Brachytherapy

Physical Properties of Sources

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Introduction

Mainly two forms of radiation therapy for treatments of cancer: teletherapy (long-range) and brachytherapy (short-range).

- Teletherapy - external beam radiation therapy in which a beam of photons/electrons is directed at the tumor from a medical linear accelerator.
- Brachytherapy - radiation therapy in which sealed radioactive sources are used to deliver radiation at short distances (< 10 cm).

Brachytherapy

Brachytherapy is also referred to as:
- Curie therapy or Endocurie therapy

Treatment is delivered by placing the sources directly into or near the volume to be treated.

The dose is delivered continuously
- Temporary implants (over a short period of time)
- Permanent implants (over the lifetime of the source)
Types of brachytherapy

- **Intracavitary**
  - sources placed in a body cavity close to the tumor
  - volume: e.g. vagina, uterus …

- **Interstitial**
  - sources implanted surgically within the tumor
  - volume: e.g. prostate, tissue sarcomas …
Interstitial Implant

Types of brachytherapy

- **Intraluminal**: sources placed in a lumen of the body: bronchial tract, esophagus
- **Intraoperative**: sources placed over the tumor or tumor beds during surgery
- **Surface (mold)**: sources placed over the tissue to be treated: eye
- **Intravascular**: single source placed into small or large arteries
Intraoperative Implant

Types of Source Loading

- **Hot Loading:**
  The applicator is pre-loaded and contains radioactive sources at the time of placement into the patient.

- **Afterloading:**
  The applicator is placed first into the target position and the radioactive sources are loaded later:
  - by hand (*manual afterloading*)
  - by a machine (*automatic remote afterloading*)

Brachytherapy vs. EBRT

- The physical advantage of brachytherapy treatments is the improved localized delivery of dose to the target volume of interest.

- The disadvantage is that brachytherapy can only be used in cases where the tumor is well localized and is relatively small.
  - Typical Rx Dept.: 10 to 20% of all Rx patients are treated with brachytherapy.
Radioactive Decay

\[ N(t) = N_0 e^{-\lambda t} \]

- \( N_0 \) is the initial number of radioactive atoms
- \( N \) is the number of atoms at time \( t \)
- \( \lambda \) is the decay constant

Half life

The half-life of a radioactive element is the time required to decay to half the initial number of radioactive atoms

\[
\frac{N(t)}{N_0} = 0.5 \quad \text{and} \quad 0.5 = e^{-\lambda t} \\
\ln(0.5) = -\lambda t \\
t = T_{1/2} = 0.693/\lambda.
\]

Characteristics of Isotopes used in Brachytherapy

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Half-life</th>
<th>Average Energy (MeV)</th>
<th>HVL in Lead (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{226}\text{Ra})</td>
<td>1620 years</td>
<td>0.830</td>
<td>8.0</td>
</tr>
<tr>
<td>(^{137}\text{Cs})</td>
<td>30 years</td>
<td>0.662</td>
<td>6.5</td>
</tr>
<tr>
<td>(^{198}\text{Au})</td>
<td>2.7 days</td>
<td>0.412</td>
<td>3.0</td>
</tr>
<tr>
<td>(^{192}\text{Ir})</td>
<td>74.2 days</td>
<td>0.380</td>
<td>2.5</td>
</tr>
<tr>
<td>(^{125}\text{I})</td>
<td>59.6 days</td>
<td>0.028</td>
<td>0.025</td>
</tr>
<tr>
<td>(^{103}\text{Pd})</td>
<td>17 days</td>
<td>0.021</td>
<td>0.008</td>
</tr>
</tbody>
</table>
Mean life

Mean-life of an isotope is defined as the time taken to decay to 1/e of its original number of radioactive atoms

\[ \frac{N(t)}{N_0} = e^{-t} \]

\[ e^{-t} = e^{-1} \Rightarrow \lambda t = 1 \]

\[ t = T_{\text{avg}} = \frac{1}{\lambda} \]

\[ T_{\text{avg}} = T_{\frac{1}{2}} \cdot 0.693 = 1.44 \cdot T_{\frac{1}{2}} \]

Mean life vs. Half life

Mean life vs. Half life

Source Strength Specifications

- **Activity:**
  - the amount of radioactivity in a radioisotope.
  - 1 Ci = \( 3.7 \times 10^{10} \) dps = \( 3.7 \times 10^{10} \) Bq
  - 1 Bq (Becquerel) = 1 dps

- **Exposure rate constant (\( \Gamma \)):**
  - exposure rate measured in air at a specified distance \( d \) (typically 1m).
Source Strength Specifications

The exposure rate \( (dX/dt)_p \) at a point \( P \) in air at a distance \( d \) from a brachytherapy source is expressed as:

\[
(dX/dt)_p = (A \cdot \Gamma) / d^2
\]

Where:
- \( A \) is the source activity (mCi or Ci)
- \( \Gamma \) is the exposure rate constant (R.cm²/mCi·hr⁻¹)

### Exposure rate constants

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( \Gamma ) (R·cm²/mCi·hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{226})Ra</td>
<td>8.25</td>
</tr>
<tr>
<td>(^{137})Cs</td>
<td>3.28</td>
</tr>
<tr>
<td>(^{198})Ir</td>
<td>4.69</td>
</tr>
<tr>
<td>(^{192})Au</td>
<td>2.38</td>
</tr>
<tr>
<td>(^{125})I</td>
<td>1.51</td>
</tr>
<tr>
<td>(^{103})Pd</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Example:

What is the exposure rate at a distance of 1 m for a 10 mCi \(^{137}\)Cs source?

\[
(dX/dt)_p = (A \cdot \Gamma) / d^2
\]

\[
= (10 \text{ mCi} \times 3.28 \text{ R.cm}^2\text{.mCi}^{-1}\text{.hr}^{-1}) / (100 \text{ cm})^2
\]

\[
= 0.00328 \text{ R/hr} = 3.28 \text{ mR/h}
\]
**Exposure rate constants**

Exposure rate at different distances:

\[
\frac{dX}{dt}\Bigg|_p = 3.28 \times 10^{-3} \text{ R/h at 1 m}
\]

\[
\frac{dX}{dt}\Bigg|_p = 32.8 \text{ R/h at 1 cm}
\]

\[
\frac{dX}{dt}\Bigg|_p = 0.328 \text{ R/h at 10 cm}
\]

*your best FRIEND is the inverse square law*

**Radiation Protection**

*Time* - Dose is proportional to exposure time. Half the time results in half the dose.

*Distance* - Radiation Exposure is inversely proportional to the square of the distance.

*Shielding* - Proportional to the energy of the photons and the HVL. For example, a 1 mm of Pb can provide enough shielding for I-125 but not Ir-192

*The “3R’s” for Radiation Protection*

**137Cs**

- 137Cs decays with a half-life of 30 yr via β decay followed by emission of γ rays of energy 0.662 MeV.

- Source activities must be corrected annually to account for radioactive decay (2% per year).

- Most commonly used brachytherapy source for intracavitary insertions especially for LDR Gyn.

- Available in several forms, such as needles, tubes and pellets (doubly encapsulated stainless steel).
192Ir

- 192Ir decays with a half-life of 74.2 d.
- Complicated $\gamma$ ray spectrum with an average energy of 0.380 MeV.
- Available in the form of:
  - wires, the radioactive core being an iridium-platinum alloy with an outer sheath of 0.1 mm thick Pt.
  - seeds, doubly encapsulated with an outer sheath of stainless steel.
  - strands of nylon ribbon containing iridium seeds 3 mm long and 0.5 mm diameter, spaced with their center 1 cm apart.

192Ir because of its characteristics and its form availability is used for almost all types of implants.

- Most common isotope for HDR brachytherapy remote afterloaders, specially designed with typical activities of 10 Ci.
- Short half-life $\Rightarrow$ new sources must be ordered
  - Possible to reuse a "used lot" of 192Ir sources for several cases
  - For HDR, a new "10 Ci" source is ordered every 3 months
198$^{\text{Au}}$

- 198$^{\text{Au}}$ decays with a half-life of 2.7 d and emits monoenergetic $\gamma$ rays of energy 0.412 MeV.
- Available in the form of encapsulated seeds or “grains”, implanted surgically into the tumor volume using special delivery “guns”. (grains sheathed in Pt(Ir), typically 2.5 mm long with an outer diameter of 0.8 mm).
- Short-lived radioisotope
  - used for interstitial, permanent implants.
  - within a few days after implantation, activity is sufficiently low that patient may be released from radiation safety supervision.

125$^{\text{I}}$

- 125$^{\text{I}}$ decays with a half-life of 59.6 d with the emission of 0.035 MeV $\gamma$ rays.
- 125$^{\text{I}}$ has generated interest for brachytherapy because of its low energy (35.5 keV) photons.
- Available in the form of encapsulated seeds. Many 125$^{\text{I}}$ seed models have been manufactured. Dosimetry is much more complex than other interstitial sources.
- Used for interstitial implants and Eye Plaques (Surface implants), and has less radiation safety problems.

125$^{\text{I}}$ seeds

- Model 6702
- Model 6711
**125I seeds**

- 125I seeds are used for interstitial implants (Prostate) and have less radiation safety problems than any other isotope.

**103Pd**

- 103Pd decays with a half-life of 17 d, by electron capture with the emission of characteristic x-rays in the range of 20 to 23 keV (average energy 20.9 keV).
- 103Pd have recently become available for use and may provide a biological advantage in permanent implants as the dose is delivered at much faster rate.
- Available in the form of encapsulated seeds. Few 125I seed models have been manufactured.
- Used mainly for interstitial implants (Prostate) and has less radiation safety problems than any other isotope.
Implant Doses

- Permanent Implant
  \[ D = \frac{dD}{dt} T_p \]
- Temporary Implant with \( T_{1/2} \ll T \)
  \[ D = \frac{dD}{dt} T \]
- Temporary Implant with \( T_{1/2} \gg T \)
  \[ D = \left( \frac{dD}{dt} \right) T_{ev} \left[ 1 - \exp\left( -\frac{T}{T_{ev}} \right) \right] \]

AAPM Task Group 43

Dosimetry of interstitial brachytherapy sources:


Task Group 43

- Incorporates latest data
- Incorporates SI units
  - Becquerel (Bq)
    - \( 1 \text{ Bq} = 1 \text{ dps} = 2.7 \times 10^{-11} \text{ Ci} \)
  - Air Kerma Strength (U)
    - \( 1 \text{ U} = 1 \mu \text{Gy} \text{ m}^2/\text{hr} = 1 \text{ Gy} \text{ cm}^2/\text{hr} \)
Air Kerma Strength

\[ S_k = \frac{dK(d)}{dt} \quad \text{U} \]

1 U = 1 \( \mu \text{Gy m}^2/\text{h} = 1 \text{cGy cm}^2/\text{h} \)

Brachytherapy source strength specified in terms air kerma rate at a point in air along the perpendicular bisector of the source. Product of air kerma rate times distance (usually 1 meter) to point.
Air Kerma Strength

\[ K = X(W/e)|\mu_n/p|/\mu_{en}/\rho \]

\[ \mu_{en}/p = (\mu_n/p)(1-g) \]

\[ g = 0 \]

\[ K = X(W/e) \]

\[ S_k = (dX/dt)(W/e)d^2 \]

\[ S_k = (dX(R/h)/dt)(0.876 cGy/R)(1m^2) \]

Dose Rate Constant

\[ \Lambda = (dD(r)/dt)/S_k \]

Dose rate to water at a point along perpendicular bisector of source 1 cm from the source for source strength of 1 U.

Geometry Factor

\[ G(r,\theta) = 1 / r^2 \quad \text{point source} \]

\[ G(r,\theta) = \beta / (L \times \sin \theta) \quad \text{line source} \]

\[ L = \text{active length} \]

\[ \beta = \theta_2 - \theta_1 \]

Accounts for variation in relative dose due to distribution of activity within the source, ignoring photon absorption and scattering.
Radial Dose Function

\[ g(r) = \frac{(dD(r,\theta_0)/dt)G(r,\theta_0)}{(dD(r_0,\theta_0)/dt)G(r_0,\theta_0)} \]

Accounts for the effects of absorption and scatter in tissue along the perpendicular bisector of the source. Similar in concept to Meisberger technique, but radial dose function is normalized at 1 cm.

Anisotropy Function

\[ F(r,\theta) = \frac{(dD(r,\theta)/dt)G(r,\theta)}{(dD(r_0,\theta)/dt)G(r_0,\theta)} \]

Accounts for anisotropy of dose distribution around the source, including effects of absorption and scatter in medium, i.e., self filtration in source, oblique filtration in walls, scattering and absorption in tissue.

Anisotropy Constant

Anisotropy factor, \( \phi_an(r) \), averaged over distance yields anisotropy constant \( \phi_an \). Used at all distance and angles for point sources considered in Task Group 43 report.
Summary of brachytherapy sources

The choice of an appropriate radioactive source for a specific brachytherapy treatments depends on several relevant physical and dosimetric characteristics.

- Photon energies and beam penetration in tissue and in shielding materials.
- Half life.
- Source Strength.
- Inverse square fall-off of dose with distance from the source.