Brachytherapy Sources, Dosimetry, and Quality Assurance for 192Ir HDR Brachytherapy

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Learning Objectives: Focus on ^{192}Ir HDR

- Radionuclide properties and their clinical applications
- Brachytherapy quality assurance strategies
  - `TG-100 approach to patient-specific HDR QA
- Brachytherapy dosimetry principles and practices
  - Measurement of brachytherapy source strength
  - Evaluation of dose rates around individual brachytherapy sources
  - Implications for QA program
- Dr. Thomadsen's Topic: brachytherapy treatment planning- the art of arranging multiple sources in various clinical settings

How do physical radionuclide properties determine their clinical applications?

Source properties: energy, half-life, specific activity

- **Dose rate:**
  - High: > 12 Gy/h
  - Low: 0.3-1.5 Gy/h
  - UltraLow: <0.2 Gy/h
- **Mode of delivery:** Interstitial, intracavitary, surface
- **Dose control mode:** temporary, permanent
- **Source transport mode:** hot loaded, manually afterloaded, remotely afterloaded
- We will consider high dose rate (HDR), temporary, remotely afterloading implants

Understand this Table

TABLE 22.1 PHYSICAL PROPERTIES AND USES OF BRACHYTHERAPY RADIONUCLIDES

Element	Isotope	Energy (MeV)	Half-Life	HVL-Lead (mm)	Exposure Rate Constant[a] Γ_δ	Source Form	Clinical Application
Obsolete Sealed Sources of Historical Significance							
Radium	^{226}Ra	0.83 (average)	1,626 years	16	8.25[b] 7.71[c]	Tubes and needles	LDR intracavitary and interstitial
Radon	^{222}Rn	0.83 (average)	3.83 days	16	8.25[b]	Gas encapsulated in gold tubing	Permanent interstitial Temporary molds
Currently Used Sealed Sources							
Cesium	^{137}Cs	0.662	30 years	6.5	3.26	Tubes and needles	LDR intracavitary and interstitial
Cesium	^{131}Cs	0.030	9.69 days	0.030	0.64	Seeds	LDR permanent implants
Iridium	^{192}Ir	0.397 (average)	73.8 days	6	4.69	Seeds in nylon ribbon; metal wires Encapsulated source on cable	LDR temporary interstitial Intravascular brachytherapy; cardiac HDR interstitial and intracavitary Intravascular brachytherapy: peripheral
Cobalt	^{60}Co	1.25	5.26 years	11	13.07	Encapsulated spheres	HDR intracavitary
Iodine	^{125}I	0.028	59.6 days	0.025	1.45	Seeds	Permanent interstitial
Palladium	^{103}Pd	0.020	17 days	0.013	1.48	Seeds	Permanent interstitial
Gold	^{198}Au	0.412	2.7 days	6	2.35	Seeds	Permanent interstitial
Strontium/Yttrium	$^{90}Sr-^{90}Y$	2.24 β_{max}	28.9 years	–	–	Plaque Seeds	Treatment of superficial ocular lesions Intravascular brachytherapy
Developmental Sealed Sources							
Americium	^{241}Am	0.060	432 years	0.12	0.12	Tubes	LDR intracavitary
Ytterbium	^{169}Yb	0.093	32 days	0.48	1.80	Seeds	HDR interstitial
Californium	^{252}Cf	2.4 (average) neutron	2.65 years	–	–	Tubes	High-LET LDR intracavitary
Samarium	^{145}Sm	0.043	340 days	0.060	0.885	Seeds	LDR temporary interstitial

HVL, half-value layer; LDR, low dose rate; HDR, high dose rate; LET, linear energy transfer.

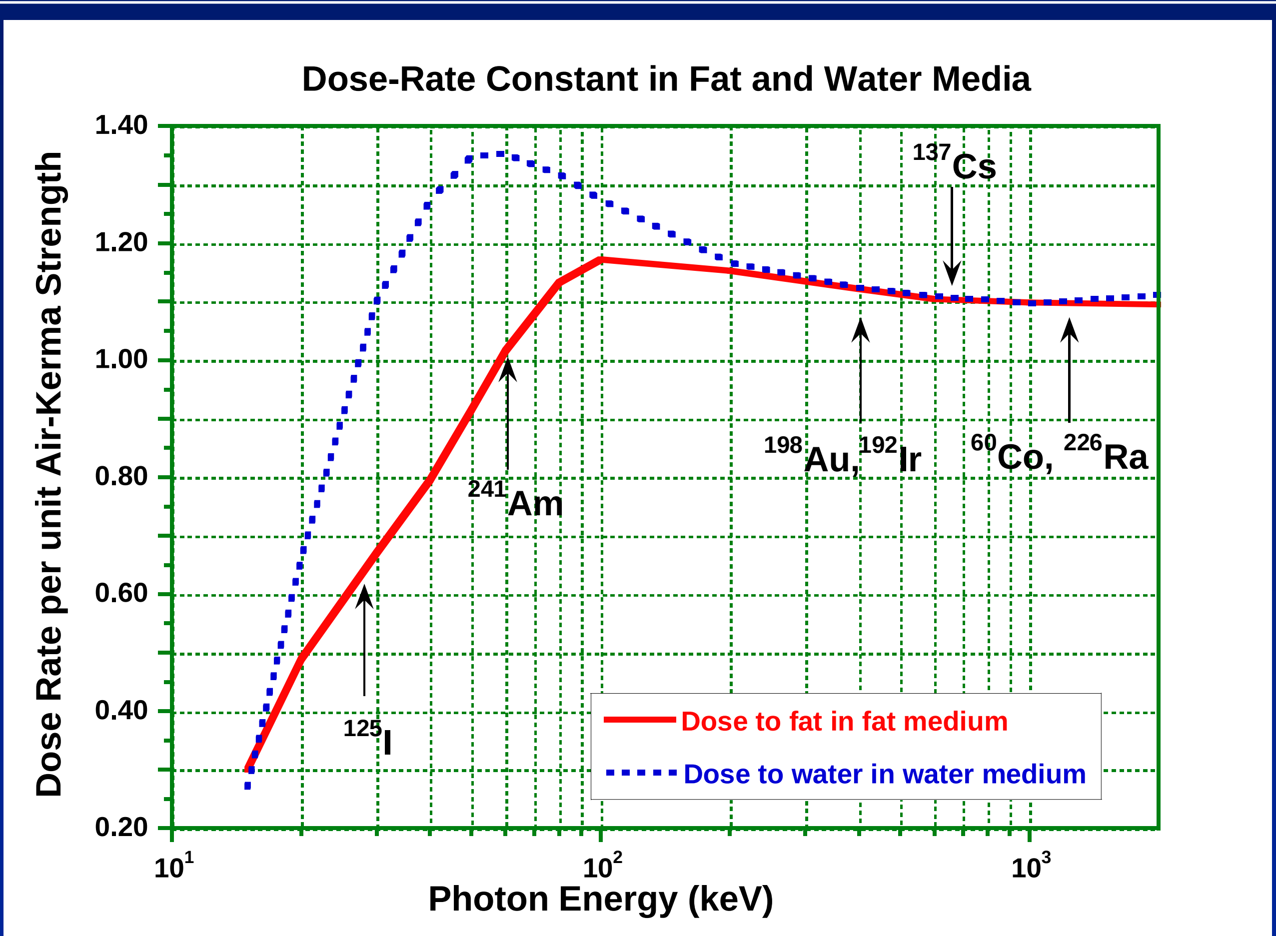
[a] No filtration in units of $R \cdot cm^2 \cdot mCi^{-1} \cdot h^{-1}$.

[b] 0.5 mm platinum filtration; units of $R \cdot cm^2 \cdot mg^{-1} \cdot h^{-1}$.

[c] 1.0 mm platinum filtration; units of $R \cdot cm^2 \cdot mg^{-1} \cdot h^{-1}$.

Williamson, Li, and Brenner, PPRO 6th ed

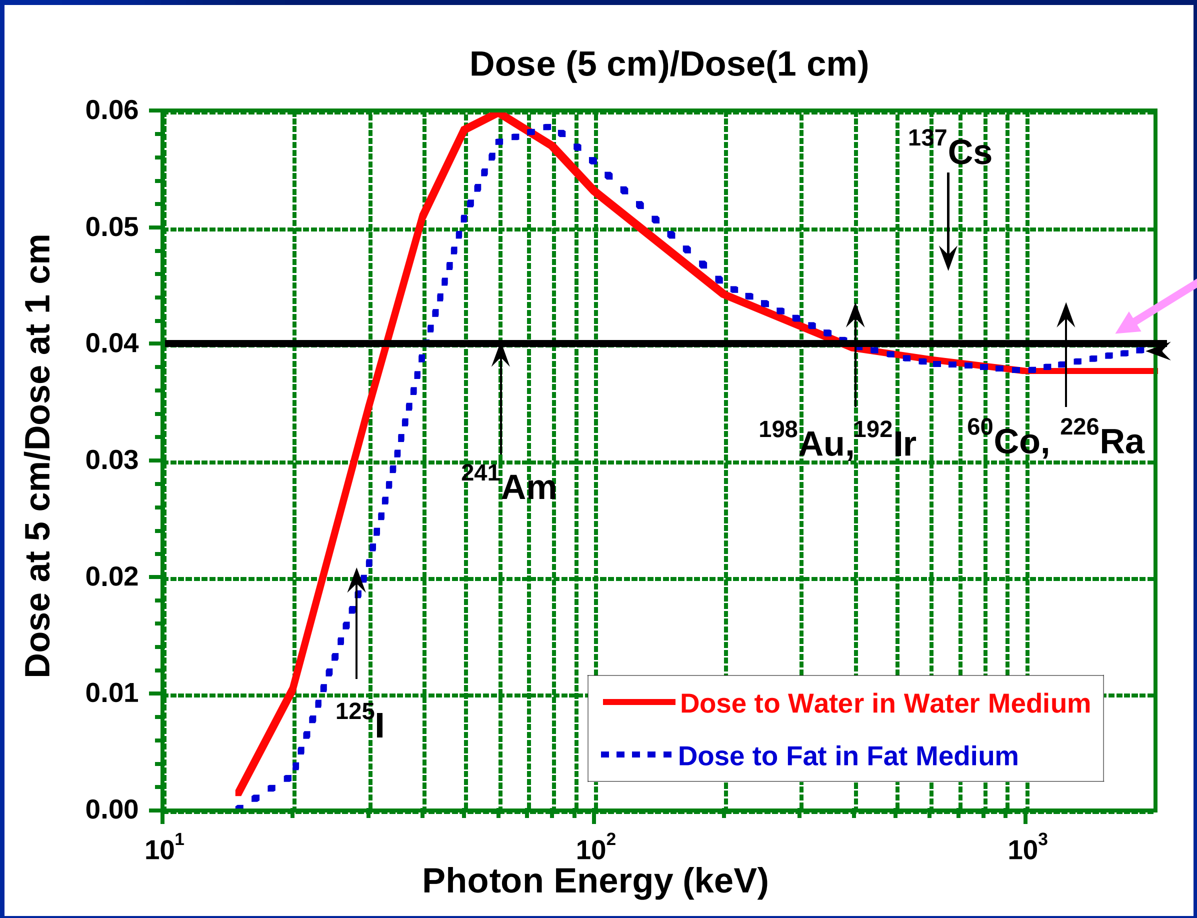
Influence of Photon Energy On absolute Dose Rate



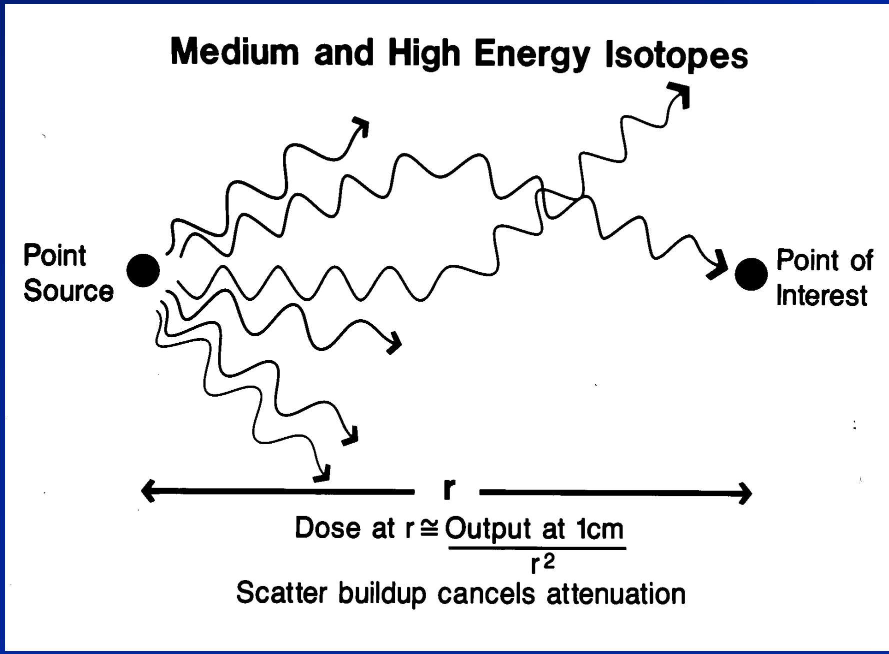
- >200 keV, all sources have same DRC, regardless of medium
- <100 keV, photo effect induces up to two-fold heterogeneity corrections

$$\Lambda = \text{Dose-Rate Constant} = \frac{\text{Dose rate in medium at 1 cm}}{\text{Air-kerma rate in free space at 1 cm}}$$

Effect of Energy on Penetration



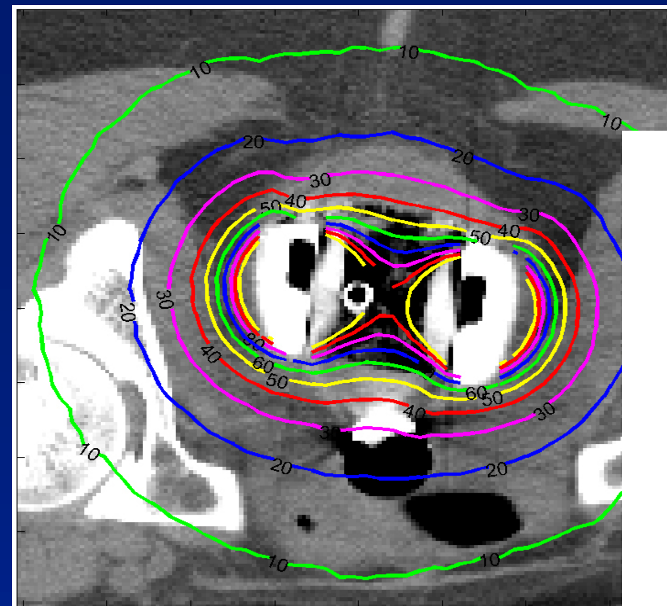
$$\left(\frac{1}{5}\right)^2 = 0.04$$

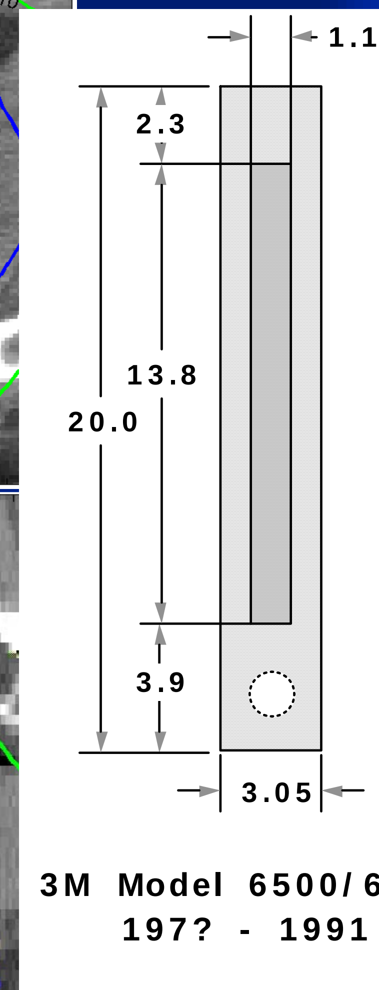


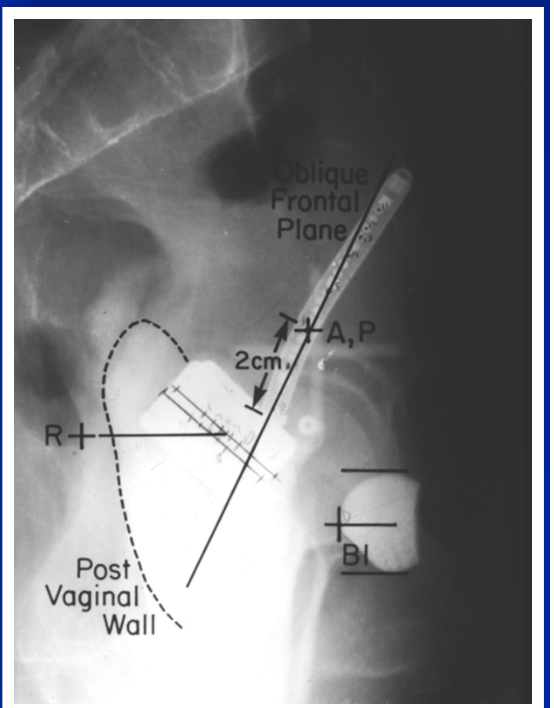
- Above 200 keV: All photon emitters have same depth dose regardless of medium

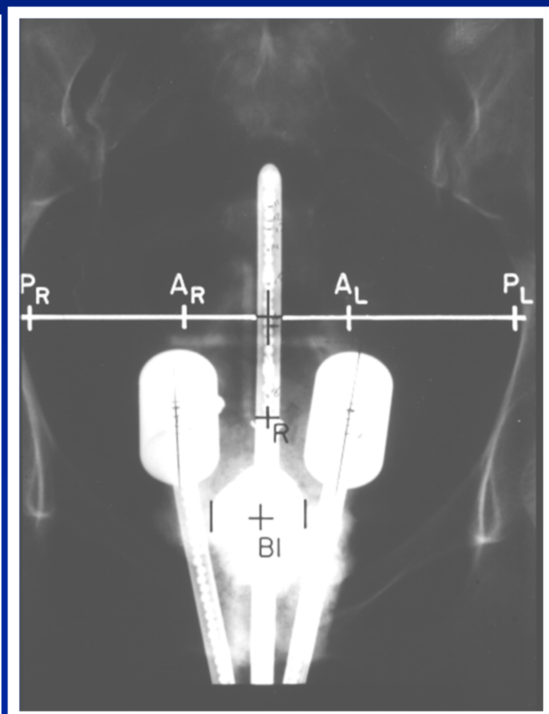
Low Dose-Rate Intracavitary Brachytherapy

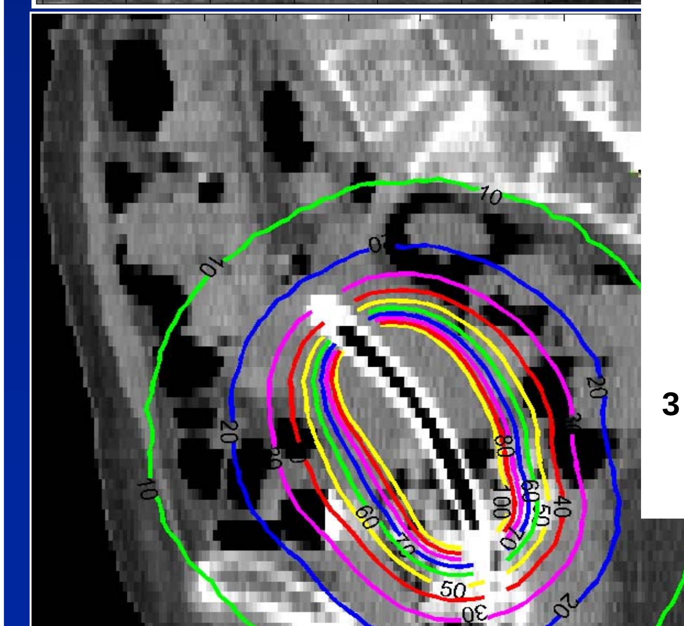
- **Cs-137 sources:**
  - Ceramic core **(low toxicity)**
  - 662 keV photons **(radiation exposure management)**
  - 30 year half life **(10 year life)**
  - Low specific activity **(LDR only)**



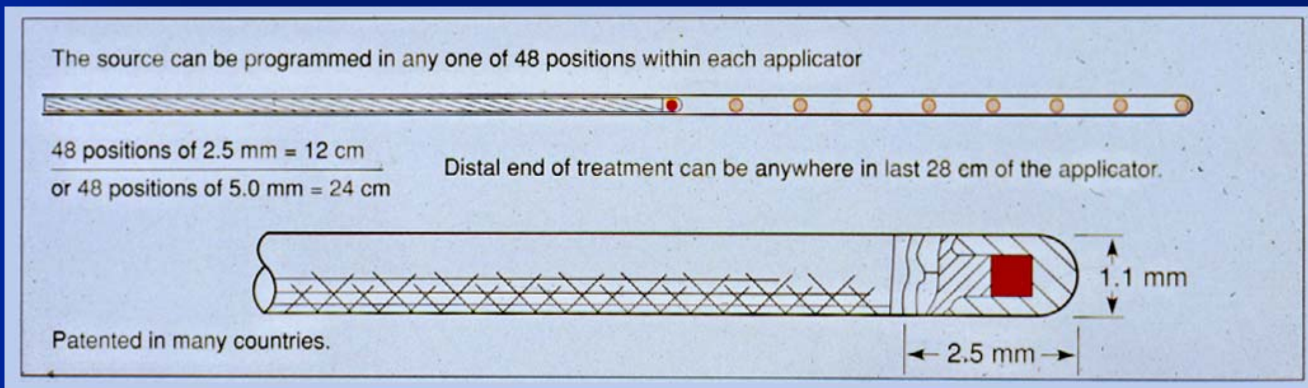








High Dose-Rate Brachytherapy
Single-Stepping source remote afterloading



- **Ir-192: Half life = 73.8 days, mean energy = 397 keV**
- **Very high specific activity**
- **HDR Ir-192 source: $S_K = 4.08 \times 10^4\ \mu Gy\ m^2\ h^{-1}$**
- **Ir-192 also used for LDR interstitial implants**

Trans-rectal Ultrasound-Guided Perineal Permanent Prostate Implant

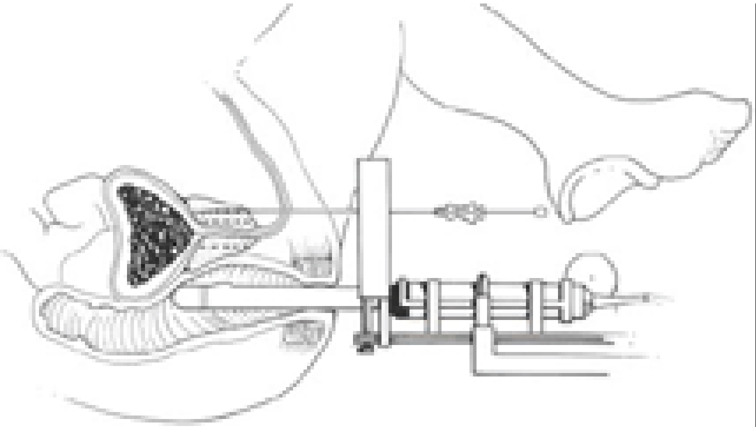
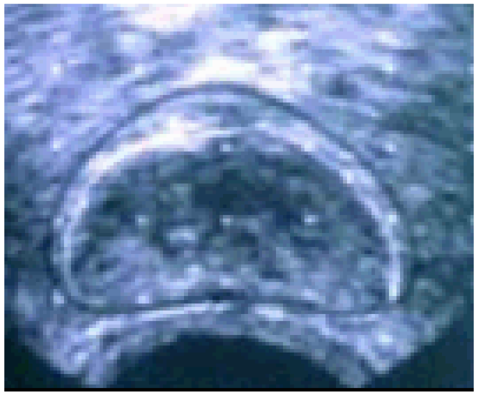


Figure 5:
Ultrasound-guded implantation technique



Ultrasound image

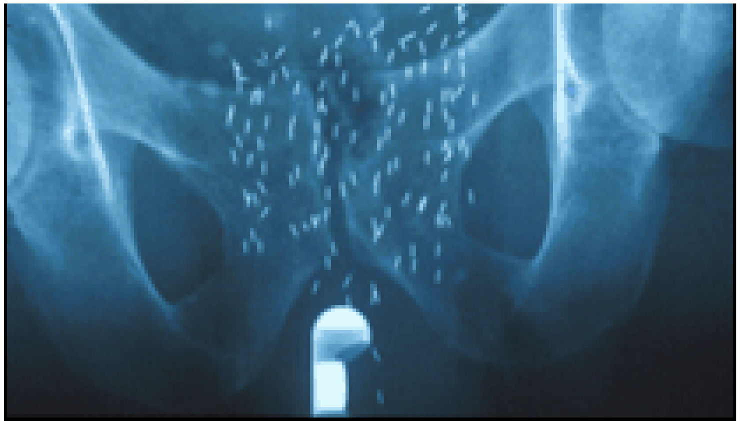
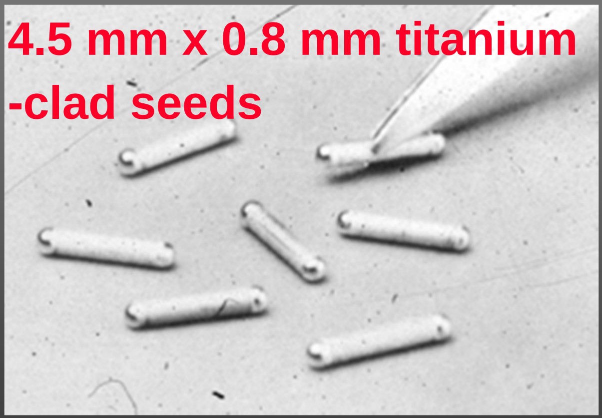


Figure 6: X-ray showing uniform distribution of seeds with ultrasound-guided implantation

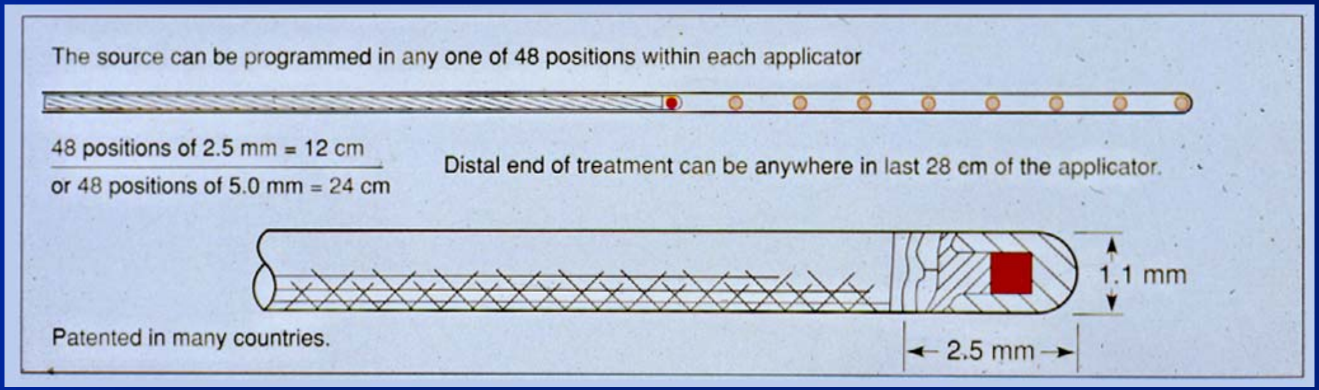


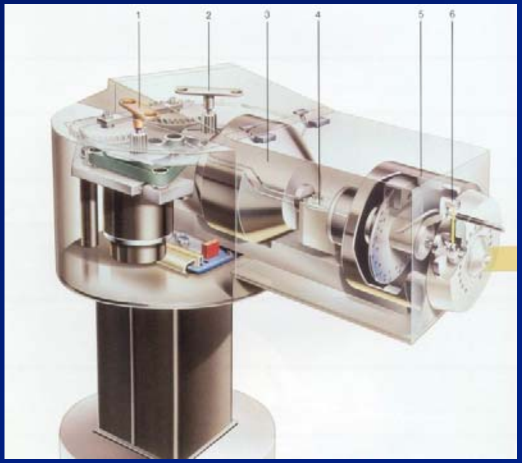
4.5 mm x 0.8 mm titanium -clad seeds

Isotope	Half-Life	Energy	Dose rate
I-125	59.6 days	28 keV	7 cGy/h
Pd-103	17.0	22	21
Cs-131	9.7	30	36
Au-198	2.7	412	105

- Patient’s tissues effectively shield staff and public from exposure

High Dose-Rate Brachytherapy





- **Greater potential for high-severity medical errors**
  - **⇑ degrees of freedom (dwell times & positions) ⇒ more error pathways**
  - **Insertion, planning and delivery in few hours ⇒ stress on staff**
  - **Source detachment ⇒ 20 mm diameter sphere receives dose of 750 cGy/min**

Quality Assurance Taxonomy

- **Quality Assurance of Devices (TG-56):**
  - Do applicators, afterloaders, sources, planning systems work properly?
  - Commissioning/acceptance testing
    - » Identify malfunctions/test users' beliefs
    - » Transform physicist into expert user
    - » Integrate device into clinical program
  - Periodic QA protocols
    - » Device still function within specs? Users' beliefs still valid?
- **Patient-specific QA or "Process" QA (TG-56 for LDR; TG-59 for HDR): none for Image guided BTx**
  - During individual patient treatments: prevent treatment delivery errors and high risk scenarios

Quality Assurance Fundamentals

- Accurately deliver dose distribution desired by radiation oncologist
  - Clinical intent correctly translated into prescribed dose and normal tissue constraints
  - spatial-temporal accuracy: correct sources placed in prescribed location for prescribed time
  - accurate dose delivery
- Specific endpoints
  - Positional accuracy (± 2 mm)
  - Temporal (timer) accuracy (± 2%)
  - Dose delivery accuracy (± 2-20%)
  - Safety: Patient, staff, public and institution

Safety Endpoints

- **Protect staff and public**
  - **Uncontrolled areas: < 0.02 mSv/h regardless of occupancy (10 CFR part 20)**
  - **General public: < 1 mSv/y to any person**
  - **Staff: < 5 mSv/y per ALARA**
- **Protect patient from catastrophic errors**
  - **Verify all critical "decision points"**
  - **Verify interlocks/ error detection systems**
  - **Emergency and error recovery procedures**
- **Institutional protection**
  - **Complete/accurate records**
  - **Adhere to/document compliance to CMMS and 10 CFR 35**

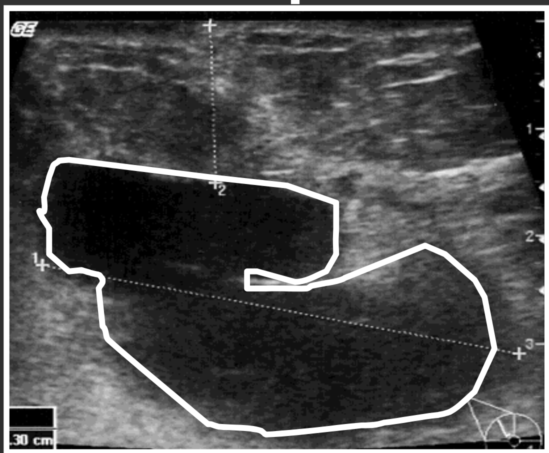
Example: Risk-Informed QM Formulation for Brachytherapy

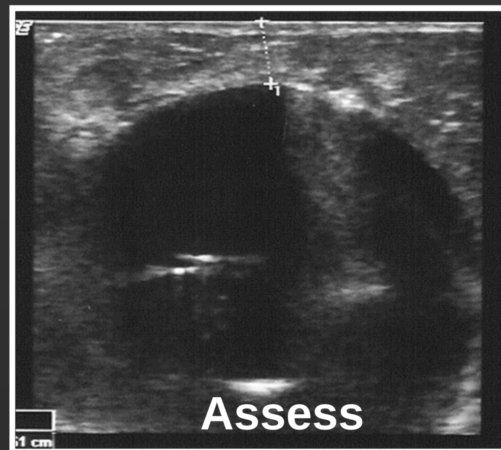
- Scenario: Accelerated partial breast irradiation using multi-catheter balloon HDR brachytherapy applicator
  - CT-based evaluation and planning
  - Multicatheter balloon applicator, e.g., Contura
  - Automated plan transfer but not full EMR charting
- "Standard" QA practice
  - Fixed, one-size-fits-all prescriptive QC protocols
  - Strong physics-centric focus on device QA
- Risk-informed QM practice: TG-100
  - Multidisciplinary
  - Focused on processes not devices
  - Uses formal risk analysis tools to create customized QMP

Image-Guided Balloon Catheter Placement

Accelerated Partial Breast: MammoSite HDR BTx

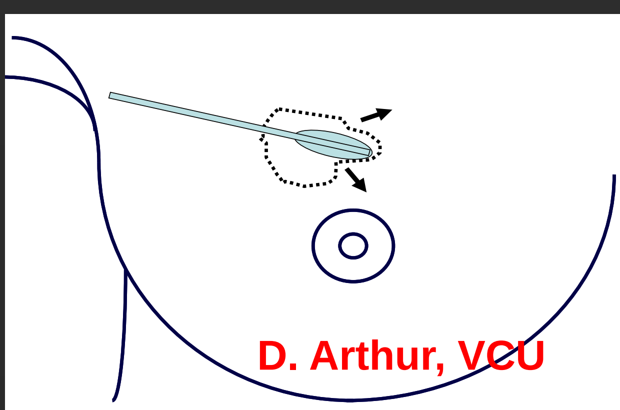
Intraoperative Ultrasound





Assess conformality

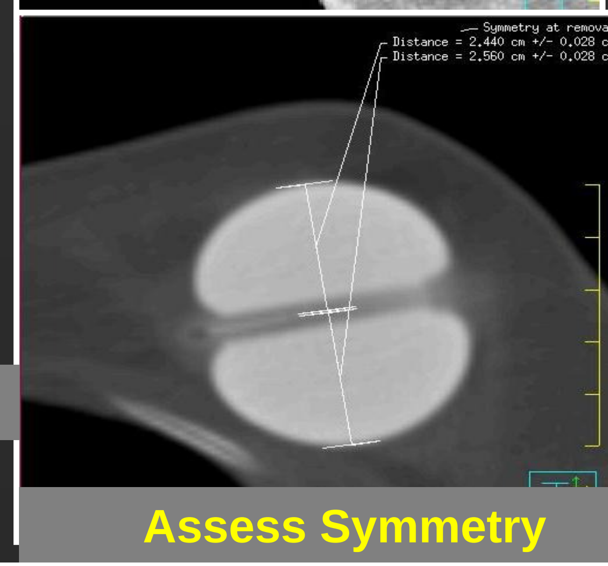
Visualize Lumpectomy Cavity: Select Approach



Intraop/PostOp CT

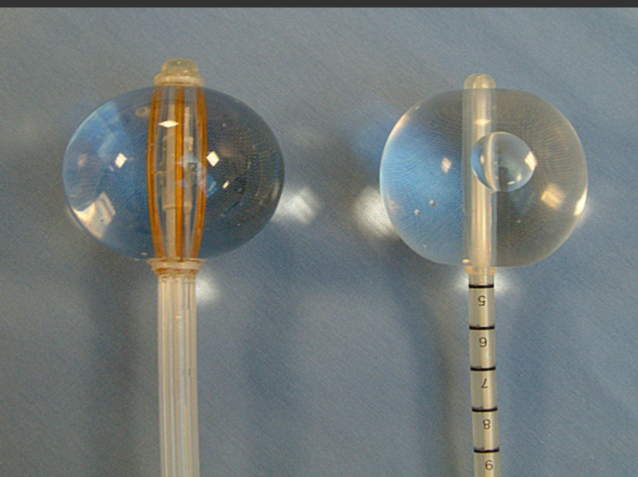
Assess conformality

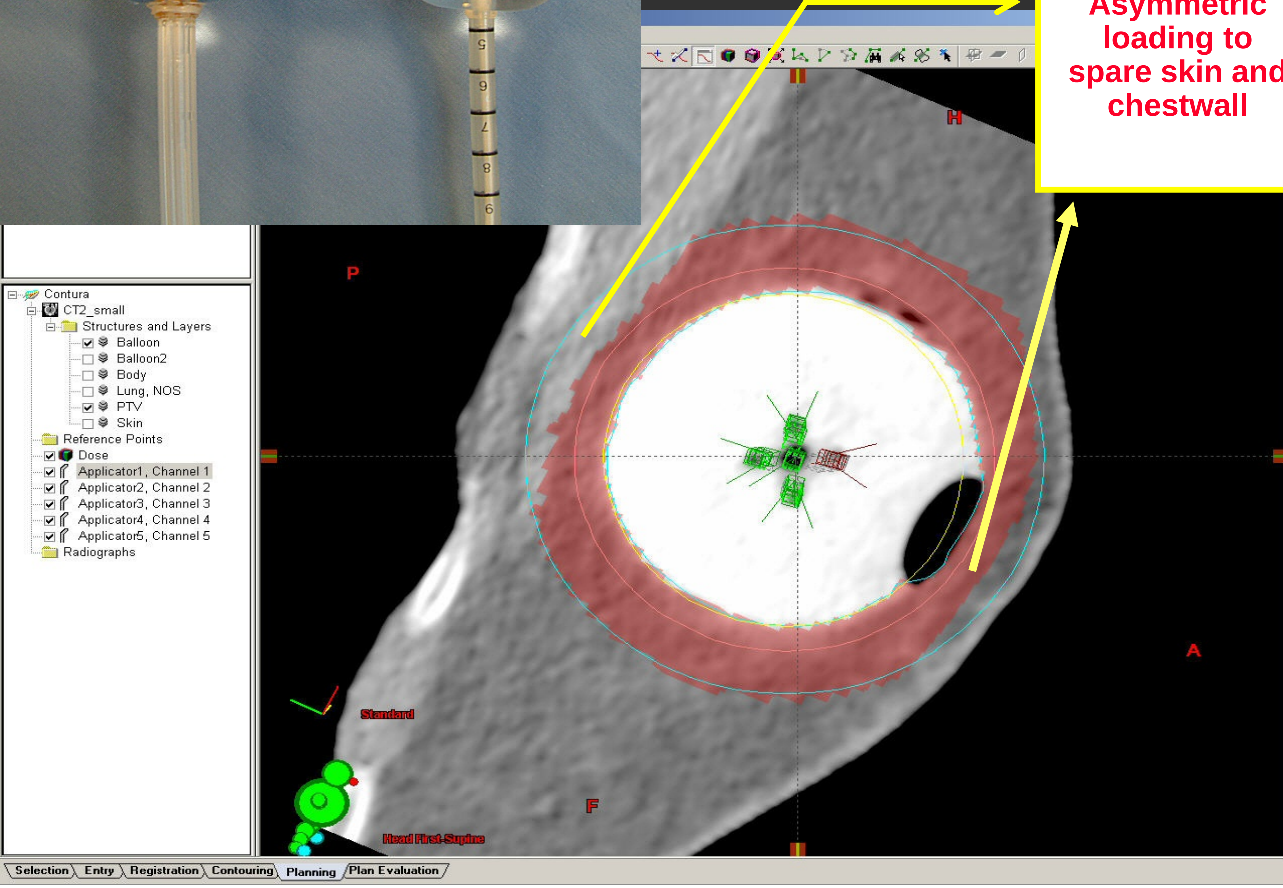
Assess Skin Distance



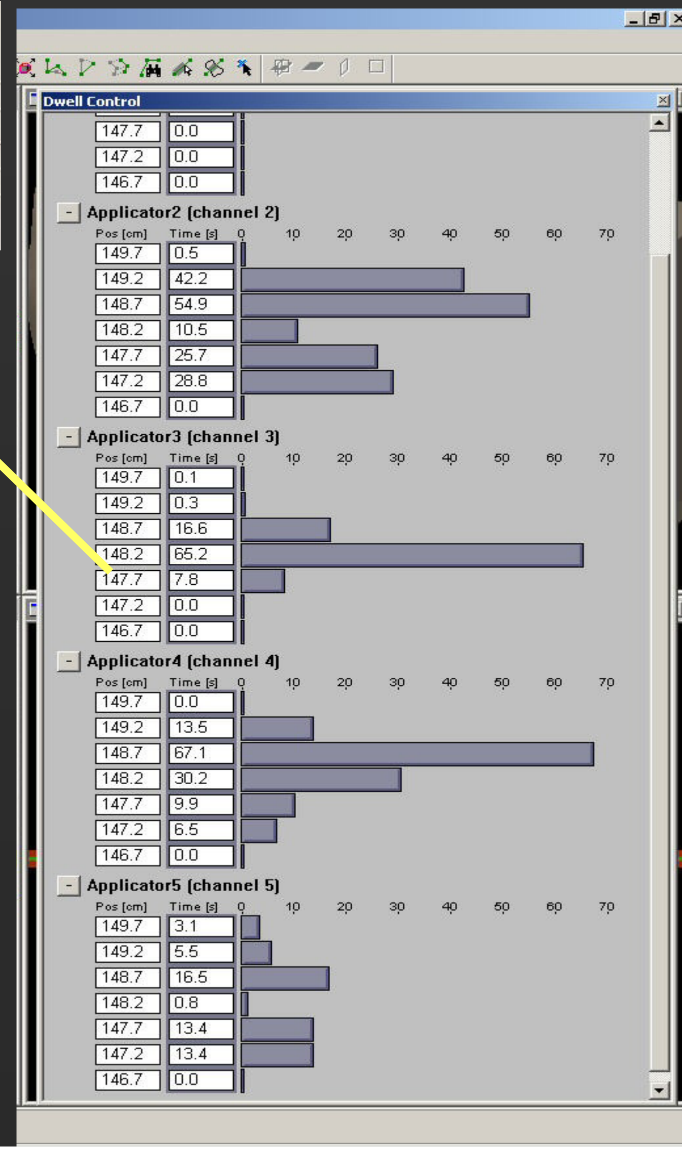
Assess Symmetry

Contura Multi-Cath Balloon Applicator Mismatch errors





Asymmetric loading to spare skin and chestwall



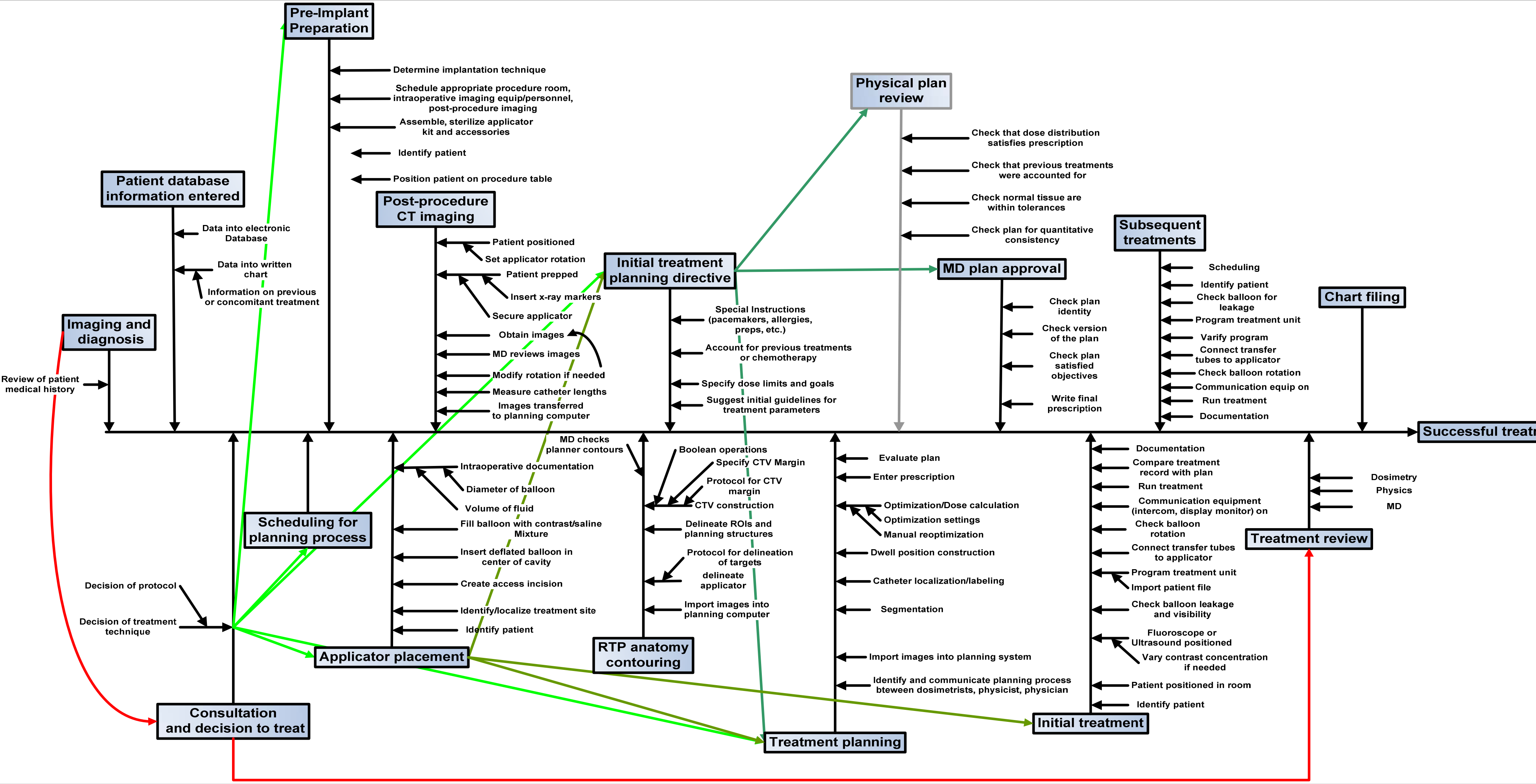
TG-100 Risk Analysis Steps

- **Steps**
  1. **Define process by creating a process map**
  2. **Failure modes and effects analysis (FMEA): Identify threats to success (failure modes) and rank according to risk**
  3. **Fault-tree Analysis (FTA): Propagation of failures through system and placement of QM interventions**
  4. **Develop QA or QC interventions to mitigate risk**

TG-100 Risk Analysis Steps

- Process Map: Step 1
  - Delineate and then understand the steps in the process to be evaluated
  - Visual illustration of the physical and temporal relationships between the different steps of a process
  - Demonstrates the flow of these steps from process start to end
- prospective risk analysis for hypothetical clinical process modeled on VCU and UW-Madison processes
  - Assumes NO QA or QC checks
  - Partial automation of EMR and data transfer
  - 4 physicists did ranking (Ibbott, Thomadsen, Mutic, JFW)

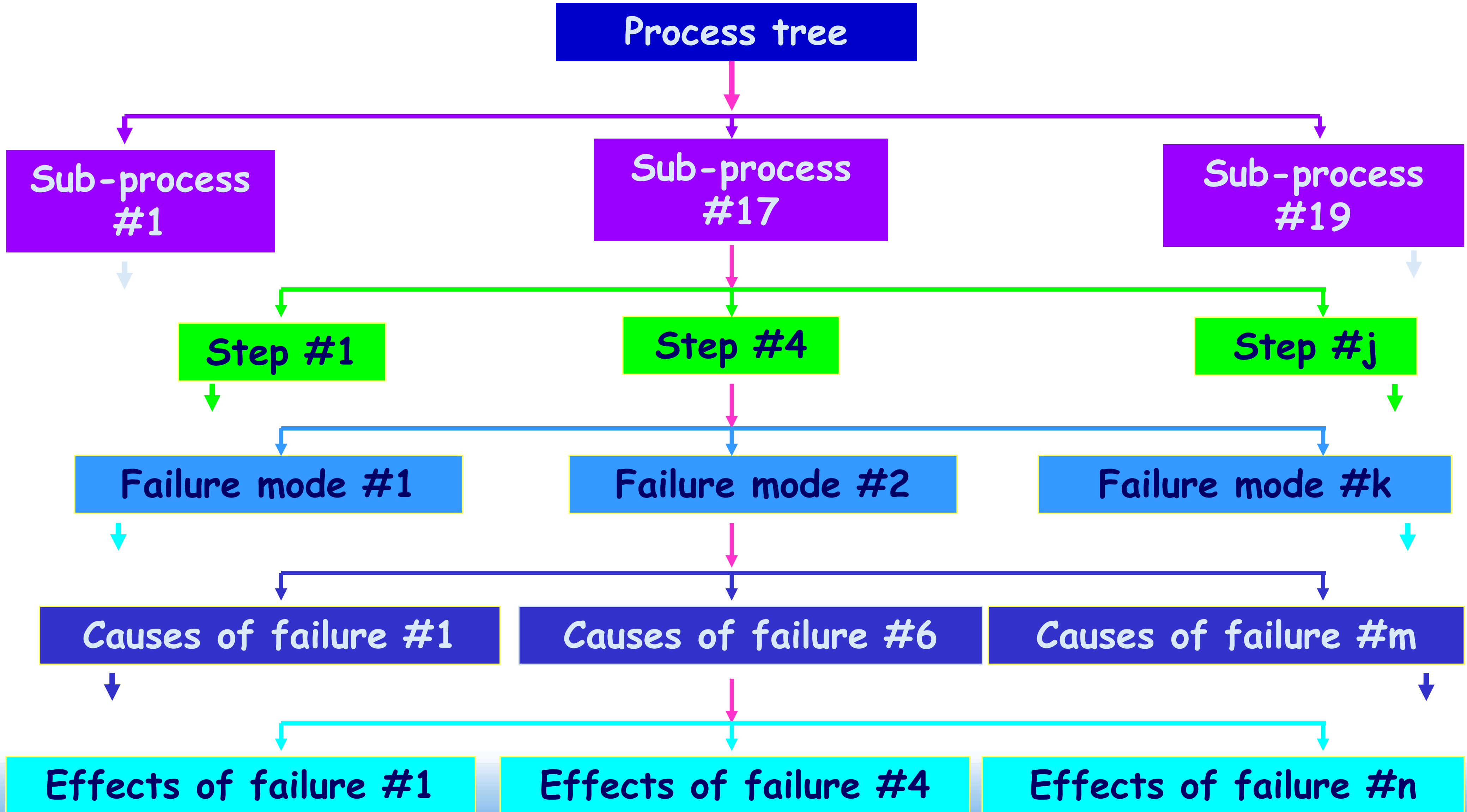
Breast Brachytherapy Process Map



TG-100 Risk Analysis
Step 2 FMEA

- Step 2a: For each process step, ask the following questions
  - What could possibly go wrong ? (enumerate/ describe failure modes)
  - How could that happen? (what are possible causes of FM?)
  - What effect would such an undetected failure have? (Potential impact on quality)
- Step 2b: Assess risk of FM by estimating O, S, and P
- Present analysis: 96 Failure Modes

Step 2a: enumerate FMEA Failure Modes



Assess Risk Posed by Each FM
Step 2b

- For each subprocess, enumerate the possible scenarios, i.e., Failure Modes (FM), that could lead an unsuccessful treatment: 96 FMs
  - Identify causes and effect on process outcome
- Assess risk to successful outcome posed by each FM **assuming no QA**

$$\text{Risk} = \begin{Bmatrix}\text{Likelihood of} \\ \text{occurrence}\end{Bmatrix} \times \begin{Bmatrix}\text{Severity of} \\ \text{consequences}\end{Bmatrix} \times \begin{Bmatrix}\text{Likelihood Error} \\ \text{Not Detected}\end{Bmatrix}$$

$$\quad\quad \text{O} \quad\quad\quad\quad \text{S} \quad\quad\quad\quad \text{P}$$

$$\text{Risk Probability Number} = \text{RPN} = \text{O} \times \text{S} \times \text{P}$$

  - Assign O,S, and P a value from 1-10
  - 4 Observers: Ibbott, Mutic, Williamson, Thomadsen
  - Significant additions/modifications by JFW
- Reorder list in terms of descending RPN

TG-100 FMEA Rating Scales

Table 9–5. Descriptions of the O, S, and D values used in the TG–100 FMEA

Score	Occurrence (O)		Severity (S)		Detectability (D)
	Qualitative	Frequency, %	Qualitative	Categorization	Estimated probability of failure going undetected, %
1	Failure unlikely	0.01	No effect		0.01
2		0.02	Inconvenience	Inconvenience	0.2
3	Relatively few failures	0.05			0.5
4		0.1	Minor dosimetric error	Suboptimal plan or treatment	1.0
5		<0.2	Limited toxicity or tumor underdose	Wrong dose, dose distribution, location or volume	2.0
6	Occasional failures	<0.5			5.0
7		<1	Potentially serious toxicity or tumor underdose		10
8	Repeated failures	<2			15
9		<5	Possible very serious toxicity or tumor underdose	Very wrong dose, dose distribution, location or volume	20
10	Failures inevitable	>5	Catastrophic		>20

First 6 Failure Modes

						Combined			
Major Processes	Step	Potential Failure Modes	Potential Causes of Failure	JFW Comments and descriptive scenario	Potential Effects of Failure	AVG O	AVG S	AVG D	Avg RPN
Imaging and diagnosis	RO reviews EMR prior to RO consult	Med Onc or Surgeon consultation misinterprets or misrepresents primary clinical findings (imaging studies, path reports, etc); incorrectly stages patient, and recommends BCT and APBI for patient that is not appropriate candidate	RO bases Tx recommendation on secondary MD report rather than reviewing primary clinical findings and discovering the upstream error	Upstream physician error potentially discoverable by Rad Onc since primary clinical data is available We should recommend that the RO performs their duties diligently.	wrong/very wrong dose distribution	5.00	**8.25**	5.50	**269.3**
Imaging and diagnosis	RO reviews EMR prior to RO consult	path or biomarker reports is incorrect due to mislabeling of surgical specimen or biomarker report . Hence patient is understaged and inappropriately offered BCS by Med Onc and Surgeon	RO recommendation for APBI is fully consistent with prior EMR	An error not easily discoverable by Rad Onc Based on the worse case.	Very wrong dose	4.25	**8.75**	8.25	**309.5**
Patient database information	Entry of patient data in RO EMR or written chart	Incorrect patient ID data	Documentation error	Wrong patient ID leading misfiling of demographic and clinical data from hospital DB; identification of wrong patient	Very wrong dose	3.00	**8.75**	2.75	**70.0**
Patient Database Information	Entry of patient data in RO EMR or written chart	Correct patient ID data but clinical findings/images from wrong patient loaded into RO EMR	Omission in entry, incomplete patient history	Incorrect clinical findings leads to faulty decision to treat or downstream peer-review correction	Very wrong dose	5.00	**7.75**	3.75	**154.5**
Consultation and decision to treat	Decision of treatment technique and protocol	Clinically inappropriate patient selected for APBI	misinterpretating of clinical findings incomplete H&P	Even though upstream clinical data are correct, Error by RO assessing indications and contraindications to APBI., e.g., SLN+ with Surg untreated axilla. RO misrepresents or neglects key finding and offers inappropriate treatment plan to patient	Very wrong dose	4.25	**7.75**	7.75	**252.8**
Consultation and decision to treat or imaging/diagnosis	Decision of treatment technique and protocol or imaging/diagnosis	patient with radiographically too large or closed seroma cavity selected	RO error in interpreting imaging studies; inappropriate imaging used; or poor imaging quality	JFW: New failure mode	Very wrong dose if not detected; more likely major inconvenience or infection from unnecessary invasive procedure	4.75	**6.25**	4.75	**140.3**

r Processes	Step	Potential Failure Modes	Potential Causes of Failure	JFW Comments and descriptive scenario	Potential Effects of Failure	AVG O	AVG S	AVG D	Avg RPN
ial treatment	Connect transfer tubes to applicator: multicatheter	Channel and applicator numbers not matched	Inadequately trained personnel, inattention, poor inter-disciplinary communication		Wrong dose/distribution	5.75	**8.25**	6.75	**374.0**
ubsequent reatments	Documentation of patient changes	Patient implant geometry changes	Lack of standardized procedures, inadequately trained, inattention	Scenario: applicator position or diameter changes due to leakage but is not detected since no daily verification imaging performed Omit SM from average since no score given	Wrong dose	5.67	**8.00**	7.33	**369.7**
ment planning	Dwell position construction	Systematic treatment length error (wrong transfer tube length, wrong sounding information, wrong dwell spacing)	Inadequately trained personnel, Commissioning or periodic device QA	Example: clinic planners are unaware that Varian QuickConnect requires 14 mm correction. Many patients treated with large offsets of treated from intended dwell positions	Very wrong dose or position	5.00	**8.50**	8.25	**348.8**
-procedure CT imaging	Catheter localization	Wrong catheter position; Catheter indicators not inserted fully	Inadequately trained personnel, lack of attention	Catheter sounding measurements (distance from channel distal tip to indexer reference plane) are inaccurate or erroneously recorded. Very serious dose delivery error if more than 2-3 mm.	Very Wrong or wrong dose Wrong dose distribution	5.50	**8.50**	7.00	**347.3**
ment planning	Catheter localization/labeling: multicatheter	Catheter trajectory inaccurately localized	Wrong catheter slice images, inadequately trained personnel, poor inter-disciplinary communication, inattention	JFW: Assume that distalmost position where treatment length position and which dwell position is to be no.1 (distalmost active dwell) are independent decisions	Wrong dose distribution	4.75	**8.00**	8.00	**326.5**
ial treatment	Run treatment	Incorrect balloon radius	Leaking balloon: Assuming no verification imaging performed with each fraction		Wrong dose, Wrong dose distribution	4.25	**8.25**	8.25	**318.3**
ial treatment	Connect transfer tubes to applicator	Wrong length transfer tube	Inadequately trained, inattention	Still a potential source of large error, since transfer tubes are not electronically ID'd	Very wrong dose distribution	4.75	**9.25**	6.75	**310.5**
naging and diagnosis	RO reviews EMR prior to RO consult	path or biomarker reports is incorrect due to mislabeling of surgical specimen or biomarker report . Hence patient is understaged and inappropriately offered BCS by Med Onc and Surgeon	RO recommendation for APBI is fully consistent with prior EMR	An error not easily discoverable by Rad Onc Based on the worse case.	Very wrong dose	4.25	**8.75**	8.25	**309.5**

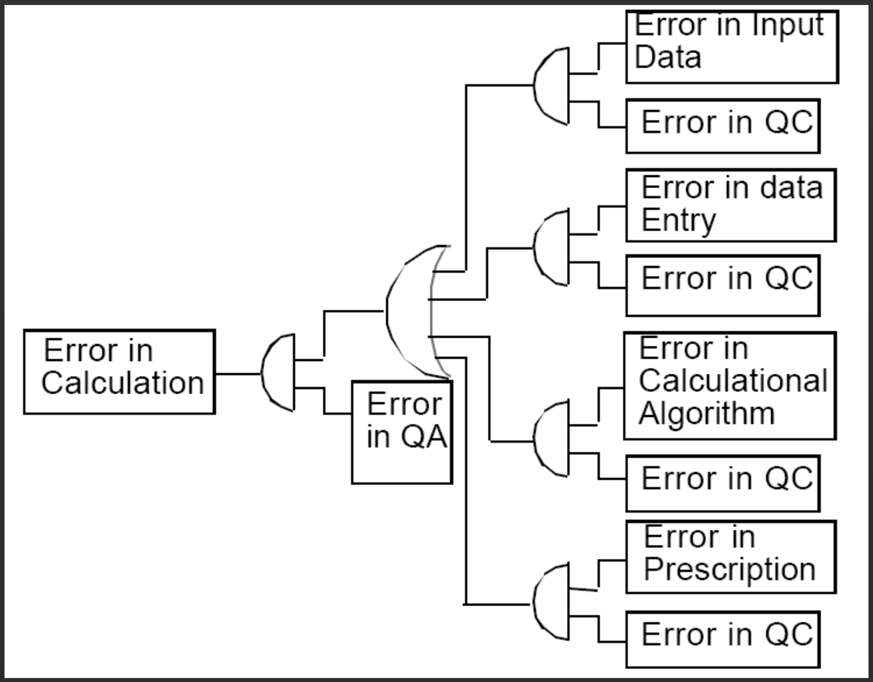
8 Highest Risk FMs

Fault Tree Analysis and Designing QM interventions Steps 3 and 4

- Step 3: Create Fault Trees (optional)
  - Time consuming: Limit FTA to selected FMs
  - Visualize interactions between FMs possibly in different process tree branches
  - JFW: helped me refine list of FMs and scenarios
- Step 4: Design QM intervention
  - Rank FMs according decreasing risk and severity
  - Mark high RPN/S FMs on fault and process trees
  - FTA guides optimal placement of intervention
  - Design intervention: balance cost, specificity, sensitivity and benefit

Fault Tree Analysis

Step 3: TG100 risk analysis methodology

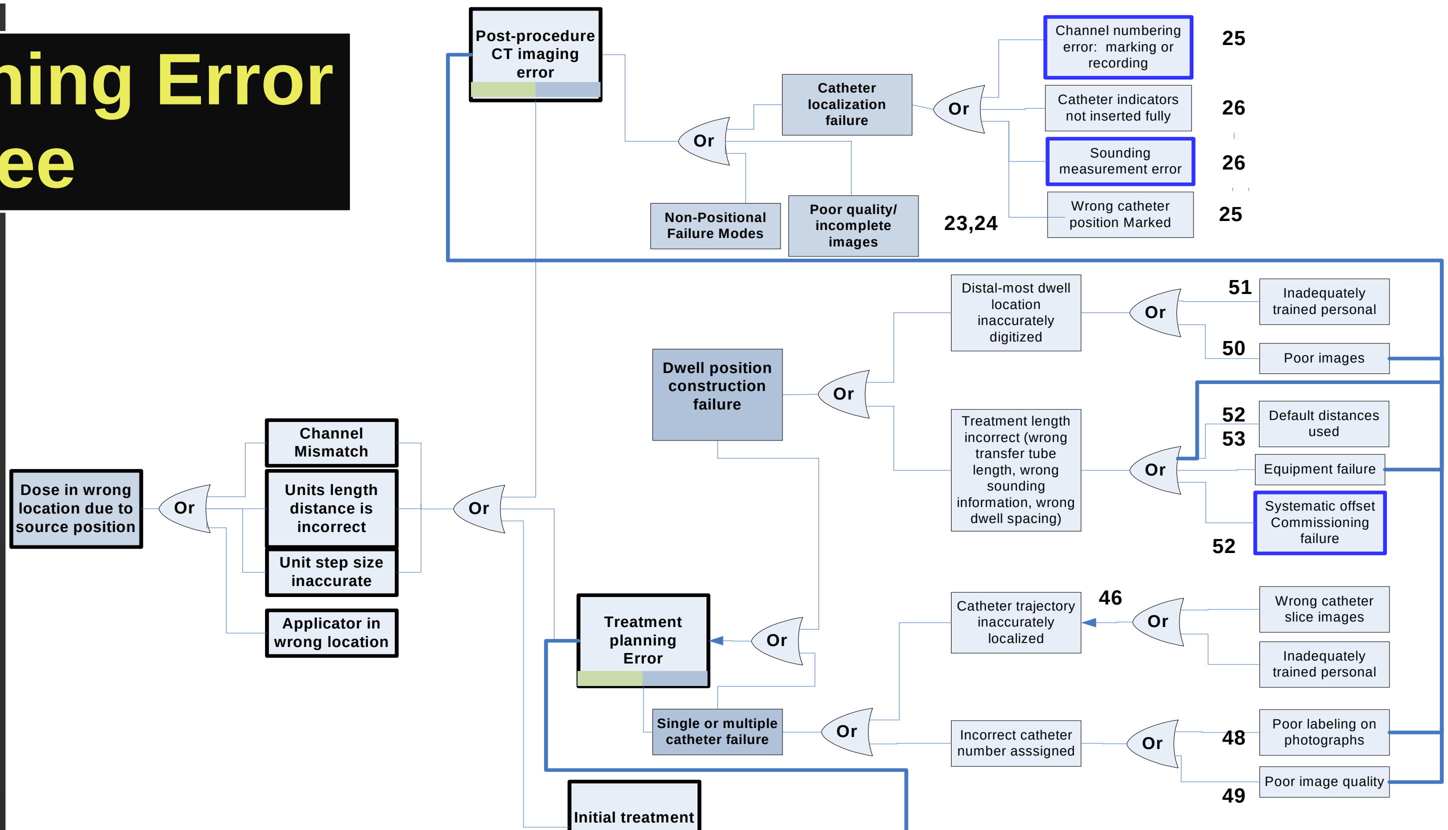


- FTA compliments process tree
- Leftmost box is the failure (error)
  - Each daughter node is a FM that could cause the error
- Works backwards in time (to the right) until root cause is reached
- Models propagation of error through system

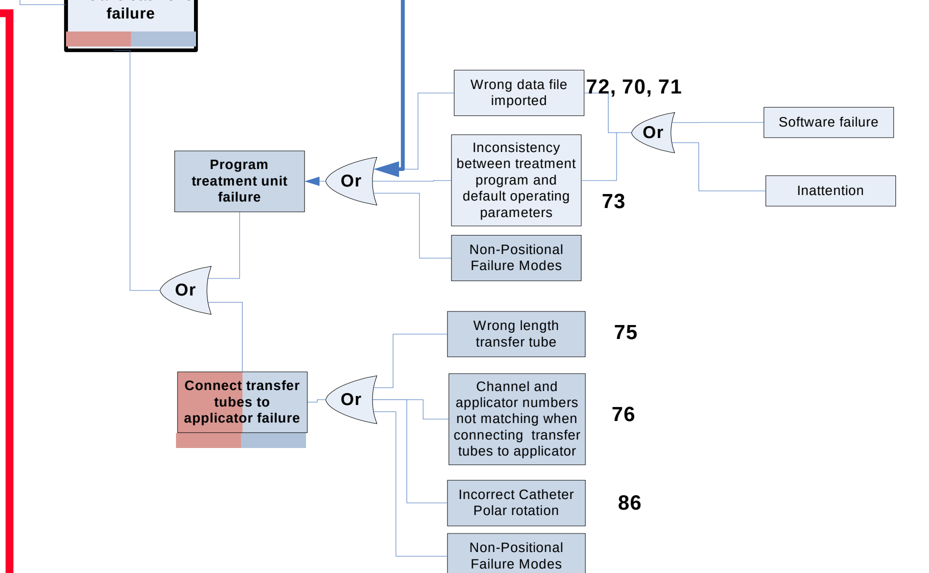
- ‘OR’ means error occurs if any one of antecedent FMs occurs
- ‘AND’ means all antecedent FM’s must be realized for error to occur

Source Positioning Error Fault Tree

- No QA/QC assumed
- Relevant FMs scattered across at least 4 process tree branches
- Interactions



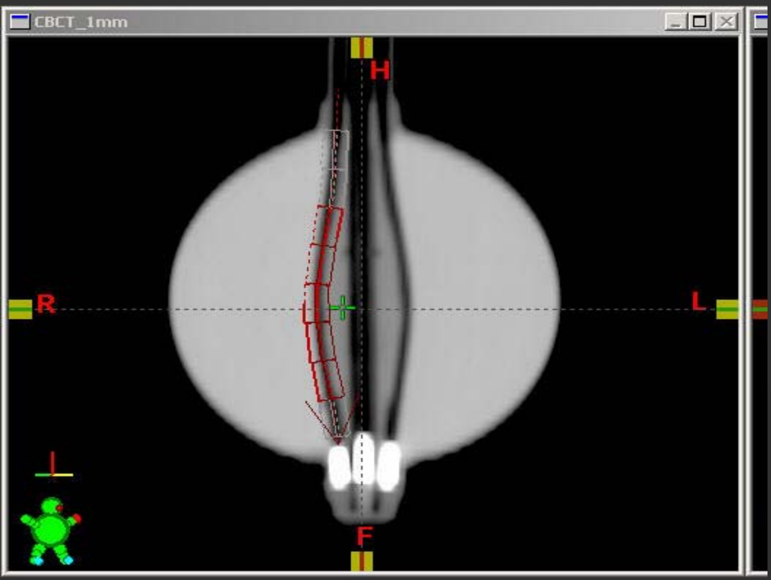
Rank	RPN	Step#	Process	Step
#1	374	76	Initial treatment	Connect transfer tubes to applicator
	FM: Channel and applicator numbers not matched			
	Related FMs: 52 (RPN 349; rank 3): Systematic error in treatment length computation 26 (RPN 347; rank 4): Errors in catheter sounding measurements 46 (RPN 326; rank 5): Inaccurate catheter localization 75 (RPN 310; rank 7): Incorrect length transfer tube selected 50 (RPN 288; rank 13): Distal-most dwell position inaccurately localized: wrong offset 53 (RPN 284; rank 15): Random error in treatment length computation 51 (RPN 281; rank 16): Distal-most dwell position inaccurately localized: poor image quality 47 (RPN 286; rank 14): Catheter trajectory localization error 86 (RPN 302; rank 10): Incorrect balloon rotation: initial treatment 49 (RPN 278; rank 17): Multi-catheter localization error from poor image quality			



Positional Accuracy

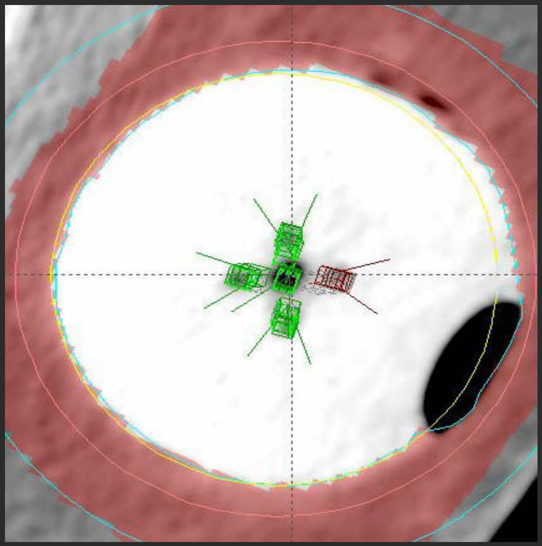
- **Each active dwell position delivered to correct location in correct applicator within ± 2 mm (TG56)**
- **"Correct" ⇒ Designated treatment positions in plan coincide with radioactive source center during delivery**
  - **actual source center = position of radiographic dummy marker**
  - **HDR unit ejects correct cable length into programmed channel**
  - **Structured set of tests for each applicator type**
    - » **transfer tube length**
    - » **HDR source-dummy seed coincidence**

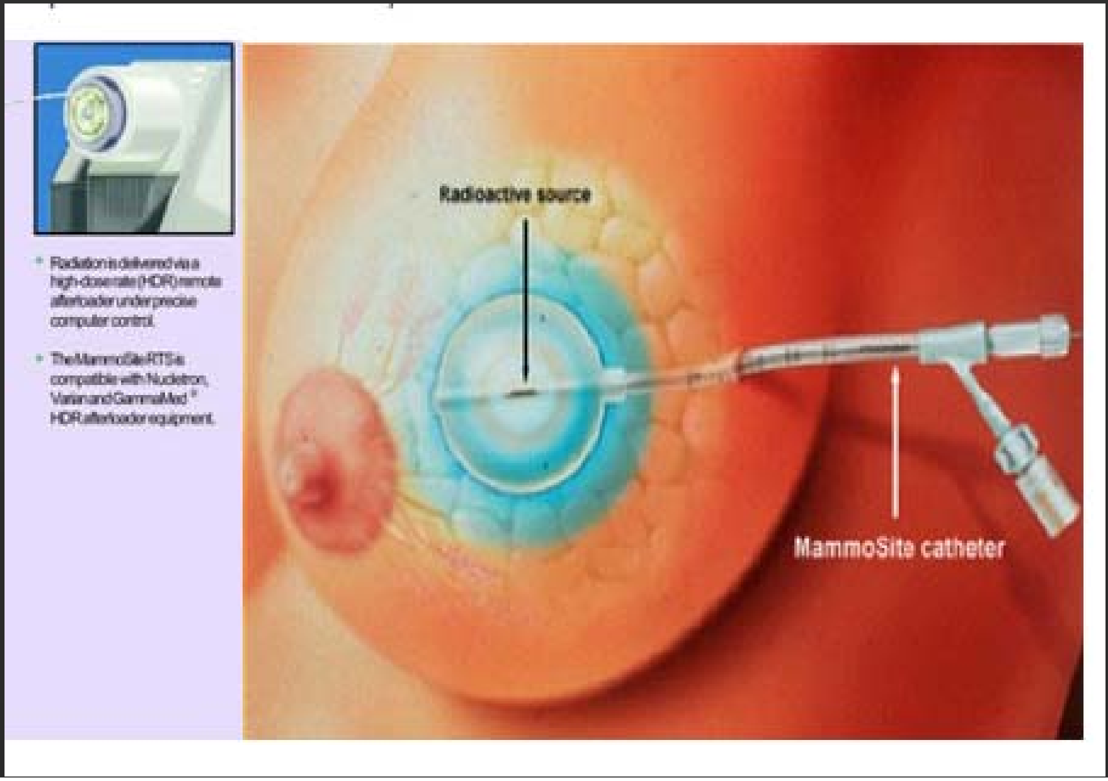
Positional Accuracy: HDR BTx



Source center accurately transported to planned position

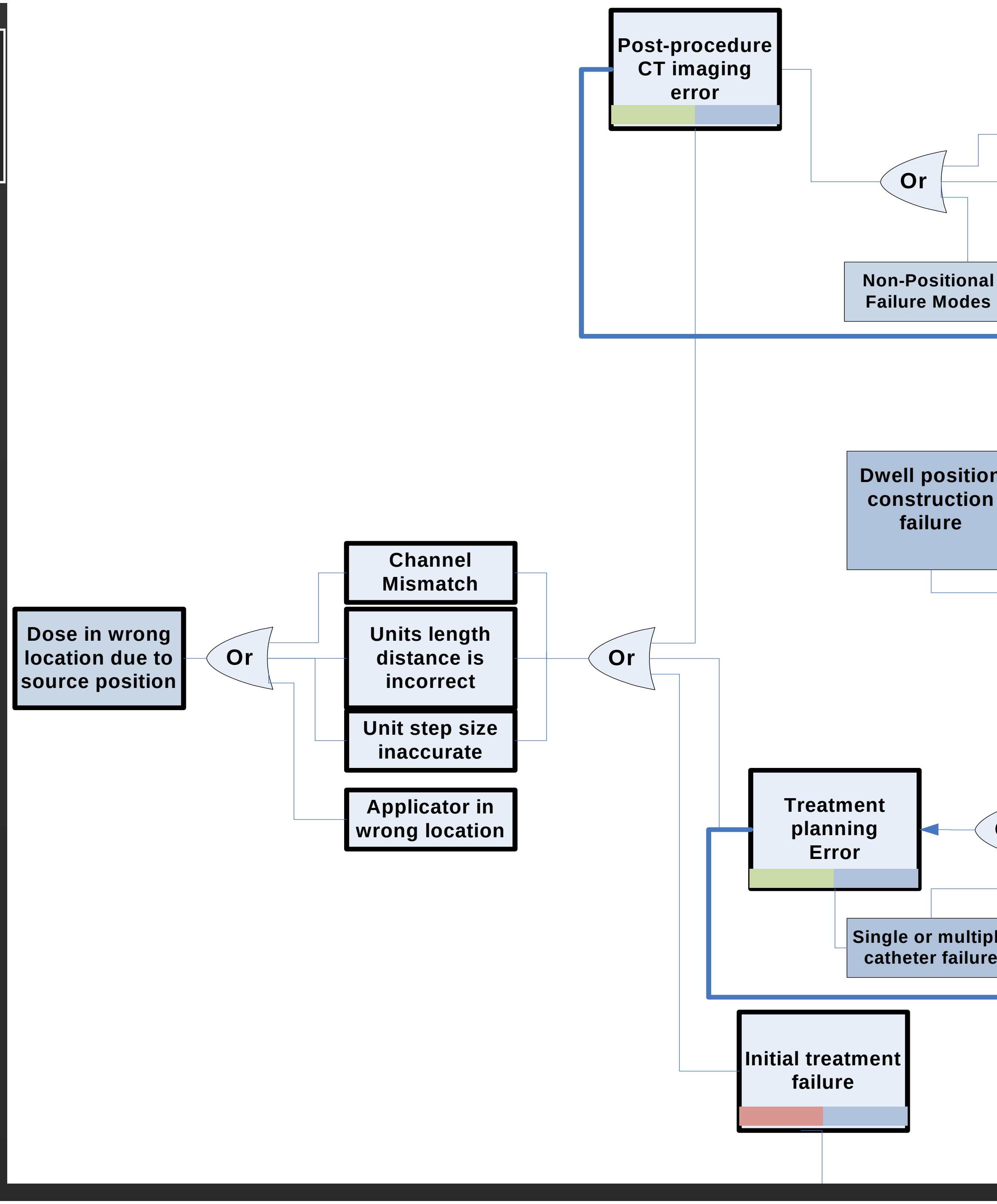
Dwell position localized in CT





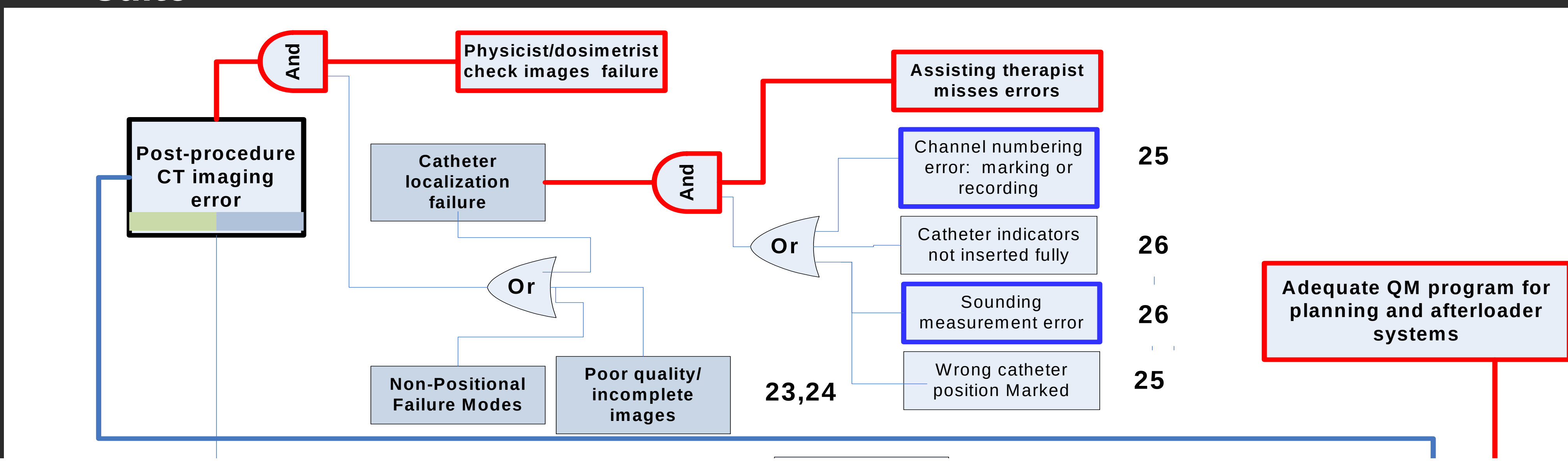
Source Positioning Error Fault Tree

- Error types
  - Channel mismatch
  - Incorrect Tx length
  - Incorrect step length
- Top level causes
  - Post procedure imaging error
  - Tx Planning error
  - Error in treatment setup or device programming

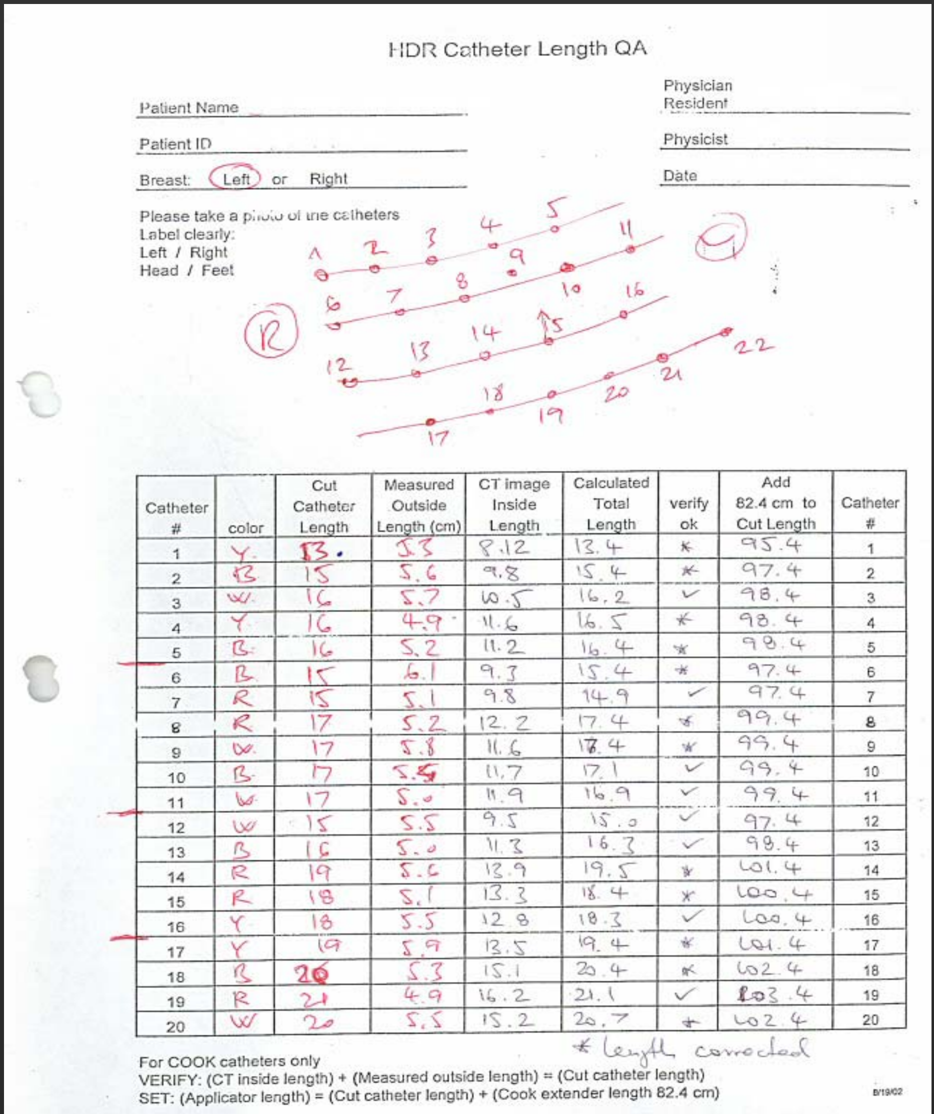


Post-procedure CT imaging Localization Errors

- Incorrect information /poor images ⇒ Dwell position programming error
  - – Channel numbering or documentation
  - – Catheter length measurement
  - – Imaging performed with incorrect marker position
- QM interventions
  - – QC: second therapist assists with measurements
  - – QA: Independent check of localization data before patient leaves imaging suite



Post-Procedure Imaging
Localization steps



HDR Catheter Length QA

Patient Name ______ Physician Resident ______

Patient ID ______ Physicist ______

Breast: (Left) or Right Date ______

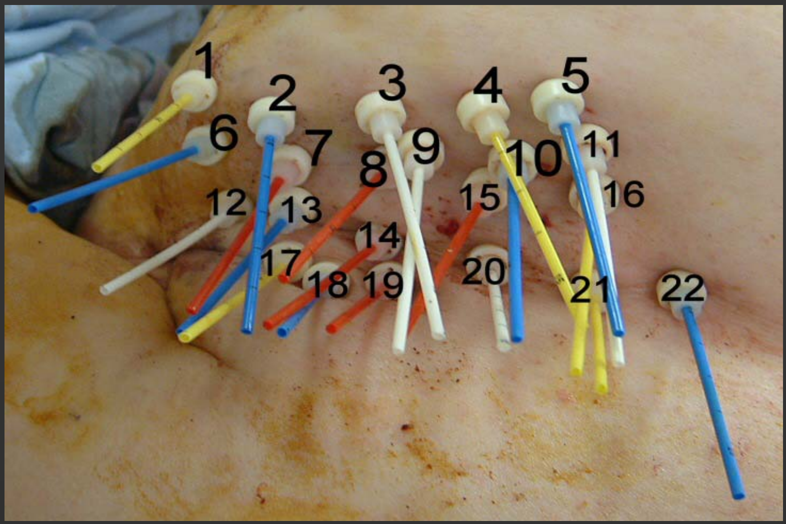
Please take a photo of the catheters
Label clearly:
Left / Right
Head / Feet

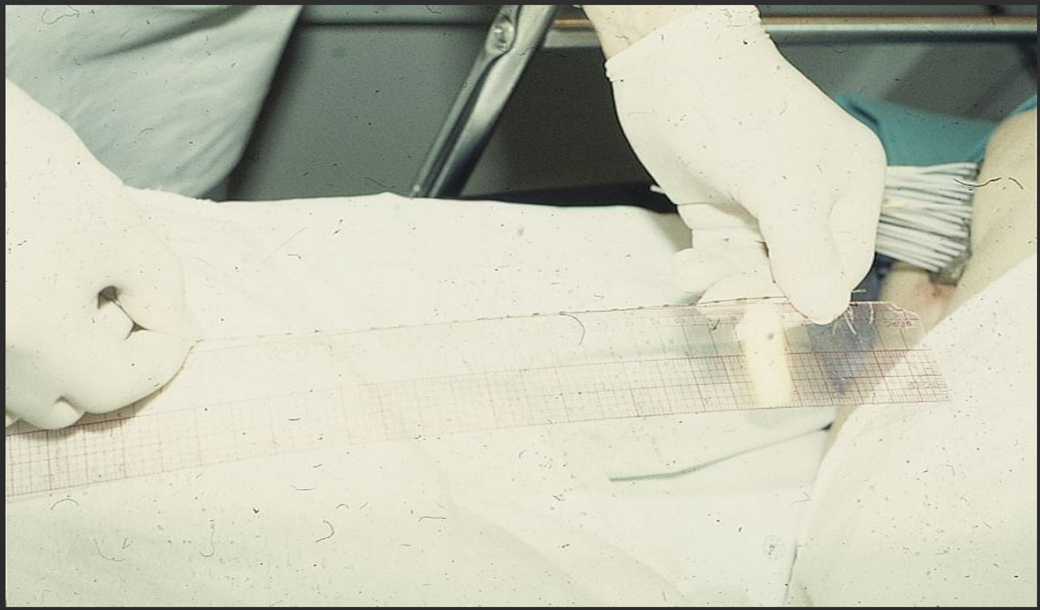
Catheter #	color	Cut Catheter Length	Measured Outside Length (cm)	CT image Inside Length	Calculated Total Length	verify ok	Add 82.4 cm to Cut Length	Catheter #
1	Y.	13.	5.3	8.12	13.4	*	95.4	1
2	B.	15	5.6	9.8	15.4	*	97.4	2
3	W.	16	5.7	10.5	16.2	✓	98.4	3
4	Y.	16	4.9	11.6	16.5	*	98.4	4
5	B.	16	5.2	11.2	16.4	*	98.4	5
6	B.	15	6.1	9.3	15.4	*	97.4	6
7	R	15	5.1	9.8	14.9	✓	97.4	7
8	R	17	5.2	12.2	17.4	*	99.4	8
9	W.	17	5.8	11.6	17.4	*	99.4	9
10	B.	17	5.5	11.7	17.1	✓	99.4	10
11	W.	17	5.0	11.9	16.9	✓	99.4	11
12	W	15	5.5	9.5	15.0	✓	97.4	12
13	B	16	5.0	11.3	16.3	✓	98.4	13
14	R	19	5.6	13.9	19.5	*	101.4	14
15	R	18	5.1	13.3	18.4	*	100.4	15
16	Y	18	5.5	12.8	18.3	✓	100.4	16
17	Y	19	5.9	13.5	19.4	*	101.4	17
18	B	20	5.3	15.1	20.4	*	102.4	18
19	R	21	4.9	16.2	21.1	✓	103.4	19
20	W	20	5.5	15.2	20.7	*	102.4	20

* length corrected

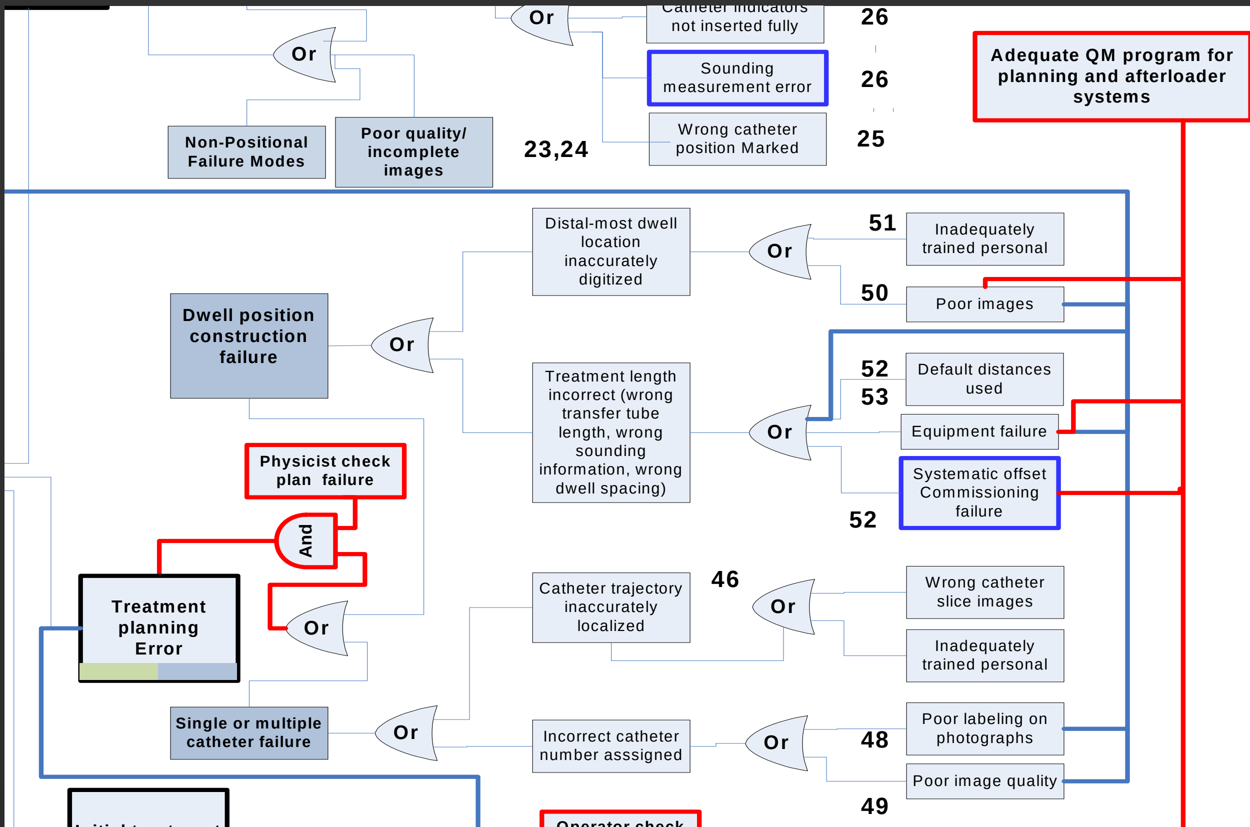
For COOK catheters only
VERIFY: (CT inside length) + (Measured outside length) = (Cut catheter length)
SET: (Applicator length) = (Cut catheter length) + (Cook extender length 82.4 cm)

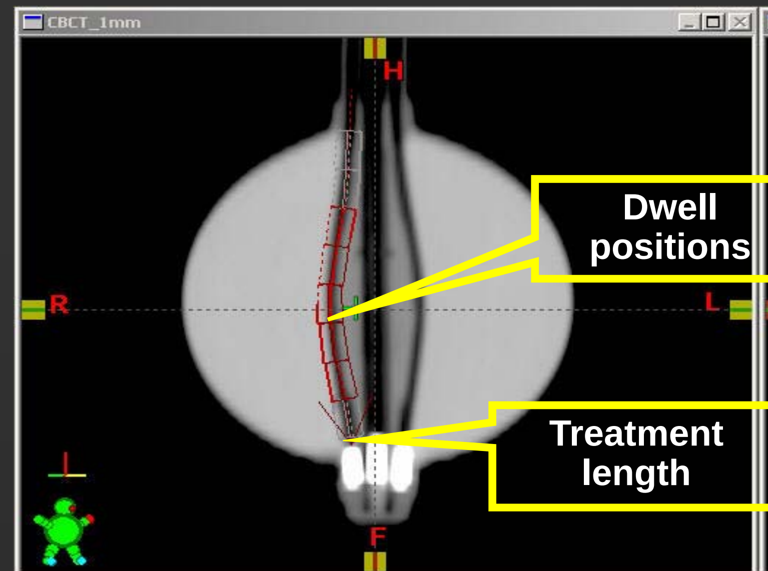
8/19/02

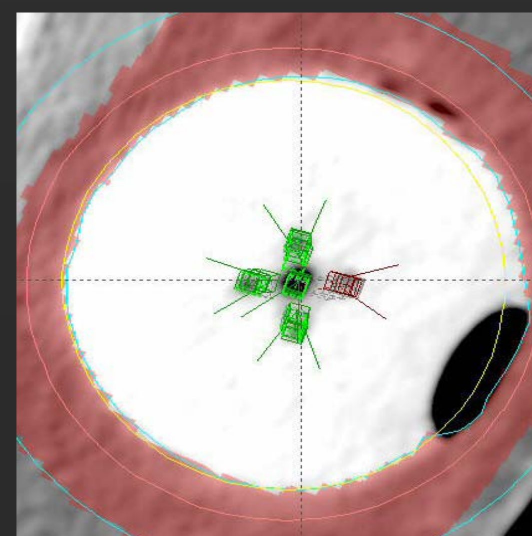




Localization FMs:Treatment Planning



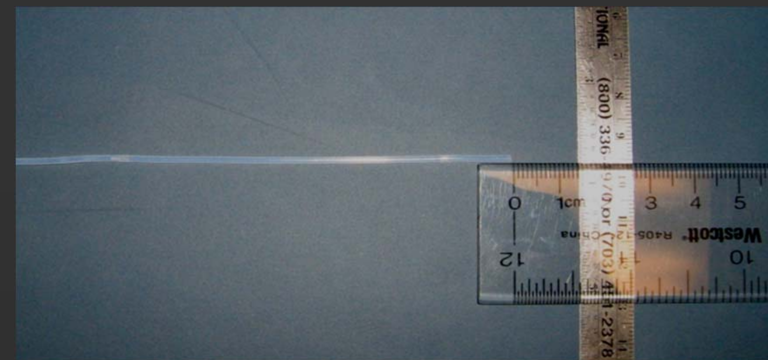




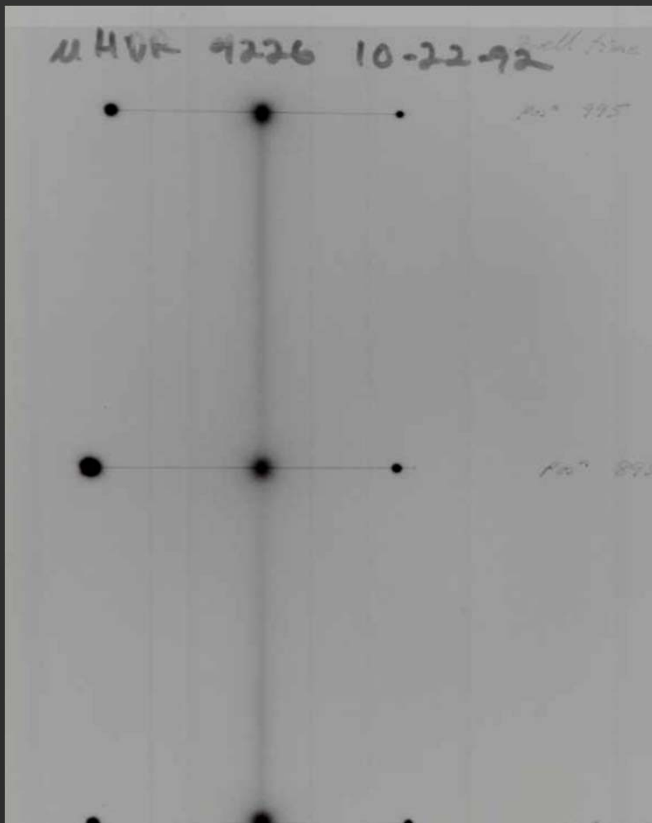
- Catheter trajectory delineation error
  - Dwell 1 length error
    - » Systematic positional offset error
  - Dwell position digitization error
- channel mismatch error

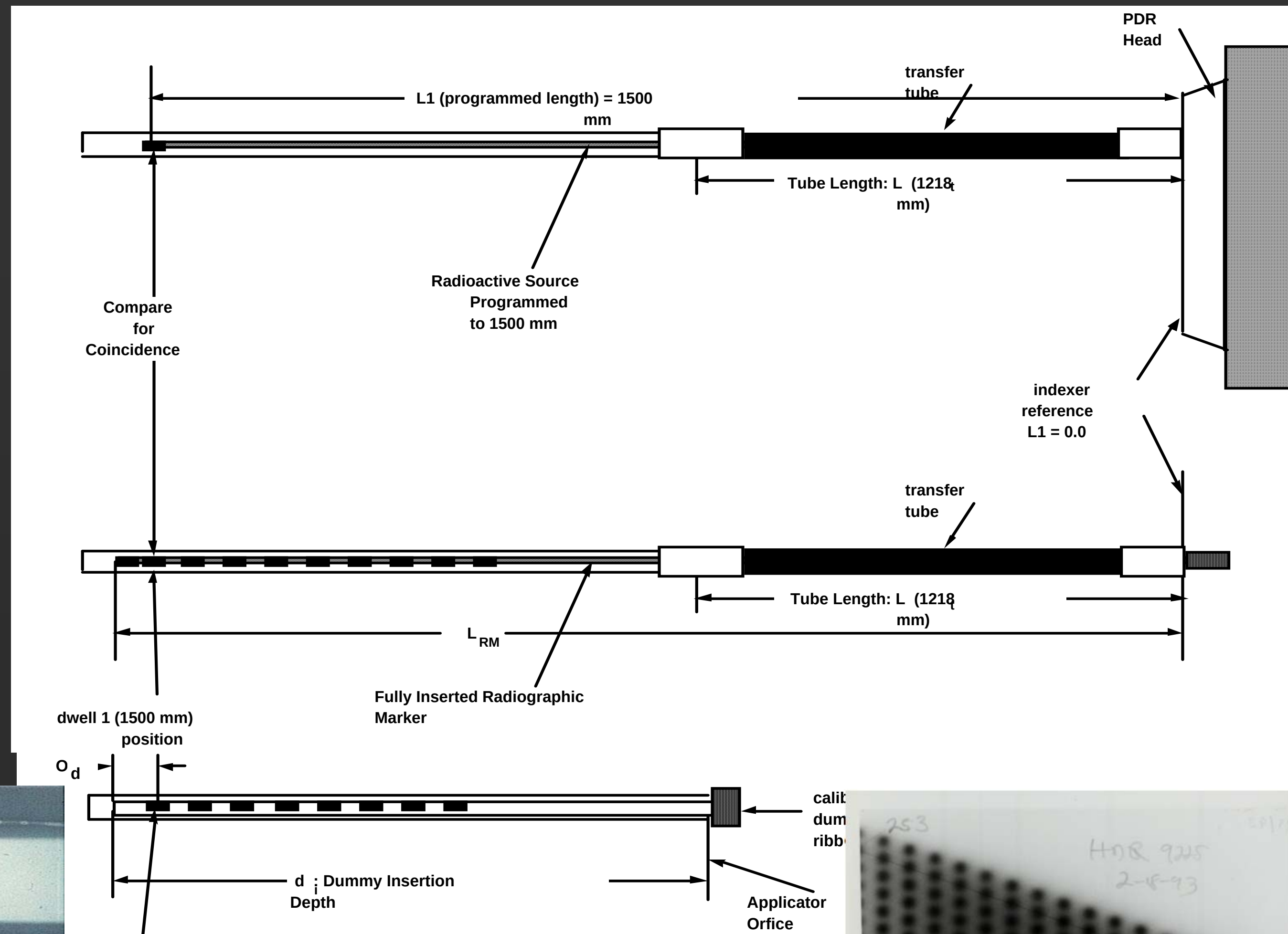
Example: Systematic Offset Error

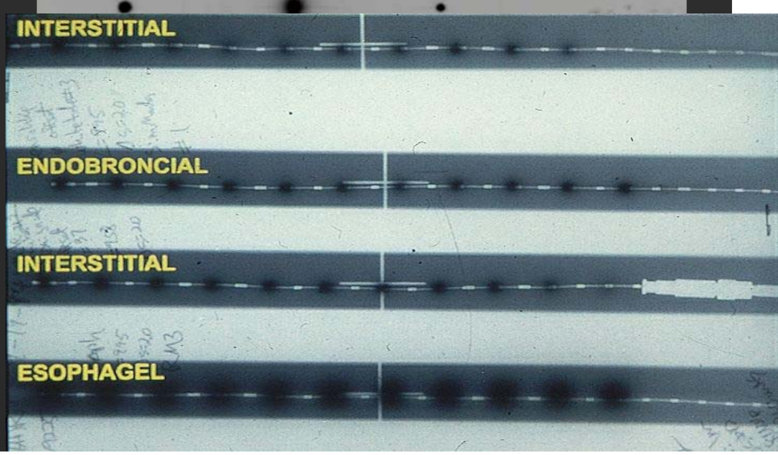
- **Systematic source positioning error: caused by invalid treatment length estimation protocol**
- **Varian "quick connect" indexer interface**
  - **14 mm offset compared to standard transfer tube connector with usual transfer tube-applicator combination length measurement**
  - **No Software offset or hardware interlock initially provided**

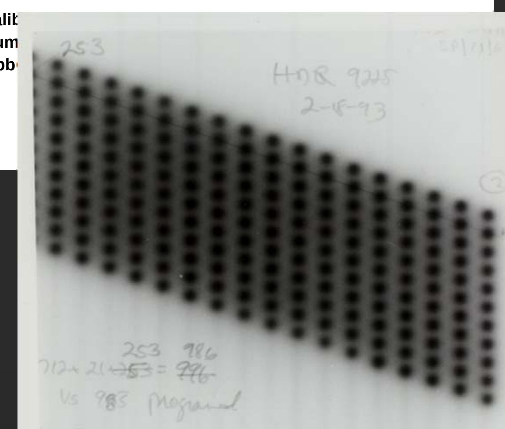


TG-56 Structured HDR Positional Accuracy Tests

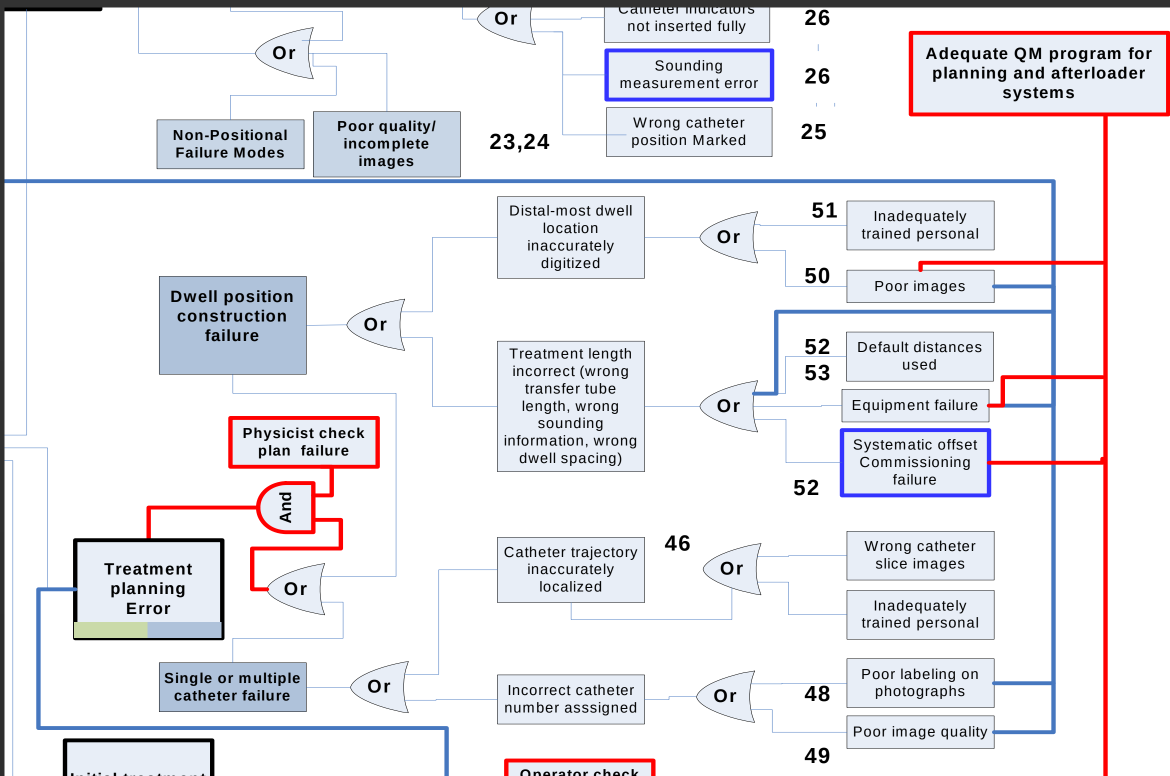








Mitigating RTP Localization FMs

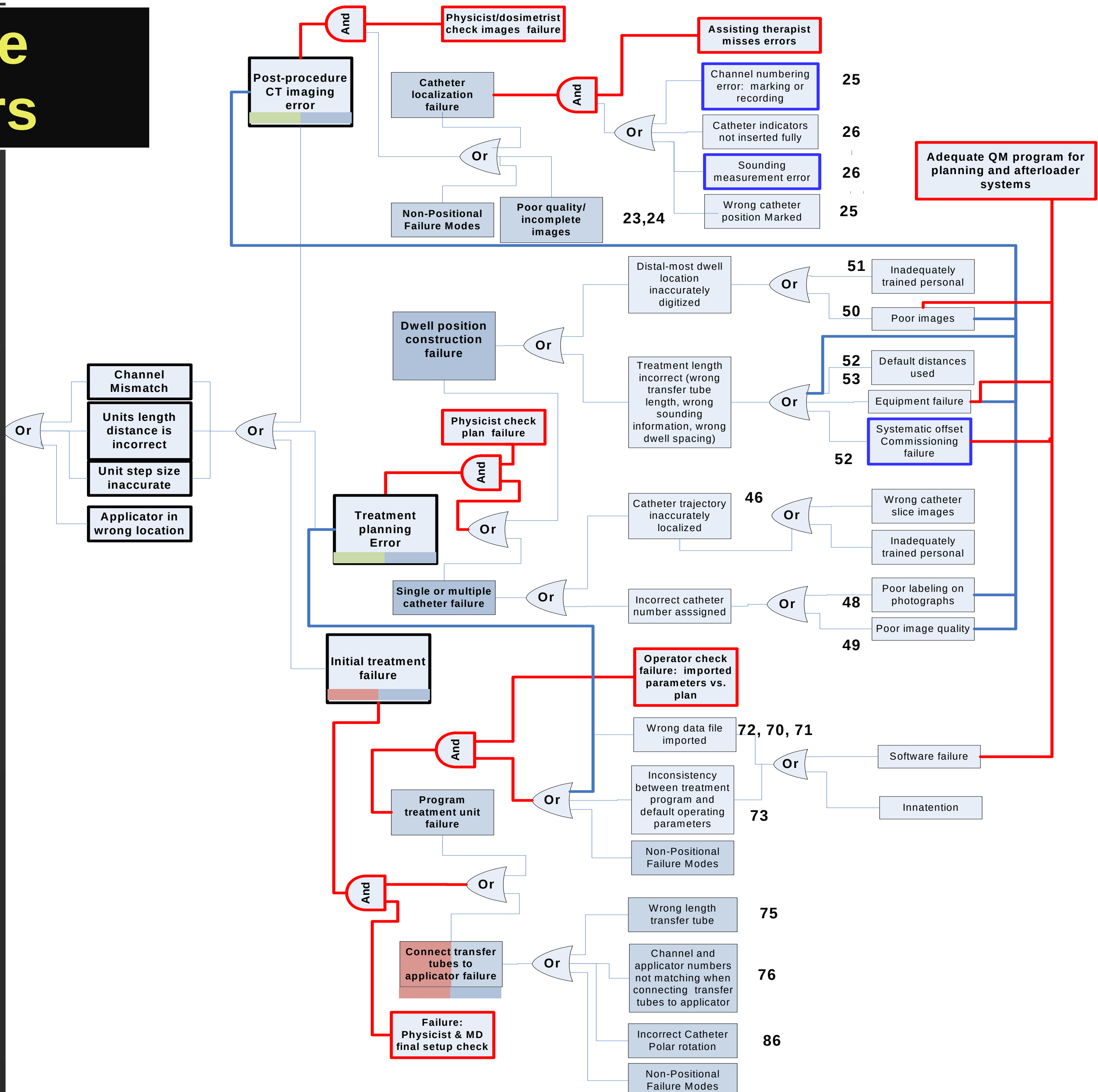


- Adequate device QA:
  - Maintain image quality
  - Eliminate offsets and incorrect default parameters
  - Consistency of procedure with device function

- Implement well-defined, rigidly followed procedures:
  - Adequate patient volume
- QC: use only one transfer tube length & use equi-length catheters
- QA: Final physics plan review focus on dwell position

Mitigating Source Positioning Errors

- QA/QC in red
- Adequate device QA protocol
- Written procedures
  - Redundancy
  - Uniformity
  - Patient volume
  - Training to ensure compliance
- Physics Checks
  - Simulation
  - Tx plan
  - Setup/RAL programming



Dose Calculation FMs

Rank	RPN	Step #	Process	Step
12	293	54	Treatment planning	Optimization settings
	FM: Optimization method, dose-point locations, prescribed dose, and other treatment goals specified incorrectly			
	Related FMs: **55** (RPN 247, rank 30): Random entry error in setting optimization parameters **59** (RPN 263; rank 20): Wrong source strength **56** (RPN 260; rank 21): Dose calculation error **60** (RPN 260, rank 22): Prescribed dose specified to wrong structure **58** (RPN 230; rank 36): Planner uses graphical tools to shape prescription isodose failing to note that other planning goals are violated			

- **Wrong source, decay correction, or units**
- **Wrong dosimetric parameters**
- **Program malfunction**
- **Input data error**

Conclusions: formal risk analysis

- **Process mapping and FMEA advantages**
  - Focuses attention on process as well as device failures
  - Provides a vehicle for team to work collaboratively to
    - » better understand the process
    - » Appreciate each other's vulnerabilities
    - » buy into core QM/QI values
  - Most expert member gets to fix FM
  - Promotes clinical process uniformity so that desired process-step outcomes get internalized
  - Better understanding of device-process interactions helps physicist prioritize device QA
- **Downsides**
  - Resource intensive to build/use FMEA expertise
  - Not a mechanical, one-size-fits-all prescriptive approach: requires judgment and individualization

Dose Delivery Accuracy

- **Algorithmic Accuracy (±2%)**
  - Given a known input, the calculated dose agrees with algorithm specifications
- **Physical Accuracy (±5%)**
  - Given perfectly positioned source and point of interest with no error in dwell time delivery then

    Dose Delivered = Calculated Dose
- **Clinical Accuracy (±10-20%)**
  - Actual dose to patient = calculated dose
  - Includes errors due to: source targeting accuracy, organ delineation error, seed migration, tissue deformation

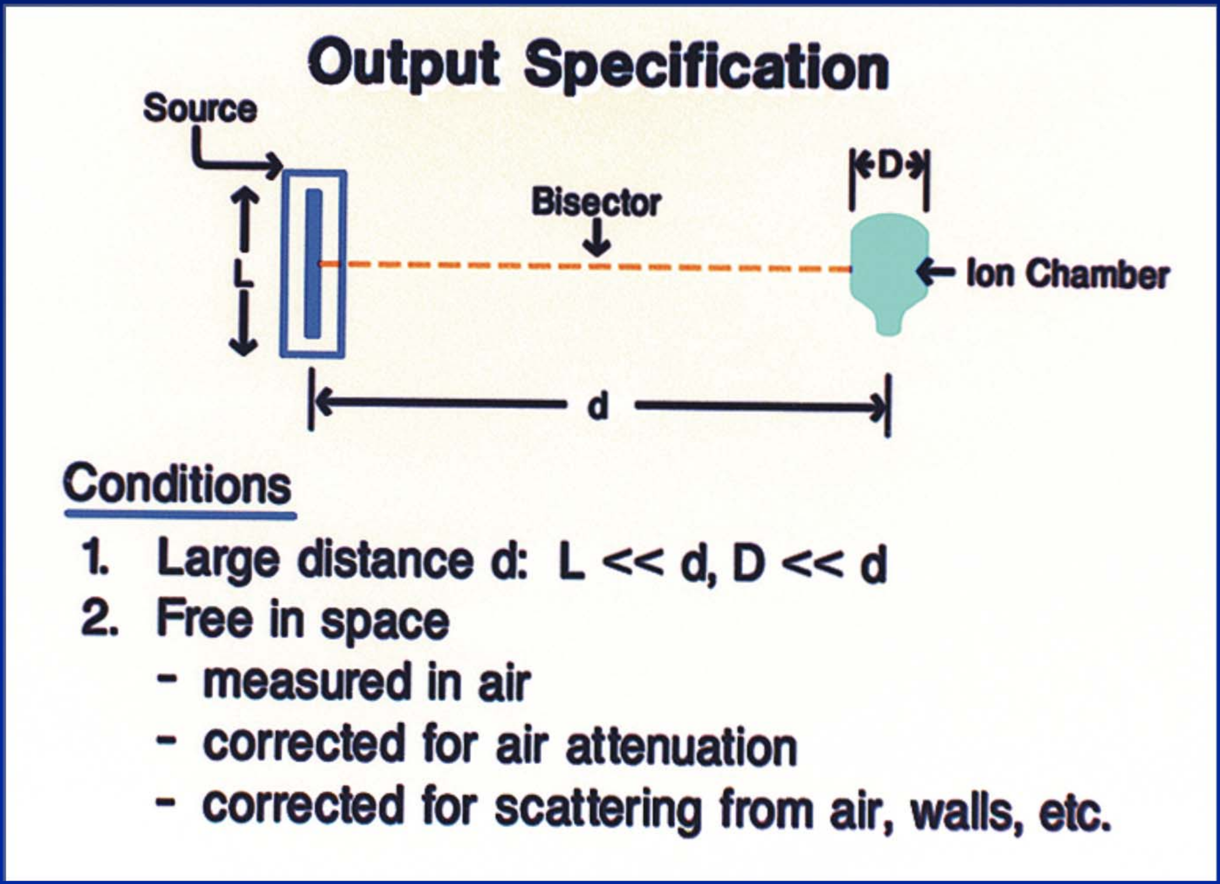
Inter-society standards for the performance of brachytherapy: a joint report from ABS, ACMP and ACRO

Subir Nag[a,*], Ralph Dobelbower[b], Glenn Glasgow[c], Gary Gustafson[d], Nisar Syed[e], Bruce Thomadsen[f], Jeffery F. Williamson[g]

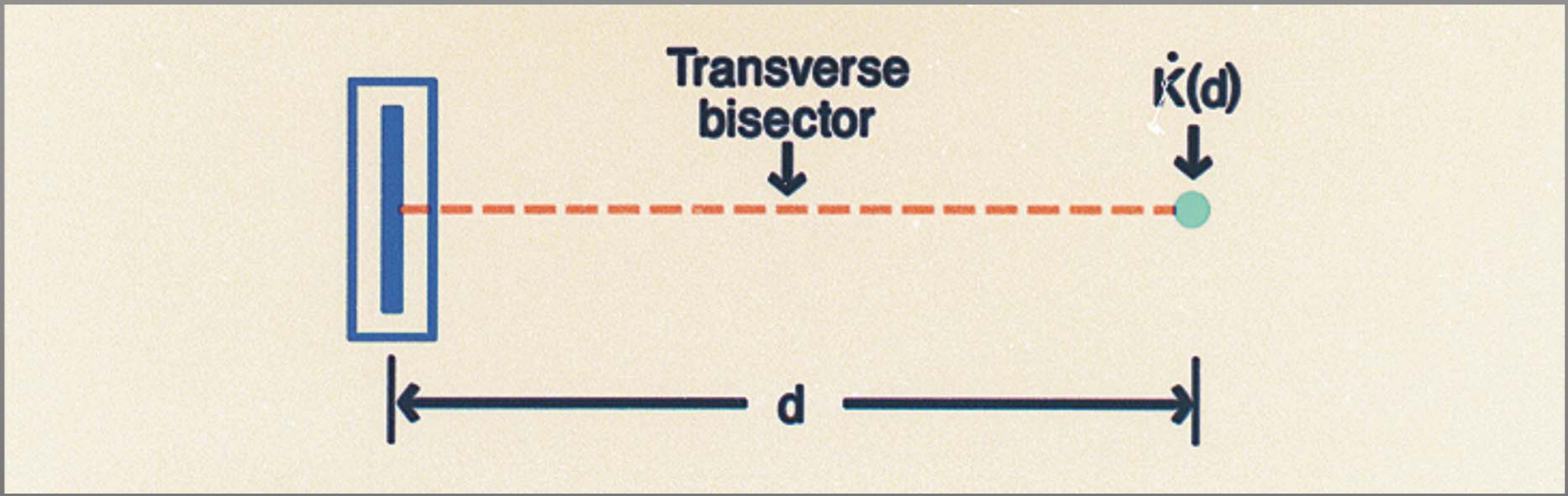
Critical Reviews in Oncology/Hematology 48 (2003) 1–17

How is strength of clinical brachytherapy sources determined?

- **Answer: In terms of air-kerma rate on transverse axis for all photon emitters**



2004 AAPM Definition of Air-Kerma Strength



$$S_K = \dot{K}_\delta(d)\, d^2 \ [\mu Gy \cdot m^2 \cdot h^{-1} = cGy \cdot cm^2 \cdot h^{-1} = U]$$

$\dot{K}_\delta(d)$ is air-kerma rate in vacuo due to photons of energy > δ (~ 5 keV), d >> L

Cutoff designed to exclude low-energy contaminant radiation

NIST Primary K_{air} and S_K Standards

- **Primary Standard: Maintained by National Institutes of Standards and Technology (NIST)**
  - **All other instruments calibrated against it**

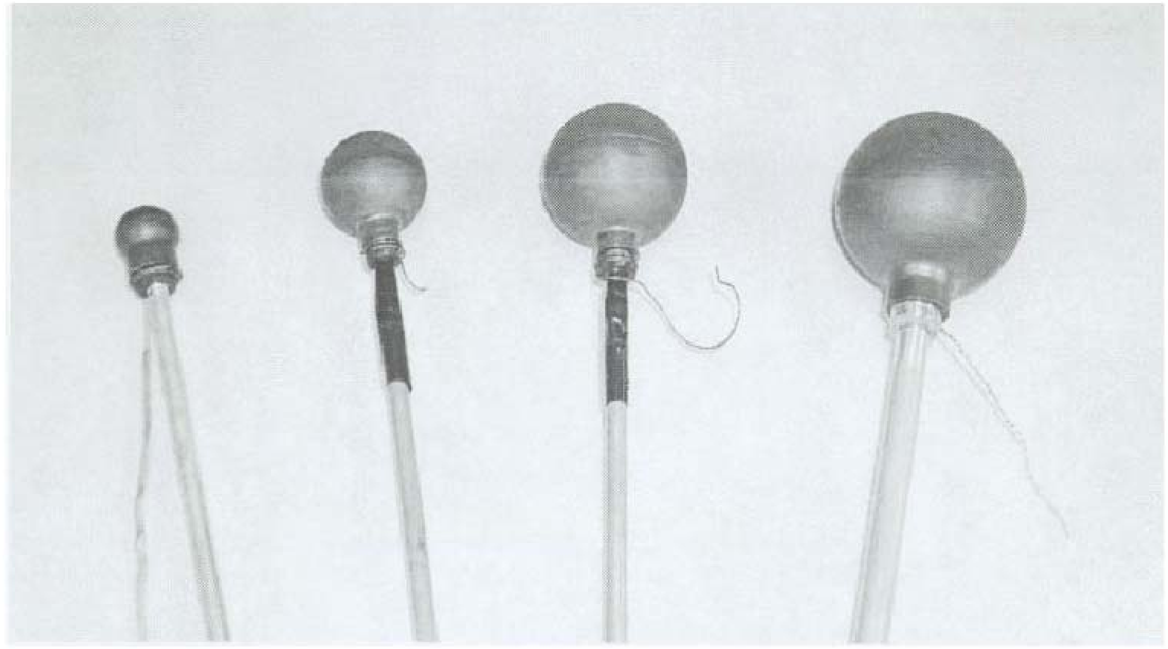


Fig. 1. NBS-NIST standard graphite-walled, air-ionization cavity chambers.

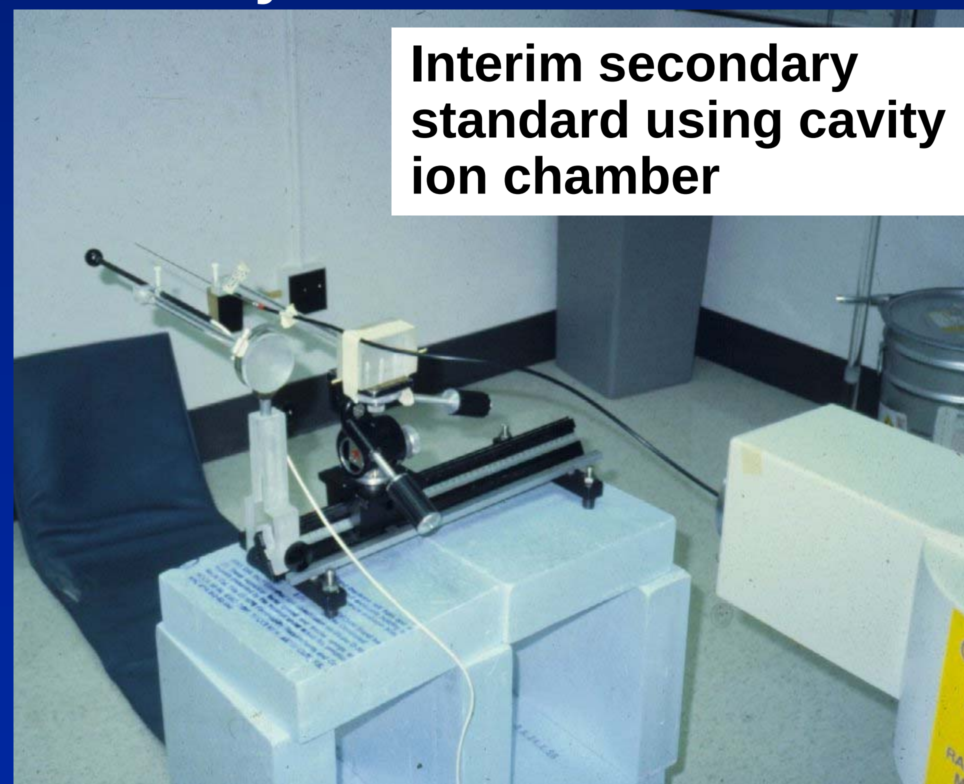
- **Measures absolute amount of a quantity in terms of time, mass, charge, length**

- **Carbon-walled spherical cavity ionization chambers**
  - **Realizes air-kerma standards for Cs-137 and Co-60 for teletherapy & brachytherapy and for Ir-192 LDR seeds**

Source Calibration Options for HDR RAL

- **TG-56: in-air method as interim secondary standard**
- **For quarterly calibration end users can**
  - **Duplicate interpolative in-air calibration technique OR**
  - **Use HDR well chamber calibrated against in-air method by ADCL**
- **TG-56 recommends independent tertiary standard as**

calibrated re-entrant well chamber



Interim secondary standard using cavity ion chamber

Traceability and AAPM Recommendations

- **ADCL:** AAPM-accredited secondary lab which can calibrate a user's source against NIST standards
- **Directly traceable calibration:** source/instrument has NIST or ADCL calibration
- **Secondarily traceable:** source or instrument intercompared to a source with 'directly traceable' calibration.
- **AAPM recommendations (TG 56 and 40):**
  - All clinical sources should have secondarily traceable calibrations
  - Each user should verify vendor calibrations with secondarily traceable S_K measurements

How are dose rates around individual sources calculated?

- By inferring dose rate to surrounding medium from measured S_K of the source
- Classical dose calculation (1940-present)
  - Dose model parameters independent of source geometry
  - Point source model and Sievert integral
- Quantitative Dosimetry (1980- present)
  - Source model-specific dosimetry parameters derived from Monte Carlo simulation and/or TLD measurement
  - TG-43 protocol: standardized table-based single-source dose-rate calculation using MC and TLD data
- For ^{137}Cs and ^{192}Ir, classical and quantitative approaches are equivalent on transverse axis

AAPM Dosimetric Prerequisites for Routine Clinical Use of > 50 keV Sources

Li Med. Phys. 34:37 (2007)

- S_K values used for planning shall be secondarily traceable to NIST WAFAC calibrations
  - Annual intercomparisons between vendor, NIST, and ADCLs
- Independent published Monte Carlo and experimental dose-rate distributions
  - For 'conventional' ^{137}Cs and ^{192}Ir, one determination sufficient
- Compliant sources listed on AAPM/RPC Registry

AAPM High Energy Brachytherapy Dosimetry (HEBD) Report

Dose calculation for photon-emitting brachytherapy sources with average energy higher than 50 keV: Report of the AAPM and ESTRO

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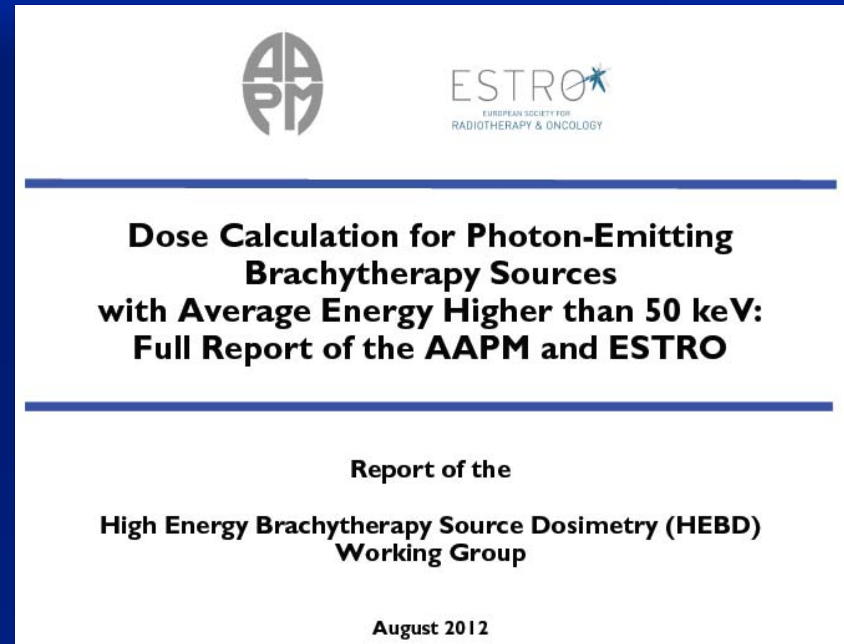
Med Phys 2012

HEBD Report contents



ESTRO
EUROPEAN SOCIETY FOR
RADIOTHERAPY & ONCOLOGY

Dose Calculation for Photon-Emitting Brachytherapy Sources with Average Energy Higher than 50 keV: Full Report of the AAPM and ESTRO

Report of the

High Energy Brachytherapy Source Dosimetry (HEBD) Working Group

August 2012

- **Extension of TG-43 formalism to higher energy and extended sources**
- **Guidelines for Monte Carlo determination of dose-rate distributions**
- **Consensus dose distributions: TG-43 parameters and away-along tables**
  - **14 HDR and PDR ^{192}Ir sources + 2 LDR seeds**
  - **2 ^{60}Co HDR sources**
  - **3 GYN ^{137}Cs tubes**
- **Nearly all datasets are Monte Carlo based**

HDR and PDR Sources with HEBD Consensus Data

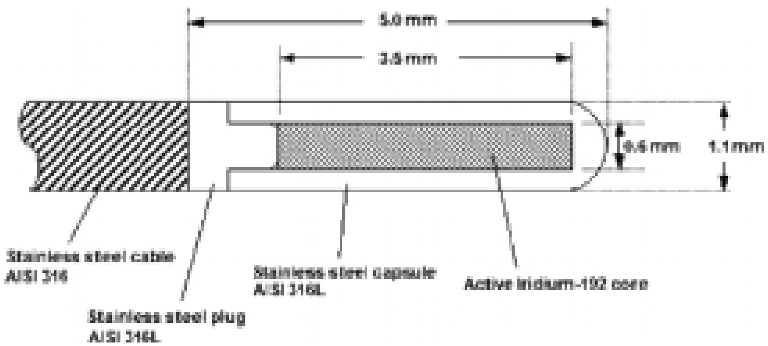
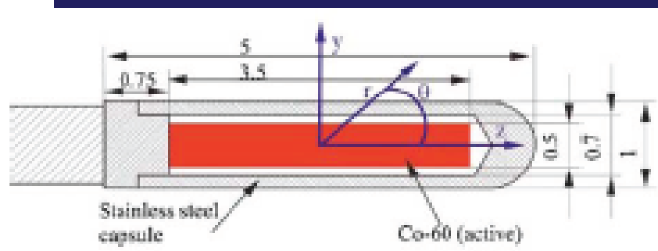


Figure 1. Schematic drawing of the Nucletron 'Classic' ^{192}Ir HDR brachytherapy source.



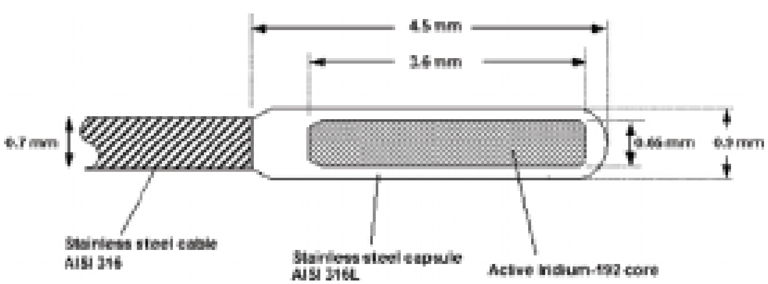
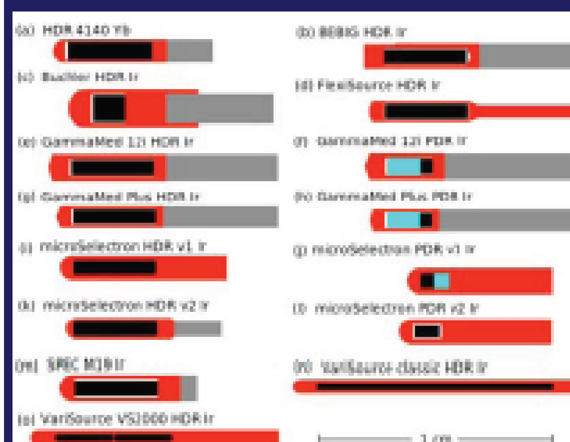
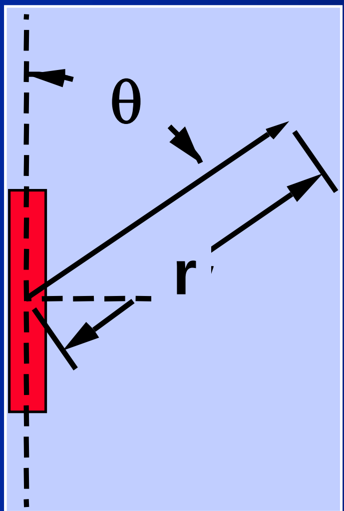


Figure 2. Schematic drawing of the Nucletron 'V2' ^{192}Ir HDR brachytherapy source.



Courtesy of Mark Rivard



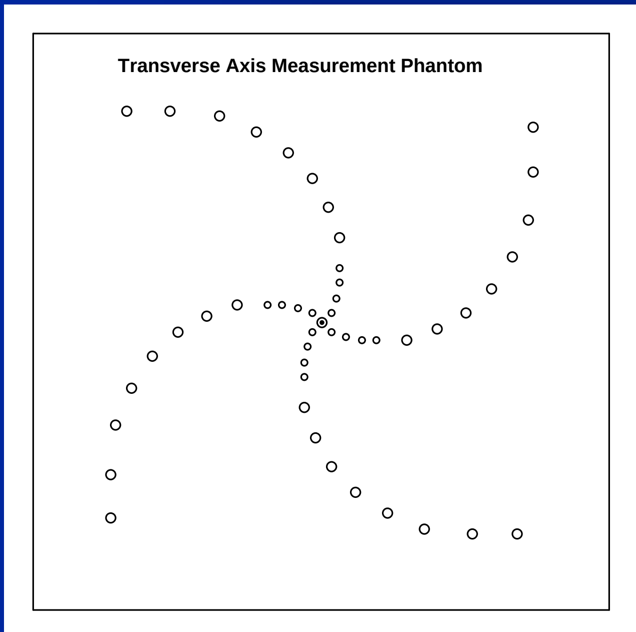
AAPM Revised 2-D Formalism

$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(1\ \text{cm}, \pi/2)} \cdot F(r,\theta) \cdot g_L(r)$$

for x = L $G_L(r,\theta) = \begin{cases} \dfrac{\beta}{L r \sin\theta} & \text{if } \theta \neq 0° \\ \left(r^2 - L^2/4\right)^{-1} & \text{if } \theta = 0° \end{cases}$ line-source approximation

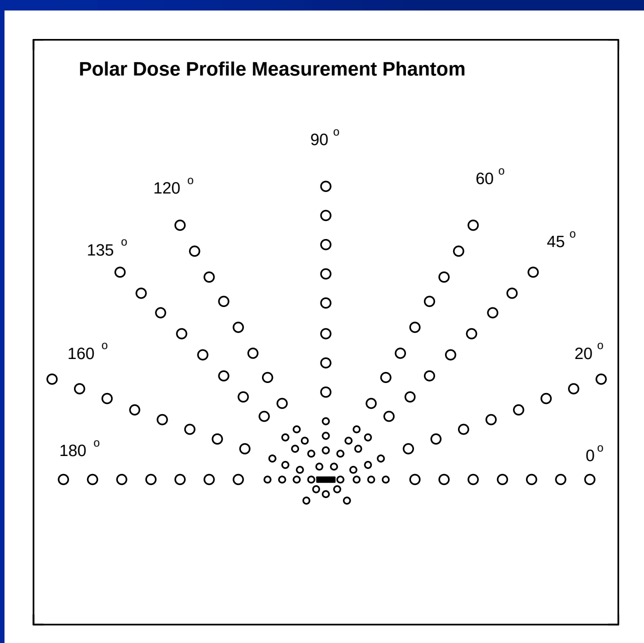
for x = P $G_P(r,\theta) = r^{-2}$ point-source approximation

Where L = effective active length of source
HEBD: Only G_L recognized



Starting Point: discrete grid of dose rates measured by TLD or calculated by Monte Carlo

- **HEBD: Assume full scatter 40 cm radius liquid water phantom**



$$\Lambda = \frac{\dot{D}_{wat} \text{ at } \begin{cases} r = 1 \text{ cm} \\ \theta = \pi / 2 \end{cases}}{S_K}$$

where $\dot{D}_{wat}$ = TLD measurement

S_K = NIST-traceable measurement

HEBD Consensus L values: ^{192}Ir HDR Sources

Derived from the consensus TG-43 dataset, an away-along dose rate table is presented ($cGy \cdot h^{-1} \cdot U^{-1}$) for TPS quality assurance purposes (Table VII).

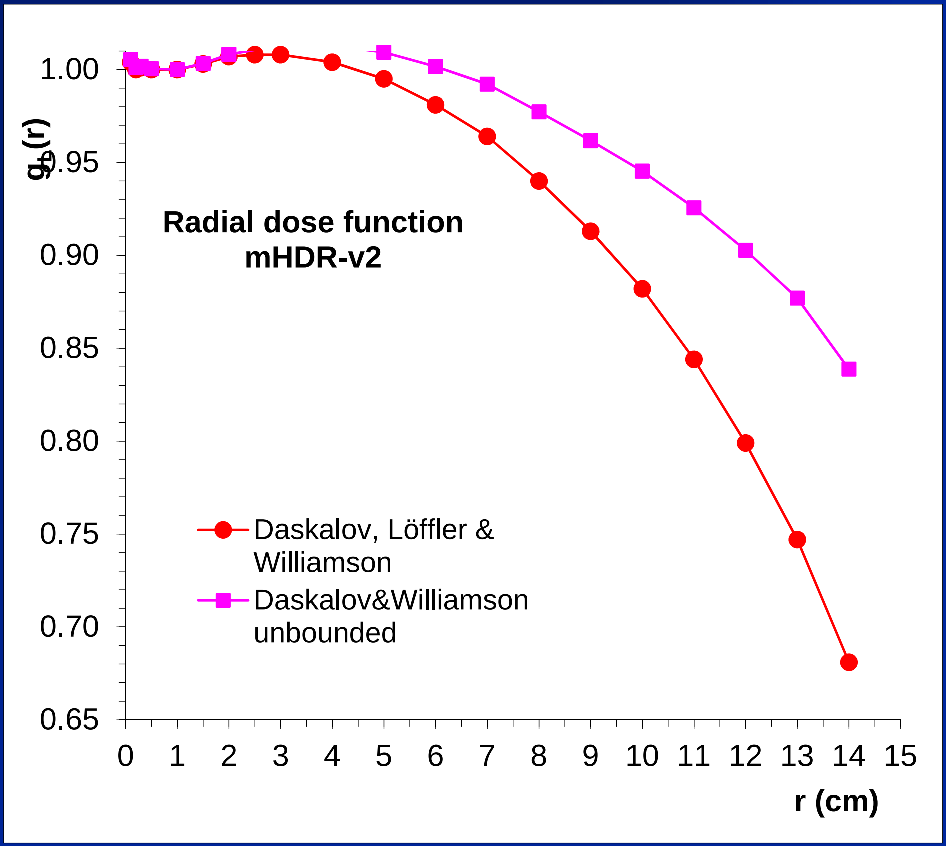
Table IV. Dose rate constant for HDR ^{192}Ir sources.

Source Name (Manufacturer)	$_{CON}\Lambda$ [$cGy \cdot h^{-1} \cdot U^{-1}$]	Statistical uncertainty ($k = 1$)	$_{CON}\Lambda / G_L(r,\theta)$ [$cGy \cdot cm^2 \cdot h^{-1} \cdot U^{-1}$]
mHDR-v1 (Nucletron)	1.116	0.9%	1.127
mHDR-v2 (Nucletron)	1.109	1.1%	1.121
VS2000 (Varian)	1.100	0.6%	1.123
Buchler (E&Z BEBIG)	1.117	0.4%	1.119
GammaMed HDR 12i (Varian)	1.118	0.4%	1.129
GammaMed HDR Plus (Varian)	1.117	0.4%	1.128
GI192M11 (E&Z BEBIG)	1.110	0.4%	1.121
Ir2.A85-2 (E&Z BEBIG)	1.109	1.2%	1.120
M-19 (SPEC)	1.114	0.2%	1.125
Flexisource (Isodose Control)	1.113	1.0%	1.124

$$\Lambda = \frac{\dot{D}_{wat}\left(r_0 = 1\ \text{cm}, \theta = \pi/2\right)}{S_{K,N99}} \approx \left(\overline{\mu_{en}/\rho}\right)^{wat}_{air} \cdot T(r_0) \frac{2 \cdot \tan^{-1}\left(L/2r_0\right)}{L r_0}$$

TG 43 Radial Dose Function: $g_L(r)$

- $g_X(r)$ = dimensionless radial dose function Describes transverse-axis dose Fall-off
- G_L-Factor suppresses dose variation due to inverse square-law fall-off



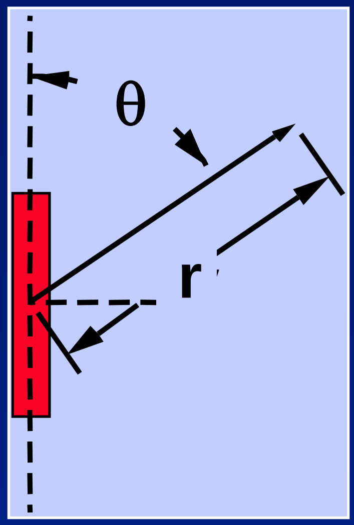
$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(1\ \mathrm{cm}, \pi/2)} \cdot F(r,\theta) \cdot g_L(r)$$

$$g_L(r) = \frac{\dot{D}(r,\pi/2) \cdot G_L(1\ \mathrm{cm},\pi/2)}{\dot{D}(1\ \mathrm{cm},\pi/2) \cdot G_L(r,\pi/2)}$$

microSelectron V2 Source

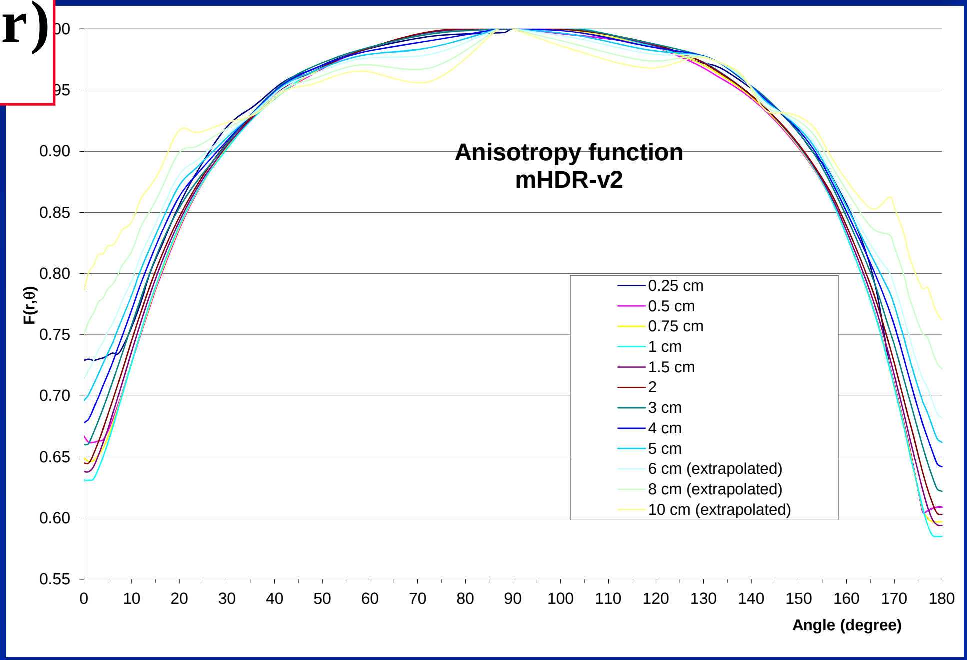
Task Group 43 2-D Anisotropy Function: F(r,❑)

- **$F(r,\theta)$ = dimensionless anisotropy function**
  - Describes angular dose variation at fixed distance
  - G_L suppresses inverse-square dose variation



$$\dot{D}(r,\theta) = S_K \cdot \Lambda \cdot \frac{G_L(r,\theta)}{G_L(1\ \text{cm},\pi/2)} \cdot F(r,\theta) \cdot g_L(r)$$

$$F(r,\theta) = \frac{\dot{D}(r,\theta) \cdot G_L(r,\pi/2)}{\dot{D}(r,\pi/2) \cdot G_L(r,\theta)}$$



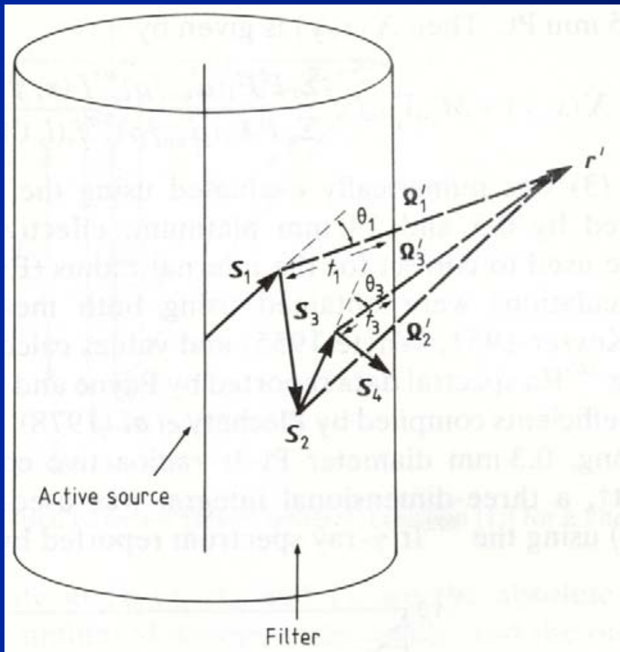
microSelectron V2 Source

TG-43 Dose-Calculation ‘Algorithm’

- **TG-43-HEBD starts with a discrete grid of Monte Carlo dose rates**
- **F(r,❑), g(r), and ϕ_{an}(r) table entries correspond to MC calculation points**
- **What does RTP do at arbitrary point (r,❑)?:**
  - **Finds $g(r_1)$ and $g(r_2)$, etc. at nearest neighbor points**
  - **Calculates g(r), etc., by bi-linear interpolation**

$$g(r) = \left[g(r_2) - g(r_1)\right]\left[\frac{r - r_1}{r_2 - r_1}\right] + g(r_1)$$

  - **Calculate exact G(r,❑) and obtain D(r,❑) from TG-43 equation**
- **QM: compare RTP single-source dose rates with manual TG-43 or HEBD away-along calcs**



Monte Carlo Dosimetry Techniques

- **Simulate photon histories for source embedded in a water phantom and a free-air calibration range**
- **Quantities calculated**

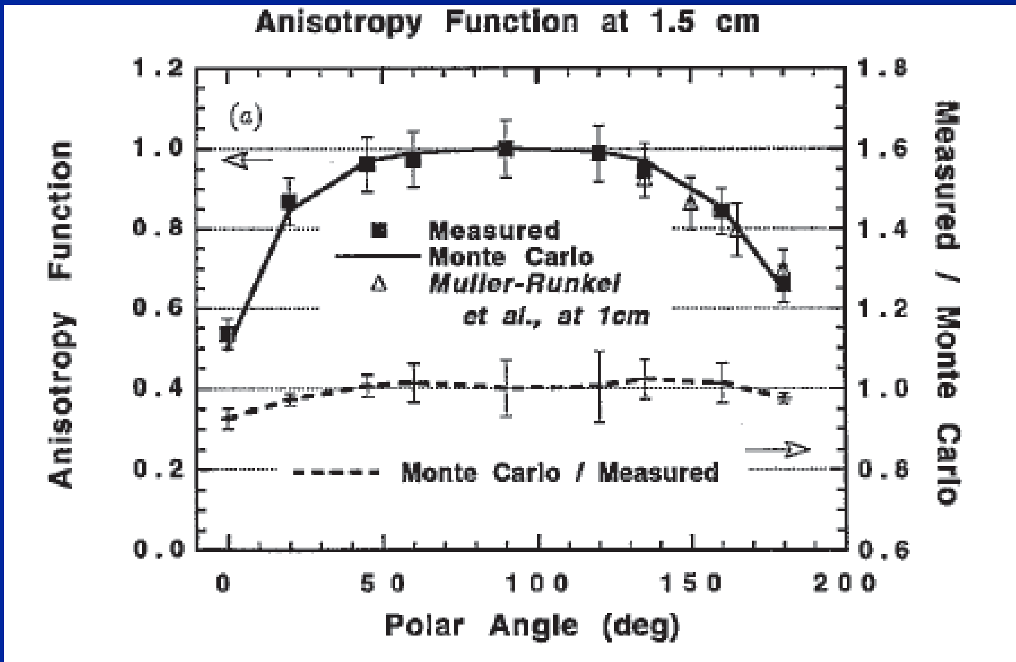
$\Delta D_{wat}(r,\theta)$ (cGy/simulated photon) in water phantom

On Transverse axis for 0.1 to 10 cm distances

As function of polar angle at 5-10 radial distances (0.25 - 10 cm)

$\Delta S_K = S_K$/simulated photon as measured by WAFAC

Calculate $\Lambda_{MC} = \left[\frac{\Delta D_{wat}(r,\theta)}{\Delta S_K} \right]_{MC}$



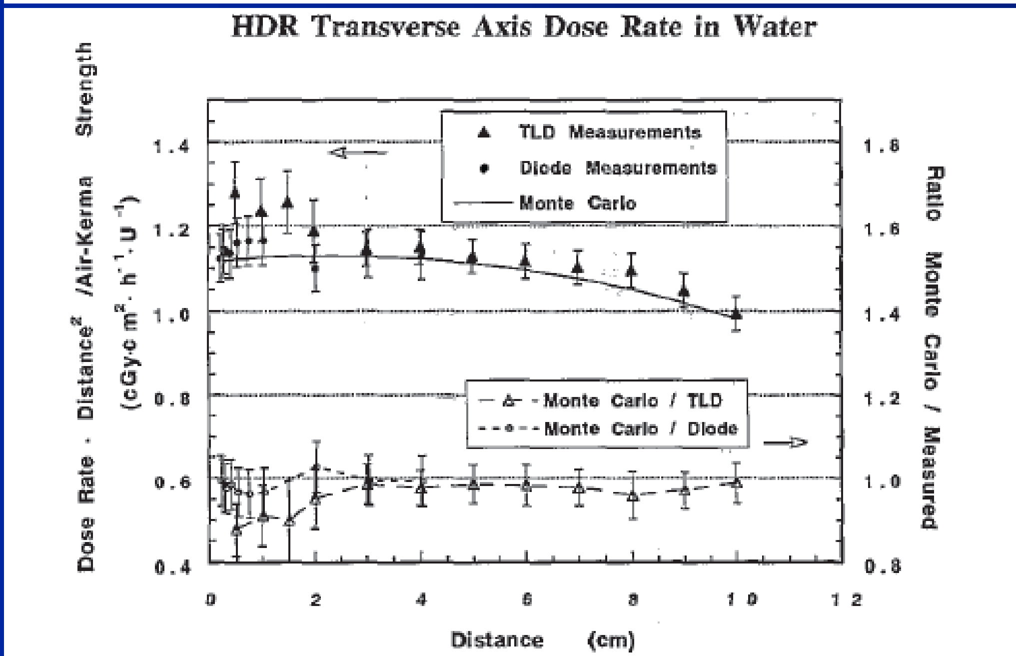


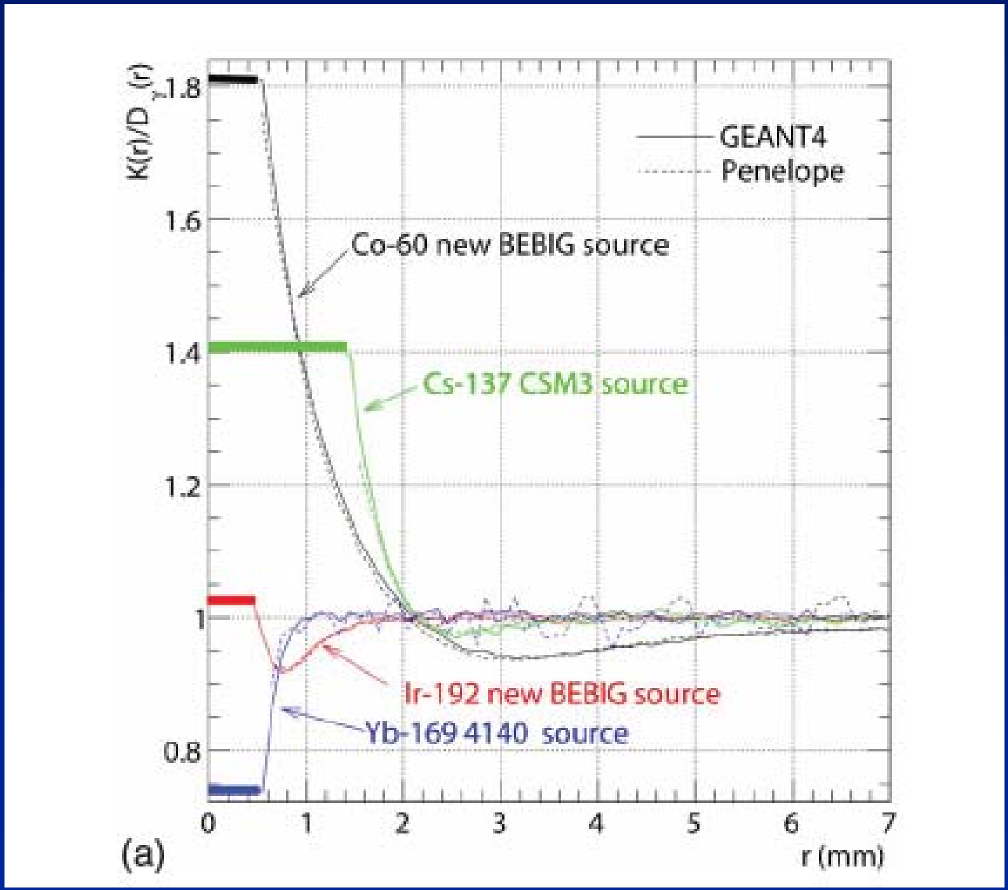
Figure 5. A comparison of the measured and simulated transverse axis dose-rate distributions in water as a function of distance along the transverse axis of the HDR source.

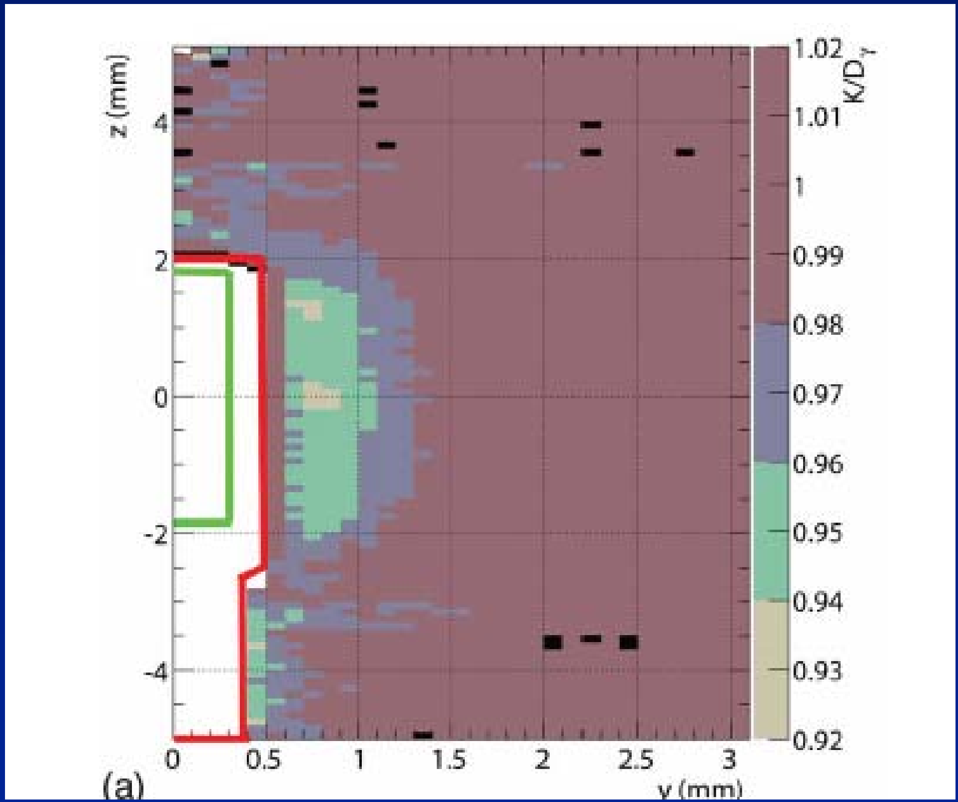
Monte Carlo Validation
^{192}Ir Brachytherapy

- **TLD and diode dose measurements show good agreement with Monte Carlo**
- **Uncertainties**
  - **Experimental: >5%**
  - **Monte Carlo: <2%**
- **HEBD: all consensus data based on MC**
  - **MC: better range and spatial resolution**

Kirov/Williamson Med Phys 2005

Importance of secondary electron transport for ^{192}Ir

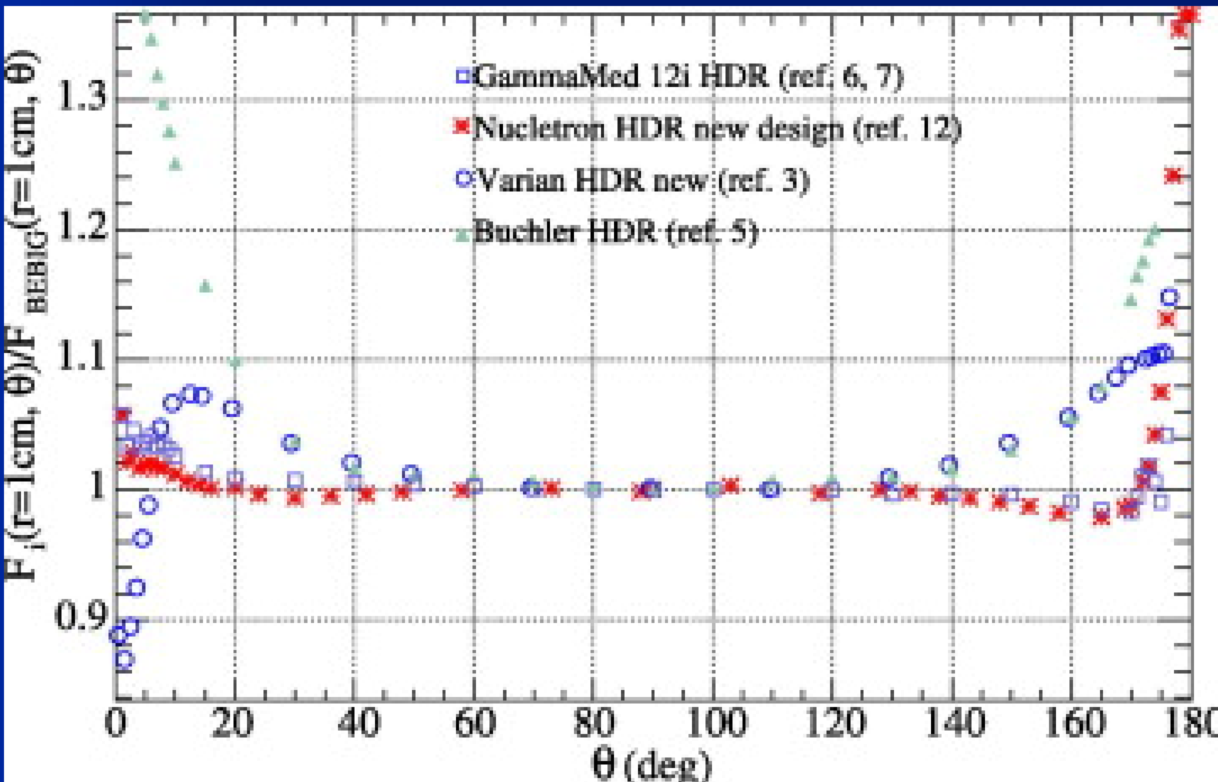




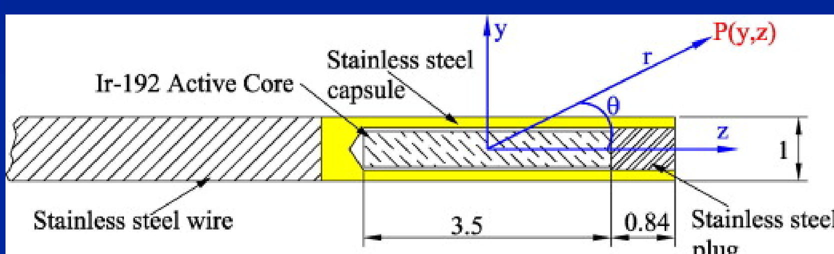
Ballester, Med Phys 2009

- <1.5 mm distance, CPE breaks down and coupled photon-electron MC is needed to achieve 2% accuracy. Elsewhere Dose ≈ Kerma

Bebig HDR Source: F(1 cm,θ)

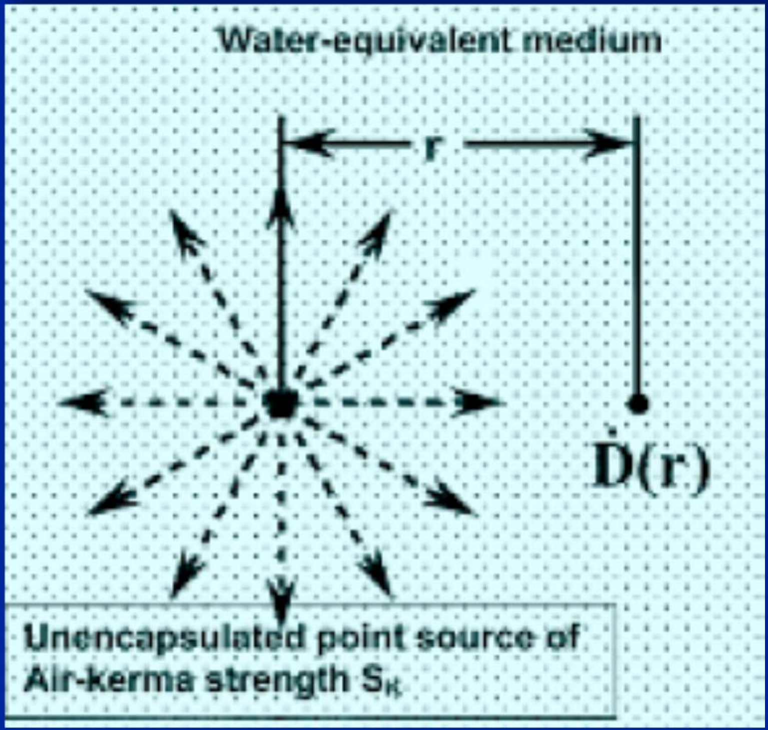


- Very small differences in anisotropy function for similar geometry sources
- Various MC codes (Penelope, PTRAN, EGSnrc, MCNP) all agree closely



Granero Radiother Oncol 2005

'Classical' Dose Calculation Model



- No radiative loss and CPE

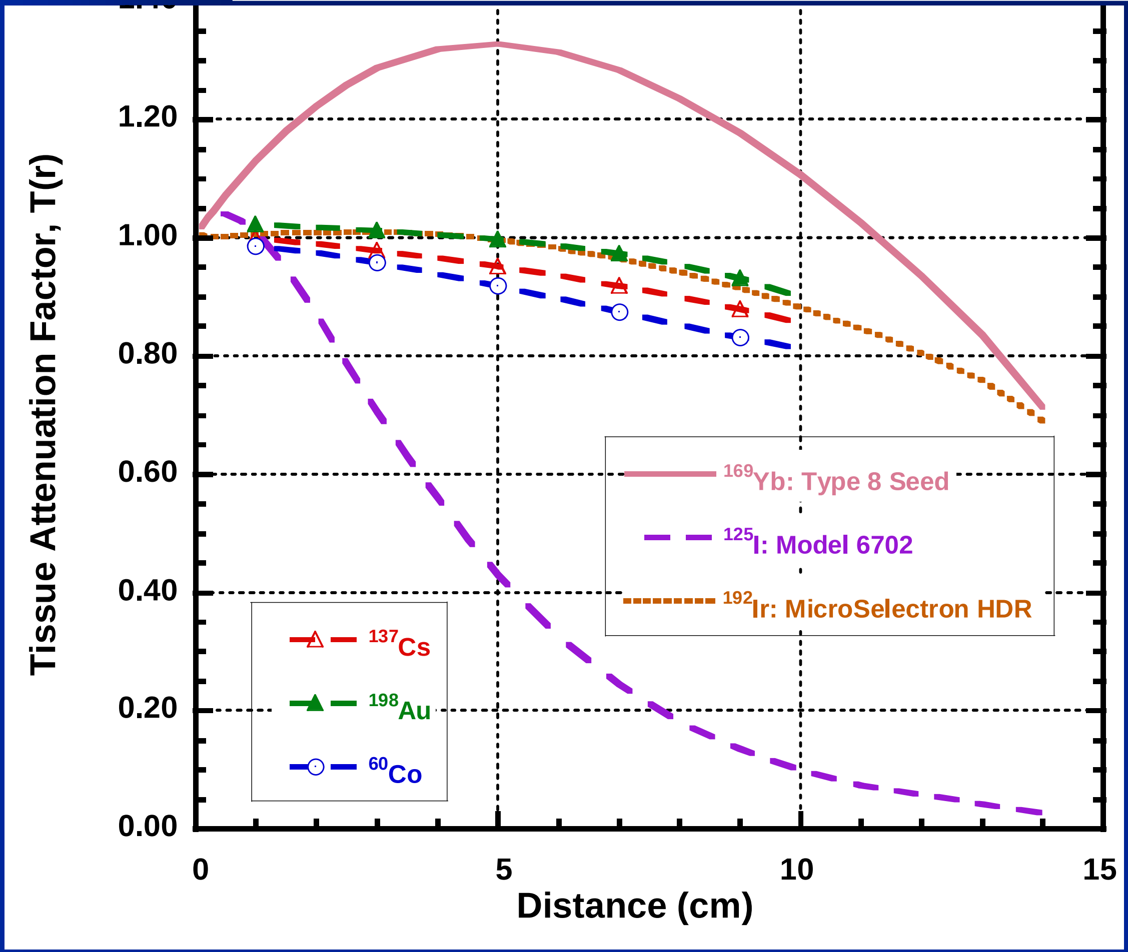
$$D_{med} = K_{air} \cdot (\overline{\mu_{en} / \rho})_{air}^{med}$$

- Then

$$\dot{D}_{med}(r) = \frac{S_K \cdot (\overline{\mu_{en} / \rho})_{air}^{med}}{r^2} \cdot T(r)$$

Where $(\overline{\mu_{en} / \rho})_{air}^{med} =$ ratio of mass energy absorption coefficients

Tissue Attenuation Factor, T(r)



- Describes competition between primary attenuation and scatter buildup
- T(r) = 1 ± 0.05 for r < 5 cm when E >200 keV
- Often derived from 1-D transport calculations

$$T(r) = \text{Tissue Attenuation Factor} = \frac{\dot{D}_{wat}(r)\ \text{in Water}}{\dot{D}_{wat}(r)\ \text{in Vacuum}}$$

Apparent Activity: A_{app}

A_{app} = activity of hypothetical unfiltered point source of same radionuclide that gives same S_K as the given source

- Units: mCi, Ci, Bq, or MBq
- Applicable to all photon emitting radionuclides
  - Commonly applied to I-125, Pd-103, & HDR Ir-192
- Uses: regulatory compliance and for interstitial implant dosimetry

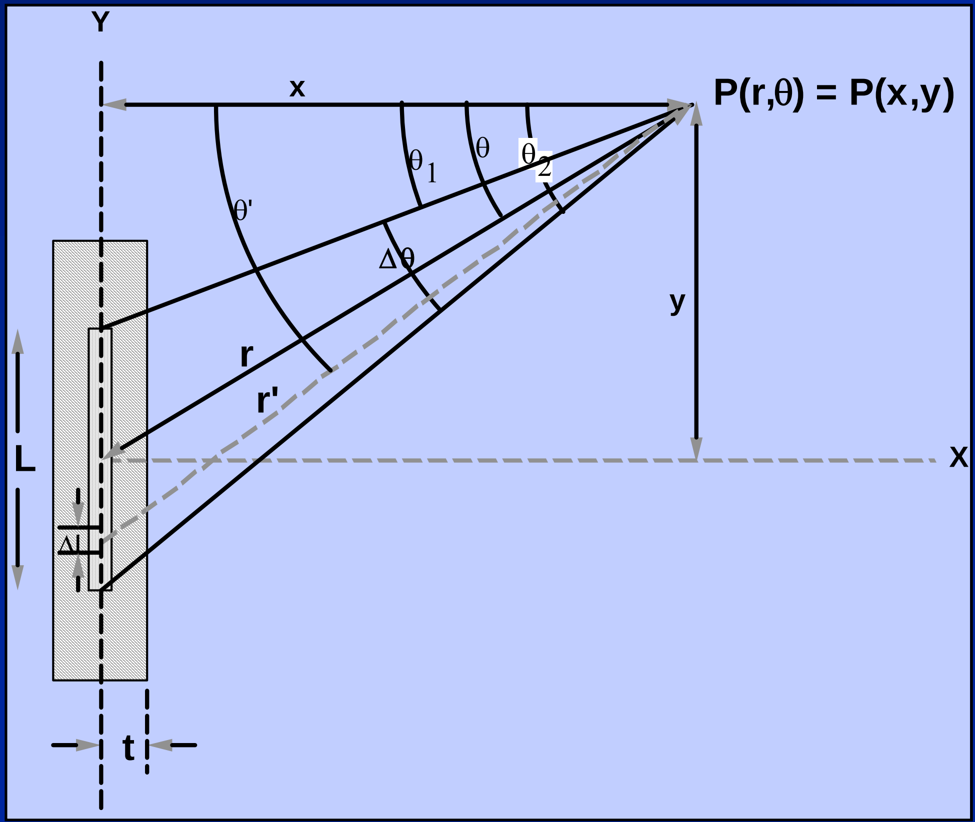
$$A_{app} \equiv S_K \Big/ \left[\Gamma_X \cdot \left({}^{W}\!\!\diagup_{e} \right) \right]$$

$$\dot{D}(r) = A_{app} \cdot \frac{\Gamma_X \cdot f_{med} \cdot T(r)}{r^2}$$

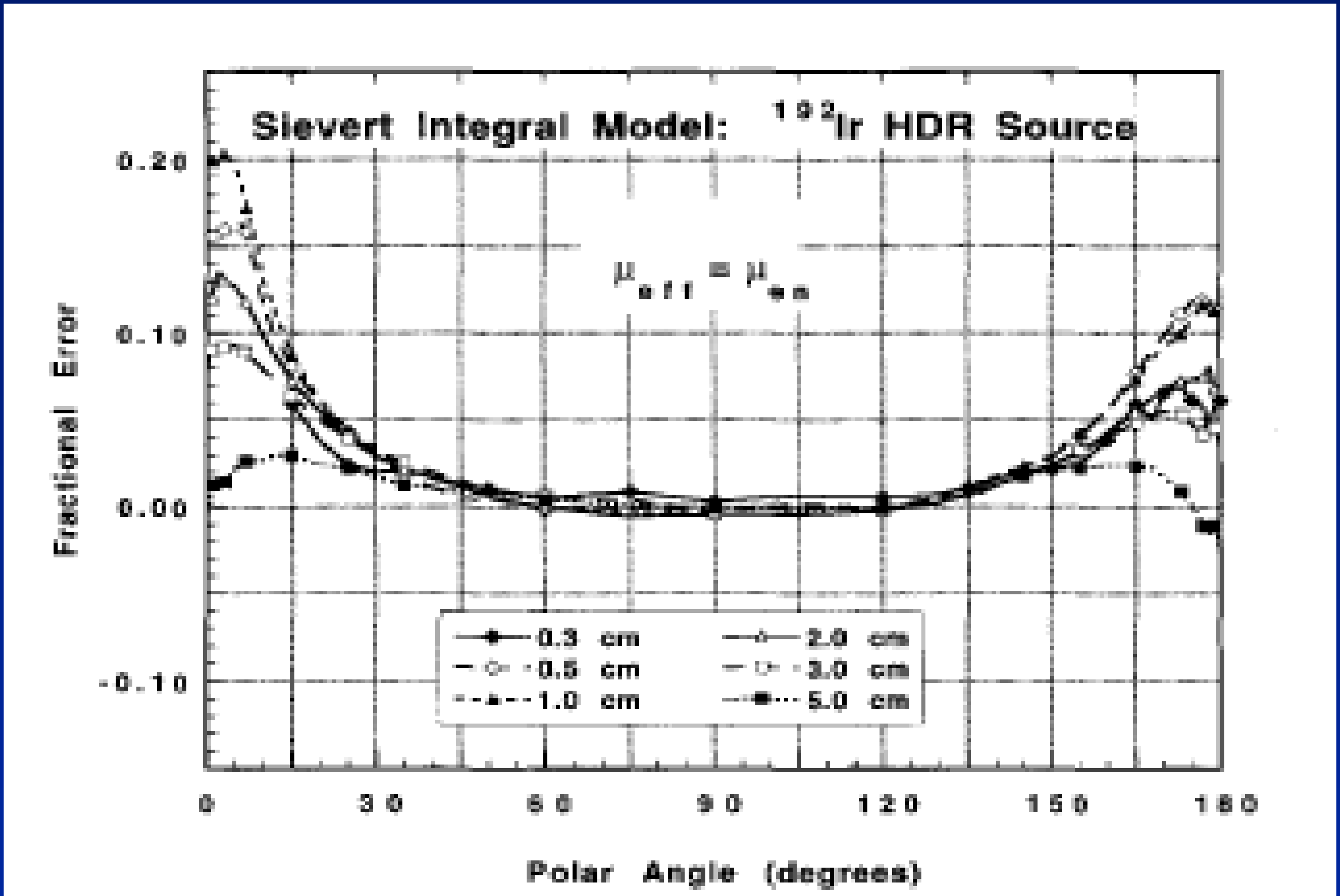
Sievert Filtered Line-Source Integral
1D Path-length Model

$$\dot{D}(x,y) = S_K \cdot \frac{(\mu_{en}/\rho)^{wat}_{air} \cdot e^{\mu \cdot t}}{L \cdot x} \cdot \int_{\theta_1}^{\theta_2} e^{-\mu \cdot t \cdot \sec\theta} \cdot T(x \cdot \sec\theta) \cdot d\theta$$

- μ = effective filtration
- Accurate on transverse axis for all sources > 100 keV
- Cs-137 tubes: accurately models 2D anisotropy
- Ir-192: >10% errors in 2D anisotropy function



1D Pathlength Model vs. Monte Carlo
microSelectron 'classic' HDR ^{192}Ir source



- **%RMS error = 6.9%**

Williamson IJROBP 1996

Dose Calculation QA

- Planning system algorithm: numerical accuracy
  - Algorithm output vs. independent calculation
- Physical accuracy
  - Algorithm output vs. Monte Carlo or measurement
  - S_K calibration accuracy
- Clinical accuracy
  - Image identification and display
  - Constructing 3D images from slices
  - Forming bit-map or surface-mesh structures from contour stacks; ray tracing, etc.
  - DVH/plan evaluation metric accuracy
  - Source/applicator reconstruction from CT or radiographs
- System integration tests: dry runs and end-to-end testing on phantoms

TABLE XV. Pretreatment physicist review of HDR treatment plan and dwell-time calculations.

End point	Check methodology
Patient identity	Compare patient names/numbers/dates printed on prescription, simulator radiographs, chart, and localization form.
Input data	As described in text
Positional accuracy/ Implant geometry	Applicators modeled in treatment plan match those of operating room description and implant diagram. Verify matching and localization calculations against radiographs if interstitial ortransluminal implant. Compare active dwell positions, dwell separation, and treatment length listed on computer plan to localization form or to appropriate treatment planning procedure. Compare three orthogonal dimensions of implant measured from AP and lateral radiographs to corresponding dimensions of graphic plan. Check radiograph orientations, distances, magnifications, and gantry anglesagainst requirements for selected source position reconstruction algorithm.
Plan optimization process	Appropriate optimization option used. Dose optimization and dose specification points in correct location relative to dwell positions on graphic plan. Expected isodose curve passes through dose specification points. Optimization algorithm produces expected distribution of dwell weights, coverage of target volume, and distribution/ magnitude of hot spots or peripheral/central minimum dose ratio. Implant quality parameters derived from dose-volume histograms, if available and previously validated, should be checked.
Dose calculation accuracy	(RAK)/dose ratio falls within expected range. Assuming distribution of dwell times on computer plan printout, manually calculated dose agrees with dose calculated by RTP system within expected tolerance. Doses at clinically important points of interest agree with values interpolated from isodoses. Isodose curves calculated in appropriate planes.
Clinical adequacy	Prescribed dose, applicator selected, and dose distribution consistent with Policies of Treatment for patient's disease or physicist's understanding of physician's clinical intent. Volume covered by prescription isodose surface consistent with all known target localization data. Maximum dose and dose to critical anatomic structures, including previously administered therapy, within accepted range.
Daily treatment record	Source strength, total dwell time, total IRAK, no. and type of applicators correctly entered into daily treatment record.

Avoiding patient-specific random errors

Physicist Pre-Tx HDR Plan Review Checklist

- **Main TG-59 strategy for intercepting/correcting major errors**
- **Comprehensive check: consistency & correctness**
  - **Prescription, Clinical policies, localization images, implant diagram, plan**
- **Physicist: avoid compromising independence**
  - **Train dosimetrist to do planning**

Patient-Specific Manual Dose check

- Independently measure CTV dimensions, assess total S_K
- Usually, 5%-10% agreement with RTP