Brachytherapy Physics: Everything you Need to Know and Controversial Issues

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Disclaimer

- The presenters have no conflicts to declare.

- Images of commercial devices have been supplied by vendors or taken by the presenters, but do not imply endorsement of any particular equipment.

Prostate Brachytherapy
Learning Objectives
Prostate Brachytherapy

- Review the isotopes in vogue, prescription ranges, and common clinical characteristics for LDR and HDR
- Compare and contrast LDR vs HDR
- Review radiation safety and release criteria

What is Brachytherapy?

Brachytherapy can be
- low dose rate or high dose rate
- permanent or temporary

What is LDR (low dose rate) brachytherapy?
- Per ICRU report 38 LDR is in the range of 0.4 to 2.0 Gy/hr (think DAYS)

What is HDR (high dose rate) brachytherapy?
- Per ICRU report 38 is a dose rate greater than 12 Gy/hr (think MINUTES)

There is also MDR (medium dose rate) that falls between 2 to 12 Gy per hour (think HOURS)

What do LDR and HDR patient selection criteria have in common?
- Typically early stage
- Gleason score 2-10
- Obstructive urinary symptoms contraindication
- Prior TURP is a challenge
- No distant metastasis

Common Sources:
- I-125, Pd-103, Cs-131

Prostate Brachytherapy

What Are LDR and HDR Patient Selection Criteria?

HDR
- General Inclusion Criteria
  - Clinical Stage: T1-T3b and selected T4
  - Gleason Score: 2-10
  - PSA: No upper limit, but in almost all cases, patient does not have documented distant metastasis

Exclusion Criteria
- Relative Contraindications:
  - Severe urinary obstructive symptoms
  - Extensive TURP defect or TURP within the prior 6 months
  - Collagen vascular disease
- Absolute Contraindications:
  - Unable to undergo anesthesia (general, spinal, epidural or local)
  - Unable to lay flat

LDR
- General Inclusion Criteria
  - Clinical Stage: T1b-T2c and selected T3
  - Gleason Score: 2-10
  - PSA: In almost all cases, a PSA < 50 ng/ml
  - No pathologic evidence of lymph node involvement
  - No distant metastasis

Exclusion Criteria
- Relative Contraindications:
  - Severe urinary irritative/obstructive symptoms
  - Extensive TURP defect
  - Substantial median lobe hyperplasia
  - Prostate dimensions larger than the grid
  - Severe pubic arch interference
  - Gross seminal vesicle involvement
  - Prior pelvic radiotherapy
  - Inflammatory bowel disease
  - Pathologic involvement of pelvic lymph nodes
- Absolute Contraindications:
  - Distant Metastasis
  - Life expectancy < 5 yrs
**HDR**

The 1st HDR Tx should be delivered on the day of the catheter placement. If multiple Fxs are delivered, consecutive Fxs should be delivered within 24 hours after the 1st Tx, but no less than 6 hours between Fxs.

**Prostate Brachytherapy HDR**

Under US guidance, typically 12-20 flexible needles are inserted into the prostate. Can use a C-arm to assist with visualization. Patient must have a treatment planning CT. Volume implant technique, "goodness of plan" similar to that of a seed implant.

*Boost: (not necessarily prior) XRT 40 - 45 Gy

What makes it a Good Plan?

- Seattle Prostate Institute Criteria pre-plan
  - Modified uniform loading
  - V100: 98-100%
  - V150: 1-125 30-40%
  - Pd-103 40-50%
  - V200: 10-20%
  - Urethra max: 100-125% (definitely <150%)
  - Rectum point: <80%
  - Margin: 3-5 mm

Seattle Prostate Institute, Class Notes, 2002

The perfect post plan

Suggested Post Implant Dosimetry Targets

**Prostate**
- I-125 D$_{90}$ > 140 Gy
- Pd-103 D$_{90}$ > 125 Gy
- Cs-131 D$_{90}$ > 115 Gy
- Boosts D$_{90}$ > reference dose

**Urethra**
- D90 < 180 Gy
- V150 < 60% reference dose

**Rectum**
- Dose to > 1 cm length of the anterior mucosal wall < reference dose
- Max dose to the anterior mucosal wall < 120% of reference dose

Brachytherapy Physics, Joint AAPM/ABS Brachytherapy Summer School 2nd Ed. 2005 Chapter 31, Bice
Post Plan Challenges

Leg position is different between pre-plan U/S and post plan CT
Where’s the base?

Prostate Brachytherapy Question:
All of the following are equivalent treatment prescription ranges for either LDR or HDR prostate treatment except?

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1. 145 Gy using $^{125}$I</td>
</tr>
<tr>
<td>20%</td>
<td>2. 125 Gy using $^{103}$Pd</td>
</tr>
<tr>
<td>20%</td>
<td>3. 115 Gy using $^{131}$Cs</td>
</tr>
<tr>
<td>20%</td>
<td>4. 2 implants, typically one or two weeks apart, of 6 to 9.5 Gy in 2 or 3 fractions</td>
</tr>
<tr>
<td>20%</td>
<td>5. 110 Gy using $^{169}$Ytterbium</td>
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3. 115 Gy using $^{131}$Cs
4. 2 implants, typically one or two weeks apart, of 6 to 9.5 Gy in 2 or 3 fractions
5. 110 Gy using $^{169}$Ytterbium
Prostate Brachytherapy question:

References
- HDR Brachytherapy for Prostate. Zoubir Ouhbib. Brachytherapy Physics, 2nd Ed, Joint AAPM/ABS Summer School, chapter 32
- Modern Advances in Prostate Brachytherapy, Eugene Lief. Brachytherapy Physics, 2nd Ed, Joint AAPM/ABS Summer School, chapter 3

Radiation Safety and release criteria
- Release criteria are based on exposure to the general public
- Where to measure @ 1 meter?
- What meter are you using?

Release Dose Calculation

NUREG-1556 vol 9 (2005) supersedes reg guide 8.35
You can release based on activity or dose rate (appendix U)

for I-125 it is 1 mrem/hr @ 1 meter

The maximum release dose rate for Cs 131 is not tabulated in NUREG – 1556
The maximum release dose rate can be calculated from the formalism in stated in NUREG – 1556
When calculated it is 6 mrem/hr

Resources
- NUREG-1556 vol 9 (2005)
Electronic Brachytherapy

- Brachytherapy using an x-ray generator instead of a radioactive source.
- At the moment, all of the units operate between 30 and 50 kVp.
- Why do users want this?
  - More control?
  - Less regulation?

Available Units

Currently, there are two devices on the market:

- The INTRABEAM, from Carl Zeiss, a stationary beam model used mostly for intraoperative applications;
- The Axxent system, from Xoft, a stepping-source device, mostly to replace conventional HDR units.

Carl Zeiss IntraBeam

- A balanced, mobile stand to allow for six degrees of freedom using electromagnetic clutches and breaking systems to ensure safe and accurate delivery of the probe to the target.
- The INTRABEAM may be rolled into any O.R. suite and no special room shielding is required.
Internal Radiation Monitor (IRM) affects radiation emitted back along the beam and is the primary monitor of patient dose delivery.

**X-ray Tube, Cathode Gun & Accelerator Section – 50 kV max**

Beam deflectors process electron beam around central axis of probe tip creating a spherical pattern.

Electron beam strikes gold target generating x-rays at probe tip.

The INTRABEAM X Ray Source

Soft x-rays produced inside tumor or tumor cavity.

**INTRABEAM Applicators**

Spherical Applicator Set Ranges from 1.5 to 5.0 cm diameters are available.

**Patient Shielding**

Sterile Shields and Drapes

- Radiation shields are devices to protect tissue from unintended radiation exposure.
- Shields are designed to be used with the spherical applicators.
- They are provided as sterile, single use items.
- Shielding material is also available as flat stock.

**Shielding:**

93% attenuation at 1 cm depth, 3 cm applicator.

**INTRABEAM Dose Distribution**

- Low energy high dose rate.
- High dose at center, steep fall-off approximately 1/r^3.
- For intracavity or surface applications, applicators may be used.
Xoft Axxent System

- Miniature X-ray source inserted into a flexible, cooling catheter
- High vacuum x-ray tube
- 50 kV operating potential
- Output: ~1 Gy/m @ 1 cm
- Water cooled
- Fully disposable device

Control Unit

Dose Distribution Pattern

Dose as a Function of Depth
Axxent® Balloon Applicator

Applicators for Breast, vagina and skin

Axxent® Vaginal Applicator Set

4 Vaginal Applicators – 20 mm, 25 mm, 30 mm, 35 mm
4 Source Channels
Reusable for 100 treatment fractions or 100 sterilization cycles

Applicator Selection

- Applicator development of 10mm, 20mm, 35mm, 50 mm
- Stainless Steel:
  - Easy to sterilize
  - Applicator Cone and Source Channel (shown with V-Groove SC)
  - Flattening Filter integrated in Cone
  - Single use cover for applicator cone

Comparisons with Sources for Breast Brachytherapy

- Electronic Brachytherapy dose is higher near the source but lower far.
- The lower energy gives some sparing of skin and pectoralis, but does not give quite as much dose beyond the prescription.
- Room shielding is not required.
- Inhomogeneities will produce a greater effect.
**Electronic Brachytherapy Dosimetry Reference**

Relative Biological Effectiveness is a function of beam energy.
- Usually relative to 200 or 250 kVp or 60Co
- For 125Ir and 103Pd, values run about 1.6 to 2.5
- RBE is a function of dose and depth: maybe running from 1.38 near the source to 1.24 2 cm away.

Electronic Brachytherapy RBE Question: Given that breast brachytherapy treatments using 192Ir use fractions of 3.4 Gy, treatments using 50kVp x rays might use which dose per fraction?
- 20% 1. 1.3 Gy, using an RBE of 3
- 20% 2. 2.8 Gy, using an RBE of 1.2
- 20% 3. 3.5 Gy, since the doses or the two are equally effective
- 20% 4. 4.1 Gy, using an RBE of 1.2
- 20% 5. 10.2 Gy, using an RBE of 3

More RBE Variables
- RBE depends on the end-point.
  - Cancer cell response, normal tissue damage, \(\alpha/\beta\)
  - Generally, RBE increases with \(\alpha/\beta\)
  - Not a lot of real information on this
- RBE depends on dose/fraction (Fowler, Dale and Rusch):
  - RBR from 1.78 for 1 Gy to 1.13 for 20 Gy, \(\alpha/\beta = 3\)
- RBE depends on dose rate (Fowler, Dale and Rusch):
  - RBR from 1.79 for 2.5 Gy/h to 1.16 for 50 Gy/h, \(\alpha/\beta = 3\)

Electronic Brachytherapy RBE Question: Given that breast brachytherapy treatments using 192Ir use fractions of 3.4 Gy, treatments using 50kVp x rays might use which dose per fraction?
1. 1.3 Gy, using an RBE of 3
2. 2.8 Gy, using an RBE of 1.2
3. 3.5 Gy, since the doses or the two are equally effective
4. 4.1 Gy, using an RBE of 1.2
5. 10.2 Gy, using an RBE of 3
References on RBE


Learning Objectives

- Review the current treatment options for breast brachytherapy
  - Balloon & hybrid devices (MammoSite, Contura, Savi)
  - Interstitial HDR
  - Accuboot
- Review the advantages and disadvantages of the current treatment options

Breast Brachytherapy Treatment

Planning question:

Using a comparison between partial breast irradiation techniques utilizing CT based 3D dose volume analysis, PTV coverage is superior with which technique:

- 20% 1. a balloon device, such as mammosite
- 20% 2. interstitial HDR
- 20% 3. 3D conformal radiation therapy
- 20% 4. there is no difference between techniques
- 20% 5. the balloon & interstitial HDR showed superiority over 3D conformal radiation therapy
Breast Brachytherapy Treatment planning question:

Using a comparison between partial breast irradiation techniques utilizing CT based 3D dose volume analysis, PTV coverage is superior with which technique:

1. a balloon device, such as mammosite
2. interstitial HDR
3. 3D conformal radiation therapy
4. there is no difference between techniques
5. the balloon & interstitial HDR showed superiority over 3D conformal radiation therapy

Reference

Hospital have published a study comparing dosimetric data from 18 patients treated with interstitial catheter-based brachytherapy, 10 patients treated with IORT brachytherapy, and 10 patients treated with external-beam IORT. The IORT patients and the IORT group seemed to have comparable coverage at 95% of the prescribed dose, but the IORT technique treated more of the breast tissue and delivered more dose from IORT. Although a valuable contribution, the report does not compare dosimetry in identical patient data sets. The patients representing the different treatment subgroups were different, and no doubt had different relevant anatomy. This could make a direct comparison of treatment techniques misleading. A true comparison would compare techniques in the same patient data set.
MammoSite

http://radonc.usc.edu/USCRadOnc/Downloadable/PalmOS/MammoSite.html

Contura

Courtesy of Scott Dodd, ROS, Cobb

Contura

Courtesy of Keith Pope, Wellstar Kennestone Hospital, GA

Savi

Picture courtesy of Rebecca Kitchens, Aurora BayCare Medical Center, WI
Skin reaction due to minimal skin spacing

Treatment Planning: Balloon to Skin Spacing

Comparison of Techniques

Balloon brachytherapy (intra-cavitary)
- single entry point, requires less skill
- various sizes and shapes available (circular, elliptical)
- performed in the surgeon's office, patient convenience
- many patients treated
- simpler dosimetry (easier? Because of library or template plans)

Interstitial brachytherapy
- technically more challenging
- shape of cavity unimportant
- excellent dose conformation

What is AccuBoost?
- Novel technique for partial breast irradiation
  - non-invasive
  - immobilization
  - image guidance
- Utilizes HDR (high dose rate) source
- Clinical applications
  - tumor bed boost
  - APBI being explored

Challenge of AccuBoost Dosimetry
- Composite DVH
  - TPS cannot model applicator collimation
  - tissue deformation

Slide courtesy of Shirin Sioshansi, M.D.
Some New Brachytherapy Applications

Intraoperative lung

- Intended to reduce recurrences
- Permanent implants of $^{125}$I sources (or possibly the like) in suture, sewn into mesh

Resources


STReTCH
Dose is 100 Gy at 5 mm from the mesh.

Sort of.

A problem is that the implant geometry may be perfect at the time of placement.

But then the surgeon closes the patient...

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**Intraoperative Interstitial Lung Brachytherapy Question: Which is true?**

1. The dose delivered is 100 Gy to the center of the plane 0.5 cm from the sources.
2. The dose follows the Manchester system.
3. Because the treatment is intraoperative in an open patient, it is more like an intracavitary treatment than interstitial.
4. Because the implant is permanent, the 100 Gy dose is equivalent to and actual 100 Gy of external beam.
5. The homogeneity of the dose distribution will likely be lower than most common interstitial treatments.
Intraoperative Interstitial Lung Brachytherapy - Reference


Some New Brachytherapy Applications

Macular Degeneration

- Concept: radiation inhibits the proliferation of blood vessels.
- Seems to work better than the anti-VEGF that is the current standard.
- Dose used in current protocol is 24 Gy to the foveola, 2.5 mm from the source.
- Toxicity not seen in animals until 123 Gy

Some New Brachytherapy Applications

Macular Degeneration

- The treatment uses 90Sr in a hand-held device.
- The treatment is delivered by a retinal surgeon, who holds it in place.
- The procedure is performed in the OR, with ports placed in the eye ball: 1 for the source and 1 for viewing.

Device Placement
Epipen Dose distribution

Errors & Reporting

Learning Objectives
Errors & Reporting

- Review the concept of Medical Event
- Review the steps to analyze a treatment variance utilizing a Root Cause Analysis

You’ve discovered a deviation now what?

- Do you know where the policy or procedure that covers this lives?
- Is this a medical event? *This is tricky*
- What is your chain of command?
  - Inform the attending physician & RSO
  - Inform the Medical Director
  - Hospital Management/Risk Management
  - Referring physician
  - Patient/Patient’s family
- Possibly the responsible regulatory agency (the State or the NRC)
Is it a "Medical" Event?


For all medical uses of NRC-licensed radioactive materials, a "medical event" occurs if **BOTH** of the following criteria are met:

1. One or more of the following representative incidents occur:
   - The dose administered differs from the prescribed dose by at least 20 (too high or too low)
   - The wrong radioactive drug is administered
   - The radioactive drug is administered by the wrong route
   - The dose is administered to the wrong individual
   - The patient receives a dose to a part of the body other than the intended treatment site that exceeds by 50 percent or more the dose expected by proper administration of the prescription
   - A sealed source used in the treatment leaks;

2. The difference between the dose administered and the prescribed dose exceeds one of the reporting limits contained in the NRC's regulations at 10 CFR 35.3045, which correspond to the annual occupational dose limits at 10 CFR 20.1201.

What is the "AND" part?

AND

A "Medical Event" does not necessarily result in harm to the patient.

The NRC requires a report of medical event because it indicates:
- Potential technical or QA problems
- A dose error > 20 percent may indicate treatment delivery problems

There is no scientific basis to conclude that such an error necessarily results in harm to the patient.
Is it a “Medical Event”?

The NRC has very clear guidelines on how to report a medical event. See: http://www.nrc.gov/reading-rm/doc-collections/part035/part035-3045.html

Ohio Department of Health (ODH) Bureau of Radiation Protection (BRP) was notified of a medical event that occurred at <<CENTER NAME & ADDRESS>>, Ohio license # XXXX at 12:30 PM on 5/12/2009. The patient received a permanent implant of 64 1-25 seeds on 5/11-12. The total activity implanted was 28.422 mCi (.444 mCi/seed). The prescribed dose to the prostate was 144.0 Gy. The post-plan CT was evaluated on 5/12-12 and determined that the prostate volume receiving the prescribed dose was 47% (i.e. V100%=47%) resulting in a 53% underdose of the prescribed dose. The patient and physician have been notified. ODH BRP will continue to evaluate this event. The licensee has initiated an internal evaluation.

A Medical Event may indicate potential problems in a medical facility’s use of radioactive materials. It does not necessarily result in harm to the patient.

Errors & Reporting question:

Under NRC 10 part 35 all of the following are medical events for the administration of brachytherapy if they occur AND the difference between the dose administered and the prescribed dose exceeds one of the reporting limits contained in the NRC’s regulations at 10 CFR 35.3045, which correspond to the annual occupational dose limits at 10 CFR 20.1201 EXCEPT??

1. Any radiation delivered involving the wrong patient
2. Any radiation delivered involving the wrong treatment site
3. Any radiation delivered involving the wrong radioisotope
4. The calculated dose differs from the prescribed dose by more than 10%
5. One or more temporary implants not removed upon completion of the procedure
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Reference
NRC 10CFR35 subpart M

Point/Counter Point: The Current NRC Definitions of Therapy Misadministration are Vague, do not Reflect the Norms of Clinical Practice, and Should be Rewritten.
Howard Amols, Jeffrey Williamson. Medical Physics, vol 31 issue 4 pp 691-694 April 2004

Root Cause Analysis (RCA)

What is an RCA?
RCA is a retrospective approach to error analysis
- Provides a process focused framework for analysis
- Attempts to identify contributing factors and all causes
- RCA has its foundations in industrial psychology and human factors engineering
- In 1997, the joint commission mandated the use of RCA in the investigation of sentinel events in accredited hospitals

When two planes nearly collide, they call it a “near miss”. It’s a NEAR HIT.
A collision is a “near miss”.
BOOM! “Look, they nearly missed!”
George Carlin, The Absurd Way We use Language
www.georgecarlin.com
**Root Cause Analysis (RCA)**

An RCA is designed to answer 3 basic questions:
1. What happened?
2. Why did it happen?
3. What can be done to prevent it from happening again?

**What happened?**
- This is the INVESTIGATION phase, a factual representation of the incident.
- Structured interviews, document review and/or observation to create a timeline of events.
- Ignore (for now) what should have happened.
- If critical evidence is not available or was destroyed in the process, consider using secondary sources BUT use plausible scenarios; test the theory to confirm or deny the explanation.

**Why did it happen?**
- This is the ANALYSIS phase.
- Analyze what happened and also the system that allowed it to happen.
- Was the process correct but inadequately followed? Was the process flawed? Did the process create or contribute to the event?
- Do not be lured into finding ways to fix what happened at this point.
- The final result should be a finite set of causes for the event that explain why it was inevitable.

**Why did it happen?**
- There are categories of factors that can influence clinical practice:
  - Institutional or Regulatory Factors
  - Corporate Culture or Communication Barriers
  - Organizational or Management Factors
  - Is the information needed available?
  - Work Environment
    - Environmental Factors (physical environment), Equipment Performance
  - Human Factors (Staff Factors, Team Factors or Patient Characteristics)
    - Staff qualifications/competencies, staff training, staffing levels
Root Cause Analysis (RCA)

- What can be done to prevent it from happening again?
  - This is the DECISION phase
  - Develop recommendations that identify what should be learned and what needs to be done
  - Beware of being overly complicated
  - There may be several competing options: evaluate based on a structured decision analysis for simplicity, effectiveness, longevity, cost, etc.
  - Consider the consequences for each recommendation
  - Have you induced new latent conditions or weaknesses to the system?

Beware of being overly complicated: There may be several competing options.

Garbage in = Garbage out
"Insanity: doing the same thing over and over again and expecting different results" attributed to Einstein

RCA resources

http://www.billwilson.net/b34.html
http://www.jointcommission.org/SentinelEvents
http://www.ahrq.gov/clinic/ptsafety/chap5.htm

Effectiveness and Efficiency of Root Cause Analysis in Medicine, Wu et al, JAMA vol.299 No.6, February 13, 2008
NRC regulations on medical uses of radioactive material, Title 10 Code of Federal Regulations Part 35
Reporting requirements for medical events, 10 CFR 35.3045
NRC's annual dose limits, 10 CFR 20.1201

Some Brachytherapy QA Issues
Some Brachytherapy QA Issues

Purchasing implant needles with the sources already loaded is convenient and time saving.

Autoradiography can show the presence of sources and the correct loading pattern.

The problem is how to check the source strength.

Assay of Sources Loaded in Needles in Sterilized Packages

The facility radiotherapy physicist still maintains the responsibility to assure that the source strengths are correct, regardless of whether the vendor calibrates sources.

For Sterile source assemblies,
- At least 10% of the assemblies by sterile insert in a well-chamber or by “quantitative image analysis” or
- Order and assay 5% or 5 (whichever is fewer) additional loose sources (check if from same batch.)

Quantitative Film Analysis

You just cannot take the film darkening to be directly proportional to source strength because:
- The distance from the sources to the receptor is not uniform due to cheap packaging;
- Each dark spot received contributions from many sources.

Assay of Sources Loaded in Needles in Sterilized Packages

The AAPM Low-energy Brachytherapy Source Calibration Working Group recommendations

For stranded source assemblies,
- At least 10% of the strands or 2 (whichever is larger) by sterile insert in a well-chamber, or
- Order and assay 5% or 5 (whichever is fewer) additional loose sources (check if from same batch.)
Assay of Sources Loaded in Needles in Sterilized Packages

The AAPM Low-energy Brachytherapy Source Calibration Working Group recommendations

**Actions to take**

- $\Delta S \leq 3\%$, enjoy!
- $3\% < \Delta S \leq 5\%$, investigate discrepancy or increase sample size.
- $\Delta S > 5\%$, contact manufacturer; if in OR, discuss with RO whether to use the average (vendor and measured) or measured.

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Assay of Sources Loaded in Needles in Sterilized Packages Question: Which is true?

1. The vendors assume the responsibility for the source strength used for patients.
2. The facility physicist is to measure at least 10% of the assemblies or loose sources or 5% additional sources.
3. If the measured source strength differs from the vendor's specified source strength by $>5\%$, use the vendor's value.
4. The source strength is easily measured using the autoradiograph.
5. Agreement within 5% is very rare.

Assay of Sources Loaded in Needles in Sterilized Packages: Reference