Radioactivity

Lecture 23

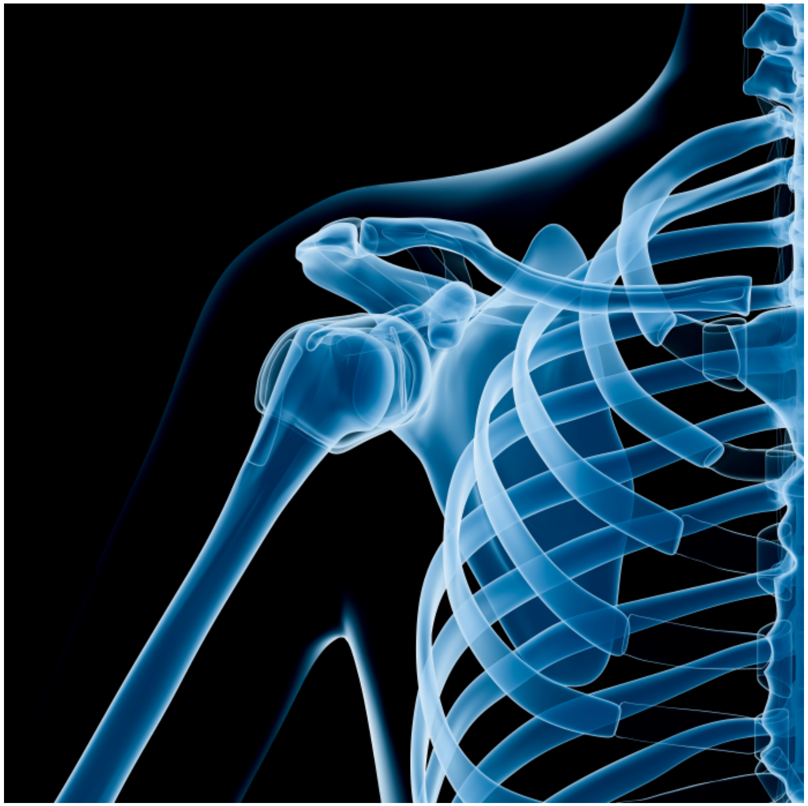
Radioactivity in Medicine

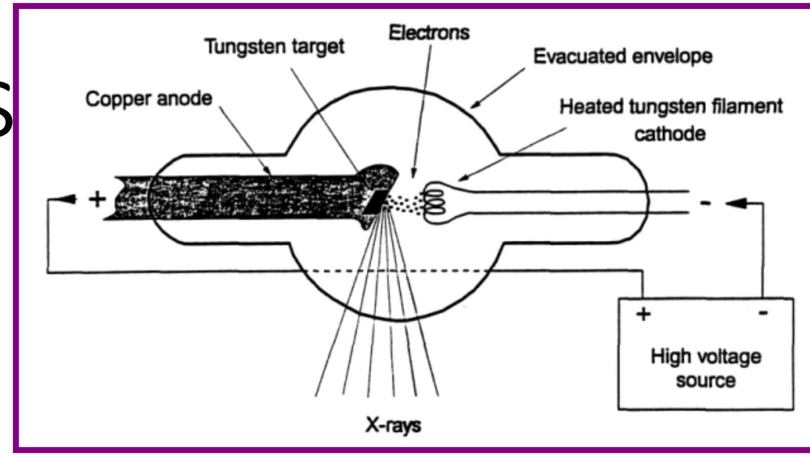
Applications of Radioactivity in Medicine

- Medical Diagnostics
  - Radiography with X-rays
  - Medical Imaging with X-rays
  - Medical Imaging with Gamma-Camera
  - SPEC and PET

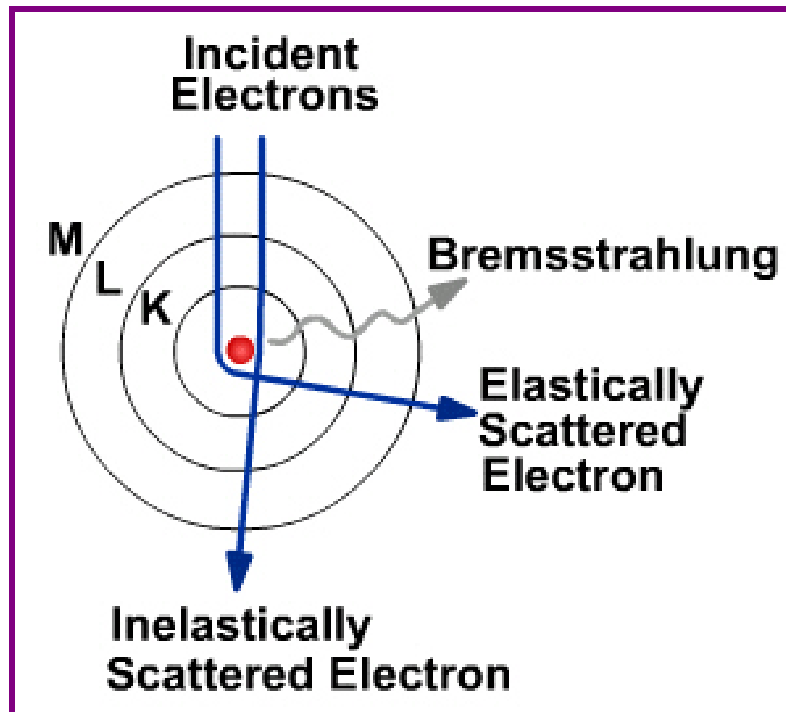
- Medical Treatment
  - Brachytherapy
  - External Beam Therapy

Medical Diagnostics



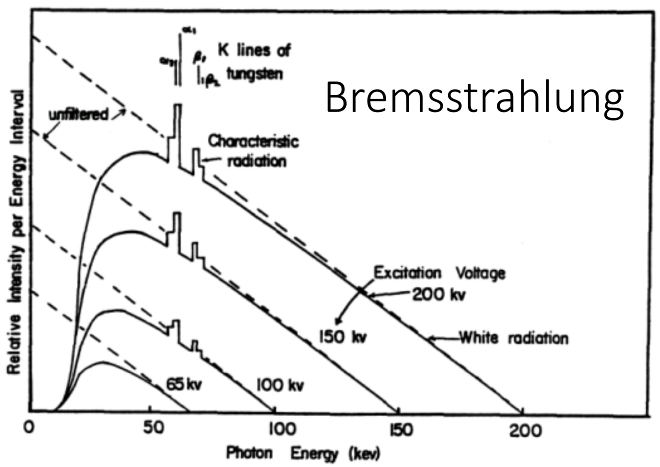


X-rays are produced by high energy electrons interacting with matter.



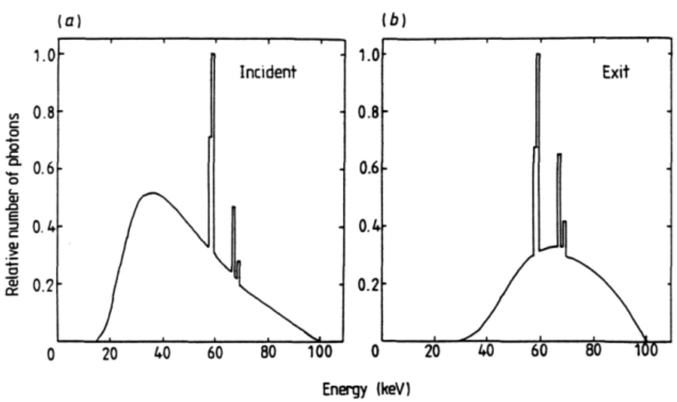
Current estimates show that there are approximately 650 medical and dental X-ray examinations per 1000 patients per year.

X-ray Spectrum

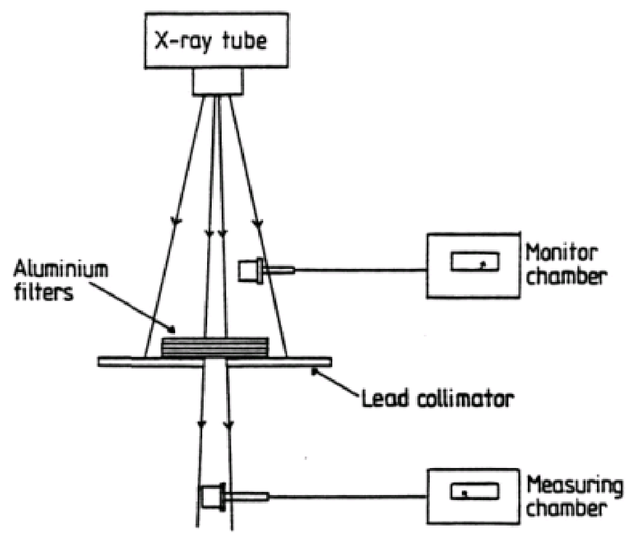


The intensity of the electron beam determines the intensity of the X-ray radiation. The electron energy determines the shape of the Bremsstrahlungs spectrum, in particular the endpoint of the spectrum. Low energy X-rays are absorbed in the tube material.

Characteristic X-rays



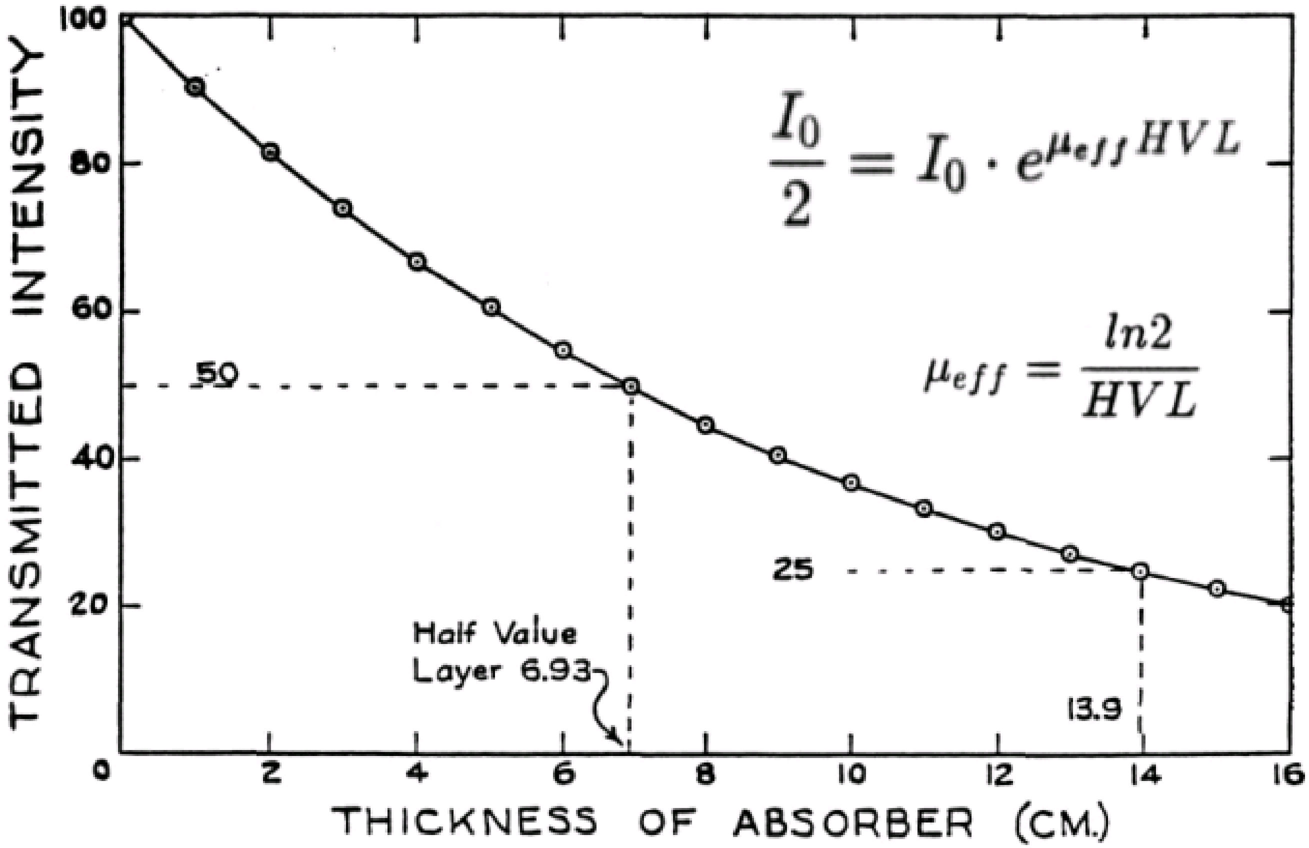
tungsten (high melting point)
good overall radiative emission



$$I(d) = I_0 \cdot e^{\mu_{eff} d}$$

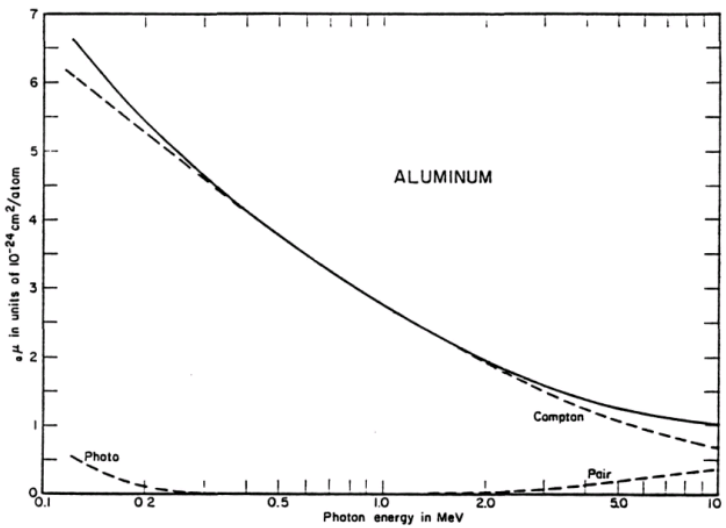
The intensity drops exponentially with the thickness d:
with μ_{eff} as material dependent absorption coefficient.

Absorption Law

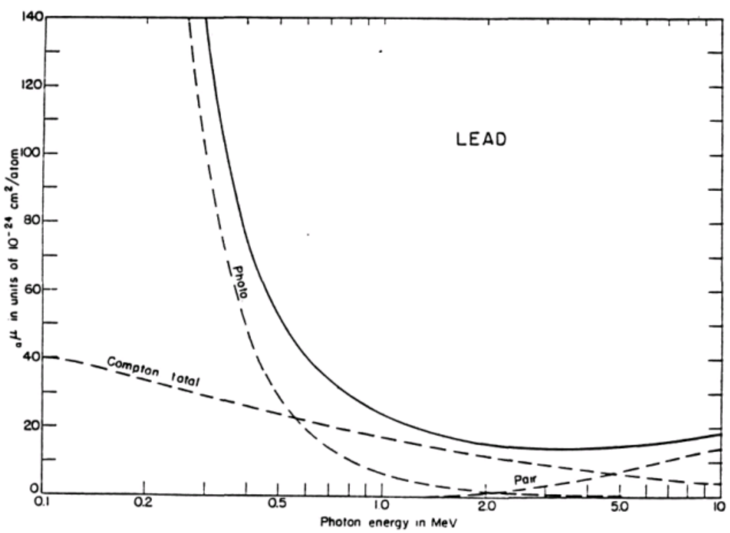


Graph showing how the intensity of an x-ray beam is reduced by an absorber whose linear absorption coefficient is $\mu = 0.10\ cm^{-1}$.

Absorption Coefficient for metals



Attenuation coefficients *vs.* energy for Al



Attenuation coefficients *vs.* energy for Pb

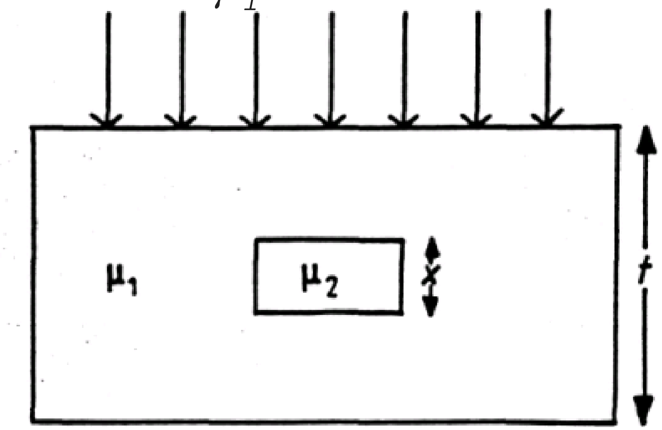
(keV)	Germanium 5.33	Cadmium 8.65	Barium 3.51	Gold 19.29	Lead 11.34	Uranium 19.1
1	1711	6829	8542	4652	5210	6626
1.5	5247	2738	4499	2089	2356	3381
2	2603	1382	2319	1137	1285	1865
3	925.7	510.9	869.6	2049	1965	769.1
4	434.0	1311	424.6	1144	1251	1329
5	239.0	746.5	241.4	666.1	730.4	889.0
6	146.1	466.0	689.9	425.3	467.2	628.4
8	66.89	219.5	333.4	207.2	228.7	310.8
10	36.40	121.3	186.0	118.1	130.6	179.1
15	90.81	40.84	63.47	163.7	111.6	65.27
20	41.90	18.81	29.38	78.82	86.36	71.06
30	13.75	37.40	9.904	27.52	30.32	41.28
40	6.165	17.67	24.57	12.98	14.36	19.83
50	3.314	9.722	13.79	7.256	8.041	11.21
60	2.011	5.941	8.511	4.528	5.020	7.034
80	0.9451	2.736	3.963	2.185	2.419	3.395
100	0.5525	1.516	2.196	5.158	5.550	1.954
150	0.2484	0.5570	0.7827	1.860	2.014	2.591
200	0.1658	0.3029	0.4045	0.9214	0.9985	1.298
300	0.1130	0.1568	0.1891	0.3745	0.4026	0.5191
400	0.09326	0.1127	0.1265	0.2180	0.2323	0.2922
500	0.08212	0.09244	0.09922	0.1530	0.1613	0.1976
600	0.07453	0.08058	0.08410	0.1194	0.1248	0.1490
800	0.06427	0.06666	0.06744	0.08604	0.08869	0.1016
1000	0.05728	0.05826	0.05801	0.06953	0.07103	0.07894
1500	0.04658	0.04673	0.04592	0.05167	0.05222	0.05586
2000	0.04087	0.04139	0.04078	0.04568	0.04607	0.04876
3000	0.03525	0.03698	0.03692	0.04201	0.04234	0.04446
4000	0.03276	0.03559	0.03598	0.04166	0.04197	0.04391
5000	0.03159	0.03536	0.03611	0.04239	0.04272	0.04463
6000	0.03108	0.03564	0.03669	0.04355	0.04391	0.04583
8000	0.03104	0.03691	0.03843	0.04633	0.04675	0.04879
10.000	0.03156	0.03853	0.04042	0.04926	0.04972	0.05194
15.000	0.03341	0.04253	0.04518	0.05598	0.05658	0.05926
20.000	0.03529	0.04587	0.04902	0.06136	0.06205	0.06511

Absorption Coefficient for soft materials

E (keV)	μ/ρ (g/cm^2)					μ/ρ (g/cm^2)			
	Air $1.2923 \cdot 10^{-3}$	Concrete 1.5 to 2.4	Glass, pyrex 2.2	Mylar 1.1	Polyethylene 0.9 to 1.0	SiO_2 1.5 to 1.6	NaI 3.67	Teflon 2.1 to 2.3	Water 1.0
1	3617	3366	3115	2920	1900	3123	7175	4722	4091
1.5	1202	1214	1142	943.0	578.1	1064	3562	1630	1390
2	530.3	1434	1481	414.3	249.9	1647	1806	741.6	618.7
3	161.7	489.6	504.7	126.2	74.67	564.5	666.8	235.3	191.3
4	77.51	238.1	231.9	53.42	31.26	257.3	322.6	102.1	81.74
5	39.94	171.8	124.0	27.26	15.85	137.9	708.8	52.82	41.96
6	23.12	103.6	73.80	15.68	9.109	82.13	518.7	30.70	24.21
8	9.721	49.35	32.17	6.580	3.843	35.85	245.4	12.97	10.18
10	5.016	26.19	16.78	3.395	2.023	18.71	136.5	6.654	5.223
15	1.581	8.185	5.136	1.106	0.7279	5.721	46.33	2.045	1.639
20	0.7643	3.605	2.264	0.5697	0.4247	2.511	21.39	0.9499	0.7958
30	0.3501	1.202	0.7893	0.2982	0.2689	0.8623	7.225	0.3979	0.3718
40	0.2471	0.6070	0.4304	0.2293	0.2269	0.4613	18.65	0.2630	0.2668
50	0.2073	0.3918	0.3004	0.2015	0.2081	0.3165	10.41	0.2123	0.2262
60	0.1871	0.2943	0.2407	0.1865	0.1968	0.2504	6.415	0.1875	0.2055
80	0.1661	0.2119	0.1886	0.1694	0.1822	0.1931	2.983	0.1630	0.1835
100	0.1541	0.1781	0.1656	0.1586	0.1719	0.1682	1.660	0.1499	0.1707
150	0.1356	0.1433	0.1388	0.1406	0.1534	0.1401	0.6087	0.1310	0.1504
200	0.1234	0.1270	0.1246	0.1282	0.1401	0.1255	0.3274	0.1189	0.1370
300	0.1068	0.1082	0.1070	0.1111	0.1216	0.1076	0.1655	0.1027	0.1187
400	0.09548	0.09629	0.09541	0.09946	0.1089	0.09589	0.1170	0.09186	0.1061
500	0.08712	0.08767	0.08696	0.09078	0.09945	0.08738	0.09488	0.08380	0.09687
600	0.08056	0.08098	0.08036	0.08395	0.09198	0.08074	0.08217	0.07748	0.08957
800	0.07075	0.07103	0.07052	0.07373	0.08079	0.07085	0.06751	0.06803	0.07866
1000	0.06359	0.06381	0.06337	0.06628	0.07263	0.06366	0.05878	0.06114	0.07070
1500	0.05176	0.05197	0.05160	0.05394	0.05909	0.05185	0.04696	0.04978	0.05755
2000	0.04447	0.04482	0.04446	0.04630	0.05065	0.04468	0.04148	0.04280	0.04940
3000	0.03581	0.03654	0.03612	0.03715	0.04045	0.03635	0.03681	0.03456	0.03969
4000	0.03079	0.03189	0.03140	0.03180	0.03444	0.03165	0.03520	0.02981	0.03403
5000	0.02751	0.02895	0.02838	0.02829	0.03044	0.02866	0.03477	0.02674	0.03031
6000	0.02523	0.02696	0.02632	0.02582	0.02761	0.02663	0.03487	0.02460	0.02771
8000	0.02225	0.02450	0.02373	0.02257	0.02383	0.02408	0.03586	0.02185	0.02429
10,000	0.02045	0.02311	0.02224	0.02057	0.02146	0.02263	0.03723	0.02020	0.02219
15,000	0.01810	0.02153	0.02045	0.01789	0.01819	0.02093	0.04082	0.01810	0.01941
20,000	0.01705	0.02105	0.01982	0.01664	0.01658	0.02036	0.04385	0.01722	0.01813

Contrast of Image

Consider that you want to image clearly a target tissue of thickness *x* with an attenuation coefficient μ_2 inside the body of thickness *t* with a lower soft body tissue attenuation coefficient μ_1



I_1 gives the energy absorbed outside the target tissue

I_2 gives the energy absorbed inside the target volume.

Approximating for an X-ray energy *E*:

$$I_1 = N \cdot \epsilon(E) \cdot E \cdot e^{(-\mu_1 t)} + S \cdot \epsilon(E)E$$

$$I_2 = N \cdot \epsilon(E) \cdot E \cdot e^{(-\mu_1(t-x)-\mu_2 x)} + S \cdot \epsilon(E)E$$

The **contrast** *C* of the target tissue volume is defined in terms of the image distribution function I_1 and I_2:

$$C = \frac{I_1 - I_2}{I_1}$$

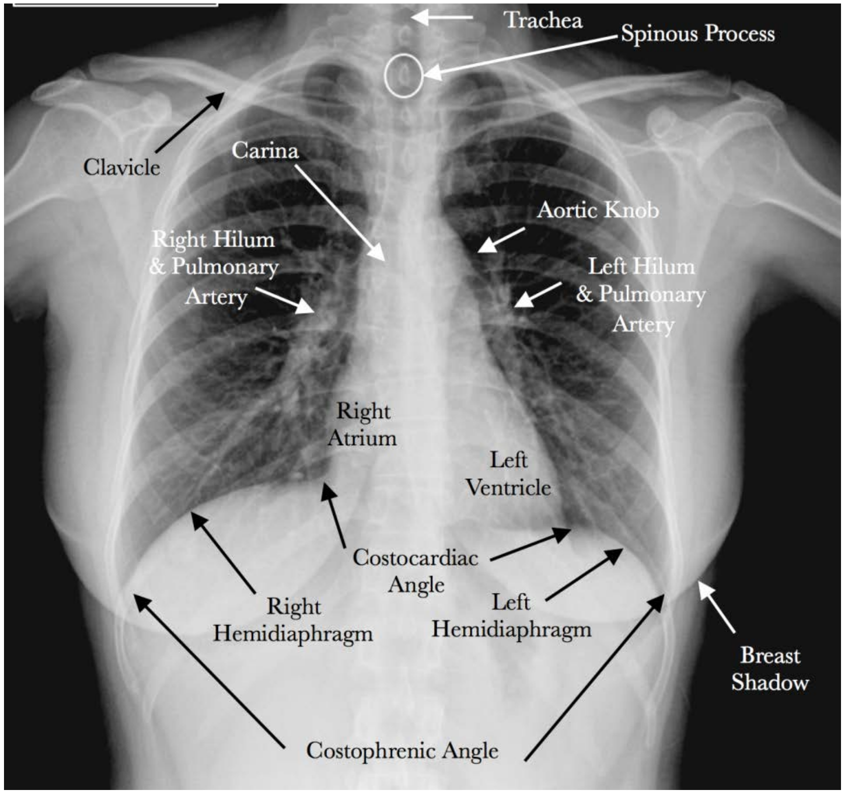
This yields for the contrast C:

$$C = N \cdot \epsilon(E) \cdot E \cdot e^{-\mu_1 t} \cdot (1 - e^{[-(\mu_2-\mu_1)x]})/I_1$$

The contrast depends mainly on the difference of attenuation coefficients μ_1 and μ_2 as well as on the ratio of scattered to primary X-ray photons. Injection of contrast medium can improve the visibility.

Example on the power of contrast

EXAMPLE Contrast in a chest transmission X-ray image



Typical chest x-radiograph.

In the shown picture of the chest X-ray, bones (ribs) with high X-ray attenuation, $\mu_{bone} = 0.48$ 1/cm show up light,

soft body tissue like blood and muscle with less attentuation $\mu_{blood} = 0.178$ 1/cm, $\mu_{muscle} = 0.18$ 1/cm, are less exposed,

the air filled lung cavity has no attenuation, $\mu_{air} = 0$ 1/cm and appears a dark spot.

The contrast can be calculated between the soft body tissue and the ≈ 1 cm thick rib or between the soft body tissue and a ≈ 1 cm air filled cavity.

(1st order of approximation: R≈0)

$$C = \frac{I_1 - I_2}{I_1} = 1 - e^{(\mu_1 - \mu_2)x}$$

for x = 1 cm, $\mu_1 = \mu_{tissue} = 0.18$ 1/cm

$$C_{tissue-bone} = 1 - e^{(0.18-0.48)} = 0.26$$

The intensity difference between the body tissue and the bone material is 26%, bone has more attenuation, the image shows 26% less exposure.

$$C_{tissue-air} = 1 - e^{(0.18-0)} = -0.2$$

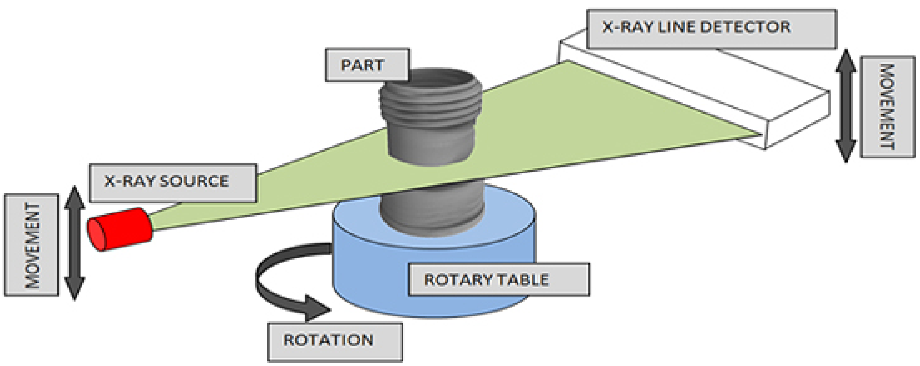
The intensity difference between the body tissue and the air filled lung cavity is 20%, air has less attenuation, the image shows 20% more exposure.

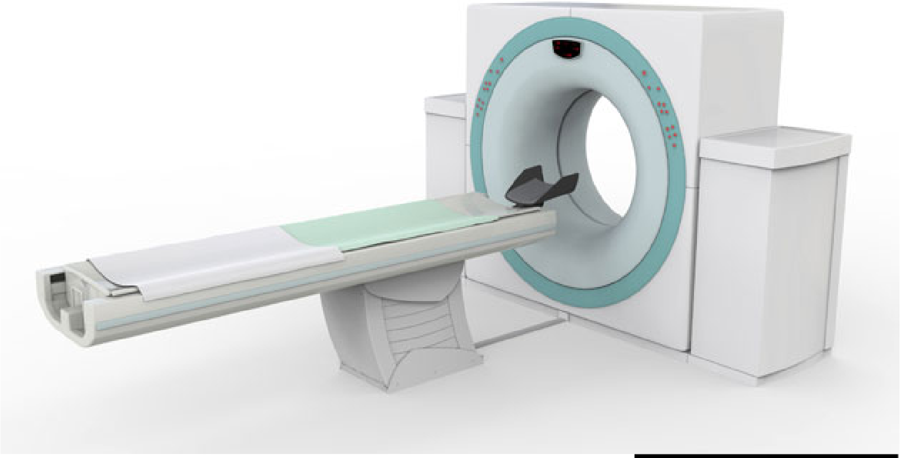
The contrast between different soft tissue components like muscle and blood is small.

$$C_{muscle-blood} = 1 - e^{(0.18-0.178)} = -2 \cdot 10^{-3}$$

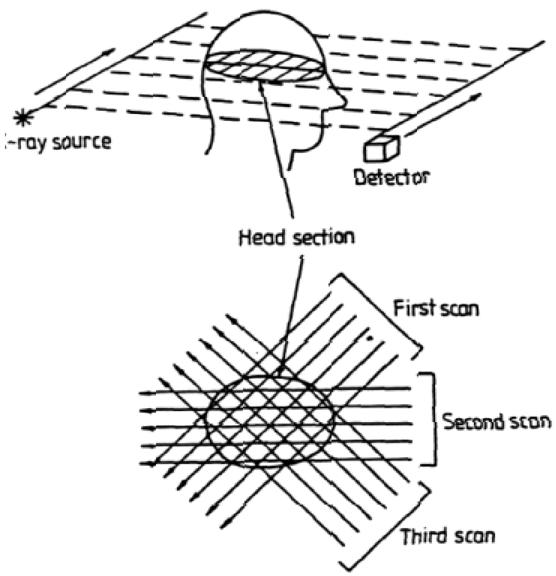
The intensity difference between muscle and blood is only 0.2% the muscle hs slightly more attenuation and its image therefore shows 0.2% less exposure.

Computed Tomography (CT)





CT is based on the principle that an image of any object can be obtained by generating an infinite number of projections through the object. To achieve that a narrow beam of x-rays is aimed at a patient and quickly rotated around the body, producing signals that are processed by the machine's computer to generate cross-sectional images (slices) of the body. A number of successive slices form a three-dimensional image of the patient.

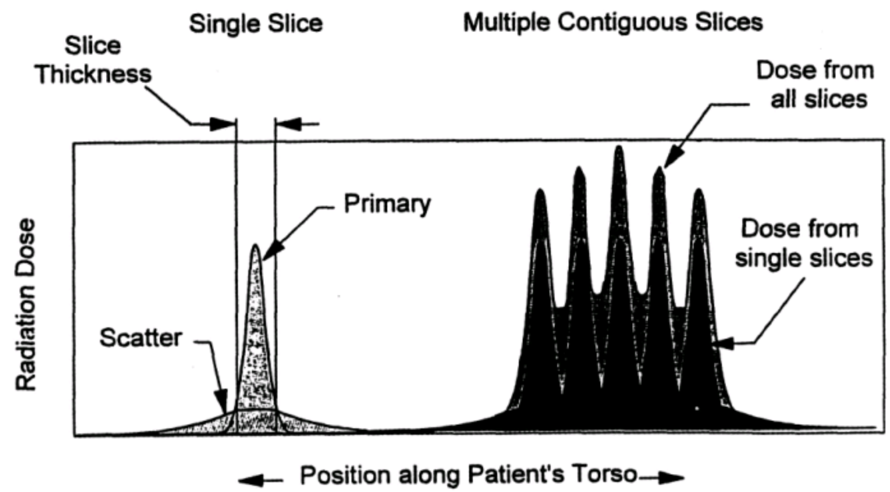


Radiation Doses in Radiographic and in CT Examination

The radiation dose received in CT is considerably higher than that of conventional screen radiography because each slice generates a certain amount of radiation dose.

To compare the two types of X-ray exposures the received dose *D* of X-ray radiation is converted to integral dose *DI,* which corresponds to the total amount of energy deposited in the body tissue of mass m:

$$DI[J] = D[\frac{J}{kg}] \cdot m[kg]$$



The dose in a CT scan is due both to the primary and the scattered radiation. The primary radiation is confined mostly to the slice thickness but is higher in the center because of the beam divergence and the penumbra effects of the collimation. The scattered radiation is more diffuse and extends laterally out in both directions away from the slice (left). Because the scattered dose contributes to the dose in adjacent slices, the dose in each slice volume is greater when contiguous slices are acquired.

Calculating the integral dose

EXAMPLE Calculate the integral dose for a head CT and radiograph. The head has a diameter of d= 16cm.
To calculate the integral dose for CT we assume that the dose for a CT scan is 30 mGy.

For one slice of 1 cm thickness of the head the cross sectional area is

$$A = \pi \cdot (8cm)^2$$

The volume of the head slice is the V=201 cm^3.
For a density of $\approx$ 1 g/cm^3 the slice has a mass of m=201g=0.2kg.

The integral dose for a head CT is:

$$DI = 30mGy \cdot 0.2kg = 6J$$

For seven slices the integral dose is:

$$DI = 7 \cdot 30mGy \cdot 0.2kg = 42J$$

Calculating the integral dose of a single X-ray radiography shot

In radiographic examinations the dose is not distributed evenly but drops from the entrance dose at the skin D_0 towards deeper layers.

The integral dose is described by:

$$DI = \left(\frac{D_0 \cdot A}{\mu}\right) \cdot \left(1 - e^{-\mu \cdot d}\right)$$

For the skull $\mu \approx 0.33\ \mathrm{cm}^{-1}$, $A \approx 200\ \mathrm{cm}^2$, d = 16 cm the typical entrance dose is $D_0 \approx 4.8$ mGy. This yields for the integral dose:

$$DI = 2.7 J$$

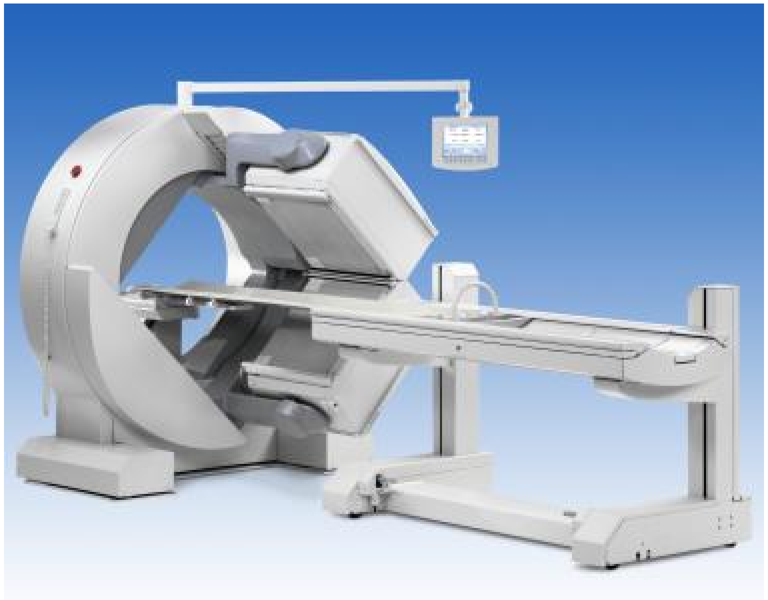
The integral dose in a seven slice head CT is about fifteen times higher than the integral dose of a single X-ray exposure.

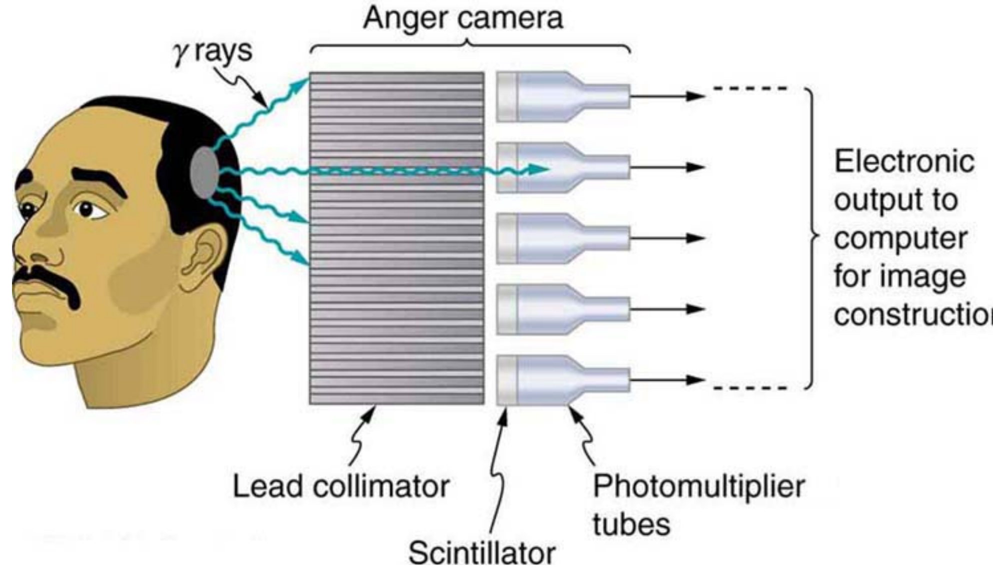
Radiological Imaging

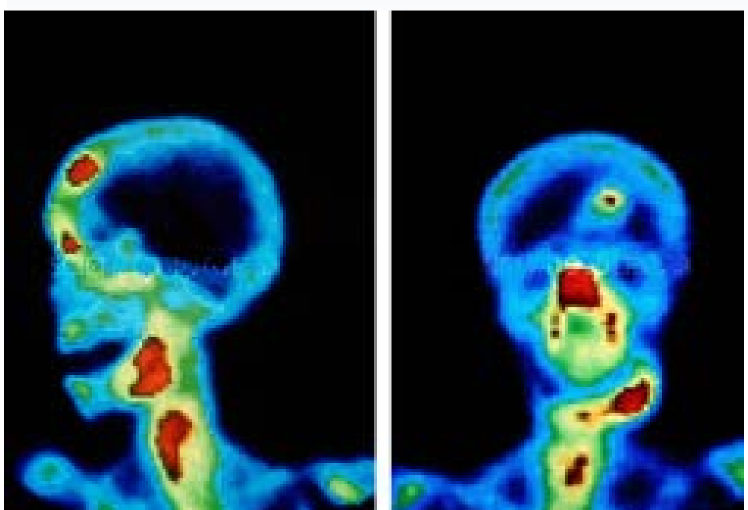
- There are a number of radiological techniques to provide detailed images of body parts.
- This requires the injection and/or accumulation of radioactive isotopes at the body part to be investigated.
- Carriers are specific radio-pharmaceuticals that accumulate in specific body parts due to their chemical design or in tumor cells with increased blood up-take capabilities.
- These radiological techniques require the production of radio-isotopes emitting characteristic gamma radiation and the chemical coupling to the design-pharmaceuticals.
- The characteristic gamma radiation can be measured by a set of external detectors arranged in specific geometry to generate a high resolution image for detailed analysis.

Gamma Cameras

Single-Photon Emission Computer Tomography (SPECT)







Gamma camera scan of the skull of a person suffering from metastatic bone cancer. The image is constructed from the geometry and the intensity of the characteristic γ radiation in the different photomultipliers This color-coded image represents the position and intensity of radiation emitted from a short-lived radioactive tracer that is metabolized or is concentrated in the part of the body under investigation - in this case, bone. The radioisotope concentrates more strongly in cancerous than in normal bone and this is represented by the red areas on the image.

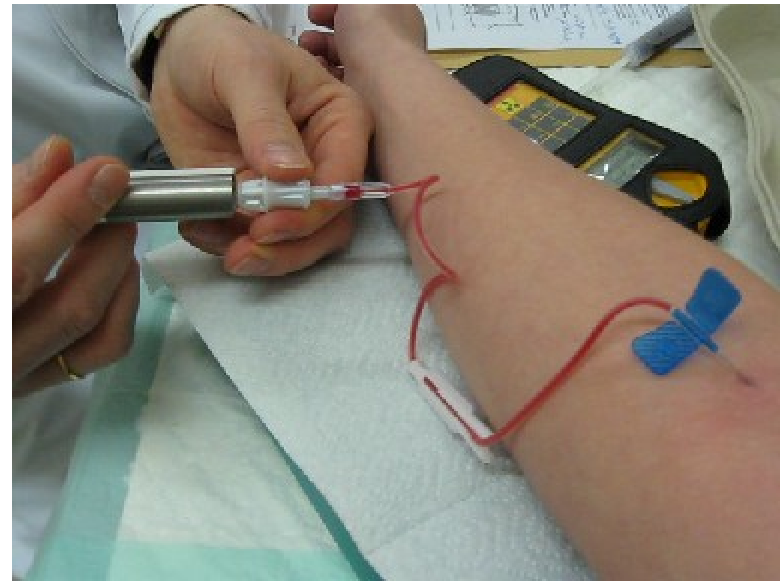
Requirements for the radio-isotopes

- The radioisotope must be sufficiently long-lived to be produced and transported to the hospital
- It must be sufficiently short-lived to decay or be removed from the body by other means. This time is determined by the effective half-live T_E, which is determined by the radiological half-life $T_{1/2}$ and the biological half-live T_B.

$$\frac{1}{T_E} = \frac{1}{T_{1/2}} + \frac{1}{T_B}$$

- Rapid removal from body will reduce the internal dose to other nearby located body parts and organs.

Radioisotopes in common use



$^{99}Tc^{m}$ ($T_{1/2}$=6.02h, E_{γ}=140 keV) is used in more than 70% of all medical applications

^{226}Ra ($T_{1/2}$=1600 a, E_{γ}=186 keV) is an α-emitter (α's are absorbed in body tissue), is used for highly localized studies

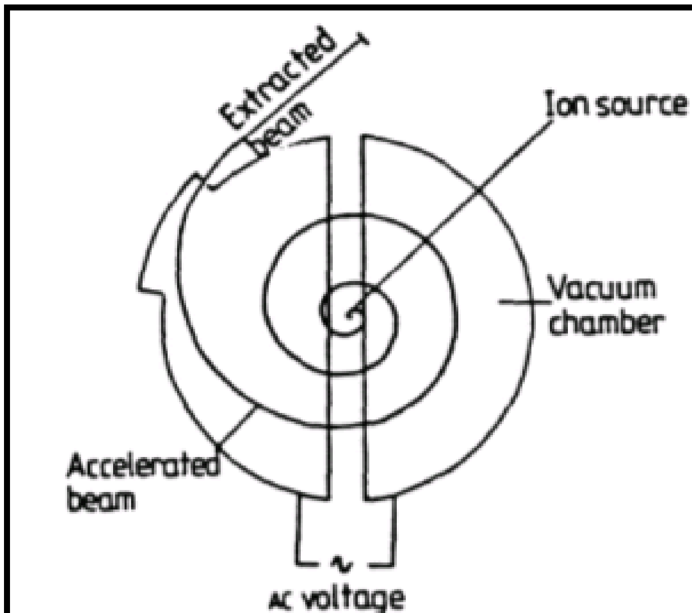
^{67}Ga ($T_{1/2}$=78.3h, E_{γ} =93 keV, 185 keV, 300 keV) is often used as tumor localizing agent (gallium citrate)

^{123}I ($T_{1/2}$=13h, E_{γ}=159 keV) bonds good with proteins and molecules that can be iodinated. It has replaced ^{131}I ($T_{1/2}$=6d, E_{γ}=364 keV) because of the reduced radiation exposure

$^{81}Kr^{m}$ ($T_{1/2}$=13s, E_{γ}=190 keV) is a very short-lived gas used to perform lung ventilation studies, (short half-life limits its application)

Production of Radioisotopes

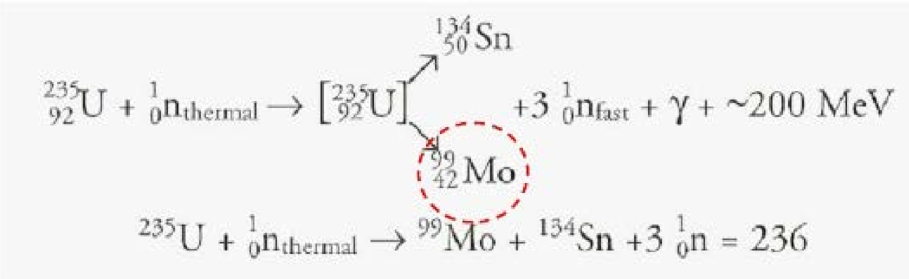
- nuclear reactor facilities through fission and separation of fission products
- Nuclear accelerator facilities through targeted nuclear reactions and extraction of reaction products.



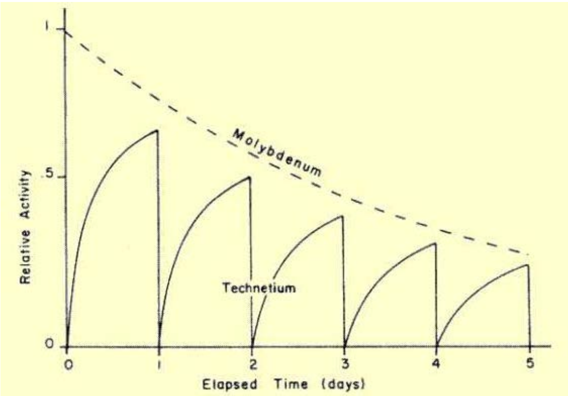
Isotope	Principal gamma-ray energy (keV)	Half-life	Reaction
^{11}C	511 (β^+)	20.4 min	$^{14}N(p,\alpha)^{11}C$
^{13}N	511 (β^+)	9.96 min	$^{13}C(p,n)^{13}N$
^{15}O	511 (β^+)	2.07 min	$^{15}N(p,n)^{15}O$
^{18}F	511 (β^+)	109.7 min	$^{18}O(p,n)^{18}F$
^{67}Ga	93 184 300	78.3 h	$^{68}Zn(p,2n)^{67}Ga$
^{111}In	171 245	67.9 h	$^{112}Cd(p,2n)^{111}In$
^{123}I	159	13 h	$^{124}Te(p,2n)^{123}I$ $^{127}I(p,5n)^{123}Xe \rightarrow {}^{123}I$
^{201}Tl	68–80.3	73 h	$^{203}Tl(p,3n)^{201}Pb \rightarrow {}^{201}Tl$

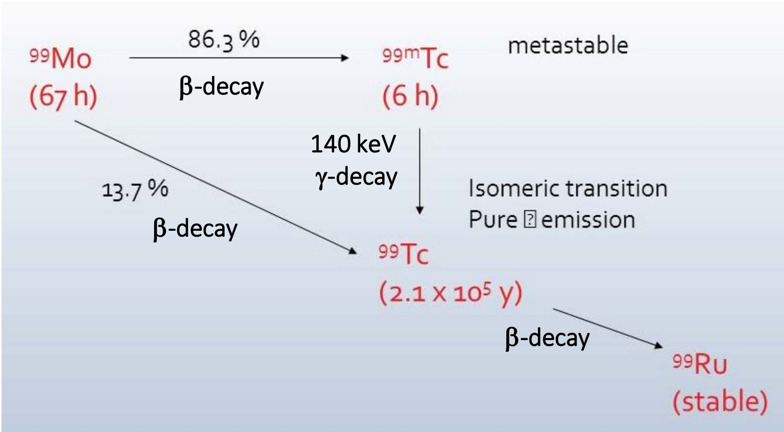
Example: $^{99}Tc^{m}$

^{99m}Tc is a so-called isomer, an intermediary long lived excited state in ^{99}Tc that decays by γ-emission to the ground state. Is produced through the β-decay of radioactive ^{99}Mo which is generated by nuclear reactor breeding ^{235}U fission. Most of it was produced by five smaller reactors using highly enriched ^{235}U. Alternative routes are the production of ^{99}Mo by neutron activation of natural molybdenum, or enriched in ^{98}Mo.



Fission products have to be extracted from reactor fuel rods and chemically separated. ^{99}Mo can be stored, and ^{99m}Tc is being extracted once a day.



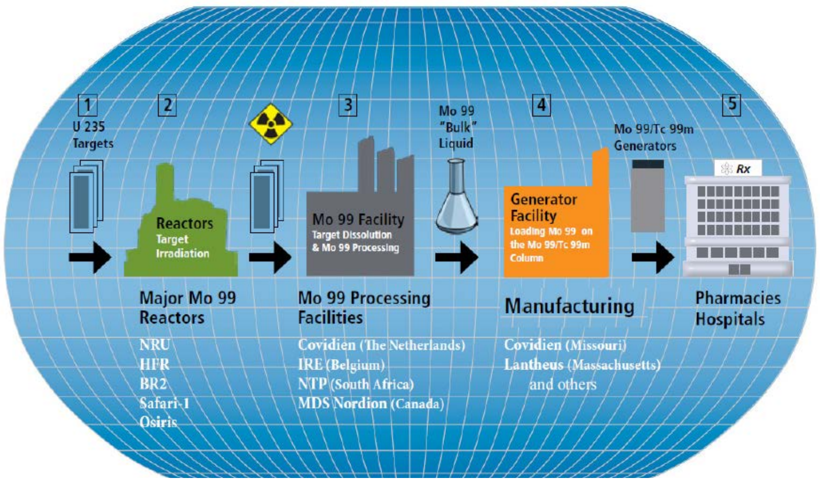


^{99}Mo is delivered to hospital and the ^{99m}Tc decay products are extracted by chemical means in Tc-99m generators.

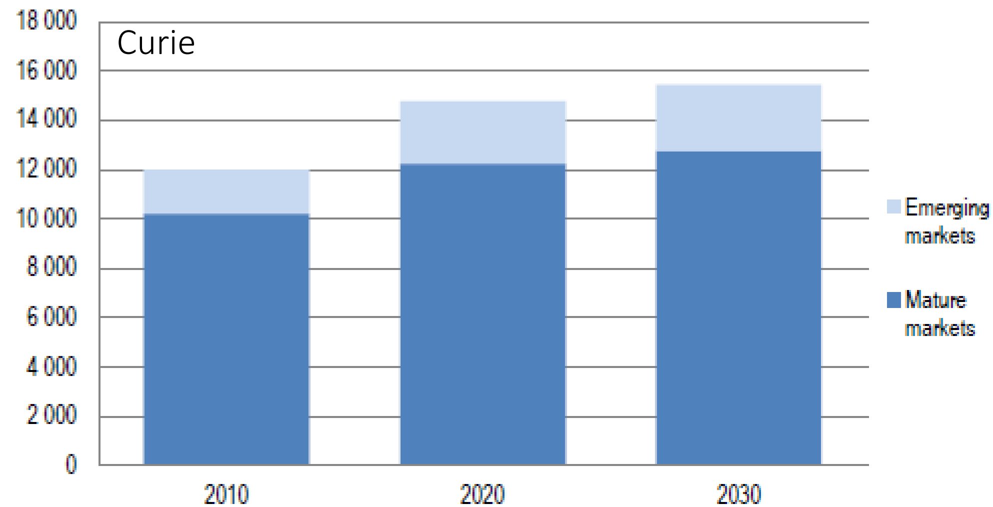
A typical dose rate at 1 meter from such a generator is 20-50 µSv/h during transport.

Demand of ^{99}Tc for medical applications

Supply chain of ^{99m}Tc. Serious shortages anticipated due to limitations of reactor fuel.



The global demand for ^{99}Mo for ^{99m}Tc production is approximately 12 000 Curies per week.



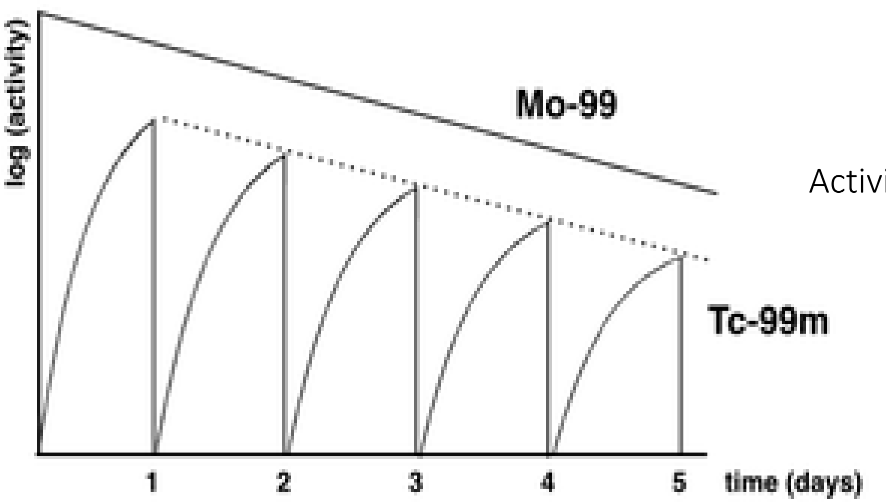
$$^{99m}_{43}\mathrm{Tc} \xrightarrow[6\ \mathrm{h}]{\gamma\ 141\ \mathrm{keV}} {}^{99}_{43}\mathrm{Tc} \xrightarrow[211{,}000\ \mathrm{y}]{\beta^-\ 249\ \mathrm{keV}} \overbrace{{}^{99}_{44}\mathrm{Ru}}^{\text{ruthenium}-99}\ \text{(stable)}$$

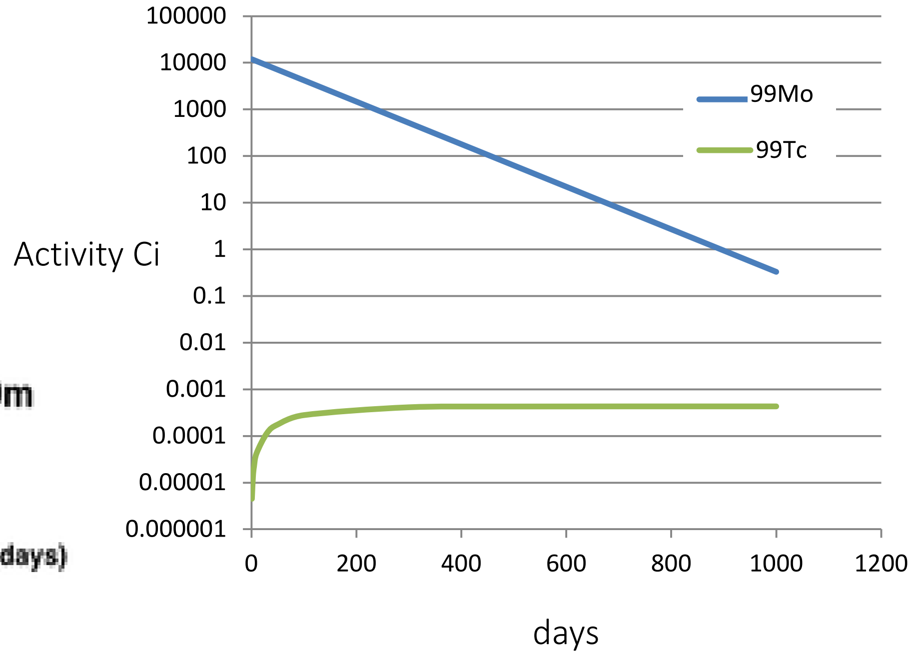
$$A(^{99}Mo) = 12{,}000\,Ci = 4.44\cdot 10^{14}\,Bq = 0.44\,PBq \qquad T_{1/2} = 66h$$

$$A(^{99m}Tc) = \frac{66h}{6h}\cdot 12{,}000\,Ci\cdot 0.83 = 109{,}560\,Ci = 4.05\,PBq \qquad T_{1/2} = 6h$$

$$A(^{99}Tc) = \frac{66h}{211{,}000\cdot 8722h}\cdot 4.3\cdot 10^{-4}\,Ci = 1.6\cdot 10^{7}\,Bq = 16\,MBq \qquad T_{1/2} = 1.84Gh$$

Activity development

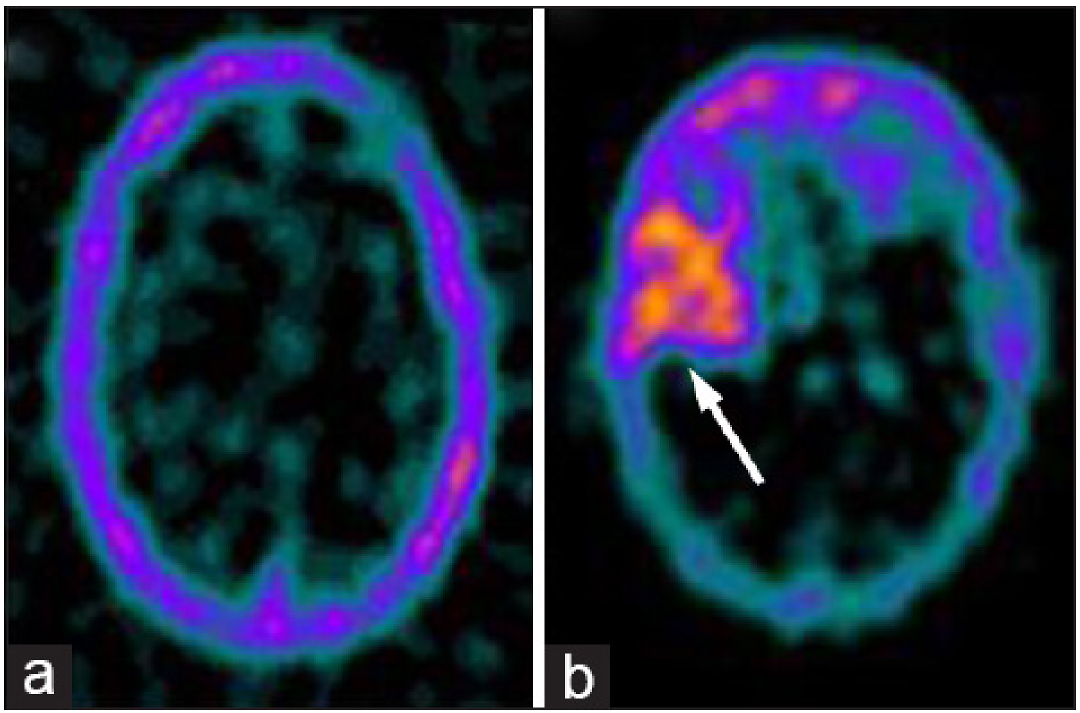




Through the decay of ^{99}Mo and ^{99m}Tc long-lived radioactive ^{99}Tc is being produced that gradually enriches the environment by naturally not occurring technetium. Considering the present production rate 1 GBq on ^{99}Tc is produced annually which decays by low energy β-decay and 90 keV γ-decay to the stable ^{99}Ru! 99Tc radioactive waste is typically stored in low level activity storage facilities….., but

^{99m}Tc applied to the patient ….

Typical quantities of technetium administered for ^{99m}Tc tests range from 400 to 1,100 MBq (11 to 30 mCi) for adults. These doses result in radiation exposures to the patient around 10 mSv (1000 mrem), the equivalent of about 500 chest X-ray exposures.



After the imaging procedure the radioactive ^{99m}Tc is biologically removed from body to minimize exposure.

Full body bone scan

What happens to ^{99}Tc? Example

Home of four radiologists with 50 patients daily, who get administered an average ^{99m}Tc activity of 500 MBq per person. This translates into a total average activity of 34 TBq annually. A fraction (guestimete 10%) gets into the public waste water system and a hopefully smaller fraction (guestimate 1%) of this amount is transferred onto plaza environment to decay to ^{99}Tc. This translates into 3.4 MBq of ^{99m}Tc into water system and river and 0.34 MBq of ^{99m}Tc being deposited onto the plaza.

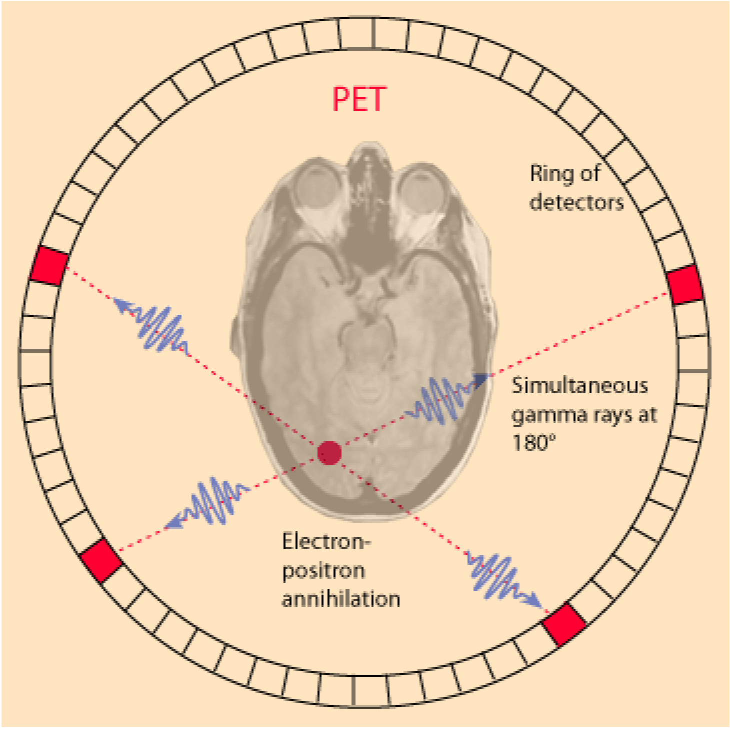
$$A(^{99m}Tc) = 34\,TBq \quad T_{1/2} = 6h$$

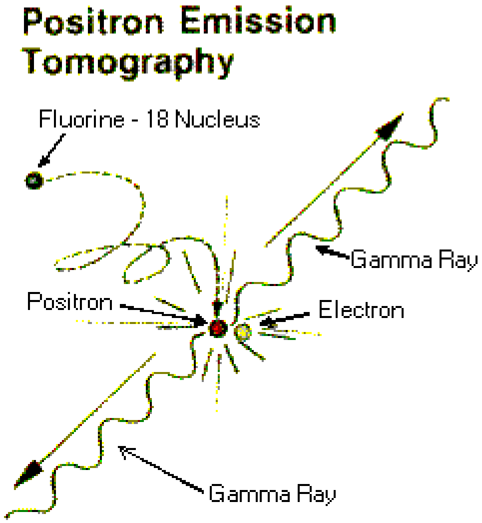
$$A(^{99}Tc) = \frac{6h}{1.84 \cdot 10^{9}\, h} \cdot 34 \cdot 10^{12}\, Bq = 1.1 \cdot 10^{5}\, Bq \qquad T_{1/2} = 1.84\,Gh$$

This means 10kBq are annually deposited into groundwater and 1 kBq is distributed by pedestrians over plaza. With a size of 5000 m^2 this accumulates to 2 Bq/m^2 over 10 years. According to lecture 16, the external exposure during 1 hour of shopping is $7 \cdot 10^{-14}$ Sv. There is significantly more in the granite paving of the plaza.

Positron Emission Tomography (PET)

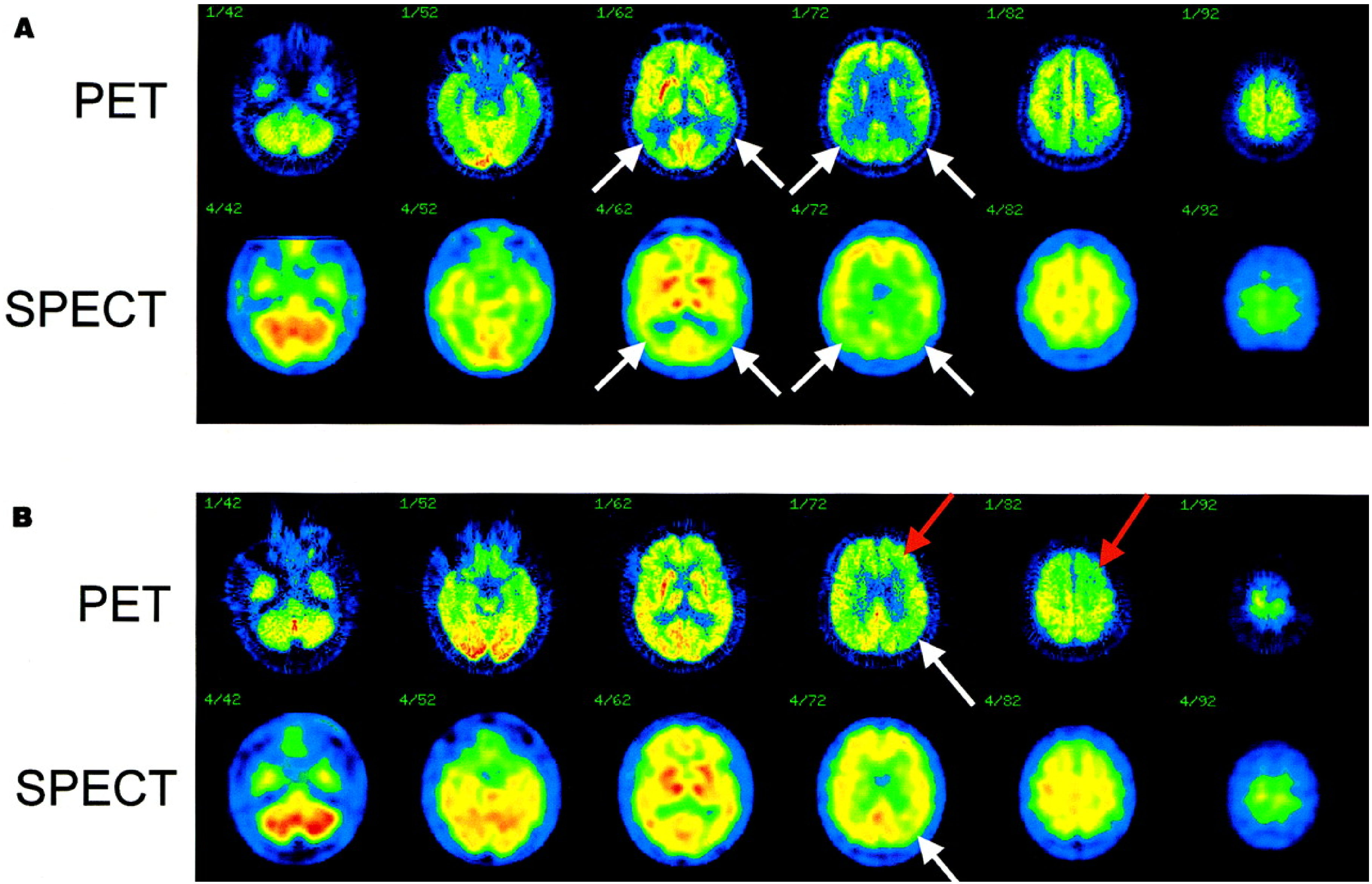
PET is superior to SPEC since it allows to obtain images with much better resolution due to gamma coincidence techniques. Neutron deficient material decays by positron devay and the positrons annihilate immediately with electrons to two 511keV γ-rays which are ejected in opposite directions. They are detected in a ring of single γ-detectors and the position of the decay event can be localized geometrically. The most common positron emitter in PET is ^{18}F with $T_{1/2}$=109.7 m.





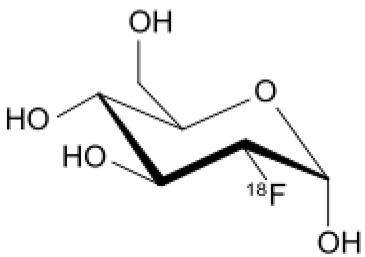
^{18}F is produced by nuclear reactions at cyclotron accelerators converting ^{18}O trough the $^{18}O(p,n)^{18}F$ reaction. ^{18}F decays back to ^{18}O.

Comparison of PET and SPECT image slices



Pet imaging

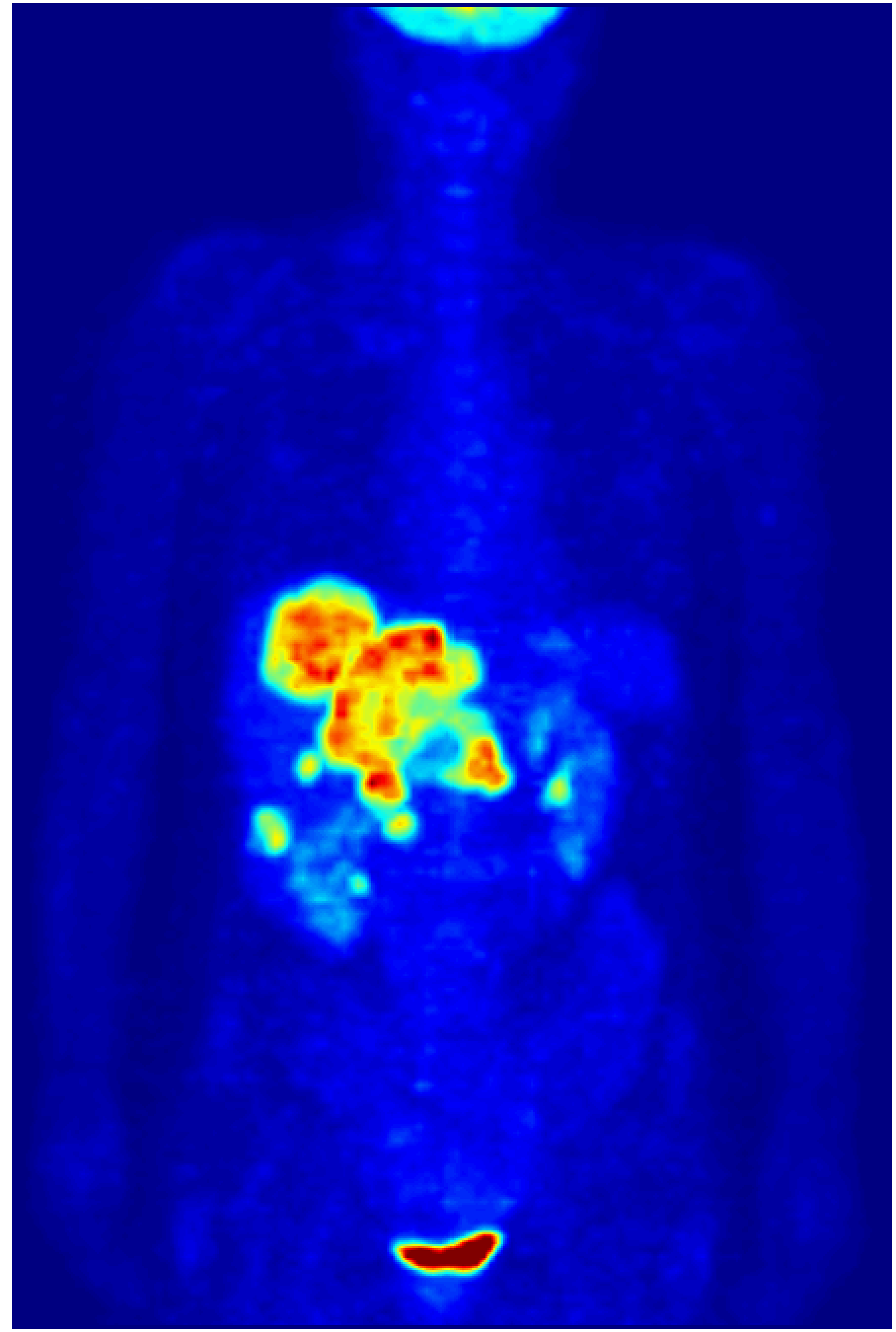
^{18}F is usually administered as sugary solution fluorodeoxyglucose or abbreviated ^{18}F-FDG.



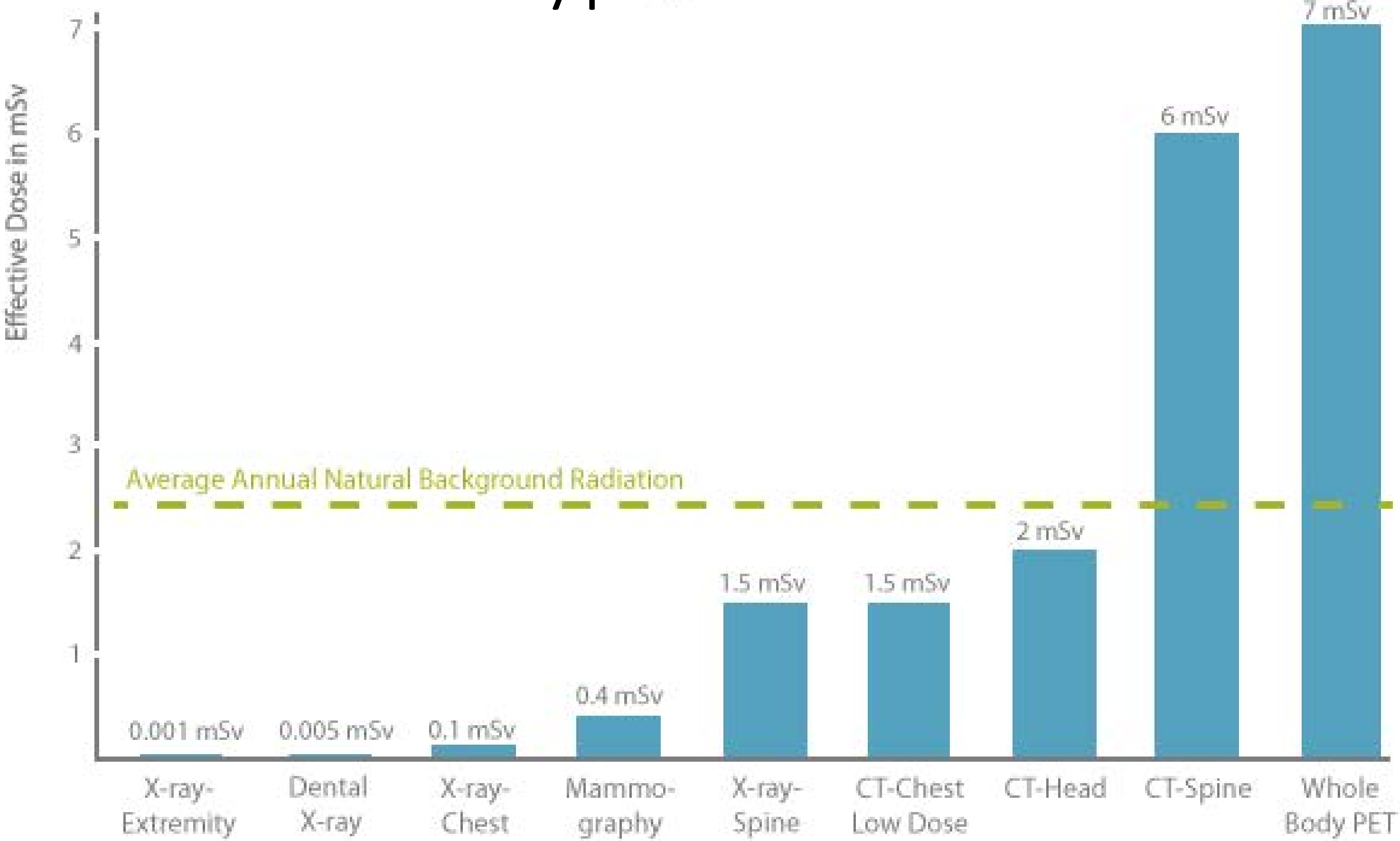
The ^{18}F-FDG accumulates in fast growing tumor cell material where is decays.

The average patient-specific effective dose from a typical injected ^{18}F-FDG activity of 450±32 MBq 1s 9.0±1.6 mSv. The high activity level is required to construct a high resolution high quality image of the 18F distribution in the tumor.

Whole-body PET scan using ^{18}F-FDG to show liver metastases of a colorectal tumor.



The typical dose …..



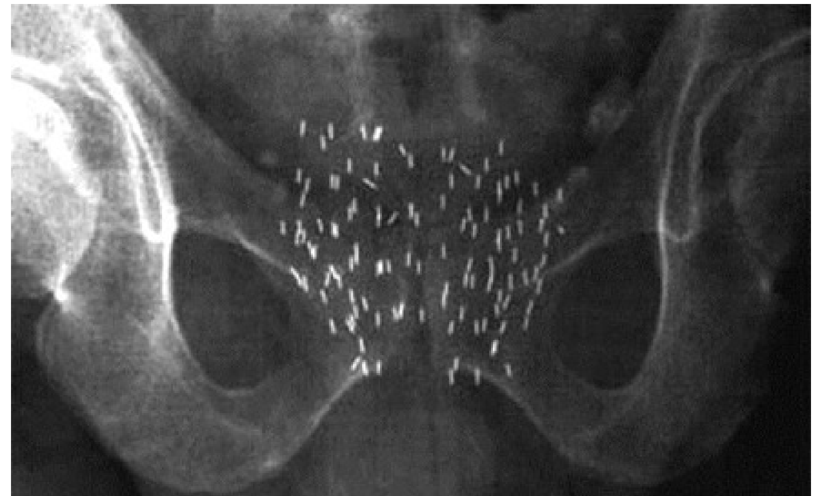
All information from radiologyinfo.org except "Whole Body PET" (Source: Radiation Exposure of Patients Undergoing Whole-Body Dual-Modality 18F-FDG PET/CT Examinations, Brix G et al., JNM, 46:4, 4/2005) and "Average Annual Background Radiation" (Source: http://www.iaea.org/Publications/Factsheets/English/radlife.html)

Medical Treatment with Radioactivity

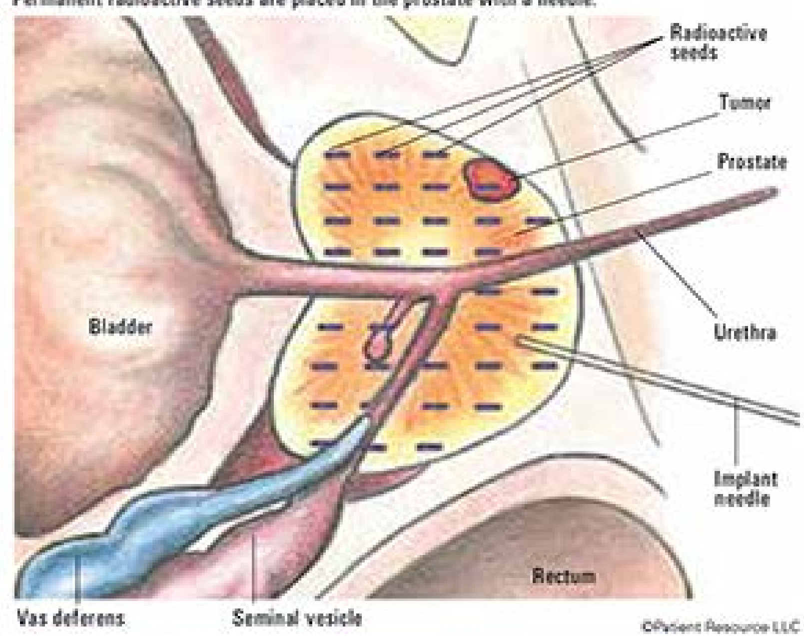
- High dose radiation treatment of tumor cells destroys the structure of the mutated cells and their genetic information.
- The exposure of neighboring cell needs to be minimized to avoid generating new mutations.
- Radiation can be administered internally by placing radioactive material next to the tumor (Brachytherapy) or externally by targeted gamma or particle irradiation. (External Beam Radiation Therapy, EBRT)

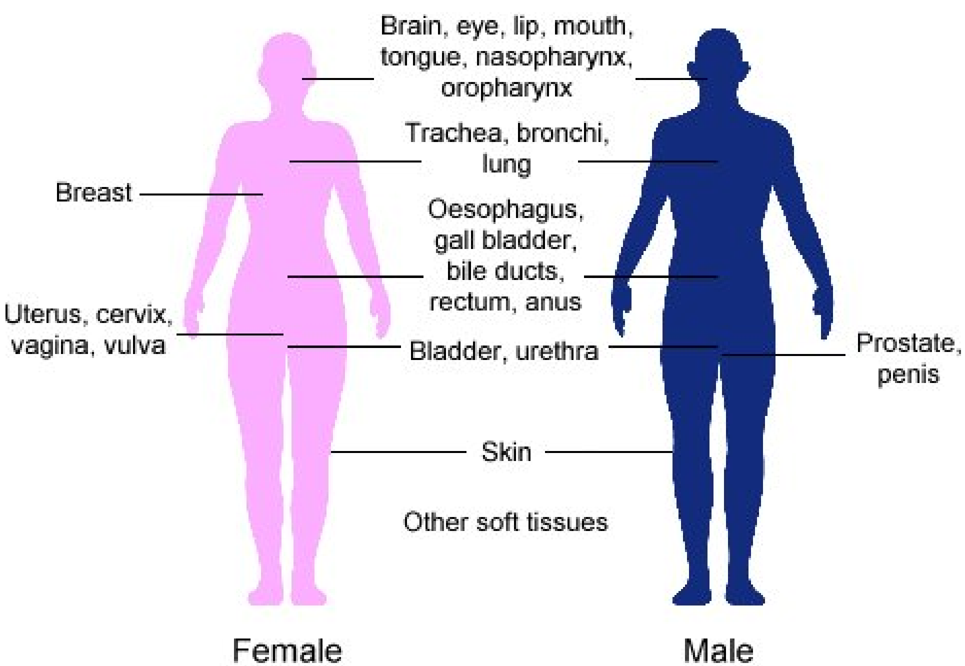
Brachytherapy

In Brachytherapy radioactive seeds or sources are placed in or near the tumor itself, giving a high radiation dose to the tumor while reducing the radiation exposure. It is primarily used for prostate cancer, breast cancer, lung cancer, gynecologic cancers, anal/rectal tumors, head and neck cancers. It is not as invasive as operation and minimizes damage to the surrounding body tissue.



Permanent radioactive seeds are placed in the prostate with a needle.





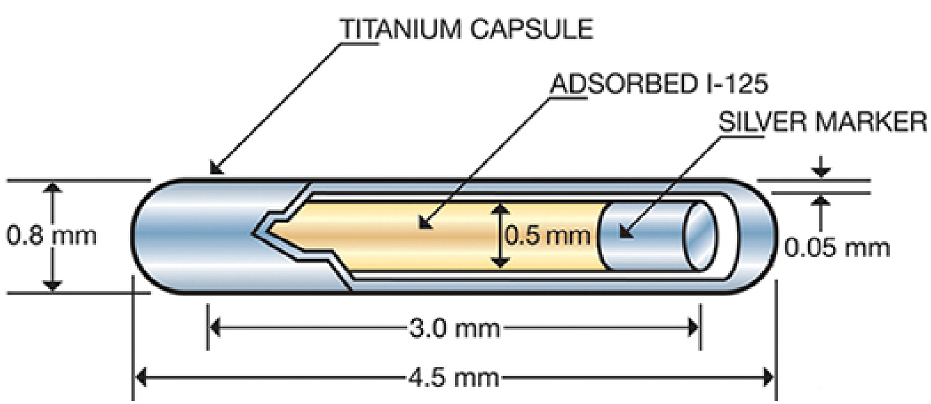
Effectiveness of Brachytherapy

Fig. 1. 1a y 1b: T1 squamous carcinoma, manifesting an ulcerous and costrous tumour affecting an external third of the inferior lip. 1c: Brachyterapy using Delclos rigid needles technique for LDR ^{192}Ir sources. 1d: Disparition of the tumour 2 months after brachytherapy with excellent esthetic and funtional results.

Radioactive sources for Brachytherapy

Radionuclide	Type	Half-life	Energy
^{131}Cs	EC	9.7 days	30.4 keV (mean)
^{137}Cs	β^--decay	30.17 years	0.662 MeV
^{60}Co	β^--decay	5.26 years	1.17, 1.33 MeV
^{192}Ir	γ-rays	73.8 days	0.38 MeV (mean)
^{125}I	EC	59.6 days	27.4, 31.4 and 35.5 keV
^{103}Pd	EC	17.0 days	21 keV (mean)
^{106}Ru	β^-- decay	1.02 years	3.54 MeV
^{226}Ra	β^-- decay	1599 years	

Treatment Parameters	Permanent seeds	Temporary seeds
Activity per source	0.1-3mCi	3-50mCi
Dose	80-700Gy	30-200Gy
Dose rate	3-30cGy/h	3-125cGy/h
Number of sources	1-171	1-28
Time to dose	infinity	4-50 days

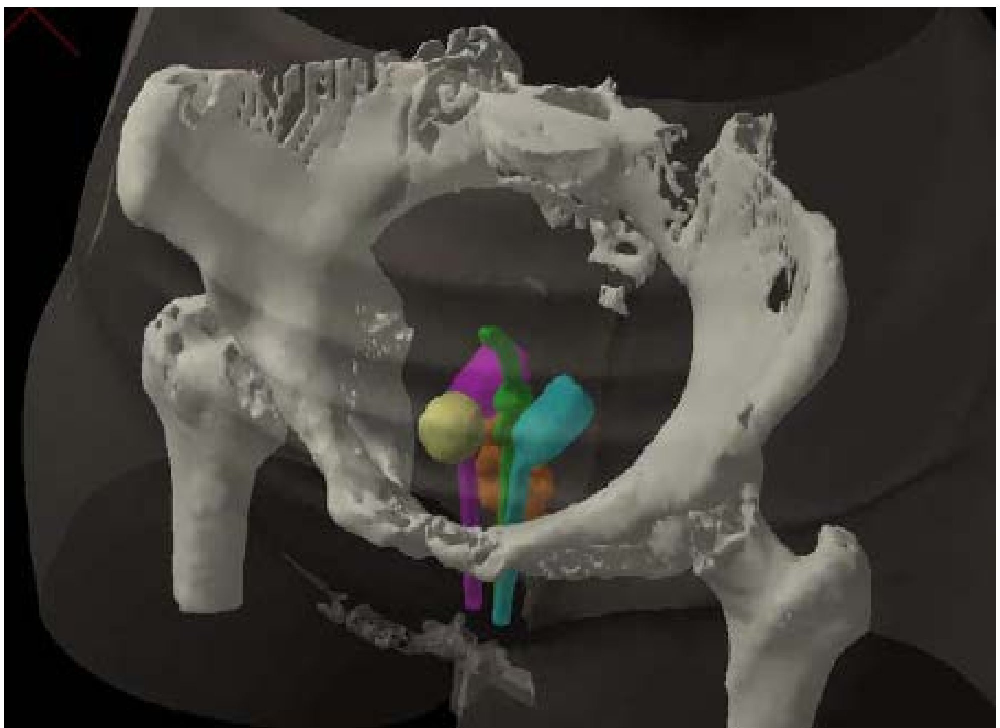


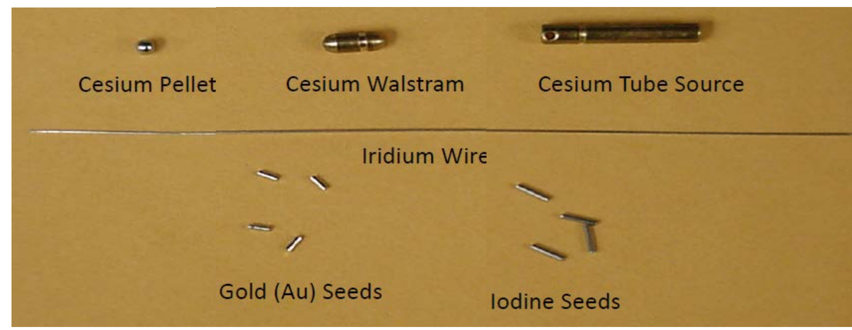
Dose rate in Brachytherapy

All of the radioactive materials used for Brachytherapy are β and/or γ emitter, the quality factor assessing the biological impact of radiation is therefore Q=1.

Low Dose Rate (LDR):
– Range of 0.4 to 2.0 Gy/hr (per ICRU #38)
– Time to deliver prescription is days

High Dose Rate (HDR)
– Dose rate > 12 Gy/hr (per ICRU #38)
– Time to deliver prescription is minutes



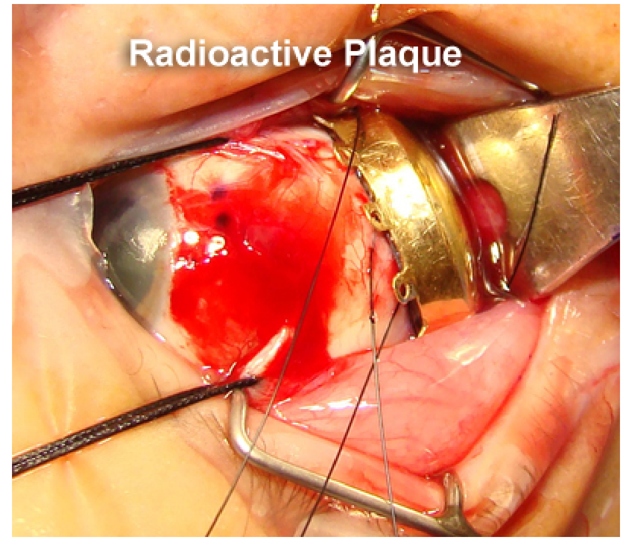


Characteristic dose of Cervical Cancer Treatment

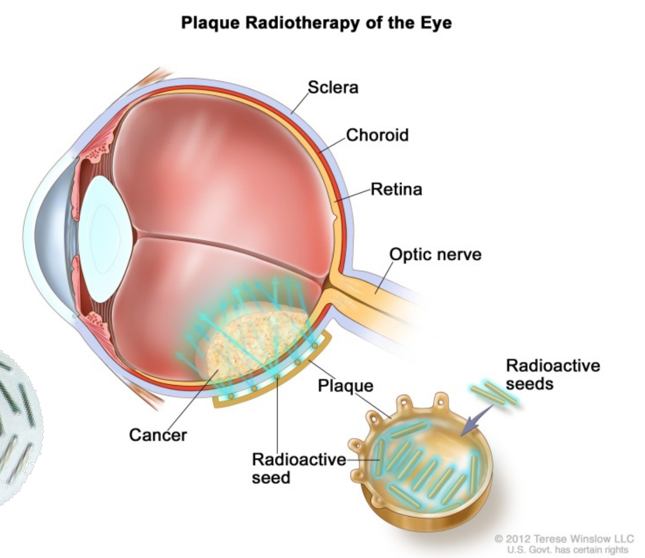
Reference point	Dose ± S.D.
Point A	87 ± 8 Gy
Bladder	70 ± 9 Gy
Rectum	70 ± 8 Gy
Vaginal surface	125 ± 15 Gy

External Contact treatment

- Places the radioactive sources on top of the area to be treated
- Long Dose Radiation time is about 72 h



Application	Annual Dose Limit	
	Occupational	**Public**
Effective Dose	20 mSv	1 mSv
Equivalent Dose to Organs		
Eye Lens	150 mSv	150 mSv
Skin	500 mSv	50 mSv
Hands and Feet.	500 mSv	-



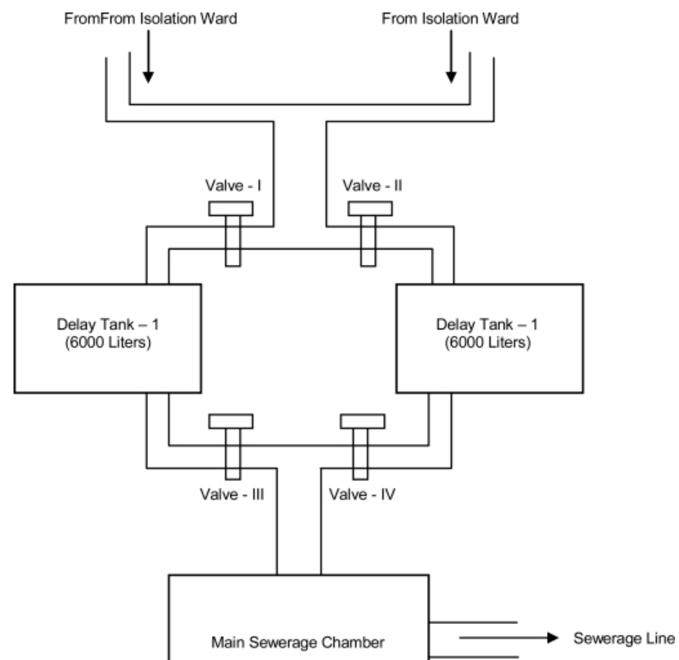
Disposal of radioactive hospital waste

Disposal limits for Sanitary Sewerage System

Radioisotope	Maximum Limit per day (MBq)	Average monthly discharge MBq/m^3
^{3}H	92.5	3700
^{14}C	18.5	740
^{24}Na	3.7	222
^{32}P	3.7	18.5
^{35}S	18.5	74
^{45}Ca	3.7	10.1
^{99}Mo/^{99m}Tc	3.7	185
^{125}I	3.7	22.2
^{131}I	3.7	22.2

Typically medical radioactive waste is short-lived, long term storage is not an issue but the increasing amount that is being released and not properly taken care of might institute a problem!

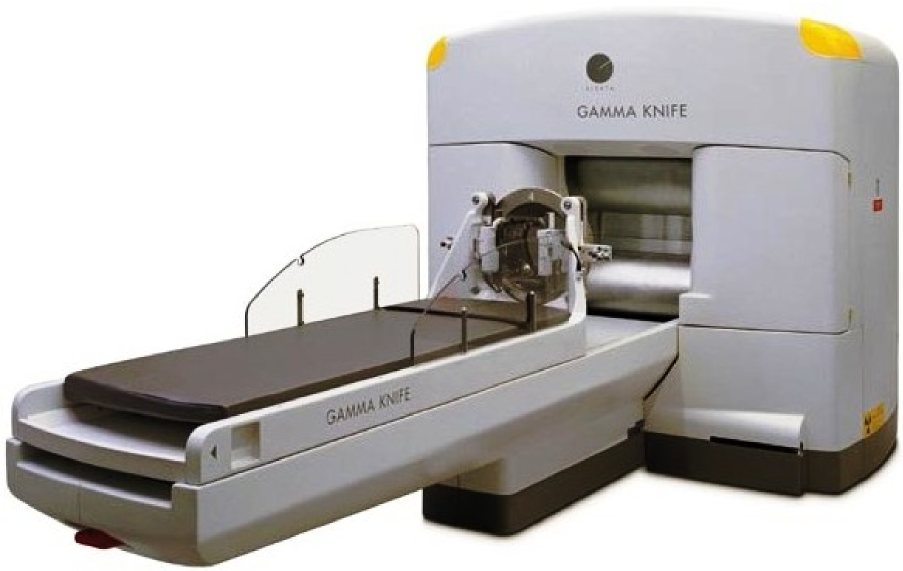
Higher level radiation levels are stored in delay tanks waiting for decay to legally acceptable levels of radiation.

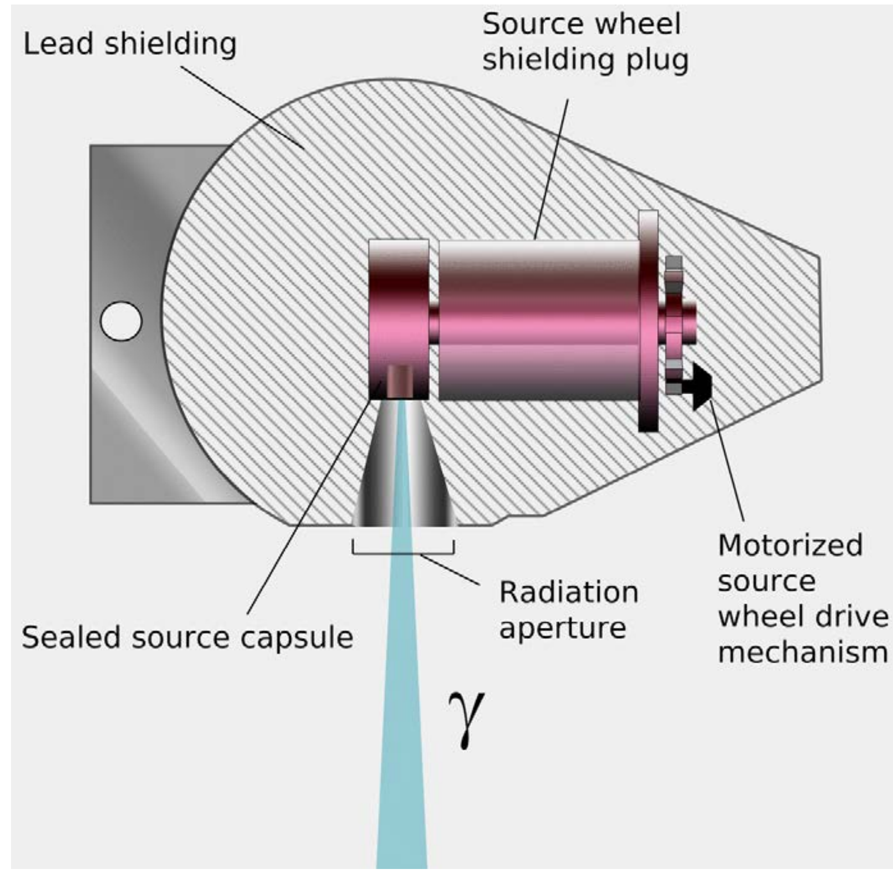


Theletherapy

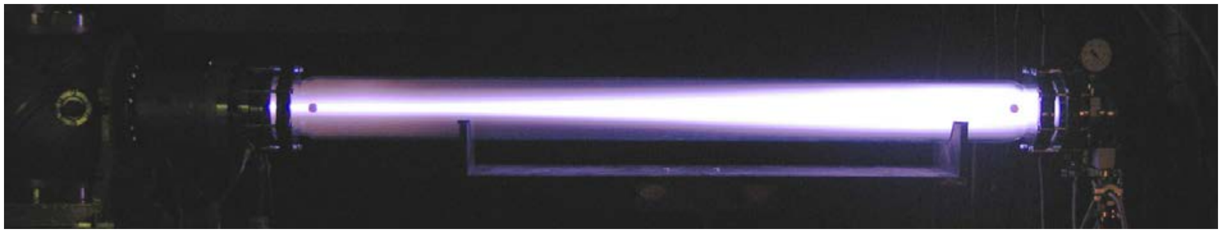
or γ/β-irradiation of tumor

- ➢ Either a Cobalt gamma source emitting 1.17 and 1.33 MeV γ rays in high intensity at tumor
- ➢ Or a linear electron accelerator producing 4-40 MeV electrons for tumor irradiation

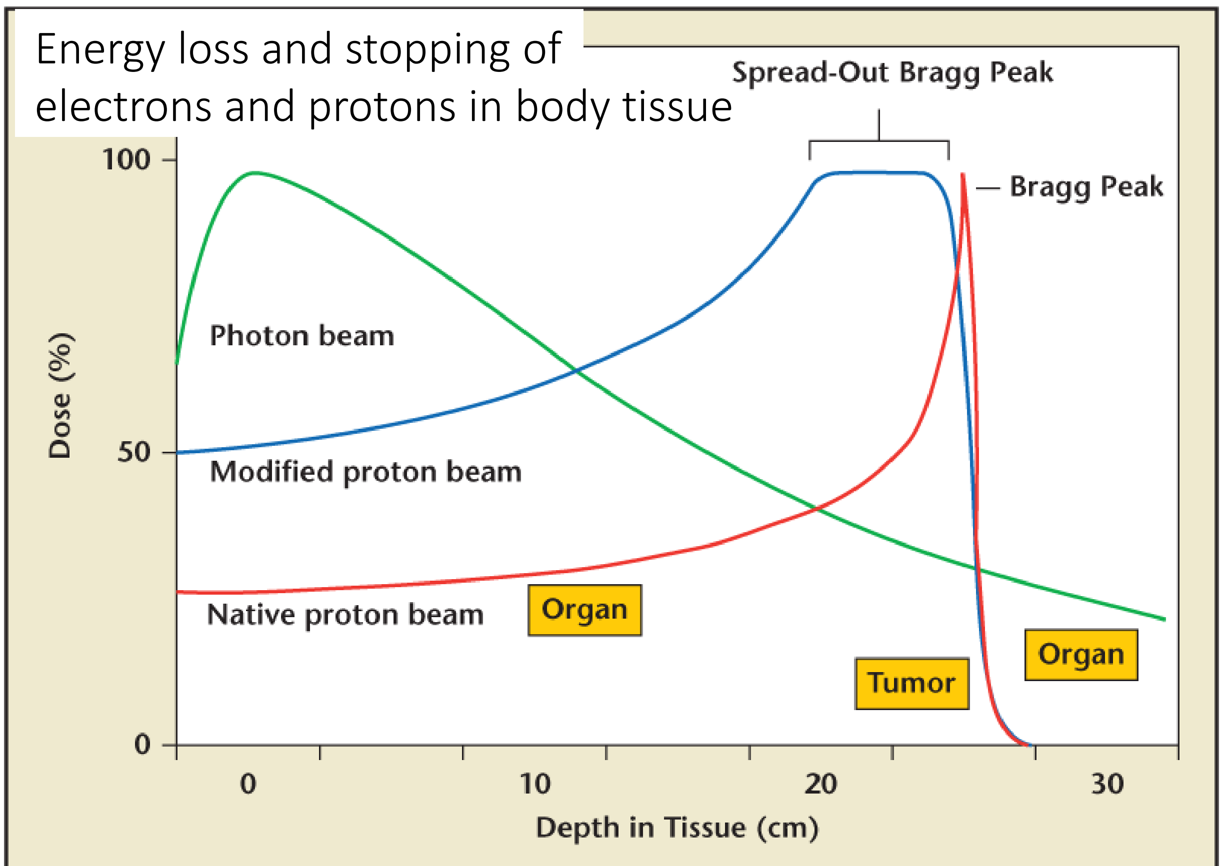


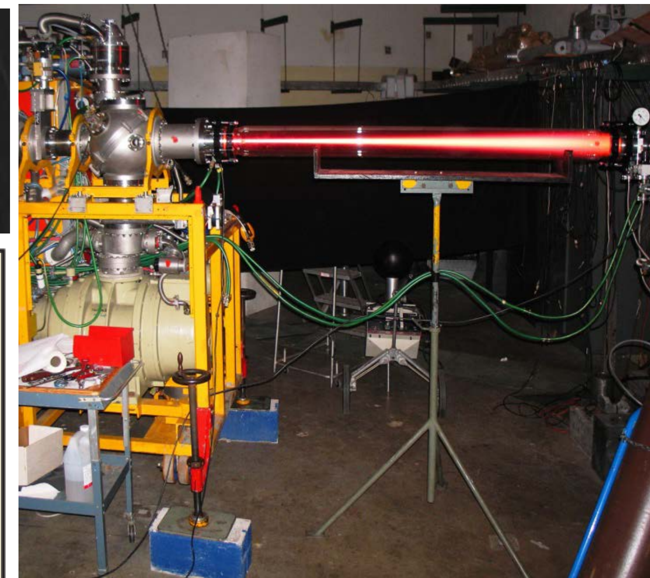


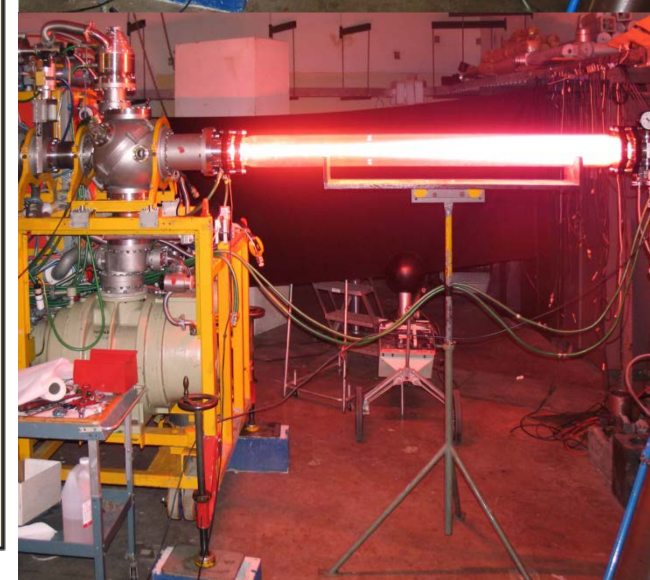
External Beam Radiation Therapy, EBRT



Energy loss and stopping of electrons and protons in body tissue

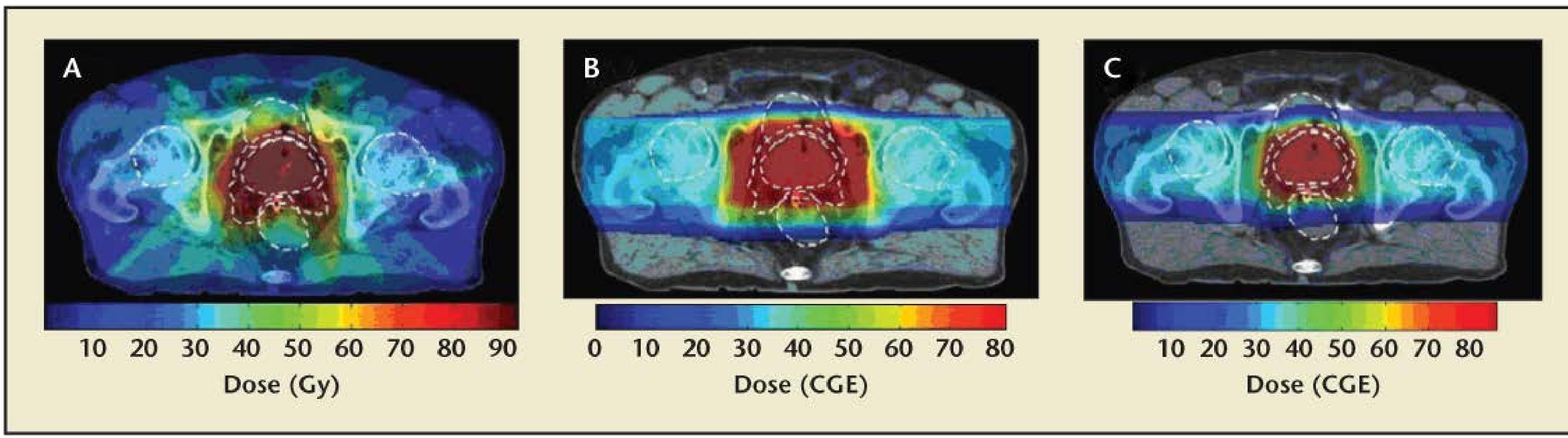






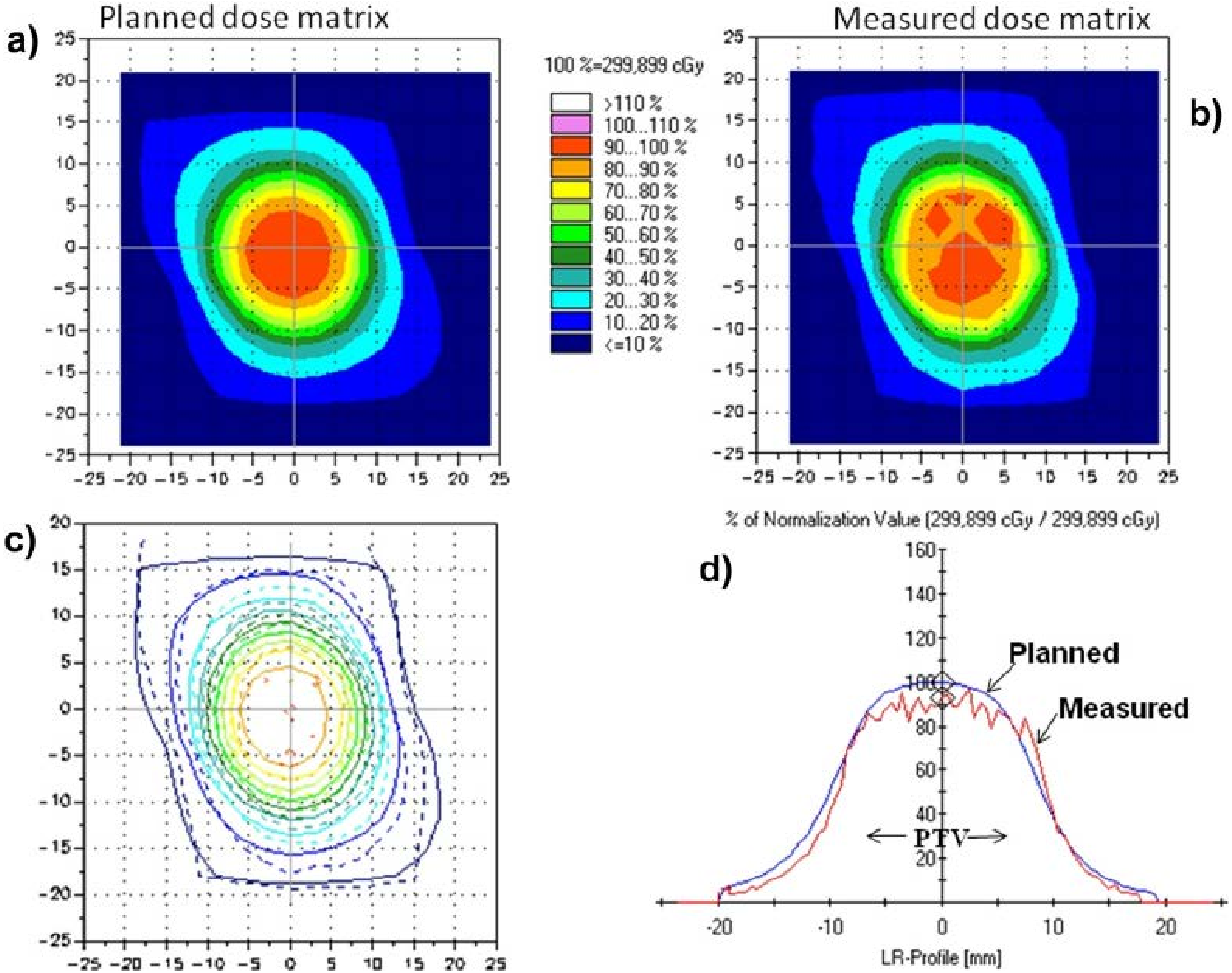
Radiation and Dose level associated with EBRT

EBRT is used to target a tumor with higher, more precise doses of radiation. The dose is not extended through the entire body, but focuses through the particular stopping conditions on well defined spots reducing damage to healthy tissue and nearby organs. It is supposed to be maximized for the so-called planning target volume (PTV) defined in preceding treatment plan.



Dose distribution during a EBRT therapy with a finely tuned proton pencil beams with different modes of modulations for the treatment plan. CGE≡Cobalt Gray Equivalent correlates to the biological dose for Sievert!

Optimization and quality of EBRT



Example on required beam intensities

The dose delivered to a specific organ requires several Gray, while minimizing the does to surrounding organ material

A proton beam of 250 MeV energy is used for radiation treatment of a tumor of 1 kg. Typically an 80% efficiency in reaching the PTV can be achieved. What is the beam intensity in Amperes needed for depositing a dosage of 2 Gy in 2 minutes?

$$D = \frac{E_{beam}}{m_{Tumor}} = \frac{250MeV}{1kg} \cdot \frac{1.6 \cdot 10^{-13} J}{1MeV} \cdot N_{beam} \cdot 120s \cdot 80\% = 2Gy$$

$$N_{beam} = \frac{2Gy}{4 \cdot 10^{-11} J/kg \cdot 120s \cdot 0.8} = 5.2 \cdot 10^{8} \frac{protons}{s} = 8.3 \cdot 10^{-11} Cb/s = 83pA$$

$$1p = 1.6 \cdot 10^{-19} Cb$$

The power of the beam deposited in the body is:

$$P = \frac{E \cdot I}{e} = 250 \cdot 10^{6} V \cdot 83 \cdot 10^{-12} A = 0.02W$$

Higher beam power beam would destroy (burn) the body tissue!