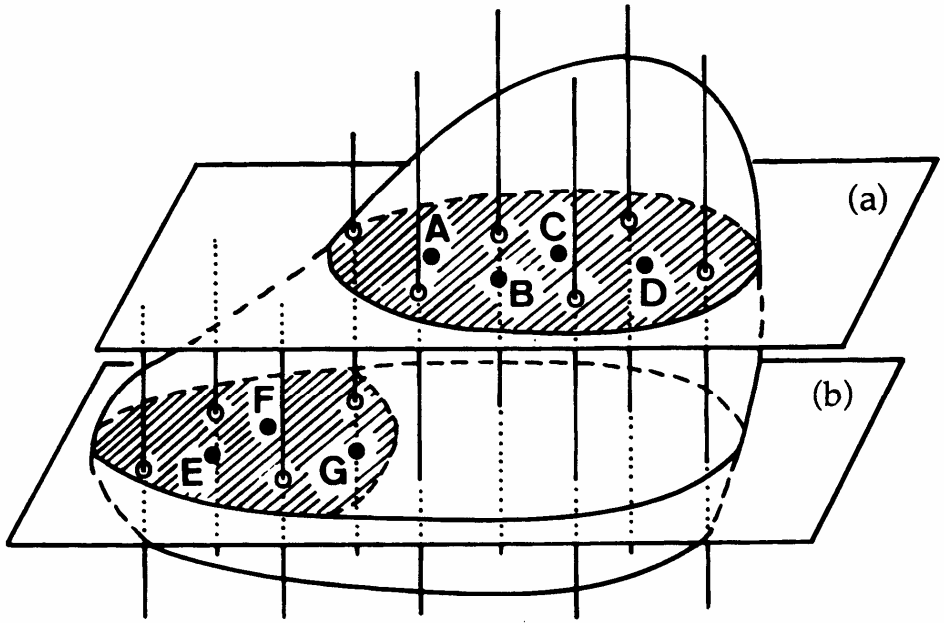
Plan Quality Evaluation

- **Point-based quality parameters**
  - **Traditional T&O: points A and B, rectum point, bladder point**
    - » **High rectum and bladder point doses should be brought to treating physician's attention**
  - **ICRU Report #58 Quantities:**
    - » **Mean Central Dose points: similar to Basal dose points in Paris system**
    - » **Mean Central Dose: Calculated as average of doses to mean central dose points**
    - » **Dose Homogeneity Index: Ratio of Mean Central Dose to Peripheral dose**
    - » **Paris system uses DHI of 0.85**
    - » **RTOG 95-17 Partial Breast Brachytherapy protocol allows DHI as low as 0.75 (Rx dose instead of peripheral dose used in DHI calculation)**

ICRU Report 58 Mean Central Dose Points

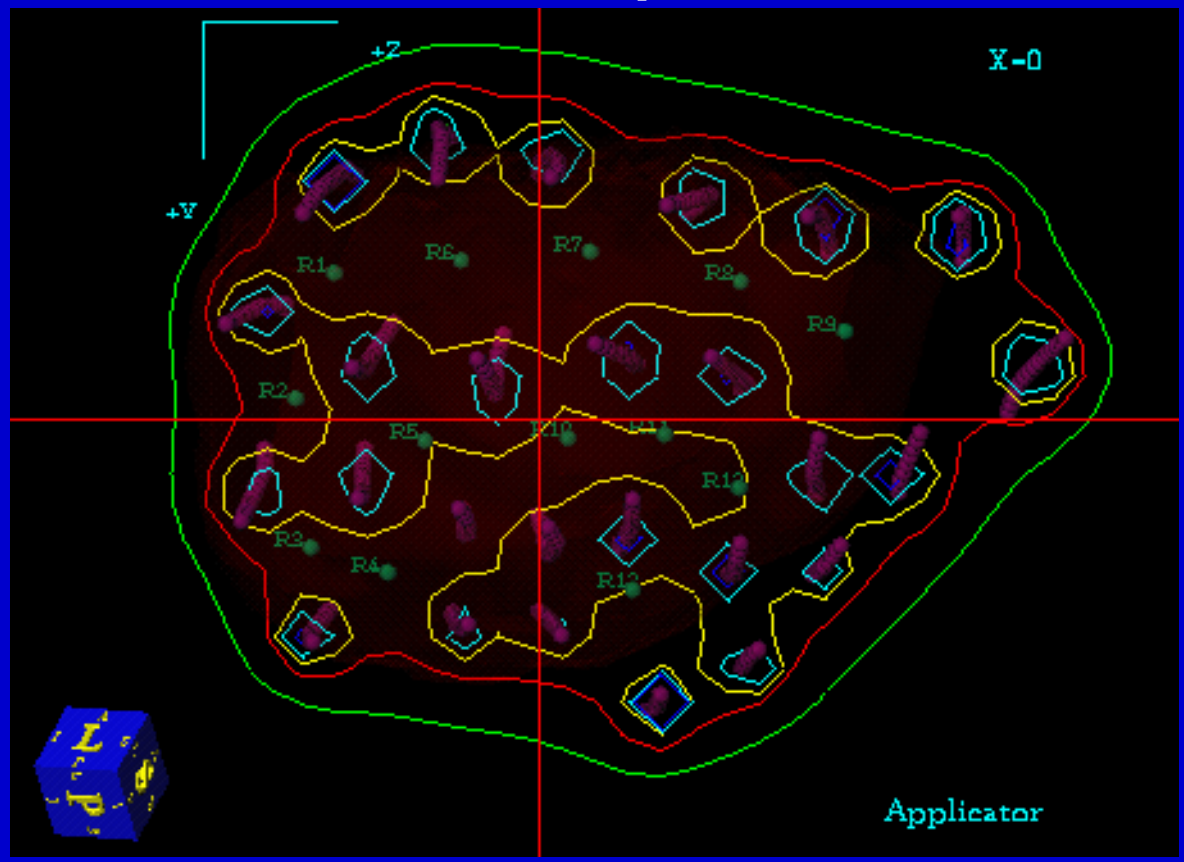


$$D_{ma} = \frac{D_A + D_B + D_C + D_D}{4} \qquad (a)$$

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

Placement of Reference Points in Accelerated Partial Breast Brachytherapy

- **Manual placement based on distance to catheters, followed by adjustment based on distance to high (200%) isodose lines after optimization**



Plan Quality Evaluation

- **Volume-dose based parameters without volumetric patient image data:**
  - **Maximum contiguous dose (Nablett):**
    - » **Reducing isodose display until an isodose covers all sources**
    - » **A surrogate to peripheral dose in the absence of a target definition**
  - **ICRU Report 58 quantities:**
    - » **High dose region (HD), low dose region (LD), prescription dose (PD)**

Plan Quality Evaluation

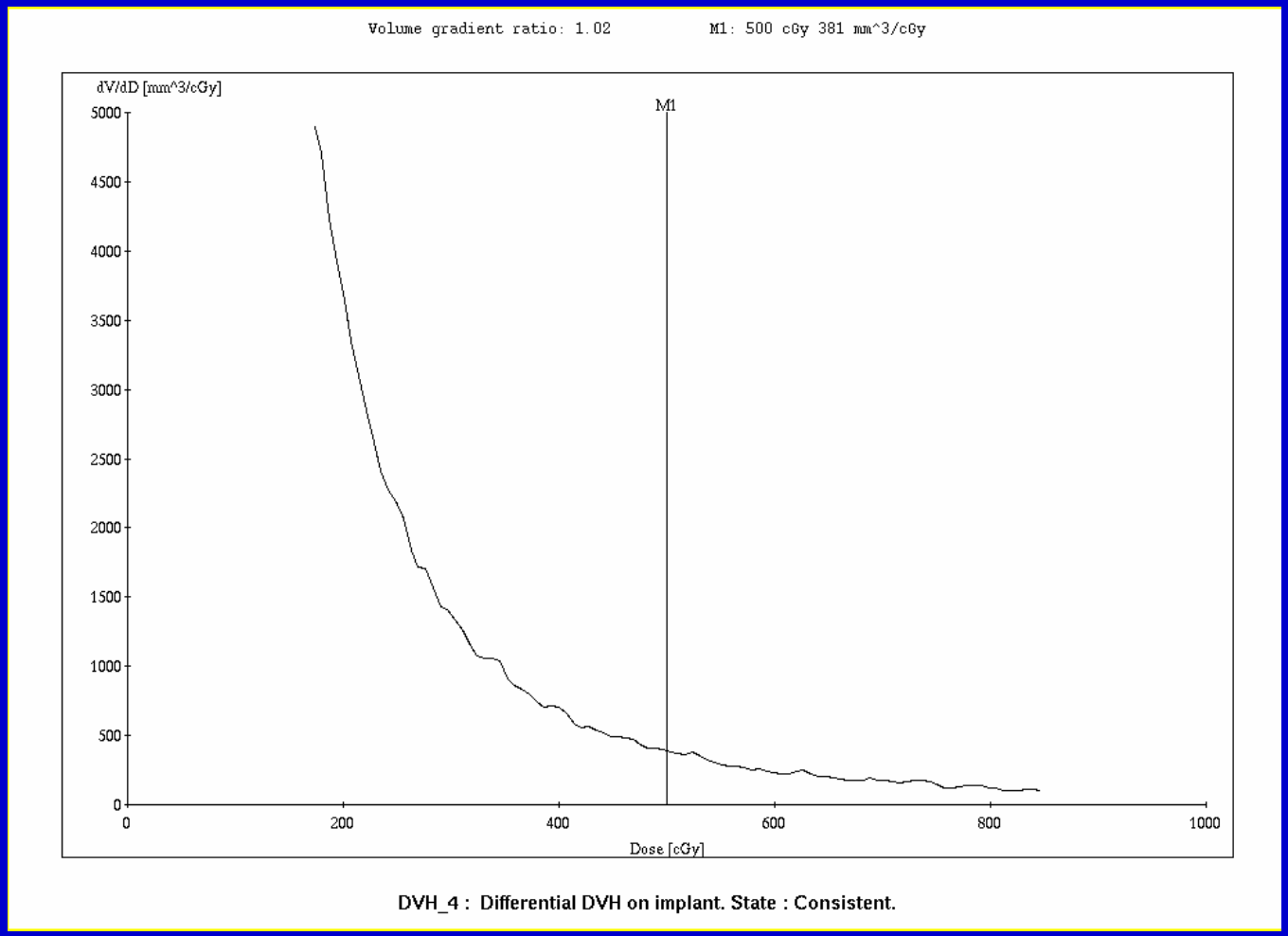
- **Volume-based parameters without volumetric patient image data**
  - **Dose volume histograms (DVH)**
    - » **Differential DVH: Tabulation of volume of patient, target, or organ receiving a given dose value**
    - » **Cumulative DVH: Tabulating of volume of patient, target, or organ receiving up to a given dose value**
    - » **Natural DVH: Differential DVH converted to remove inverse square dependence of dose distribution**

Plan Quality Evaluation

- **Volume-based parameters using volumetric patient image data**
  - ***Limited* Dose volume histograms (DVH)**
    - » **Differential DVH, Cumulative DVH, and Natural DVH can be calculated for segmented target and critical organs**
  - **Indices derived from DVHs:**
    - » **Coverage Index (CI): Percentage of target volume receiving prescription dose**
    - » **Dose Non-homogeneity Index (DNI) (Saw and Suntharalingam)**
      - **Ratio of high dose volume to tissue receiving prescription dose**
      - **RTOG 0413 Partial Breast Irradiation protocol requires DNI (called DHI in protocol) of 0.75 or higher**

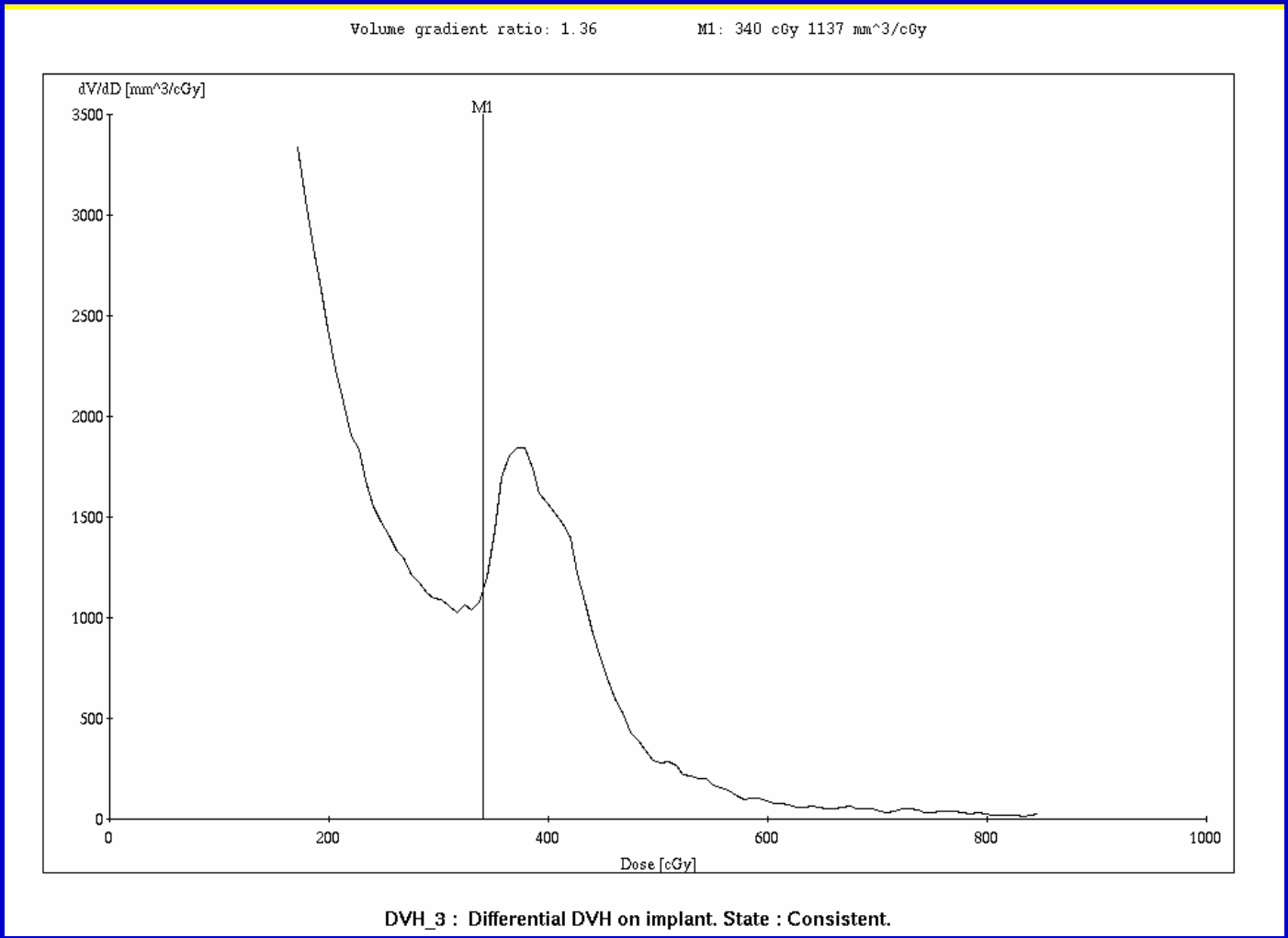
Differential DVH for A Single Source

- **Differential DVH for MammoSite breast plan (no peak)**



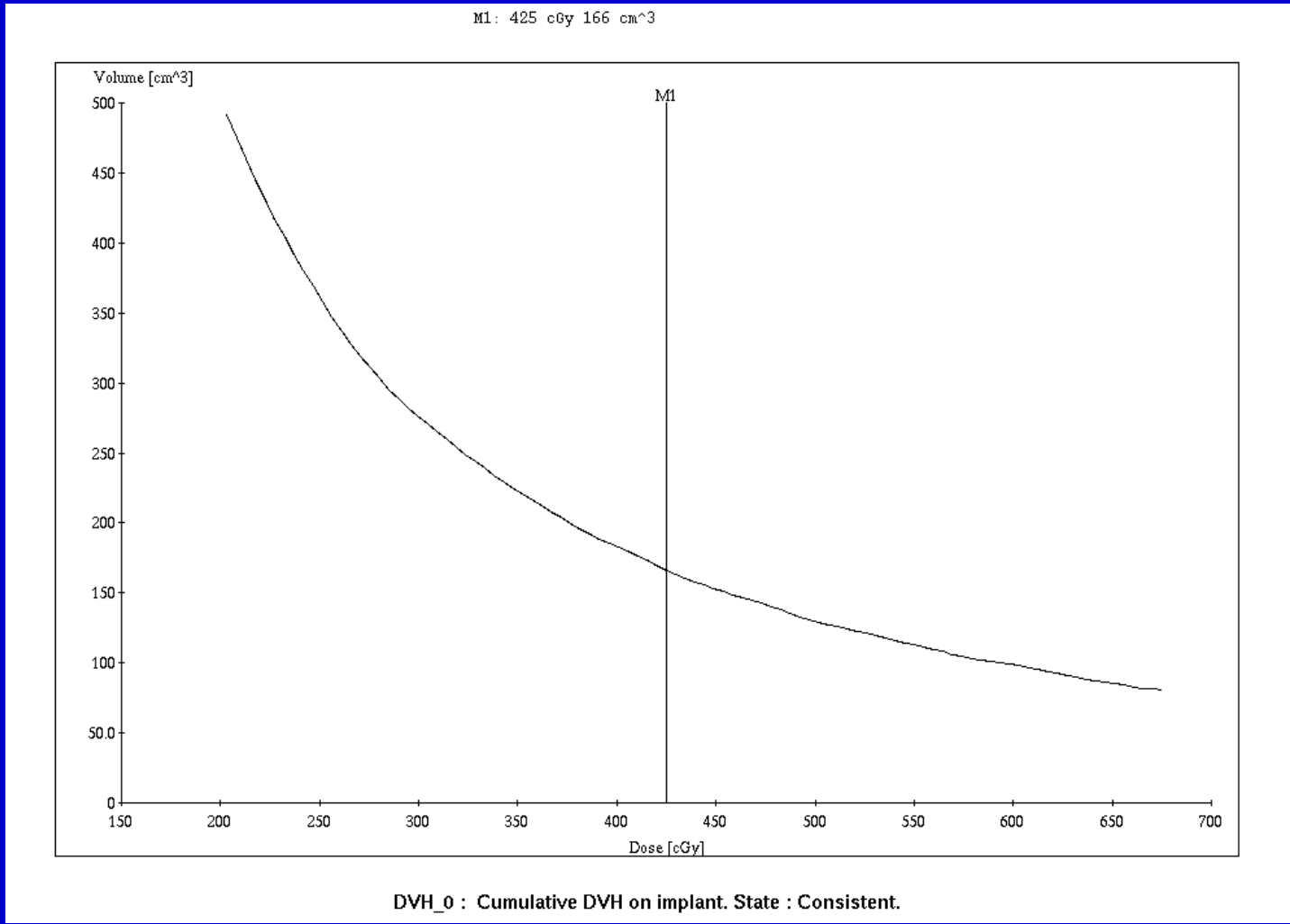
Differential DVH for Optimized Plan

- **Differential DVH for an optimized interstitial breast plan (note peak near Rx dose)**



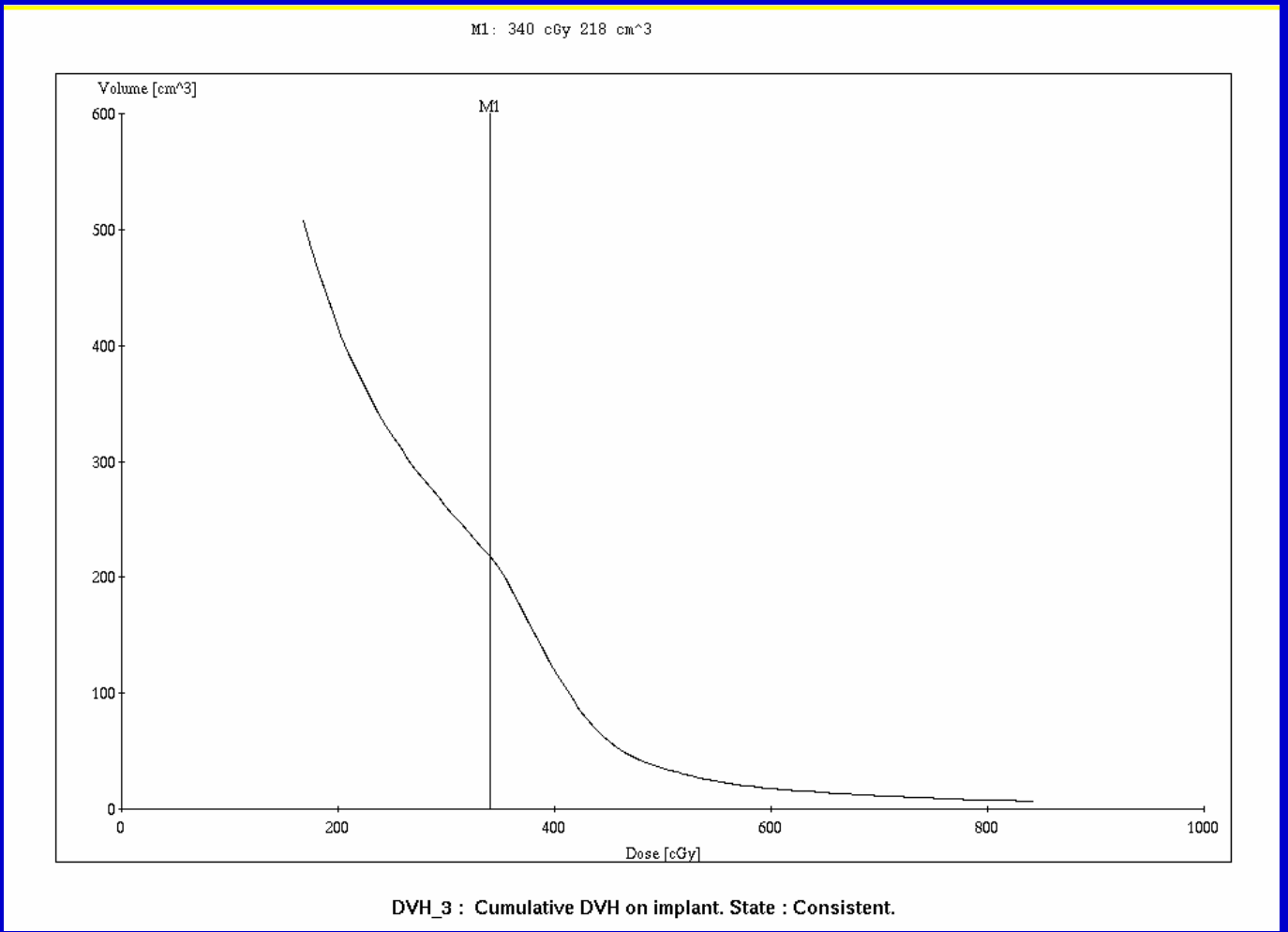
Cumulative DVH for a Single Source

- **Cumulative DVH for MammoSite (no deflection)**



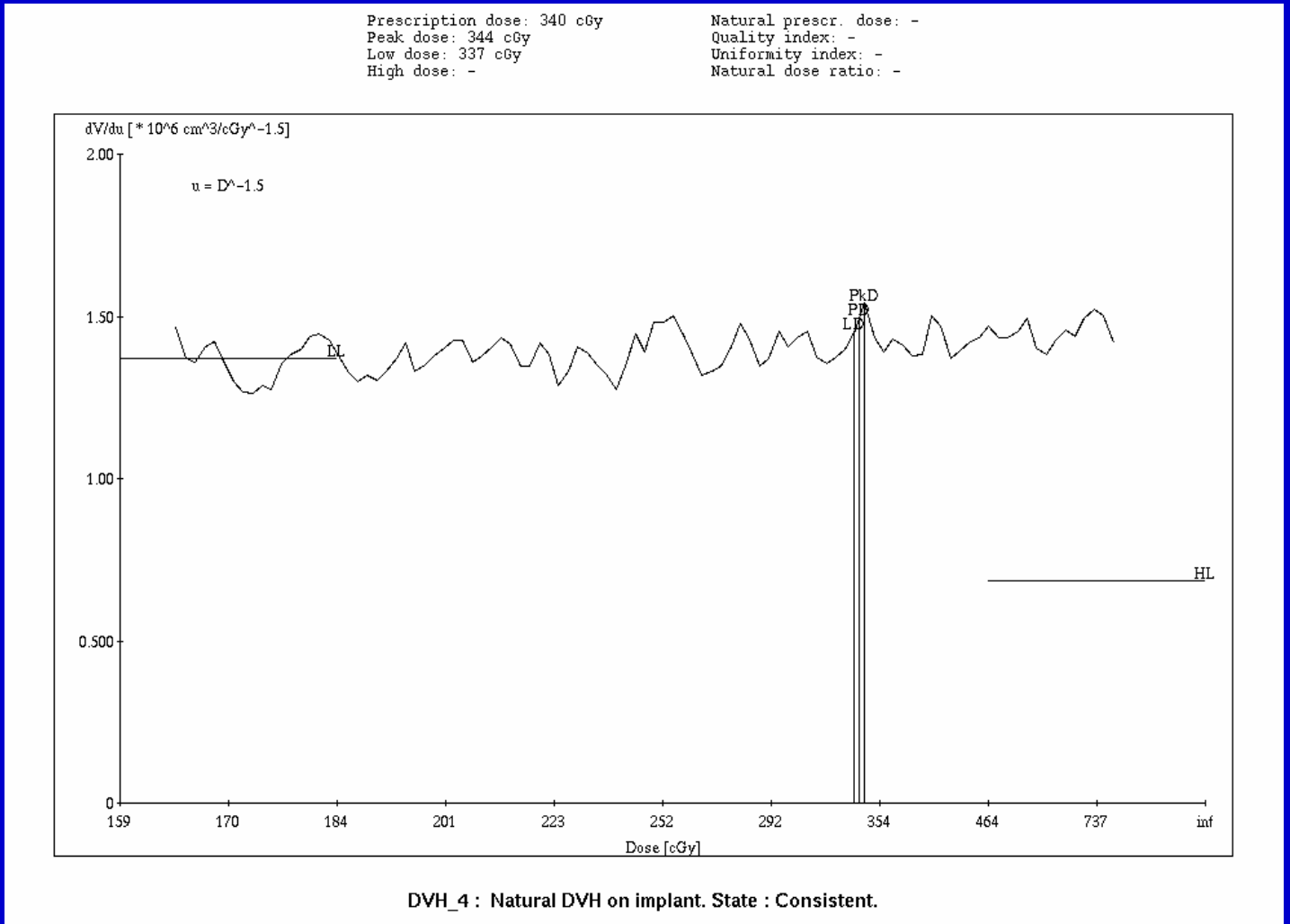
Cumulative DVH for Optimized Plan

- **Cumulative DVH for an optimized interstitial breast plan (note deflection near Rx dose)**



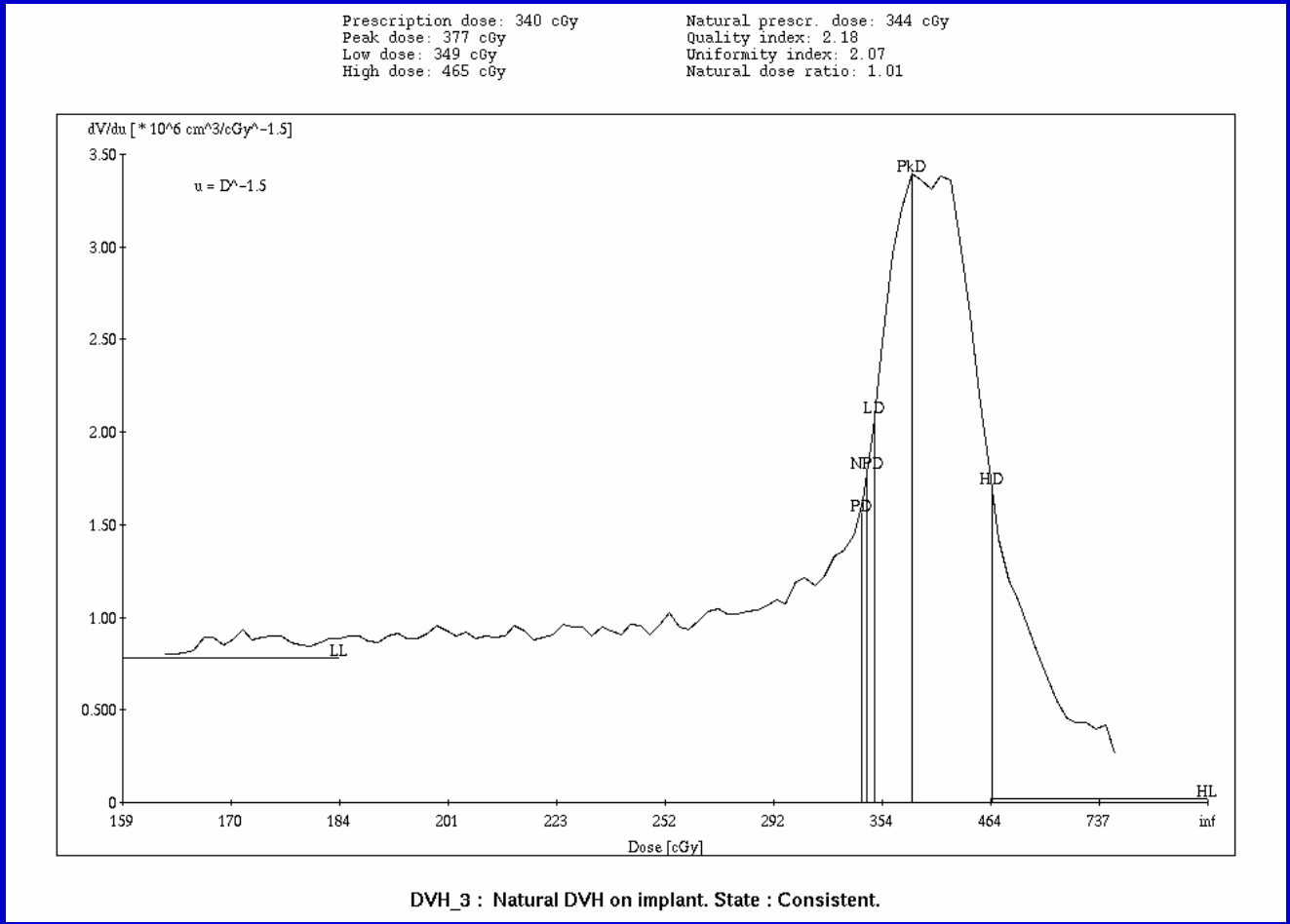
Natural DVH for a Single Source

- **Natural DVH for MammoSite (no peak, no fallof)**



Natural DVH for Optimized Plan

- **Natural DVH for an optimized interstitial breast plan (note peak near Rx dose and sharp falloff in high dose region)**



Plan Quality Evaluation

- **Clinical application of DVHs for plan evaluation**
  - **Empirically developed shapes and parameters from DVH useful for plan quality evaluation**
    - » **Breast: RTOG 0913 protocol specifies DVH values for HDR partial breast irradiation**
      - **Coverage Index (CI) ≥ 90%**
      - **Treated tissue receive 150% and 200% of prescription dose (V150 and V200) ≤ 70 cc and 20 cc respectively**
      - **DNI (defined as [1 – V150/V100]) of treated tissue ≥ 0.75**
    - » **Prostate: D90 of PTV in prostate implant ≥ 140 Gy (pre-TG43 dosimetry) associated with apparently optimal outcome (Stock *et al*, 2002)**

Plan Quality Evaluation

- **Slice-by-slice isodose review**
  - **All aggregate metrics (DVH, DNI, CI *etc*) lose the geometric information of where the high and lose regions are**
  - **Locations of overdose of critical organs and underdose of target remain identifiable only through slice-by-slice review of isodose distributions**
    - » **A 20 cc volume of 200% or high dose region may have different clinical consequences depending on whether it is a contiguous volume or distributed locally throughout the treated volume**

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Why Independent Calculation Check?

- **All TPS should be rigorous tested during acceptance testing and commissioning, however**
  - **Not all functions of a modern, 3D brachytherapy TPS can be tested**
  - **Software errors are often only associated with a particular sequence of operational steps.**
  - **Human (data input and transcription) and data transfer errors causing gross errors in plan**
  - **Regulatory compliance – NRC requires independent calculation check of brachytherapy plans**

How to Perform Independent Calculation Check?

- **Various methods available and/or proposed**
  - **Manual measurement of source locations and estimate of dose to points using away-along tables**
  - **Use of simplified analytical solutions (unfiltered line source Sievert integral)**
  - **Use of classical implant systems (Manchester, Quimby, Paris) for interstitial implants**
  - **Empirical lookup tables, linear/ polynomial/ exponential function fits and/or combinations thereof, for example, nomograms**
  - **Manual digitization or digital transfer of source locations into a 2nd TPS and re-calculate dose**

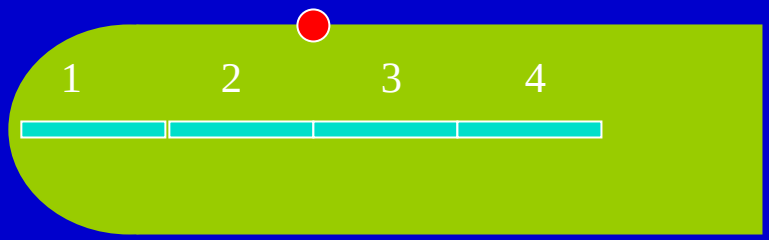
Independent Calculation Should

- Allow quick calculation check of the output of a treatment plan, using preferably the primary input data (source locations on images, target dimensions), a different computational algorithm, and arriving at a plan output parameter (dose to target)
- Have high sensitivity to data input and manipulation errors
- Provide insights to relation between prescribed doses, target, and source parameters (isotope, strength, distribution)

LDR Cylinder Surface Dose Calculation

LDR cylinder of radius r cm using 3M 6500 ^{137}Cs Tubes:

Use Away-Along Table

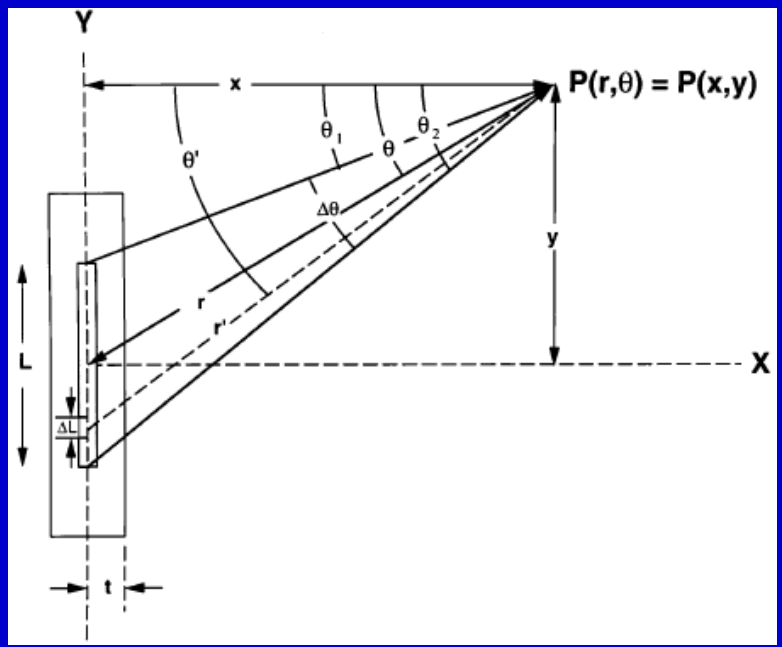


Source No.	Away dist. (cm)	Along dist. (cm)
1	*r*	3
2	*r*	1
3	*r*	1
4	*r*	3

Distance along length of source (cm from center)	Transverse distance from center of source (cm)									
	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
0.0	21.052	6.808	3.241	1.866	1.204	0.837	0.614	0.468	0.368	0.296
0.5	17.445	5.997	2.996	1.773	1.162	0.816	0.602	0.461	0.364	0.293
1.0	8.404	4.177	2.409	1.536	1.051	0.758	0.569	0.441	0.351	0.285
1.5	3.663	2.597	1.777	1.245	0.902	0.676	0.521	0.411	0.331	0.271
2.0	1.943	1.639	1.275	0.975	0.750	0.585	0.464	0.375	0.307	0.255
2.5	1.187	1.093	0.925	0.757	0.613	0.498	0.407	0.336	0.280	0.236
3.0	0.794	0.768	0.686	0.591	0.500	0.420	0.353	0.298	0.253	0.216
3.5	0.566	0.564	0.522	0.466	0.408	0.353	0.304	0.262	0.226	0.196
4.0	0.422	0.429	0.407	0.374	0.336	0.298	0.262	0.230	0.202	0.177
4.5	0.326	0.335	0.325	0.304	0.279	0.252	0.226	0.201	0.179	0.159
5.0	0.258	0.268	0.263	0.250	0.233	0.214	0.195	0.177	0.159	0.143

Unfiltered Sievert Integral

- **Integration over all active source material using point source model inside a physical source**

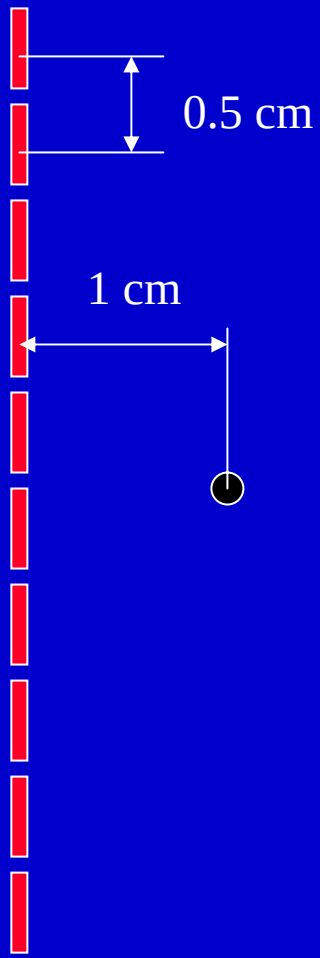


$$\Delta\dot{D}(x,\,y) = A \cdot \frac{\Delta L}{L} \cdot \frac{(\Gamma_\delta)_X \cdot f_{med}}{(x/\cos\theta)^2} \cdot T(x/\cos\theta) \cdot e^{-\mu' \cdot t/\cos\theta}$$

Unfiltered Sievert Integral

$$\dot{D}(x,L) = \frac{S_k \cdot \overline{(\mu_{en}/\rho)_{air}}^{med}}{x \cdot L} \cdot 2 \cdot \tan^{-1}\left(\frac{L}{2 \cdot x}\right)$$

Unfiltered Line Source Approximation: Practical Applications



- **^{192}Ir HDR source of 3.50 cGy-m^2/hr source strength, stepping through 10 dwell positions with 5 mm step sizes, dwell time = 5 seconds for all dwell positions.**
- **For ^{192}Ir $\overline{(\mu_{en}/\rho)}_{air}^{med}$ = 1.12**
- ***L* = 5 cm, *x* = 1 cm**
- **Total source strength**

  = 10 x 5/3600 (hour) x 3.5 x 100^2 cGy-cm^2/hour

  = 486.1 cGy-cm^2
- **Dose at 1 cm away from mid-catheter**

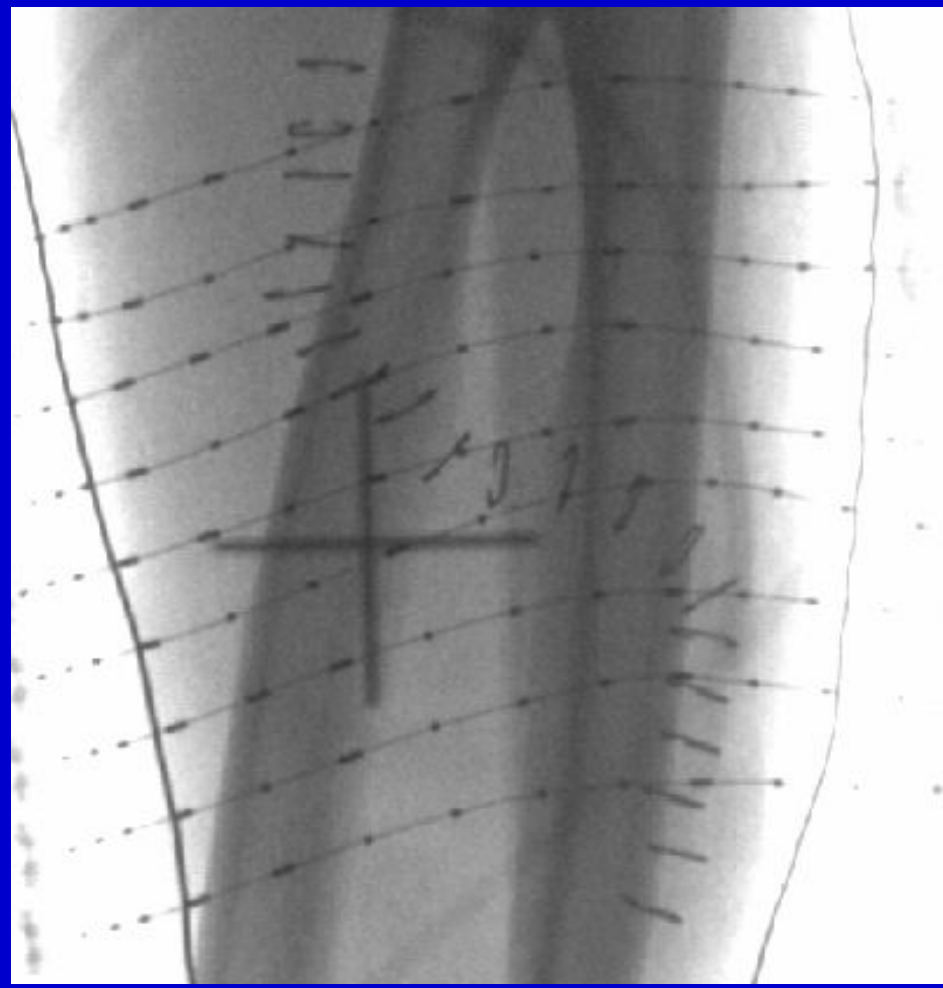
$$= \frac{486.1(cGy \cdot cm^2) \cdot 1.12}{1(cm) \cdot 5(cm)} \cdot 2 \cdot \tan^{-1}\left(\frac{5}{2}\right)$$

$$= 648\ cGy$$

Note: Make sure to use *radian* for inverse tangent calculation

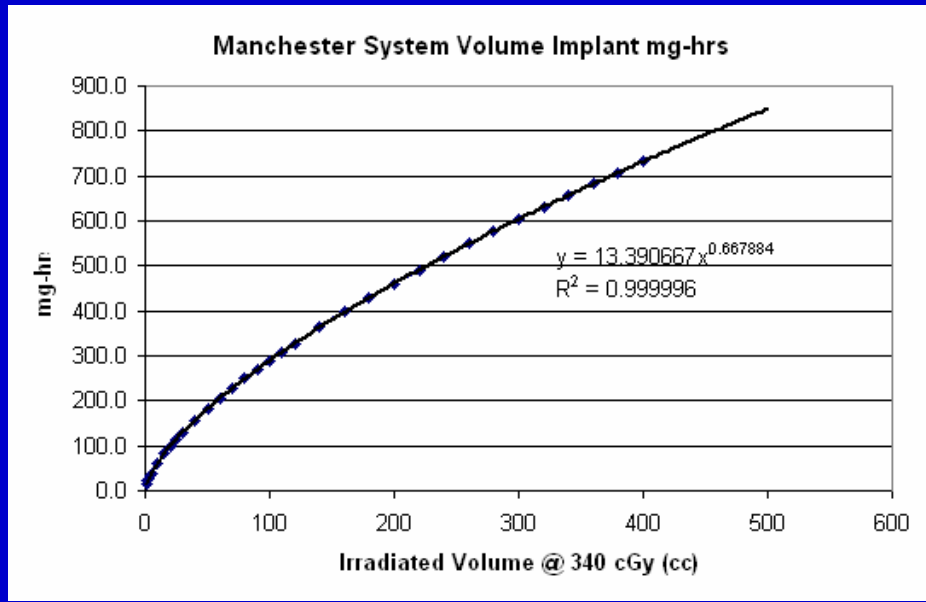
Use of Classical Implant Systems for Independent Calculation Check – Planar Implants

- Measure area of *activated* implant off film or isodose distribution
- Correct for prescription depth
- Look up total exposure (mg-hrs) in (corrected) Manchester table
- Correct for elongation
- Compare with TPS plan



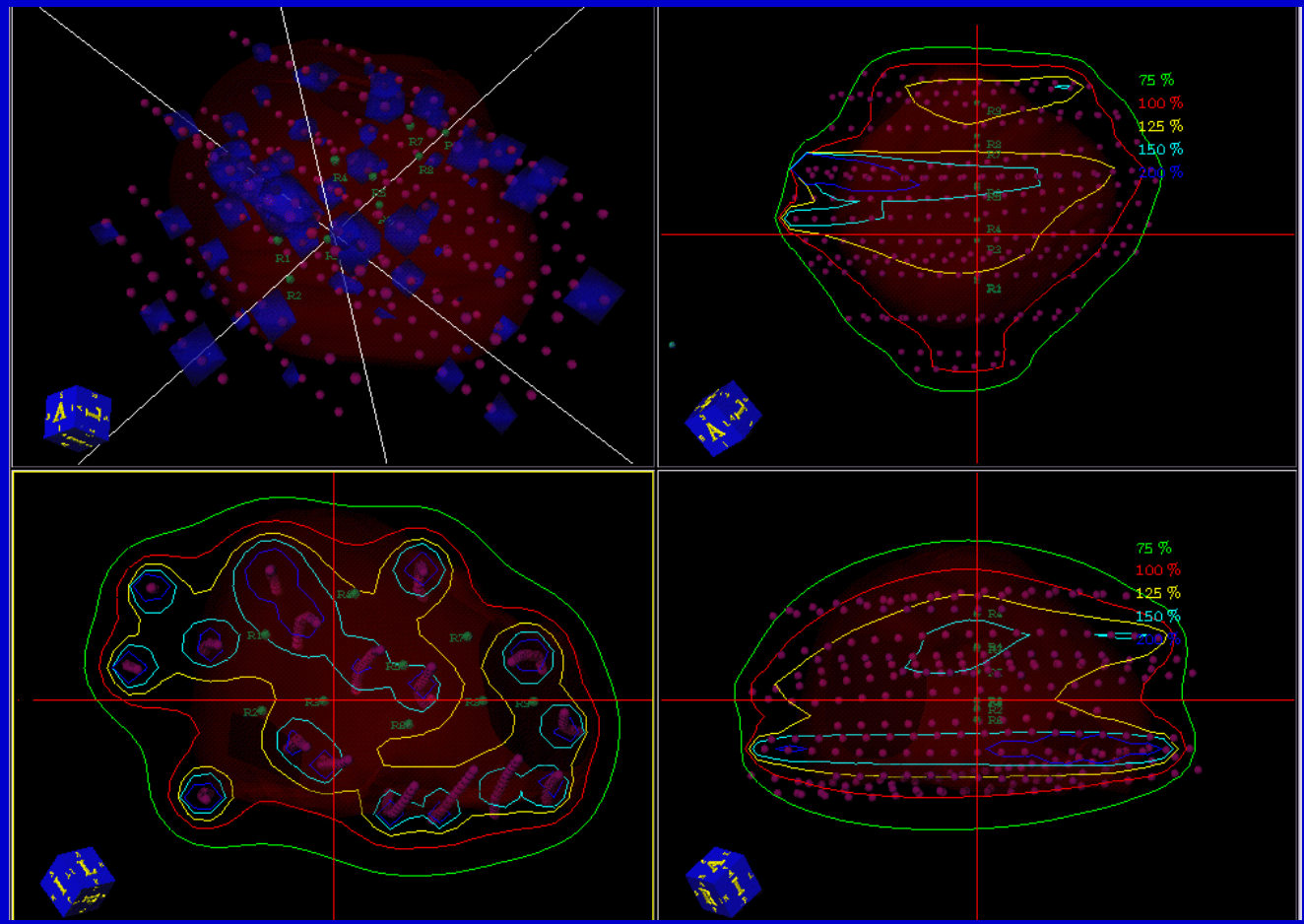
Use of Classical Implant Systems for Independent Calculation Check – Volume Implant

- Measure treated volume off orthogonal dose distributions (alternatively, may use volume of tissue receiving prescription dose from DVH calculations)
- Look up total exposure from (corrected) Manchester System table
- Correct for elongation
- Compare with TPS value



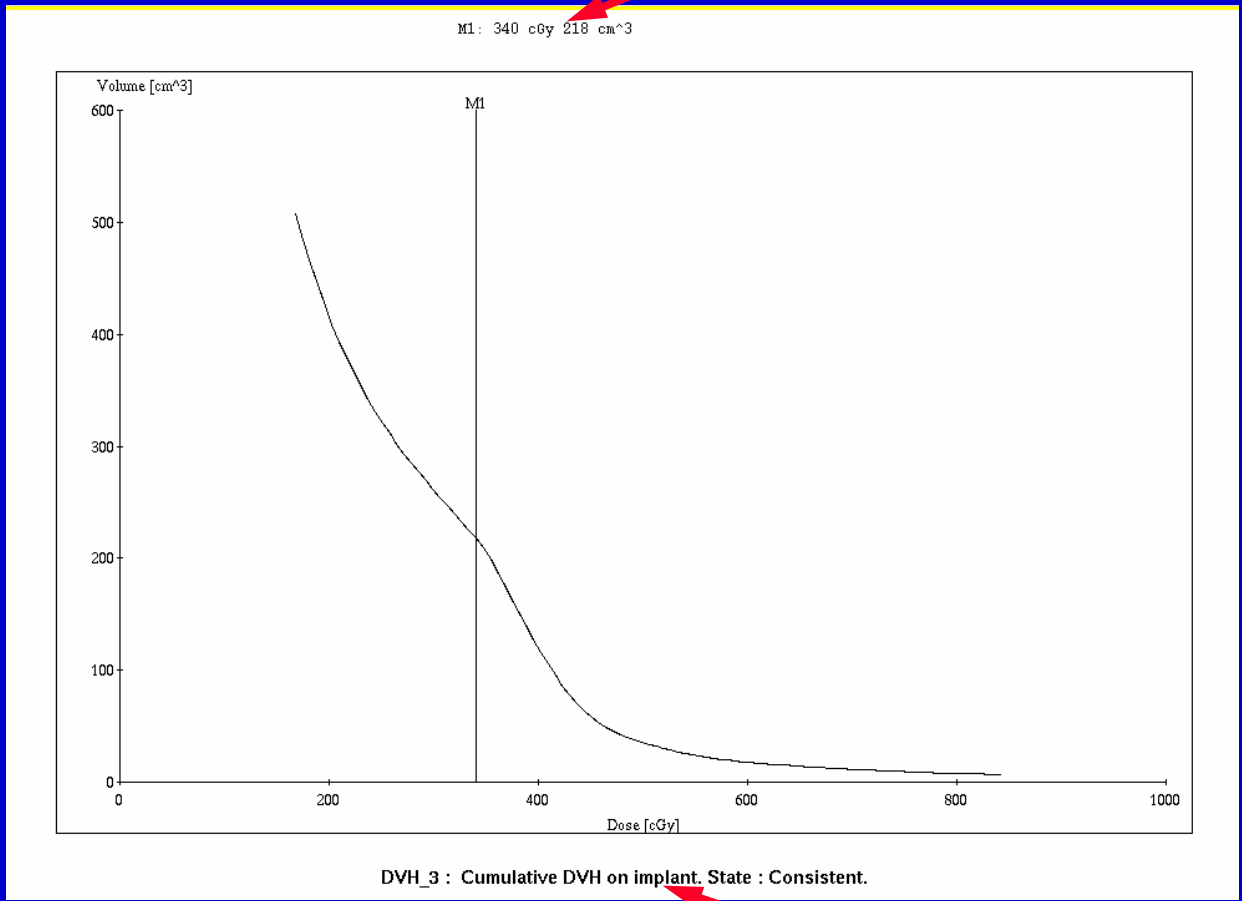
Volume Estimate for Independent Calculation Check

- **A practiced art to estimate volume from these dose distributions.**



Volume Estimate from TPS Calculated DVH – Assumes Correct Source Localization

M1: 340 cGy 218 cm^3



Cumulative DVH on implant.

Empirical Lookup Tables

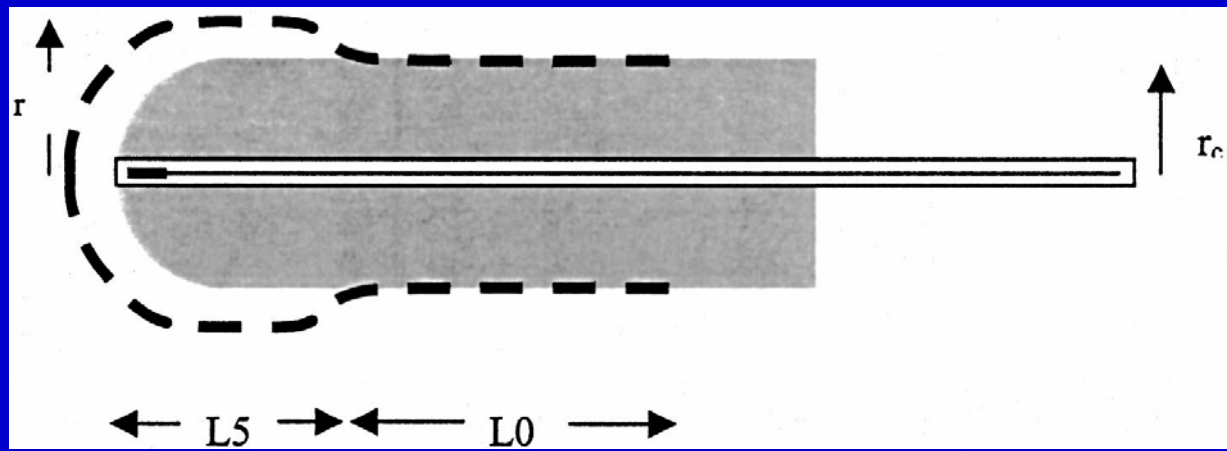
Table for Tandem and Ovoid Plan Manual Calculation Check Used at Mallinckrodt Institute of Radiology. HDR Treatment Dwell Times Are Scaled to Achieve Identical Loading Patterns.

Applicator Component	Loading (mgRaEq)	Dose Rate (cGy·h^{-1}) per mgRaEq^{+}		
		Point A	Point B	Point P
Small tandem	20	1.545	0.295	0.205
Medium tandem	10-20	1.543	0.297	0.207
Standard tandem	10-10-20	1.070	0.260	0.185
Endometrial tandem	10-20-10	1.308	0.278	0.195
2.0 cm colpostats*	20-20	0.553	0.250	0.183
2.5 cm colpostats*	25-25	0.474	0.244	0.182
3.0 cm colpostats*	30-30	0.418	0.228	0.173
Mini-ovoids (1.6 cm colpostats)	10-10	0.660	0.255	0.190

Multiply above numbers by total mgRaEq in each component.
$^{+}$3M ^{137}Cs tubes, 1.4 cm active length.
No correction for decay.
*Includes 6% applicator attenuation correction.

Independent Calculation Check of Cylinders

- **Calculation check scheme dependent on dose prescription and optimization scheme**
- **Mayo and Ulin: Dose prescribed to 5 mm depth at tip of cylinder and surface at lower part. Total treatment time $TT = K \times D/Sk$.**
  - ***K* = fitting constant; *D* = *Rx dose;* S_k = source strength**



Intraluminal Plan Independent Calculation Check

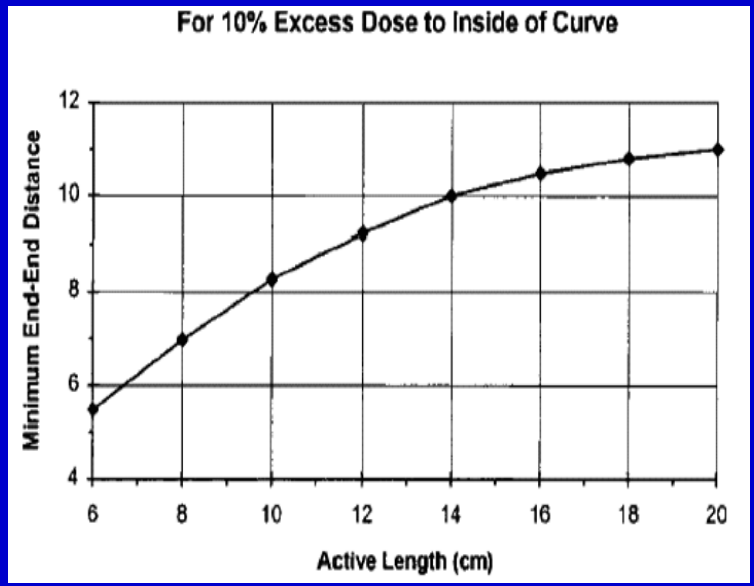
- **Unfiltered Sievert integral for single catheter treatment**
- **Rogus *et al:***

$$t(d,L)_{ref} = \left(-1.35 + 7.74\,d + 0.322\,d^2\right) + \frac{L-50}{50}\left(-0.591 + 6.92\,d + 0.0230\,d^2\right)$$

  - ***d*** **= Rx dose point distance to source**
  - ***L*** **= catheter active length**
  - ***t*** **= total treatment time**
  - **Fitting formula assumes straight or moderately curved catheters**

Single Catheter Plan Independent Check: How Straight?

- **Ezzell: Ratio of cord length to active length appropriate**



Planar Implant Independent Calculation Check

- Manchester system in general applies well
- Ezzell developed empirical fitting formula for planar implant independent calculation check

If

$$I = \frac{Dose \times area}{Source\ strength \times Total\ time}$$

then

$$I = A(T) + B(T) \times E + C(T) \times E^2$$

Where T = treatment thickness, E = side of equivalent square of implant

$$A = 3.245 - 1.269 \times T + 0.1014 \times T^2$$

$$B = 1.030 - 0.0728 \times T$$

$$C = -0.02083 + 0.001925 \times T\,.$$

Volume Implant Independent Calculation Check

- **Radium-equivalent sources (Cs-137, Ir-192, Au-198): Manchester system**
- **Low energy sources (I-125, Pd-103): Empirical nomograms (Cohen *et al*, 2002)**

I-125 (Rx dose = 144 Gy)

$$\frac{S_k}{U} = 1.524\left(1.09\frac{d_{avg}+0.8}{cm}\right)^{2.2}$$

Pd-103 (Rx dose = 140 Gy)

$$\frac{S_k}{U} = 5.395\left(1.09\frac{d_{avg}+0.8}{cm}\right)^{2.56}$$

where d_{avg} = average distance between peripheral needles/seeds in AP/PA, lateral and superior-inferior directions

5 mm treatment margins assumed except posterior

Final Documentation Review

- Site- and/or technique-specific isodose plots as well as image and text printouts should be defined
- Plan documentation reviewed for completeness and accuracy.

Summary

- QA review of a brachytherapy plan includes both medical and technical aspects of the treatment
- Familiarity with site-specific institutional treatment policies and procedures is a must in performing this task
- Quality evaluation of treatment plans is site-specific and often institution-specific as well
- An independent calculation check that provides insight into the physical aspects of the plan in relation to prescribed doses is an important step in plan QA review
- Vigilance in plan QA review goes a long way toward prevention of significant errors