Brachytherapy

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Brachytherapy

- Method of treatment using sealed radioactive sources to deliver radiation at a short distance by:
  - Interstitial
  - Intracavitary
  - Surface application
- Prefix *brachy* comes from the Greek for "short-range"
  The term, brachytherapy, 1st coined by Forsell in 1931, refers to the treatment of cancer by placing sources very close to, or within, the tumor or target.

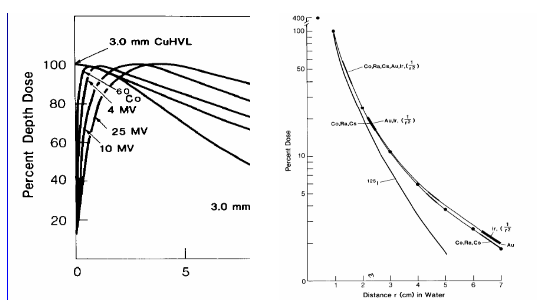
EBRT vs. Brachytherapy

- EBRT
  - 30 fractions
  - 6 week treatment
  - Major facility construction
  - Massive equipment
  - Major power consumption
  - Risk of downtime electromechanical malfunctions
- Brachytherapy
  - 1-5 Fractions
  - 1-5 days of treatment
  - Typical one-day surgery suite
  - Small equipment
  - No power needed for radioactive decay
  - No downtime for radioactivity

EBRT vs. Brachytherapy

- EBRT
  - Uniform dose within a target
  - Sensitive to errors due to internal and external patient motions
  - Sensitive to errors in daily patient repositioning errors
- Brachytherapy
  - High dose gradients near sources
  - Insensitive to errors due to internal and external patient motions
  - Less sensitive to errors due to seed placements in a single procedure

EBRT vs. Brachytherapy



Radioactive Sources

- **Radium** $$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He}(\alpha) + \gamma$$
  - Half life: 1620 years
  - Gamma producer: 0.184-2.45 MeV with average around 0.83 MeV when filtered by platinum
  - Specified by: active length, physical length, activity or strength, filtration
  - Exposure rate constant: numerically equal to exposure rate in R/h at a point 1 cm from a 1mCi point source (mg Ra for radium)
  - 8.26 $\mathrm{Rcm^2\,h^{-1}\,mg^{-1}}$ for 0.5 mm platinum filtered radium
  - Radon leakage is significant hazard with radium sources

Radioactive Sources

- **Radium**
  - Part of a radioactive series starting with U-238 and ending with Pb-210
  - Naturally occurring radioisotope
  - Decays with alpha emission to Rn-222 along with gamma emissions
  - Alpha absorbed by encapsulation
  - Comes in tubes and needles
  - Extensively used for uterine cervical cases
  - Manchester system developed with this source
  - Temporary implants (intracavitary & intersitial)

Ra^{226}

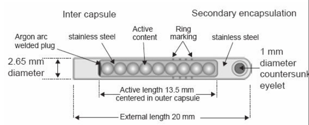
- Most brachytherapy procedures were developed using Ra^{226}
  - Ra^{226} was the first radioisotope to be isolated and identified
  - Most of the isotopes have their dosimetry based on the original work done with Ra^{226} and are referred to as Ra^{226} substitutes
  - Radium has a high specific activity which made it very practical to use

Radium Sources

- A typical radium source consists of:
  - Radium salts placed inside .1-.2 mm thick gold foil cells *
    - about 1 cm long and 1 mm in diameter
  - Cells are sealed to prevent radon gas leakage
  - The sealed cells are in a sealed metal (platinum) sheath
  - One radium source contains
    - 1 to 3 cells depending on the source length
  - Variety of lengths and activities
  - Radium sources are available in needle or tube form
  - Filtration (shell thickness) provided by the metal casing (.5 mm platinum) is sufficient to absorb the low energy gamma rays and alpha particles produced in the decay process

Radioactive Sources

- **Cesium-137**
  - Fission product from U-238
  - Half life: 30.2 years
  - Gamma emitter: 0.662 MeV
  - HVL = 5.5 mm Pb
  - Γ =3.26 Rcm^2 h^{-1} mCi^{-1}



Radioactive Sources

- **Cesium-137**
  - Stainless steel encapsulation
  - Available in tubes, needles and with remote afterloaders
  - Used for temporary implants (intracavitary)
  - Decays by Beta Minus to Ba-137

$$^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\mathrm{e} + \gamma$$

Radioactive Sources

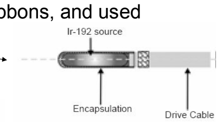
- **Cobalt-60**
  - Produced by neutron activation (neutron bombardment) of Co-59
  - Half life: 5.26 years
  - Decays by beta minus to Ni-60

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}\mathrm{e} + \gamma$$

  - Gamma emitter: 1.17, 1.33 MeV
    - 1.25 MeV average energy
  - 13.07 Rcm^2 h^{-1} mCi^{-1}
  - 11 mm Pb HVL
  - Temporary implants

Radioactive Sources

- **Iridium-192**
  - Produced by neutron activation (bombardment) of Ir-191 $^{192}_{77}\mathrm{Ir} \rightarrow {}^{192}_{78}\mathrm{Pt} + {}^{0}_{-1}\mathrm{e} + \gamma$
  - Half life: 73.83 days
  - Gamma emitter: 0.38 MeV
  - 4.69 R cm^2 h^{-1} mCi^{-1}
  - 2.5 mm Pb HVL
  - Usually in the form of wires, ribbons, and used remote afterloading devices
  - Temporary implants
    - Interstitial & Intracavitary



Radioactive Sources

- **Iodine-125**
  - Produce by neutron activation of Xe-124
    $^{124}_{54}\mathrm{Xe}\ (n,\gamma)\ {}^{125}_{54}\mathrm{Xe} \rightarrow {}^{125}_{53}\mathrm{I} + {}^{0}_{-1}\mathrm{e}$
  - Half life: 59.4 days
  - Low photon energy: 0.028 MeV
  - Low energy gamma emitter with HVL = 0.025 mm
  - Decays by electron capture to Te-125
    $^{125}_{53}\mathrm{I} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{125}_{52}\mathrm{Te} + \gamma$
  - Primarily used for prostate seed implants
  - Higher activity seeds also used for temporary implants (eye plaque brachytherapy)

Radioactive Sources

- **Palladium-103**
  - Produced by neutron activation (bombardment) of Pd-102
  - Half life: 17 days
  - HVL = 0.008 mm Pb
  - Higher dose rate (shorter half-life than I-125)
  - Gamma emitter: 20.9 keV average energy
  - Decays by electron capture to Rh-103
    $$^{103}_{46}\mathrm{Pd} + {}^{0}_{-1}\mathrm{e} \rightarrow {}^{103}_{45}\mathrm{Rh}$$

Radioactive Sources

- **Gold-198**
  - Produced by neutron activation (bombardment) of Au-197
  - Half life:2.7 days
  - 2.5 mm Pb HVL
  - Used for interstitial implants (permanent implants)
  - Gamma emitter: 0.412 MeV (nearly monoenergetic)
  - Comes in the form of grains
  - Used for permanent implants in Head & Neck cases
  - Decays by Beta Minus to Hg-198

$$^{198}_{79}\mathrm{Au} \rightarrow {}^{198}_{80}\mathrm{Hg} + {}^{0}_{-1}\mathrm{e} + \gamma$$

Radioactive Sources

- **Cesium-131**
  - Half life: 9.7 days
  - Used for interstitial implants (permanent implants)
  - Gamma emitter: 30 keV average energy
  - Decays by electron capture to Xe-131 followed by characteristic x-ray emission

Radioactive Sources

- **Strontium 90 (beta emitting radionuclide)**
  - Fission Product
  - Sr-90 decays to Y-90 via beta minus $^{90}_{38}\mathrm{Sr} \rightarrow {}^{90}_{39}\mathrm{Y} + {}^{0}_{-1}\mathrm{e}$
    - 240 keV Beta minus is too low for therapy
  - Unstable daughter product decays via <u>beta</u> minus with an energy of <u>2.27 MeV</u> $^{90}_{38}\mathrm{Y} \rightarrow {}^{90}_{40}\mathrm{Zr} + {}^{0}_{-1}\mathrm{e}$
  - T ½ (Sr-90) =28.5 yrs
  - T ½ (Y-90) = 64.2 hrs
  - Secular Decay
  - Used in IVB
  - Used as eye applicator for Pterygium
    - Delivers 20-80 cGy/sec on surface
    - 55 mCi

Radioactive Sources

Phosphorus-32

- Pure beta emitter
- 14 day half-life
- Beta decays to S-32 with a maximum energy of 1.7 MeV
- Often used as a liquid in a balloon
- Used as wire in an intravascular brachytherapy delivery system
- Even more limited depth of penetration compared to Sr-90

Radioactive Sources

Californium-252

- Neutron-emitting radionuclide
- Half-life: 2.65 years
- Decays by: Alpha decay (97%); Fission (3%)
- Fission neutrons
  - Average neutron energy 2.15 MeV
- Average photon energy 0.8 MeV
- Pt-Ir encapsulation
- Small tube sources available
- Limited use only
- Temporary intracavitary brachytherapy
- Difficult to shield the OR
- Risk of neutron-induced carcinogenesis

Brachy Sources (Khan)

Physical Characteristics of Radionuclides Used in Brachytherapy

Radionuclide	Half-Life	Photon Energy (MeV)	Half-Value Layer (mm lead)	Exposure Rate Constant ($Rcm^2/mCi\text{-}h$)
^{226}Ra	1600 years	0.047–2.45 (0.83 avg)	8.0	8.25*† ($Rcm^2/mg\text{-}h$)
^{222}Rn	3.83 days	0.047–2.45 (0.83 avg)	8.0	10.15*‡
^{60}Co	5.26 years	1.17, 1.33	11.0	13.07‡
^{137}Cs	30.0 years	0.662	5.5	3.26‡
^{192}Ir	73.83 days	0.136–1.06 (0.38 avg)	2.5	4.69‡
^{198}Au	2.7 days	0.412	2.5	2.38‡
^{125}I	60.2 days	0.028 avg	0.025	1.46‡
^{103}Pd	17.0 days	0.021 avg	0.008	1.48‡

Brachytherapy Advantages

(Rationale for use):

- Radioactive material inserted into the "heart of the tumor" allows for highly localized dose to a small tumor volume yielding high local control which is well tolerated.
- Sharp fall-off of dose in surrounding normal tissue generally follows $1/r^2$ law.
- Prescribed dose is usually minimum peripheral dose (in good implant!), most of tumor receives substantially higher dose

Brachytherapy Advantages

- Several purported **radiobiological** advantages for continuous LDR irradiation including
- **Redistribution** effect (cells in less radio-sensitive S-phase move to more sensitive M-phase providing biological advantage)
- **Reoxygenation** effect (of hypoxic tumor cells with hence become more radiosensitive)

Disadvantages

- Hazard of radiation exposure to family, friends, and strangers (manageable with current use of low energy sources and afterloading techniques)
- Hospitalization increases inconvenience and cost (again, now can be minimized with remote afterloaders)
- Special skill and training required
- Sharp fall off makes it less forgiving to imperfection (severe underdosing can occur in poor implant)
- Implantation is typically surgical in nature, and although generally image guided and minimally invasive using current technology, risk from trauma still exists

Surgical Approach

1. Intracavitary - inserting sealed radioactive source into patient's natural body cavity.
   - *Ex: cervix (tandem & ovoid), vagina (cylinder), bronchus, bile duct (temp)*
2. Interstitial - inserting sources directly into tissue.
   - *Ex: prostate, breast, tongue (temp/perm)*
3. Intravascular - inserting sources into arteries or veins.
   - Ex: coronary artery (temp)
4. Surface - molds or plaques containing sources are applied.
   - *Ex: eye (temp)*

Dose Delivery Control & Source Loading

Dose delivery control:
a) Temporary - 1 to 7 days.
   Ex: cervix, vagina, esophagus
b) Permanent – forever.
   Ex: prostate

Source loading technology:
a) Preloaded
b) Manually afterloaded
c) Remotely afterloaded

Dose Rate

(all ICRU Report #38 except ultra-low, but important since PPB)

Dose Rate Zone	Range (cGy/hr)	Range (cGy/min)	Clinical Examples
Ultra-low	1-30	0.02–0.5	I, Pd perm prostate brachy
Low	40–200	0.67 – 3.33	Cs temp GYN tandem & ovoid or cylinder
Medium	200–1200	3.33 – 20.0	
High	> 1200	> 20.0	Ir temp HDR remote afterload GYN cylinder implant; IVB, prost boosts

LDR vs. HDR

- Low Dose Rate Brachy Therapy (LDR)
  - 0.3 mCi to 100 mCi/seed
- High Dose Rate Brachy Therapy(HDR)
  - 1 to 10 Ci/seed

HDR vs. LDR

Advantages

- Optimization of dose distribution
- Outpatient treatments
- Elimination of staff radiation exposure

Disadvantages

- Uncertainty in biological effectiveness
- Potential for accidental high exposures and serious errors
- Increased staff commitment

HDR vs. LDR

- LDR is the traditional treatment method.
  - Tremendous amount of clinical history.
  - Increased radiation exposure to staff.
  - Limited care during implant.
- HDR gaining clinical acceptance.
  - Much easier to optimize dose distribution.
  - Used widely in Europe.
  - Large fraction size.
  - Multiple insertions.
  - Scheduling problems; both physician & patient.

Radioactive decay

- The key relationship in understanding radioactivity is
  - N= number of atoms
  - t= the time

$$\frac{\Delta N}{\Delta t} \propto N$$

- The change in the number of atoms per change in the time is **proportional** to the number of atoms present

Activity Equation

- $A = A_o e^{-\lambda t}$
- This formula is commonly used to calculate activity of a radioisotope after some length of time has passed

Half Life

- The half-life is the amount of time it takes for the activity to decay to one half its original value
- Half-life is related to the decay constant by this formula:

$$T_{1/2} = \frac{.693}{\lambda}$$

- The relationship between the half-life and activity is inversely proportional
- As half-life increases the activity decreases

Activity and Half-Life

- Depending on what info you have will dictate which formula you use:

$$A_x = A_o e^{-\lambda t}$$

or if you do not know the decay constant:

$$A_x = A_o e^{-\left(\frac{.693}{T_{1/2}}\right)t}$$

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Half-life

Determine the activity of a Cs-137 source with an initial activity of 10mgRa eq measured 15 years ago.

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Mean Life (Average Life)

$$T_{avg} = T_{½} / \ln 2$$
$$= 1.44\ T_{½}$$
$$= 1/\lambda$$

What is the average life of a permanent seed implant using I-125? Pd-103?

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Activity and Dose Rate

$A = A_O \exp(-\lambda t) = A_O \exp(-\ln 2 * t / T_{½})$

$D = D_O \exp(-\lambda t) = D_O \exp(-\ln 2 * t / T_{½})$

Calculate Dose

- For **shorter treatment times** (< 4 days for ^{192}Ir and < 3 days for $^{I-125}$), the approximate expression below is accurate to within 2% and may be used:
  Dose(T) = DoseRate x Txt Time
- For **permanent implants**, the total dose administered to the patient D_{total} resulting from complete decay of the implant can be obtained
  Dose(T) = DR x T_{avg} = DR x 1.44 x Txt Time

Radioactive Equilibrium

- Transient Equilibrium
  - Half-life of the Parent is **not much longer** than that of the Daughter
- Secular Equilibrium
  - Half-life of the Parent is **MUCH longer** than that of the Daughter

Secular or Transient Equilibrium?

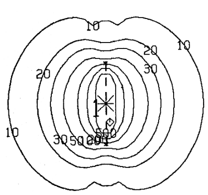
- Half-life of Radium (parent) is 1622 years
- Half-life of Radon (daughter) is 3.83 days

Source Construction

- Encapsulation of radioactive sources constructed with metal walls
  - Platinum-iridium, gold, stainless steel
- Walls filter out alpha, most beta particles, and low energy gamma rays.

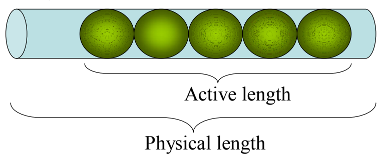
Anisotropy

- Relative symmetry of the dose distribution around a source
- Isotropic source is a perfect point source or sphere that emits the same dose at the same distance in all directions
- Anisotropy results when the source construction causes a non-uniform dose distribution
  - Length
  - Unequal encapsulation
  - Off-center radioactive material



Active Length

- Active length: Length of the source over which the radioactive material is distributed
- Physical length: Entire length of the source, including encapsulation.



Linear sources

- Dose distribution determined by summing contributions from small lengths where the attenuation and absorption of the source, the wall, and tissue have been taken into account
- Cs-137 tubes replaced radium tubes for gynecological LDR implants
- Dose distribution is almost identical
- Tables of dose in tissue at various distances from a Cs-137 have been published and used to calculate dose.

Along and Away Tables

V. KRISHINASWAMY

TABLE II: GAMMA DEPTH DOSE IN RADS PER HOUR FOR A MG RA-EQIVALENT ^{137}CS SOURCE.
(Active length 1.0 cm; wall thickness 1.0 mm stainless steel)

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	24.398	7.254	3.349	1.903	1.220	0.845	0.618	0.471	0.370	0.298
0.5	17.494	6.155	3.058	1.800	1.175	0.823	0.606	0.463	0.365	0.294
1.0	7.260	4.056	2.404	1.543	1.056	0.762	0.572	0.443	0.352	0.284
1.5	3.314	2.484	1.747	1.239	0.902	0.677	0.522	0.412	0.332	0.272
2.0	1.825	1.577	1.249	0.965	0.747	0.584	0.464	0.375	0.307	0.255
2.5	1.140	1.060	0.906	0.748	0.609	0.496	0.406	0.336	0.280	0.238
3.0	0.773	0.750	0.674	0.584	0.496	0.418	0.352	0.297	0.253	0.210
3.5	0.556	0.553	0.515	0.461	0.405	0.351	0.303	0.262	0.226	0.196
4.0	0.418	0.422	0.402	0.370	0.333	0.296	0.261	0.229	0.201	0.177
4.5	0.325	0.331	0.321	0.301	0.277	0.250	0.225	0.201	0.179	0.159
5.0	0.260	0.266	0.261	0.248	0.232	0.231	0.194	0.176	0.159	0.143

TABLE III: GAMMA DEPH DOSE IN RADS PER HOUR FOR A MG RA-EQUIVALENT ^{137}CS SOURCE
(Active length 1.4 cm; wall thickness 1.0 mm stainless steel)

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	0.616	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

Seeds

- Primarily used for interstitial implants
- I-125 & Pd-103 most common
  - Low energy radiation emission
  - Gives rise to anisotropy along the long axis of the seed due to self-absorption
  - Tissue attenuation correction for these sources due to tissue attenuation not compensated by scatter build-up in tissue
    - At short distances, does not follow inverse square law
- Considered as point sources

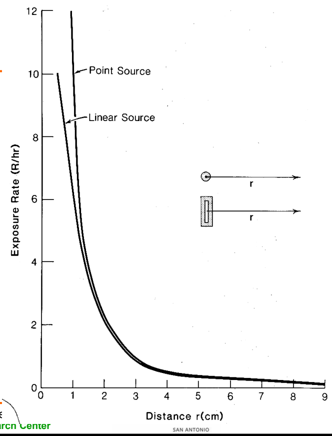
Specific Activity

- Activity per unit mass
- Ra 226 → 1 Ci/g

The higher the specific activity, the smaller the source can be

Factors which Influence the Dose Distribution

1. **Distance (inverse-square)**
   a. Assumes no attenuation and scattering of photons by surrounding medium.
   b. Will not accurately describe "collective dose fall-off" unless r_1 and r_2 >> active source
   c. The most dominant factor influencing dose distribution (dose decreases by 100 from 0.5 to 5.0 cm).



Factors Which Influence the Dose Distribution

2. Absorption and scatter <u>within</u> the active core and capsule

a) Responsible for **<u>dose anisotropy about source</u>**

b) Because brachytherapy sources are cylindrically symmetric, dose distribution will be **<u>equatorially isotropic</u>**

c) **<u>Encapsulation</u>** – prevents radioactive material from leaking out of the source and absorbs no penetrating radiation (beta, alpha, low energy photons) which would otherwise contribute nothing to the therapeutic effect. Generally, only photons (gamma's or characteristic x-rays, with energies > 15 keV contribute therapeutically significant doses over the 3-20 mm distance range relevant to brachytherapy).

Factors which Influence the Dose Distribution

3. Attenuation in the surrounding medium

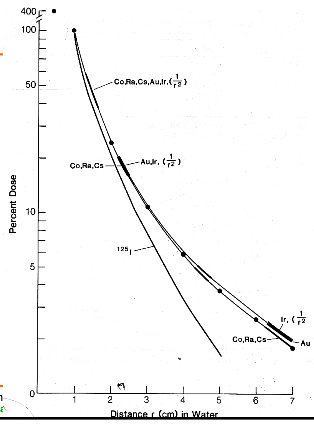
Attenuation & Scatter compete

4. Scatter in the surrounding medium

a) > 200 keV – PDD over 1-5 cm is not a f(E) or f(Z, fat vs. water) due to photon attenuation & scatter build up equilibrium.

b) 60 – 120 keV – the ideal range where dose distributions are still approximately radium equiv but very thin layers of lead provide significant shielding

b) **< 40 keV – PDD significantly deviates from inverse square**, PDD over 1-5 cm IS a f(E) and f(Z) because of increased photoelectric effect (absorption rather than Compton scatter) such that scatter build up is unable to compensate for loss of dose due to attenuation.



Dose Rate

- Near the source, the Dose rate follows 1/r
- As the distance increases, the dose rate follows $1/r^2$
- At a distance twice the source length, the source can be treated as a point source
- Ir-192 and Au-198 follow Inverse Square Law
- Co-60, Ra-226 and Cs-137 follow ISL but with some attenuation
- I-125 and Pd-103 deviate from ISL due to attenuation (low E → Photoelectric effect / no scatter)

Inverse Square

- Dose rate and exposure rate follows inverse square law.
- Inverse square law has the biggest affect on dose distribution

Brachytherapy Source Strength

- **Specification of Source Strength**
  1. Activity
  2. Exposure rate at specified distance
  3. Equivalent mass of radium
  4. Apparent activity
  5. Air kerma
- **Exposure Rate Calibration**
  - Open-air measurements
  - Well-type ion chambers

Exposure Rate Constant $(\Gamma_\delta)_x$

- Activity of radionuclide emitting photons & the exposure rate in free space, $X_0(r)$ at distance r (in cm) due to photons of E are related by the fundamental quantity, the exposure rate constant, Γ_δ

$$(\Gamma_\delta)_x = \frac{X_0(r)\, r^2}{A}$$

  - **Units: R cm^2 mCi^{-1} hr^{-1}**
  - **Equal to exposure rate in R/hr at 1 cm from 1 mCi source**

Problems

- Determine the exposure rate from a 10 mCi Ir-192 source 1 meter away.
  - XR = A(mCi) Γ(R cm^2/mCi/hr) / r^2 (cm^2)
- Determine the dose rate in air
  - DR = XR * f_{air}
- Determine the dose if a person stood at that location (1m away) for 30 min.
  - Dose = DR * t

  Is that person in within the allowed dose limit?

Activity

- Specified in mCi
- Activity is proportional to product of exposure rate and inversely proportional to exposure rate constant

Activity

- Rate of nuclear disintegration or transformation in the point source
  - Each transformation releases radiation
- Transformations give rise to g-rays, annihilation photons, characteristic x-rays, Bremsstrahlung photons
- Other products of decay (a, b, neutrinos, have low probability of transferring energy to matter)
- Current (SI) unit: 1 Becquerel = 1 Bq = 1 dps
- Traditional unit: 1 Curie = 1 Ci = 3.7×10^{10} Bq

Examples

- Need to order 300 mCi of I-125 in terms of Becquerels.
- Measured 388×10^{9} disintegrations per second for a new Ir-192 source. What is activity in GBq and Ci?

Equivalent Mass of Radium

- Historically used
- Should be used only to provide output comparison with radium sources
- One effective equivalent mass of radium, mgRaeq, of a radium substitute yields an exposure rate, at 1 m, of 0.825 mR/h.
- This unit appears to be a unit of mass, it actually is a specification of the exposure rate at a distance.
- 1 mgRaeq = 8.25 R/h at 1 cm
- 10 mgRaeq = 82.5 R/h at 1 cm

mgRaeq to mCi

$$\text{mg Ra eq}*(\Gamma_\delta)_{Ra\ 0.5}\ (\text{Rcm}^2/\text{mg-hr}) = \text{mCi}*(\Gamma_\delta)_X\ (\text{Rcm}^2/\text{mCi-hr})$$

$$\text{mg Ra eq} * [(\Gamma_\delta)_{Ra\ 0.5} / (\Gamma_\delta)_X] = \text{mCi}$$

- How many mCi of Cs-137 from 10 mgRaeq?
  10 mgRaeq x [8.25/3.26] = 25.3 mCi
- What is the activity in mCi for 5 mgRaeq of Ir-192?
- Determine the mgRaeq for 50 mCi of Cs-137.

Apparent Activity (A_{app})

Source output relative to that of a hypothetical unfiltered point source

- Is the activity of a hypothetical unfiltered point source that has the same S_k as that of a given source
- Units typically used: mCi

Air Kerma Strength (S_k)

- Currently used in North America to specify brachy source strength as recommended by AAPM & ABS
- Defined as the product of air-kerma rate in free space on the source transverse axis $K_{air}(d)$, and the square of the measurement distance

$$(S_k) = K_{air}(d)\ d^2$$

  – Distant independent because d >> L so source = point
  – **Units: 1 cGy cm^2 hr^{-1}** = 1 mGy m^2 hr^{-1} = **1 U**
  – Exposure to Air kerma strength
  – S_k = XR(R/hr) f_{air} (0.876 cGy/hr) at 1 m

Air Kerma Strength

Source strength, S_k

1 U = 1 uGy m^2 /hr = 1 cGy cm^2 /hr

S_k from Activity (mCi)

S_k = A (mCi) $\Gamma_{Isotope}$ f_{air}

where f_{air} = 0.876 cGy/R

S_k from Activity (mgRaeq)

S_k = A (mg) Γ_{Ra} (8.25 Rcm^2/mg-hr) f_{air}

where f_{air} = 0.876 cGy/R

S_k = 7.227 * A(mgRaeq)

A_{app} to S_k

An $^{I-125}$ seed has A_{app} = 0.5 mCi. What is S_k?

A $^{Pd-103}$ seed has A_{app} = 1.78 mCi. What is S_k?

Air Kerma Strength

Questions:

What is the S_k of a Pd-103 source with an activity of 1.54 mC?

A $^{Cs\text{-}137}$ tube has a strength of 22 mgRaEq. What is S_k?

What is the activity of Ir-192 when the source strength given is 41084 U?

Calibration of Sources

- TG-56: -"Every institution practicing brachytherapy shall have a system for measuring source strength with secondary traceability for all source types used in its practice."
- Secondary traceability: -use an instrument that has been calibrated at an ADCL (or NIST) for that source type OR
- compare with a source of the same type that has been calibrated at an ADCL (or NIST)

Calibration

Open-air measurements

- place source large distance from detector and away from potential scattering surfaces
- detector should have large chamber volume to receive a large signal
- not suitable for routine calibration checks

Well-type ion chambers

- response is dependent on source position in well and length of source
- energy dependence from absorption and scattering of photons and secondary electrons in chamber walls and gas.
- High detection efficiency

Well chamber

- Measurements are best done with a well-type chamber
- Ideal for LDR and HDR sources
- Photon and Beta emissions
- Source holders for most existing source(s)→ individual or train/ribbon
- Calibration every two years at calibration lab for each source that will be measured

Acceptability of Long-lived sources

- If the measured source strength agrees with the manufacturer's specification to within 3%, then either may be used for dose calculations.
- Differences larger than 3% should be investigated
- Differences larger than 5% should be reported to the manufacturer.
- When sources are batched for dosimetry purposes, then the 3% tolerance applies to the mean of the batch, and the range of source strengths within the batch should not exceed 5%.

Leak Testing

- Long-lived sources need to be leak tested at intervals specified by the radioactive materials license, typically 6 months or 3 years, depending on the source type.
- Such sources should have certified leak tests before being shipped, and that documentation can show initial compliance.
- Users of sources such as Cs-137 tubes may decide to repeat the leak test locally during acceptance; certainly that should be done if there is any suggestion of damage.
- Properly leak testing sealed sources requires
  - sensitive instrumentation, such as a NaI well counter,
- United States, the Minimal Detectable Activity must be less than 0.005 μCi.

Short-lived Sources

For short-lived sources such as I-125 seeds, TG-56 recommends the following steps:

1. Document the physical/chemical form and encapsulation based on the manufacturer's specification in order to support dosimetry calculations.
2. Verify the uniformity of the activity distribution within each source, where applicable, or the distribution of seeds along an extended ribbon.
3. Calibrate the sources, either individually or as a batch.

Acceptability of short-lived sources

- For large batches of loose seeds, at least 10% of the total batch or at least 10 seeds.
- For large numbers of seeds in ribbons, a minimum of 10% of the seeds or two ribbons, whichever is larger.
- It is possible to obtain inserts for well chambers that allow ribbons to be coiled into reproducible positions, but it may be necessary to develop correction factors for ribbons of different lengths

Acceptability of short-lived sources

- Calibration should agree with that provided by the manufacturer within 3%
- The range of source strengths should not exceed 5%
- For sources purchased in a sterile assembly, TG-40 recommends, "purchasing and calibrating a single (non-sterile) seed for each designated-strength grouping."
- Calibrating a loose seed as a surrogate for the actual seeds implanted assumes that there is some meaningful connection between the manufacturing process that produced the loose seed and that for the assembly.

Absorbed Dose in Medium

Dose Calculation Formalism (1D Point Source Approximation)

- Actual brachytherapy sources differ from theoretical ones in the following respects:
  - emitted photons are attenuated and scattered by the source structure .
  - practically all sources are cylindrical giving rise to dose anisotropy.

Absorbed Dose in Medium (pre TG 43)

Dose Calculation Formalism (1D Point Source Approximation)

- $D_{med}(r) = A_{app} (\Gamma_{\delta})_X f_{med} T(r) / r^2$

$D_{med}(r)$ is the dose rate at distance r from source
A_{app} is the apparent activity
$(\Gamma_{\delta})_X$ is the exposure rate constant
$T(r)$ is the tissue attenuation factor
f_{med} is the exposure to dose conversion factor (0.96 cGy/R)

TG43

- *Dosimetry of interstitial brachytherapy sources: Recommendations of the AAPM Radiation Therapy Committee Task Group No. 43*, Nath, et al, Med Phys 22 (2), Feb 95, 209-234
- TASK: Review recent publications of interstitial brachytherapy source dosimetry & recommend dosimetry protocol which would include a formalism for dose calculation and data set for values of source parameters
  - Both 2D and 1D models
  - Standardized data sets for ^{192}Ir, $^{I\text{-}125}$, and $^{Pd\text{-}103}$
  - Improved accuracy
  - Laid foundation for data presentation for new sources

Absorbed Dose in Medium

Dose Calculation Formalism (1D Point Source Approximation)

- TG43: $DR_{med}(r) = S_K \ \Lambda \ g(r) \ \phi_{an} \ / \ r^2$

$DR_{med}(r)$ = Dose rate in water

S_K = Air kerma strength (U, 1 U = 1 cGy cm^2/hr)

Λ = Dose Rate constant

- includes source geometry, spatial distribution, encapulation, self filtration and scattering in water

$g(r)$ = Radial dose function

- includes effects of absorption and scattering along the transverse axis

ϕ_{an} = anisotropy factor

r^2 = inverse square

Air Kerma Strength, S_k

- First introduced in AAPM TG-32 report (Nath et al., 1987)
- Should be the quantity used for specifying brachytherapy source strength for the purpose of
  - defining calibration standards
  - documenting source strength on calibration reports and
  - for all aspects of dose calculation and treatment prescription.
- Air-kerma strength has units of μGy·m^2·h^{-1} and is numerically identical to the quantity Reference Air Kerma Rate recommended by ICRU 38 and ICRU 60
- Easier to use U

Dose Rate Constant

$$\Lambda = \frac{\dot{D}(r_0, \theta_0)}{S_K}$$

- Dose rate constant in water
- Ratio of dose rate at the reference position and S_k
- (cGy/hr)/U
- The dose-rate constant depends on both the radionuclide and source model
- It is influenced by both the source internal design and the experimental methodology used by the primary standard to realize S_K.

Radial Dose Function g(r)

- The radial dose function, g(r), accounts for dose fall-off on the transverse-plane due to photon scattering and attenuation, i.e., excluding fall-off included by the geometry function.
- g(r) is defined by

$$g_{\cdot}(r) = \frac{\dot{D}(r,\theta_0)}{\dot{D}(r_0,\theta_0)} \frac{G_X(r_0,\theta_0)}{G_X(r,\theta_0)}$$

- It is equal to unity at r_0 = 1 cm

Radial Dose Function g(r)

- It is sometimes convenient to approximate the radial dose function as a polynomial, where fitting parameters a_0 through a_5 should be determined so that they fit the data within ±2%.

$$g\ (r) = a_0 + a_1 r + a_2 r^2 + a_3 r^3 + a_4 r^4 + a_5 r^5.$$

1-D Anisotropy Function, $\phi_{an}(r)$

- the ratio of the solid angle-weighted dose rate, averaged over the entire 4 π steradian space, to the dose rate at the same distance r on the transverse-plane

Source Geometry Variations

- Source geometry and internal construction are highly manufacturer-specific and can affect the dosimetric characteristics of the source.
  - Source models vary with regard to weld thickness and type,
  - Radioactivity carrier construction
  - Presence of radio-opaque material with sharp or rounded edges
  - Presence of silver (which produces characteristic x-rays that modify the photon spectrum)
  - Capsule wall thickness
- Radioactive carriers may consist of a radio-transparent matrix, a radio-opaque object coated with radioactivity, or a radiotransparent matrix with highly attenuating radioactive coating.

Low Dose Rate Brachytherapy

- The use of isotopes in treating tumors was first suggested soon after the discovery and separation of radium
- Dose to healthy surrounding tissues in brachytherapy is a function of
  - placement of the radioactive sources and
  - type and energy of the radiation
    - the ability of the radiation to penetrate distances greater than the dimensions of the tumor
  - the physical design of the source

History of LDR Brachytherapy

- Shorter treatment time in brachytherapy generally overcomes accelerated tumor repopulation
- Since in an implant, the dose to adjacent normal tissue is typically reduced, accelerated treatment has less effect on normal tissue.
- Low dose rate (LDR) irradiation generally reduces late effects in normal tissue more than it reduces tumor control

LDR History – Implant Systems

- Before computers were placement rules, dose tables, and dose specification criteria for particular plane and volume geometries.
- Manchester (Paterson & Parker, 1934, 38)
- Quimby (1944) Uniform
- Paris (Pierquin, *et al.* 1978) 192Ir wires / strands
- Parker sought uniform dose in the implant where some regions have more or stronger sources than others.
- Modern prostate implants achieve this using non-uniform distribution of (typically) identical sources.

Classical Interstitial Brachy Optimization

- Three methods: Manchester (Paterson -Parker), Quimby, and Paris.
- Each method has rules to determine loading of sources.
- These systems/methods have been developed to achieve a desirable dose distribution.
- Used before the computer age but still work well.
- Designed for higher energy sources > 80 KeV

Paterson–Parker or Manchester System

- Guidelines/dosimetry method developed in the 1930's
- Prior to this method pt were implanted prior to planning
- If followed, a dose of +/- 10% will be provided within the implanted area
- Implant procedure strives to deliver a "uniform dose" to a plane or volume
- This system uses a "non-uniform" distribution of radioactive material to get a **uniform dose distribution**
  - Assumes **linear sources**

Quimby System

- **Uniform distribution of sources** throughout the region.
- **Non uniform dose**
- Dose at center of region much higher.
  - May be an advantage.
- Used in early seed implants.
- Uses ALONG & AWAY tables (cGy/mg-hr of Cs-137)

Quimby/Memorial Dosimetry System

- Similar to Paterson/Parker System
  - Tables used to calc dose
  - given a number of parameters- area, volume, total activity
  - Quimby method the implant is **"uniform" source distribution** which results in a **"non-uniform" distribution of dose**
  - Quimby method less often used than the Paterson-Parker method, but has been adapted into a system called the Memorial system and the tables are based on computer calculations accounting for filtration, modern units of activity and dose

Paris System

- Developed in the 1920's
- Uniform distribution of sources as in the Quimby method
- Based on three principles:
  - The sources must be rectilinear and arranged so that their centers are in the same plane, which is perpendicular to the direction of the sources and is called the central plane
  - Dose is defined and calculated in this plane but not restricted to this plane
  - Sources have uniform linear activity
  - Sources must be uniformly spaced, even if more than one plane
- Iridium 192 wires

Dose Distributions

- Low dose rate (LDR) interstitial implants most often have been carried out using uniform activity sources, yielding a Quimby-like dose distribution.
- With remote afterloading and variable dwell times, planar implants seeking dose uniformity in planes parallel to the implant planes will yield optimized activity distributions similar to those of the Manchester system.

Clinical Applications

- Surface mold/plaque
  - Eye plaque
- Intracavitary
  - Tandem & Ovid
  - Cylinder
- Transluminal
  - Endobronchial
  - Endoesophageal
  - Hepatic Duct
- Interstitial
  - Prostate
  - Breast
  - Syed
  - Head & neck
  - Pelvic sidewall
  - Sarcomas

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Eye Plaques

- LDR
- Temporary
- Treats intraocular tumor
- I-125 and Pd-103
- Delivers 85 cGy to base of the tumor
- 3-7 day procedure
- Outpatient basis

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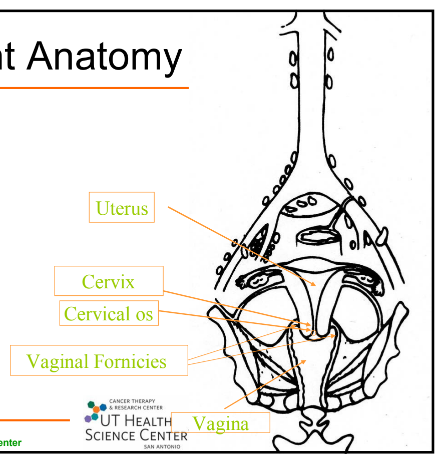
Intravascular Brachytherapy

- Prevent restenosis after angioplastic treatment or stent replacement
- Prescription dose: 14 Gy at 2mm from center of source; not to exceed inner lumen dose of 30 Gy
- Gamma emitter
  - Ir-192
- Beta emitters
  - Sr-90
  - P-32

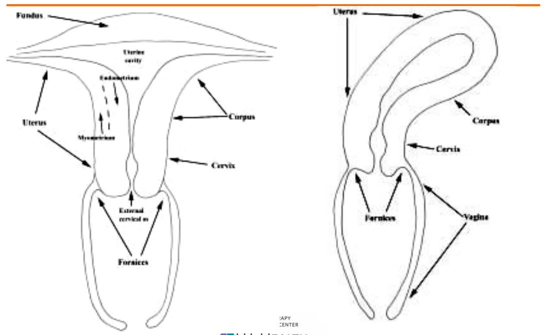
Intracavitary Implants

- Placement of radioactive sources in a body cavity
- Cancer of cervix, uterus, and vagina
- Gynecological implants
- Cervix applicator
  - Tandem & ovoids (or colpostats)
  - Cs-137 (or Ir-192 in HDR)

Important Anatomy



Important Anatomy



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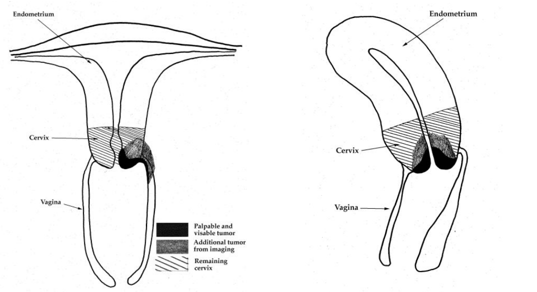
Important Anatomy



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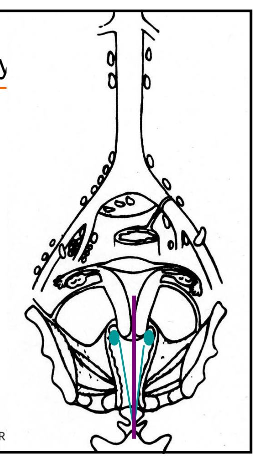
Placement of Tandem and Ovoids Relative to Anatomy

The vaginal ovoids should be flush against the face of the cervix

The tandem should be placed midway between the ovoids



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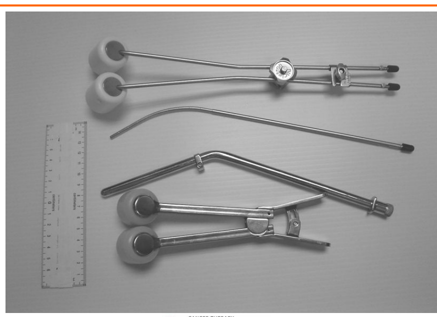
Treatment of Uterine Cervix

- Two "systems"—Stockholm and Paris, which came into clinical practice in 1911 and 1919, respectively
- Used the product of the total mass (mg) of radium used in the application and duration (hours) of the application (denoted as mg•h) for reporting the treatment.
- Both systems used a fixed number of mg•h, with the premise that for any given geometric arrangement of specified sources, dose at any point is directly proportional to the amount of activity in the sources and the duration of the implant.

Cervical Implants

- Applicator is called Tandem & Ovoids
- Tandem placed through the cervix to fundus of the uterus.
- Ovoids sit in vaginal fornices.
  - Caps placed on ovoids to displace tissue.
- Dose prescribed to point 2 cm superior and 2 cm lateral to cervical OS (point A).
  - Uterine artery crosses the ureter.

Tandem & Ovoids



mg-h Approach

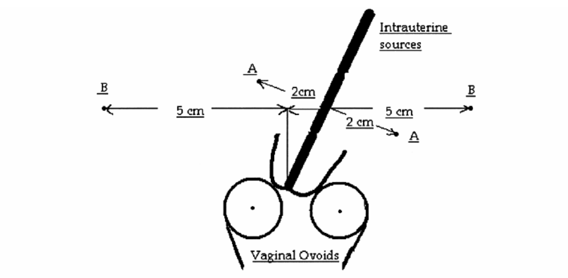
- Uterine sources in both systems were arranged in a line extending from the external os to nearly the top of the uterine cavity.
- Both systems preferred the longest possible intrauterine tube to increase the dose to the paracervical region and the pelvic lymph nodes.
- There was a limited use of external beam therapy in the Stockholm system, whereas the Paris system used external beam therapy before the implant.

Dose specification in Gynecological Treatment Planning

- Follow the Manchester system for GYN cases
- Dose to four points: A, B, Bladder and Rectum
- Duration of implant is based on the dose rate at point A
- Point A is located 2 cm superior to the cervical os and 2 cm lateral to the cervical canal
- Point B is defined 3 cm laterally to point A if the central canal is not displaced
- If the central canal is displaced, point A moves with the canal, but point B remains fixed at 5 cm from the midline

A & B points

- **Point A** represents the location where the uterine vessels cross the ureter.
  - It is believed that the tolerance of these structures is the main limiting factor in the irradiation of the uterine cervix.
- **Pt B** was intended to quantify the dose delivered to the obdurator lymph nodes



Dose Limiting Structures

Vaginal Mucosa

- The tolerance of vaginal mucosa is such that not more than about 40% of the total dose to point A can safely be delivered through the vaginal ovoids and this should be taken into account in planning the differential loadings.

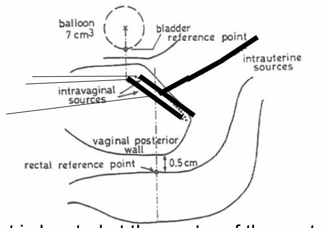
Rectovaginal Septum

- The probable dose on the rectovaginal septum for any technique should be less than that at point A.
- In their experience in Manchester, dose to this area could be reduced to less than 80% of the dose to point A by carefully packing gauze to a thickness of at least 1.5 cm to pack ovoids away from the rectum.

Dose Limiting Structures

- ICRU 38 Points
  - Bladder – taken as center of Foley balloon on AP film, posterior intersection on lateral
  - Rectum – On lateral film either from the lower end of the uterine source or middle of vaginal sources, 5 mm posterior to the vaginal wall.
  - Lymphatic trapezoid
  - Pelvic Wall
- Typical LDR loading
  - Tandem – 15-10-10 mgRa
  - Ovoids – 15 mgRa
  - Best loading is with long tandem and large ovoids

ICRU 38: Bladder & Rectal Dose Points



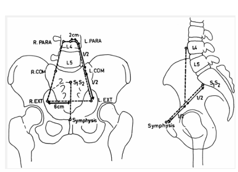
- Bladder point is located at the center of the posterior surface of the bladder Foley balloon
- Rectal point is located directly posterior to the lower end of the intrauterine source, 0.5cm behind the posterior vaginal wall

Dose specification in Gynecological Treatment Planning

- Doses to **bladder** and **rectum** are reduced by the use of packing and some shielding in the ovoids
- As ovoid diameter increases, vaginal surface dose decreases
- Doubling the tandem length increases the pt B contribution & decreases the uterine cavity surface dose

Lymph Nodes

- The contribution of the intracavitary brachytherapy to the regional lymph nodes, while not curative, needs to be included in their tally.
- Two methods, both based on skeletal anatomy:
  - **Pelvic-Wall Reference Point**
  - **Lymphoidal Trapezoid**
- These points correspond to the paraortic and iliac nodes



Typically Prescriptions of LDR T&O

- Intracavitary brachytherapy treatment utilizing T&Os is given as two 48-hour applications
- For the two intracavitary applications and the external beam treatment,
  - the bladder dose is limited to 75 to 80 Gy,
  - the rectal dose is limited to 70 to 75 Gy, and
  - the vaginal surface dose is limited to 120 to 140 Gy.
- A limit of 6000 to 6500 mgRaeq-hours is also observed.

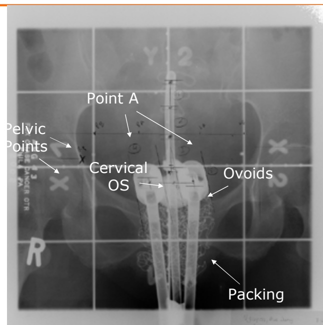
LDR Cervical Implants

- Applicator placed in OR
  - Use radio-opaque packing to displace rectum and bladder from sources.
- Patient transferred to Rad Onc for Simulation.
- At Simulation orthogonal films are taken for 3D planning.
  - Points of interest are digitized into a computer planning system for Cs source selection.

LDR Cervical Implants

- Patient transferred to hospital room while planning is performed.
- Radioactive sources are prepared, transferred to patient's room, and loaded in applicator.
- Exposure rate measurements are taken next to the patient and all areas around the patient's room.
- Any area outside patient room receiving greater than 2 mR/h is evacuated.
  - 2 mr/h regulated by NRC.

AP Cervix



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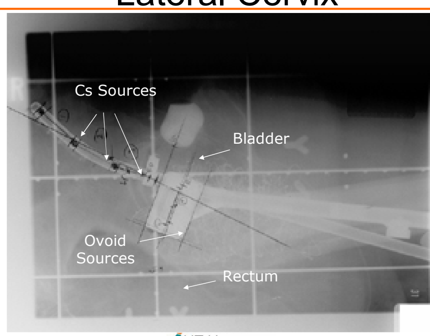
Lateral Cervix



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Cervical Cancer Treatment with HDR

- Usual source is Iridium-292
- Inserted by afterloader into catheters
- Source moves in 5 mm increments
- “Dwell time” is length of time in each position
- Usual dwell time is 5-15 minutes
- Standard of care is 5 treatments

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Side Effects for Cervical cancer brachy txt

- Short term side effects: dysuria, constipation, bloody discharge, cramping
- Long term side effects: vaginal fibrosis, chronic constipation, diarrhea

Endometrial Cancer

Incidence: 39,080 Deaths: 7,400

Adjuvant radiation indicated when malignancy invades >50% of myometrium

Endometrial Implants

- Vaginal cylinder used
- Treat top 1/3 to 1/2 of vagina
- Dose prescribed 5 mm from cylinder surface.
  - HDR: 3 x 400-700 cGy
  - LDR: single implant 2000 cGy
- Anterior surface of rectum receives 100 percent of the implant dose along the treated area.
- Bladder also receives dose.
- Can use either HDR or LDR

V. KRISHNASWAMY

Along and Away Table

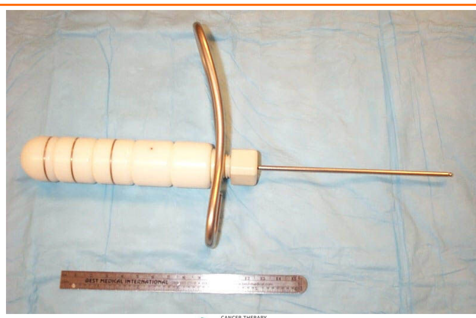
TABLE II: GAMMA DEPTH DOSE IN RADS PER HOUR FOR A MG RA-EQIVALENT ^{137}CS SOURCE.
(Active length 1.0 cm; wall thickness 1.0 mm stainless steel)

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	24.398	7.254	3.349	1.903	1.220	0.845	0.618	0.471	0.370	0.298
0.5	17.494	6.155	3.058	1.800	1.175	0.823	0.606	0.463	0.365	0.294
1.0	7.260	4.056	2.404	1.543	1.056	0.762	0.572	0.443	0.352	0.284
1.5	3.314	2.484	1.747	1.239	0.902	0.677	0.522	0.412	0.332	0.272
2.0	1.825	1.577	1.249	0.965	0.747	0.584	0.464	0.375	0.307	0.255
2.5	1.140	1.060	0.906	0.748	0.609	0.496	0.406	0.336	0.280	0.238
3.0	0.773	0.750	0.674	0.584	0.496	0.418	0.352	0.297	0.253	0.210
3.5	0.556	0.553	0.515	0.461	0.405	0.351	0.303	0.262	0.226	0.196
4.0	0.418	0.422	0.402	0.370	0.333	0.296	0.261	0.229	0.201	0.177
4.5	0.325	0.331	0.321	0.301	0.277	0.250	0.225	0.201	0.179	0.159
5.0	0.260	0.266	0.261	0.248	0.232	0.231	0.194	0.176	0.159	0.143

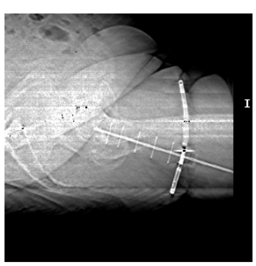
TABLE III: GAMMA DEPH DOSE IN RADS PER HOUR FOR A MG RA-EQUIVALENT ^{137}CS SOURCE
(Active length 1.4 cm; wall thickness 1.0 mm stainless steel)

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	0.616	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

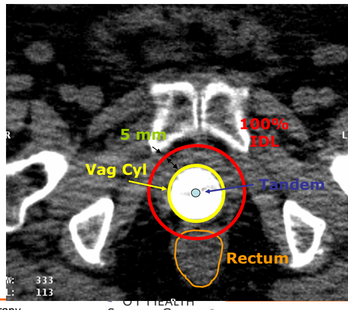
Vaginal Cylinder



Vaginal Cylinder Placement



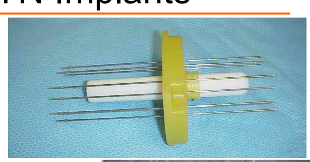
Axial CT with Vaginal Cylinder

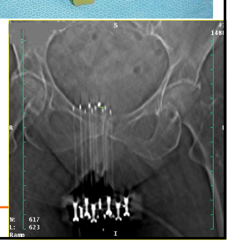


HDR Treatment

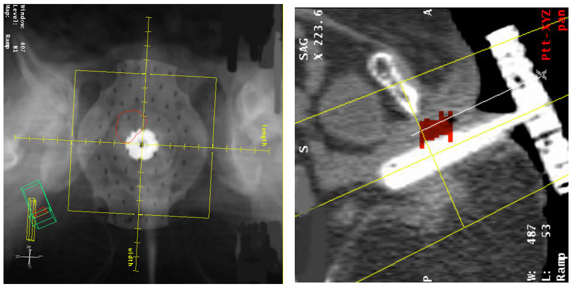
SYED GYN Implants

- Interstitial brachytherapy should be considered for patients with disease that cannot be optimally encompassed by intracavitary brachytherapy.
- Syed→Interstitial implant
  - Uses vaginal cylinder, sometimes tandem
- Utilized when disease > 5 mm depth
- LDR or HDR
- Good site for preplanning.



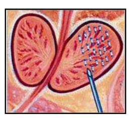


SYED

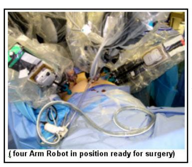


3 Typical Options for Prostate Cancer Patients

1) Brachytherapy



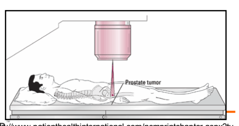
www.coreoncology.com/images/imp_pop_img1.jpg



2) Radical Prostatectomy

http://www.roboticurology.com/Robotic_radical_Prostatectomy(new).htm

3) External-Beam Radiotherapy



http://www.patienthealthinternational.com/ncmprintchapter.aspx?type=article&param=501121

Permanent Implant

Prostate implant
- I-125 and Pd-103
- Ultrasound or CT guided placement of seeds
- Conformal dose distribution
- Low energy from seeds mostly absorbed by patient
- Can be performed on out-patient basis
- I-125 ~ 160 Gy w/ seed activity =0.35mCi
- Pd-103 ~ 110 Gy w/ seed activity = 1.4 mCi

Prostate Brachytherapy

- Prostate brachytherapy is appropriate as monotherapy for men with low risk favorable disease (T1-2a, Gleason score ≤6 and PSA < 10)
- Due to its higher dose rate, Pd-103 is often prescribed for higher grade tumors with I-125 reserved for their low grade counterparts
- The ABS recommends that CT-based post-implant dosimetry be performed on every patient undergoing a permanent prostate seed implant

Clinical Procedure

- Prostate Volume Study (TRUS, MRI, CT)
- Pre-Planning (optional)
- Seeds ordering
- Seeds reception and calibration
- Sterilization and preparation
- Real time planning (optional)
- Seed loading and implant
- CT post-dosimetry check (day 0, day 21)
- Documentation

Volume Study

- Transrectal ultrasound (TRUS) volumetric study of the prostate gland is obtained 1-2 weeks prior to implant
- Volume study should not be performed on patients undergoing hormonal therapy unless the initiation of andgrogen deprivation therapy was at least 2 month prior.
- Volume study is acquired with the patient in the dorsal lithotomy position using TRUS probe mounted securely to a stepper and stabilizer unit
- Patient is scanned at 5 mm intervals starting from the proximal seminal vesicles just superior to the bladder neck/base of the prostate gland

Volume Study

- The path of the urethra should be visualized on each ultrasound slice by either infusing an aerated gel via the penile urethra or by placing a urinary catheter prior to the procedure.
- It is very important to ensure that the catheter bulb is well within the bladder and that there is no tension applied to the catheter in order to minimize catheter distortion of the prostate.
- Other structures frequently contoured are the rectum and bladder.

Coverage of Prostate

- The centers reporting the best brachytherapy results almost all treat with dosimetric margins
- One way to add a treatment margin to the prostate is to plan the implant so that the source positions and source strength are selected to maintain the 100% isodose line at the desired distance from the prostate
- Creating an explicitly drawn PTV clearly documents the volumetric planning goals and allows detailed dose calculations for that structure.
- By requiring the prescription isodose to completely cover the PTV, the dosimetric margin everywhere will be at least as great as the chosen physical margin.

Pre-OR Planning

- Planning prior to encountering the patient in the OR is cost effective
- The volume study is performed by the no more than a few weeks prior to the implant
- There is negligible change in the prostate, and fewer than 1% of patients exhibit changes from the time of the volume study to the operating room volume capture that necessitate modification of the plan
- Having a plan also saves valuable OR time and allows the use of pre-loaded needles
- It is important that the patient be set up the same, use similar tables and patient leg support as in the volume study

Intraoperative planning with Nomogram

- An activity nomogram is then used to determine the total seed strength to bring to the OR
- In the OR, an ultrasound planimetry determined volume is used to determine the total activity to implant
- Dividing by the available individual seed strength gives the total number of seeds to be implanted
- The nomogram calls for 75% of the total strength to be placed on the periphery of the gland
- Not cost effective

Interoperative / interactive planning

- Treatment planning can be moved from the clinic to the OR
- Consumes valuable OR time
- Can save time by evaluating the actual needle positions based on the plan
- Modification of the plan can be updated based on needle position

General Implant Guidelines

- In all treatment planning philosophies, it is considered poor technique to use single seed needles
- Also the planner should minimize the number of specially loaded needles
- As a final general rule, be sparing in your use of back-to-back seeds
  - These are typically used to build up dose at the prostate base and apex
  - Double sources create contiguous high dose regions that may place the bladder neck and urethra at risk

Appropriate Seed Strengths

- Increasing the seed strength will reduce the cost of an implant by increase the source strength and reducing the number of seeds. (manufacturers and hospitals bill by the number of seeds ordered and not by the total strength)
- However, the number of seeds required is not a linear function of seed strength
- For example, doubling the seed strength from 2-4 U to deliver a monotherapy dose to an average size prostate only reduces the seed count by about 25%.

Seeds used for prostate implant

- I^{-125} -- Iodine -125 source
  - Half life = 59.4days -- 60.2days
- Pd^{-103} -- Palladium-103 Source
  - Half life = 17.0days

Advantages of Pd-103 vs. I-125

- Lower energy
  - more conformal treatment
  - radiation protection advantage
- Shorter half life
  - treat more aggressive cancer
  - radiation protection advantage
- Availability

Advantages of I-125 vs. Pd-103

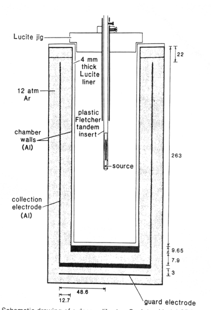
- Higher energy
  - less sensitivity to seed placement
- Longer half life
  - treat less aggressive, early stage disease
- Cost
  - Procurable in suture material

Stranded vs. Loose Seeds

- Part of the loss of Dxx may be due to residual edema at 2 weeks post implant,
- Part of the loss in Dxx coverage and the increase in V200 may have been due to their use of stranded seeds for all the implants

Seeds reception and calibration

- Wrap test
- Documentation
- Calibration
  - 10% of seeds and no less than 10
  - performed in a well-type chamber
  - The equipment should be calibrated regularly
  - ±3% is acceptable
  - 3-5% need to be investigated
  - >5% is not recommended to use



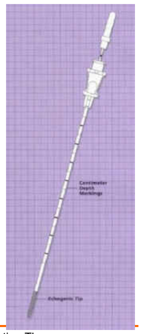
Equipment

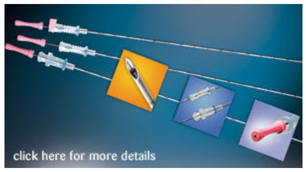
- Couch
- Ultrasound machine
- Stepper
- Stabilization arms and the head
- Template
- Seed loader
- Stabilization needles
- needles/ (mick applicator)
- seeds and spacers
- Tweezers
- Survey meter
- Computer, printer and cables
- Some other tools and radiation signs

Ultrasound machine

Stabilizer and Stepper

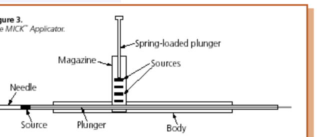
Needles





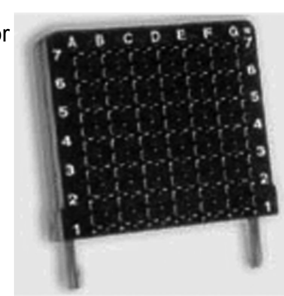
Mick Applicator

Figure 3.
The MICK™ Applicator.



Template

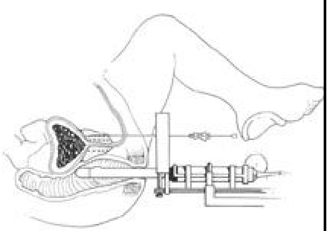
Transperineal template for inserting needles in prostate LDR brachytherapy implants



Dress Up

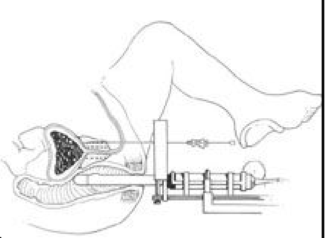
Implant

- Patients may be required to drink only clear fluids 48 hours prior to implant
- Fast 8 hours before procedure
- Bowel prep night before or enema morning of implant
- General or spinal anesthesia



Implant

- Stabilizer with stepper to hold template and TRUS device
- Dorsal lithotomy position
- Transperineal interstitial implant
- C-arm Fluoroscopy used fo seed and needle visualization and guidance (unable to see prostate, but can see urethra with catheter and Foley balloon



After implant

- After seed implant
  - Check the number of seed left
  - Survey anywhere in the room
  - Survey the urine

Post dosimetry (day 0 and day 21)

- CT scan the patient
- Contouring
- Transfer to seed implant computer
- Copy the contours
- Find the seeds
- Calculate the dose

Post Implant CT

- Timing of the post-implant CT affects the dosimetry
- Imaging performed immediately post implant (day-0) results in lower doses being depicted on the post-implant treatment plan than imaging preformed at any time thereafter
- Advantages of 0-day imaging is immediate feedback and convenience for the patient
- Catheter still in patient→ able to localize urethra

Suggested Post-Implant Dosimetry

Structure	Intent	Goal
Prostate Gland	Cure	D_{90} for iodine monotherapy > 140 Gy D_{90} for palladium monotherapy > 125 Gy D_{90} for boosts > reference dose
Prostate Gland	Urethral complications	D_{90} < 180 Gy V_{150} < 60% reference dose
Membranous Urethra	Urethral complications	Dose to the membranous urethra < reference dose
Rectum	Rectal complications	Dose to > 1 cm length of anterior mucosal wall < reference dose Max dose to anterior mucosal wall < 120% of reference dose
Rectum	Rectal complications	Annular DVH of rectum < 1.3 cm³ to 160 Gy (iodine)
Rectum	Rectal complications	Surface area of outer rectal wall < 5 cm² to reference dose

Release the patient

- Measure the patient's radioactivity
- Check the urine
- Check the area patient stayed
- Safe for going back home

Documentation

- Prescription sheet and treatment record
- Real time Plan or Pre- plan, dose distribution, and DVH
- Post dosimetry (dose distribution, DVH)

Discharge Instructions to the Patient

- After the discharge, institution no longer accountable for the implanted radioactive sources
- Instructions given to patient about radiation safety aspects of implant
- Dose rate at skin is very small
- Patient may stay in bed with partner and be in same room with children
- Abstinence for 1 -2 months or wear condom
- Avoid prolonged close contact with children under 18 yrs (i.e. sitting on lap) and pregnant women for at least 1 $T_{1/2}$

Discharge Instructions to the Patient

- Pt receives card/letter with information about implant, medical doctor and contact info
- Document provides explanation of radioactivity for airport screening devices or from radiological examination
- Chance of loose seed escaping during urination- flush it. If on floor, use tweezers and flush it
- Chest radiograph taken at 1st follow-up visit to scan lungs for migrated seed(s) – low risk of this occurring, but still possible

Questions

- Which of the following is not a unit currently used to specify activity or source strength in brachytherapy?
  a) Mg Ra eq
  b) mCi
  c) Bq
  d) Air Kerma Strength
  e) J/kg

  Answer: e

Problem

- The total dose from a permanent seed implant is 1600 cGy. The half-life is 17 days. The total dose delivered in the first 34 days is _____ cGy.
  a) 1400
  b) 1200
  c) 800
  d) 400
  e) 40

Half of the dose is delivered in the first half-life. 25 percent during the second half-life. 800 cGy + 400 cGy = 1200

Answer is b

Example Problem

- Cesium 137
  - The original activity on September 3, 1995 was 69.5 mCi. What would be the activity for this source 365 days later? The half-life of cesium 137 is 30 years.
  - We are not given the decay constant so we will use the formula with the half life

$$A_x = A_o e^{-(\frac{.693}{T_{1/2}})t}$$

  - A=.0695Ci $e^{-(\frac{.693}{30yrs})1}$
  - A=.06791Ci or 67.91 mCi

Problem

Determine the exposure rate (mR/s) at 2 meters for Ir-192 and I-125?

The activity of each brachytherapy source is 0.005 Ci.

$$\dot{X} = \frac{A\Gamma}{r^2} \qquad A = 0.005\,\text{Ci} \times \frac{1000\,\text{mCi}}{1\,\text{Ci}} = 5\,\text{mCi} \qquad r = 2\,\text{m} \times \frac{100\,\text{cm}}{1\,\text{m}} = 200\,\text{cm}$$

$$\dot{X}_I = \frac{A\Gamma_I}{r^2} = \frac{(5\text{mCi})\left(1.48\frac{\text{R}\bullet\text{cm}^2}{\text{mCi}\bullet\text{hr}}\right)}{(200\text{cm})^2} = 0.000185\frac{\text{R}}{\text{hr}} = 0.185\frac{\text{mR}}{\text{hr}}$$

$$\dot{X}_{Ir} = \frac{A\Gamma_{Ir}}{r^2} = \frac{(5\text{mCi})\left(4.69\frac{\text{R}\bullet\text{cm}^2}{\text{mCi}\bullet\text{hr}}\right)}{(200\text{cm})^2} = 0.000586\frac{\text{R}}{\text{hr}} = 0.586\frac{\text{mR}}{\text{hr}}$$

Problem

What is the total dose to the Rx point delivered by a permanent prostate seed implant using I-125 seeds? The dose rate to the Rx point is 2.4 cGy/hr

$$\text{Dose} = 1.44 \bullet T_{1/2} \bullet \text{Dose Rate}$$

$$\text{Dose} = 1.44 \times 60\text{days} \times \left(\frac{24\text{ hrs}}{1\text{ day}}\right) \times 2.4\frac{\text{cGy}}{\text{hr}} = 4977\text{ cGy}$$

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Cancer Therapy & Research Center

Problem

A patient was treated using the initial activity of 9 Ci for a vaginal cylinder HDR treatment. 100 days later the same plan is to be used. How should the dwell times change and by how much to deliver the same dose?

$D_{orig} = D_{100d}$ (same dose delivered)

Dose changes are due to activity and dwell times, Original activity is 9 Ci,

$$\text{Decayed activity is } A = A_0 \exp\left(-\frac{0.693}{73.83\text{ d}} \times 100\text{d}\right) = 3.5\text{ Ci}$$

$A_{orig} t_{orig} = A_{100d} t_{100d}$

$9\text{ Ci } t_{orig} = 3.5\text{ Ci } t_{100d}$

$2.6 = \frac{t_{100d}}{t_{orig}}$, the new activity is alot lower, so the new dwell times must be larger

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Problem

- A 2 cm thick lead shield is used to reduce the dose rate from a radioactive implant. If the HVL for this radiation is 5 mm, the dose rate will be reduced by a factor of:
  a) 2
  b) 4
  c) 10
  d) 16
  e) 100

$$\frac{I}{I_o} = \exp\left(-\frac{0.693}{\text{HVL}} \times t\right) = \exp\left(-\frac{0.693}{5\text{mm}} \times 20\text{mm}\right) = 0.06 = 6\% \text{ or } \frac{1}{16}$$

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Cancer Therapy & Research Center

Problem

- Match the half-life to the appropriate radioisotope
- Co-60
- C-137
- I-125
- Ra-226
- Pd-103

- Half-lives
  - 60 days
  - 30 years
  - 5.26 years
  - 17 days
  - 2000 years

Problem

- For an Ir-192 implant, it is found that the sources were 0.5 mg-Ra equivalent instead of 0.5 mCi. The consequence is that the dose rate in the patient is …

$$\dot{D} = \dot{X} f_{air} = \left(\frac{A\Gamma}{r^2}\right) f_{air}$$

$$\dot{D}_{mg} = \left(\frac{0.5\text{mg} \times 8.25 \dfrac{\text{R cm}^2}{\text{mg hr}}}{1\text{cm}^2}\right)\left(0.876 \frac{\text{cGy}}{\text{R}}\right) = 3.6 \frac{\text{cGy}}{\text{hr}} \text{ at 1 cm}$$

$$\dot{D}_{mCi} = \left(\frac{0.5\text{mg} \times 4.69 \dfrac{\text{R cm}^2}{\text{mg hr}}}{1\text{cm}^2}\right)\left(0.876 \frac{\text{cGy}}{\text{R}}\right) = 2.05 \frac{\text{cGy}}{\text{hr}} \text{ at 1 cm}$$

A larger dose rate is used

Problem

- How many HVLs of Pb are required to reduce the exposure level at 1 meter from a 155 mgRaeq source to 2 mR/hr?

$$155 \frac{\text{mR}}{\text{hr}} \rightarrow \text{1st HVL} \rightarrow 77.5 \rightarrow \text{2nd HVL} \rightarrow 38.75 \rightarrow \text{3rd HVL} \rightarrow$$
$$19.44\text{th HVL} \rightarrow 9.7 \rightarrow \text{5th HVL} \rightarrow 4.8 \rightarrow \text{6th HVL} \rightarrow 2.4 \rightarrow \text{7th HVL} \rightarrow$$
$$1.2 \frac{\text{mR}}{\text{hr}}$$

Problem

At 4 meters, what is the DOSE rate for a 60 mg Ra eq source? Assume a point source and that the patient absorbs 30% of the radiation.

Convert 4 meters to cm and 30% attenuation is 70% transmission

$$\dot{D} = \dot{X} f_{air} = \left(\frac{A\Gamma}{r^2}\right) = \left(\frac{60\ \text{mg} \times 8.25 \frac{\text{R cm}^2}{\text{mg hr}}}{400^2\ \text{cm}^2}\right)\left(0.876 \frac{\text{cGy}}{\text{R}}\right) \times 0.70 = 0.0019 \frac{\text{cGy}}{\text{hr}}$$

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Problem

Co 60 source with a certificate stating the exposure rate at 1 m is 120 R/min on January 15. The source is installed on June 15th. What is the **dose rate (cGy/min)** to a small mass of tissue in **air** on June 15?

$$\dot{D}_{calib} = \dot{X} f_{air} = \left(120 \frac{\text{R}}{\text{hr}}\right)\left(0.876 \frac{\text{cGy}}{\text{R}}\right) = 105.1 \frac{\text{cGy}}{\text{min}}$$

$$\dot{D}_{5month} = \dot{D}_{calib} \exp\left(-\frac{0.693}{5.26y} \times 0.5y\right) = 98.4 \frac{\text{cGy}}{\text{min}}$$

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Problem

- A Cs-137 source has an activity of 15.5 mg Ra eq in December 1980. What is the activity in June of 2007?

$$\text{Activity is } A = A_0 \exp\left(-\frac{\ln 2}{T_{1/2}} \times t\right)$$

$$A = 15.5\ \text{mg} \exp\left(-\frac{0.693}{30\ \text{y}} \times 26.5\text{y}\right) = 8.1\text{mg}$$

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Problem

- Define Point A (location and what it represents)
  - **Point A** represents the location where the uterine vessels cross the ureter.
- Define Point B (location and what it represents)
  - **Pt B** was intended to quantify the dose delivered to the obdurator lymph nodes
- How much time generally passes for a 1% reduction in activity for Co-60? Ir-192? Cs-137?

  1 month, 1 day, and 6 months respectively

Problem

- The initial dose rate of an I 125 permanent seed implant is 10 cGy/hr, then what is the total dose delivered?

$$\text{Dose} = 1.44 \bullet T_{1/2} \bullet \text{Dose Rate}$$

$$\text{Dose} = 1.44 \times 60\ \text{days} \times \left(\frac{24\ \text{hrs}}{1\ \text{day}}\right) \times 10\frac{\text{cGy}}{\text{hr}} = 20{,}736\ \text{cGy}$$

Problem

- A 3 cm thick lead shield is used to reduce the dose rate from a radioactive implant. If the HVL for this radiation is 10 mm, the dose will be reduced by a factor of _____

$$\frac{D}{D_o} = \left(\frac{1}{2}\right)^{t=30\text{mm}/\text{hvl}=10\text{mm}} = (0.5)^3 = 0.125 \text{ or } 12.5\%$$

Problem

- 50 cm away from an Ir-192 implant the dose rate is 50mrem/hr. What is the dose to the lens of a nurse that spends 6 min 25 cm from the patient?

$$D_{50cm} = \dot{D}t = 50\,\frac{\text{mrem}}{\text{hr}}\left(6\text{ min} \times \frac{1\text{ hr}}{60\text{ min}}\right) = 5\text{ mrem}$$

$$D_{25cm} = D_{50cm}\left(\frac{50\text{ cm}}{25\text{ cm}}\right)^2 = 20\text{ mrem}$$