Radiation Protection

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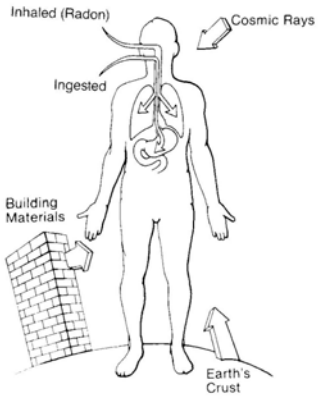
Slides from E. Podgorsak. PhD

Radiation Risk

- Risks associated with radiation exposure can only be restricted but cannot be eliminated entirely because:
  - Radioactive substances producing ionizing radiation occur naturally and are permanent features of the environment
  - Man-made radiation sources are now widespread
  - Sources of ionizing radiation are essential to modern life, in health care, industry, and agriculture

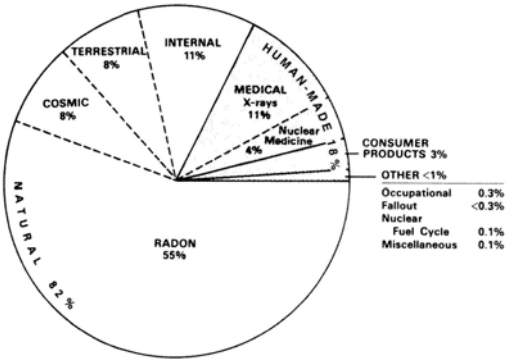
Natural Background Radiation

- Natural background radiation delivers doses to humans
- Two categories of sources:
  - Natural sources:
    - Cosmic rays
    - Natural radioactive materials
    - Radionuclides naturally in the body
  - Enhanced natural sources
    - Air travel
    - Phosphate mining
    - Radon exposure



Annual Background Rad.

- Average Effective Dose: 360 mrem
- Radon largest source of radiation
- Medical diagnostic x-rays largest from human activities
- Overall effective dose of background (w/o radon) equal to medical radiation



Radiation Effects

- Exposure to radiation can cause detrimental health effects that fall into one of two categories:
  - Deterministic
  - Stochastic
- In addition to deterministic and stochastic effects in adults, other health effects may occur in infants due to exposure of the embryo or foetus to radiation, such as:
  - Greater likelihood of leukaemia (stochastic effect).
  - Severe mental retardation and congenital malformations (deterministic effects).

Deterministic Effects

- Deterministic effects occur at relatively large doses and are called deterministic because they are certain to occur, if the dose exceeds a threshold level
- Deterministic effects are the result of various processes, mainly cell death and delayed cell division, caused by exposure to large radiation doses
- Severity of a particular deterministic effect in an exposed individual increases with the dose above the threshold for the occurrence of the effect

Stochastic Effects

- Radiation exposure can also induce delayed effects such as malignancies and hereditary effects, which:
  - Are expressed after a latency period
  - May be epidemiologically detectable in a population
  - Are called stochastic effects because of their random nature
- This cancer induction is assumed to take place over the entire range of doses without a threshold level:
  - The probability of occurrence of cancer is higher for higher doses
  - The severity of cancer that may result from irradiation is independent of dose

Objectives in Radiation Protection

- To prevent occurrence of non-stochastic disease
- To limit the risk of stochastic effects
- Agencies –
  - International Commission of Radiological Protection (ICRP)
  - National Council on Radiation Protection and Measurements (NCRP)
  - Nuclear Regulatory Commission (NRC)

Radiation Protection Quantities

- Other dose related quantities have been introduced to account not only for physical effects but also for biological effects of radiation upon tissues
- The special radiation protection quantities are:
  - Organ dose
  - Equivalent dose
  - Effective dose
  - Collective dose

Radiation Protection Quantities

- Organ dose D_T is defined as the mean dose in a specified tissue or organ T of the human body, given by:

$$D_T = \frac{1}{m_T} \int_{m_T} D \, dm = \frac{\varepsilon_T}{m_T}$$

  - m_T is the mass of the organ or tissue under consideration
  - ε_T is the total energy imparted by radiation to that tissue or organ.

Radiation Protection Quantities

- Equivalent dose H_T is defined by the organ dose $D_{T,R}$ multiplied by a radiation weighting factor w_R to account for the effectiveness of the given radiation in inducing biological detriment or harm:

$$H_T = w_R \, D_{T,R}$$

  - $D_{T,R}$ is the absorbed dose delivered by radiation type R averaged over a tissue or organ T.
  - w_R is the radiation weighting factor for radiation type R.

Radiation Protection Quantities

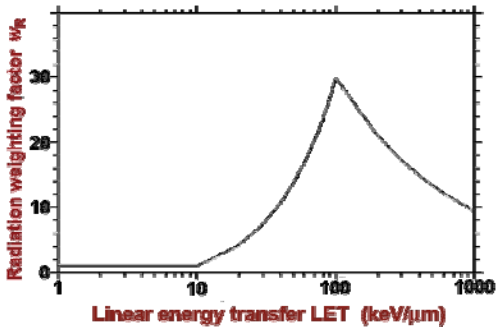
- The biological detriment to an organ depends upon:
  - The physical average dose received by the organ
  - The pattern of the dose distribution that results from the radiation type and energy.
- For the same dose to the organ, alpha or neutron radiation will cause greater harm compared with gamma rays, x rays, or electrons because the ionization events produced by alpha or neutron radiation will be much more closely spaced.

Radiation Protection Quantities

- Radiation weighting factor w_R is a dimensionless number ($w_R \geq 1$) which depends on the way in which the energy of the radiation is distributed along its path through the tissue.
  - $w_R = 1$ for all x rays, gamma rays, and electrons
  - $w_R = 5$ for protons $E_K > 2$ MeV; for neutrons $E_K < 10$ keV
  - $w_R = 10$ for neutrons 10 keV < E_K < 100 keV and $E_K > 2$ MeV
  - $w_R = 20$ for neutrons 100 keV < E_K < 2 MeV
  - $w_R = 20$ for alpha particles, fission fragments, heavy nuclei

Radiation Protection Quantities

- The linear energy transfer (LET) of the radiation describes the rate of energy deposition along the track (in keV/μm):
  - High LET radiation: heavy charged particles
  - Low LET radiation: x rays, gamma rays, electrons (beta particles)



Equivalent Dose

- The SI unit of equivalent dose H_T is J/kg and its name is the Sievert (Sv).
- The old unit of the equivalent dose H_T is the rem.
- The relationship between the Sievert and the rem is:

  1 Sv = 100 rem.
- Example:
  - For 1 Gy of photon dose to an organ (organ dose D_T = 1 Gy), the equivalent dose dose H_T = 1 Sv, since w_R = 1 for photons.
  - For 1 Gy of organ dose of 20 keV neutrons, the equivalent dose H_T = 10 Sv, since w_R = 10 for 20 keV neutrons.

Effective Dose

- Effective dose E is defined as the summation of tissue equivalent doses, each multiplied by the appropriate tissue weighting factor w_T, to indicate the combination of different doses to several different tissues in a way that correlates well with all stochastic effects combined.

$$E = \sum w_T H_T$$

- The unit of effective dose E is J/kg and its name is the sievert (Sv).

Effective Dose

- Tissue weighting factors w_T are tabulated in ICRP Publication 60 and in the IAEA Basic Safety Standards (BSS).
- Despite depending on the sex and age of a person, for purposes of radiation protection the values for w_T are assumed constant and applicable to the general public:
  - $w_T = 0.20$ for gonads
  - $w_T = 0.12$ for lung, red bone marrow, colon, stomach
  - $w_T = 0.05$ for bladder, breast, liver, oesophagus, thyroid
  - $w_T = 0.01$ for skin, bone surface
  - $w_T = 1.0$ for whole body total

Effective Dose

- The weighting factors w_T and w_R are mutually independent:
  - The tissue weighting factors w_T are independent of radiation type.
  - The radiation weighting factors w_R are independent of tissue type.
- The effective dose E and the organ dose H_T are given as:

$$E = \sum w_T H_T \qquad H_T = \sum w_R D_{T,R}$$

- The effective dose then is:

$$E = \sum_T w_T \sum_R w_R D_{T,R} = \sum_R w_R \sum_T w_T D_{T,R}$$

Effective Dose

- When one deals with only one type of radiation in a given situation, the effective dose *E* is given as:

$$E = \sum_{T} w_T D_{T,R}$$

- The effective dose *E* is a measure of dose designated to reflect the amount of radiation detriment likely to result from the dose.
- Annual dose limits for occupational and public exposure are given in terms of annual effective dose.

Collective Dose

- The organ dose, equivalent dose, effective dose, and the committed dose all relate to the exposure of an individual.
- The collective dose relates to exposed groups or populations and is defined as the summation of the products of the mean dose in the various groups of exposed people and the number of individuals in each group.
- The unit of the collective dose is the man-sievert.

Radiation Exposure

- The radiation exposures cover normal and potential exposures of three distinct groups:
  - Workers pursuing their occupations (occupational exposures)
  - Patients in diagnosis or treatment (medical exposures)
  - Members of the public
- Radiation exposures are thus divided into three categories:
  - Occupational exposure
  - Medical exposure
  - Public exposure

Radiation Worker

- Any individual that receives radiation as a result of performing job duties
- Individual taking care of therapy patient is a radiation worker
- Radiation worker must be 18 or older
- Radiation worker may not be pregnant
- Radiation worker must receive safety training

Radiation Exposure

- Occupational exposure is defined as all exposures of workers incurred in the course of their work.
- Medical exposure is defined as the exposure incurred:
  - By patients as part of their medical diagnosis or treatment.
  - By individuals, other than those occupationally exposed, while voluntarily helping in the support and comfort of patients
- Public exposure is defined as exposure incurred by members of the public from radiation sources, excluding any occupational or medical exposure.

Radiation Exposure Dose Limits

<u>Occupational Limits</u>	
Effective Dose	
Annual	5 rem (50 mSv)
Equivalent Dose for tissues/organs	
Lens of Eye	15 rem (150 mSv)
Skin, hands/feet	50 rem (500 mSv)
<u>General Public</u>	
Effective Dose	
Annual	0.1 rem (1 mSv)
Hourly limit	2 mrem in any 1 hr
Equivalent Dose for tissues/organs	
Lens of Eye	1.5 rem (15 mSv)
Skin, hands/feet	5 rem (50 mSv)
<u>Embryo/fetus (monthly)</u>	
Equivalent Dose	50 mrem (0.5 mSv)

Pregnant Radiation Worker

- Declared Pregnant Worker must:
  - Declare in writing & give conception date (Have a form to be completed and returned)
  - Limit is 500 mrem per term
    - Recommended 50 mrem/mo
  - Must be voluntary
  - May be un-declared in writing
  - Wears dosimeter at umbilicus level

Shielding Calculations

- Attenuate using an absorber to reduce the radiation beam
- Proper shielding yields reduced radiation exposure
- Mobile lead shields available & positioned

General Shielding Calculations

- The three important parameters that influence external radiation exposure are: time, distance, and shielding
- The radiation dose received by individuals:
  - Is proportional to the time they spend in the radiation field; the dose is reduced by limiting the time spent in the radiation field.
  - Generally follows and inverse square law; the dose is reduced significantly by increasing the distance from the radiation source.
  - Is reduced if shielding attenuates the radiation; hence the dose will be reduced if the amount of shielding is increased.

Classification of Areas

- Areas of a practice can be classified as either controlled or supervised:
  - A controlled area is defined as an area in which specific protection measures and safety provisions are needed for controlling normal exposure and for preventing potential exposure.
  - A supervised area is an area that should be kept under review even though specific protection measures and safety provisions are not normally needed

Classification of Areas

- In radiotherapy practice controlled areas are:
  - All irradiation rooms for external beam radiotherapy.
  - Remote afterloading brachytherapy treatment rooms.
  - Operating rooms during brachytherapy procedures using real sources.
  - Brachytherapy patient rooms.
  - All radioactive source storage and handling areas.
- It is preferable to define controlled areas by physical boundaries such as walls or other physical barriers marked or identified with radiation signs.

Classification of Areas

- Supervised areas may:
  - Include areas requiring a regular review of the radiological conditions to determine whether there has been some breakdown of control in the procedures.
  - Involve areas surrounding brachytherapy patient rooms or around radioactive source storage and handling areas.
- All areas designated neither controlled nor supervised areas should provide protection required for the general public.

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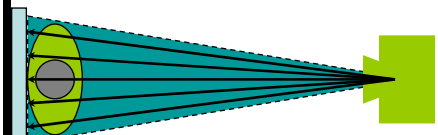
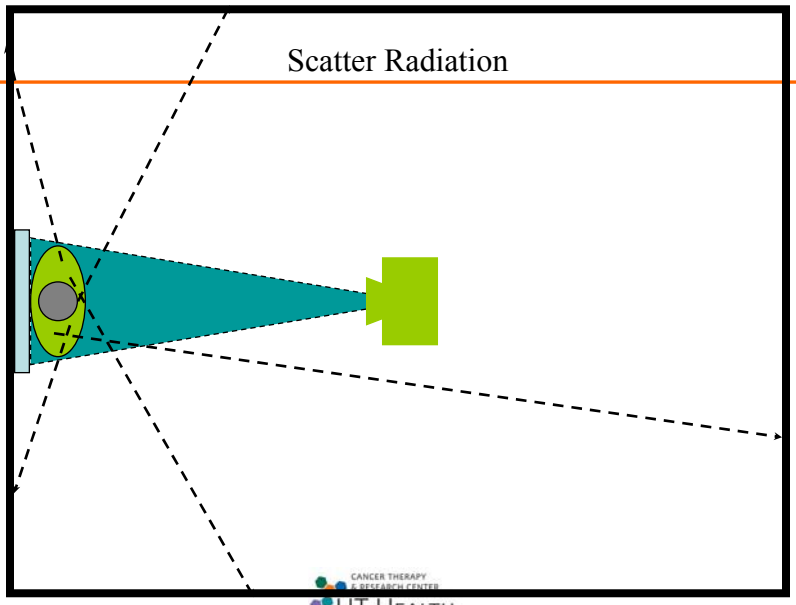
Structural Shielding Design

- Protective barriers are designed to ensure that the dose equivalent received by any individual does not exceed the applicable maximum permissible value
  - Areas surrounding the room are designated as controlled or uncontrolled
    - Dose Equivalent = 0.01 rem/week for uncontrolled areas
    - Dose Equivalent = 0.1 rem/week for controlled areas
  - Protection is required against 3 types of radiation
    - Primary Radiation
    - Scattered Radiation
    - Leakage Radiation

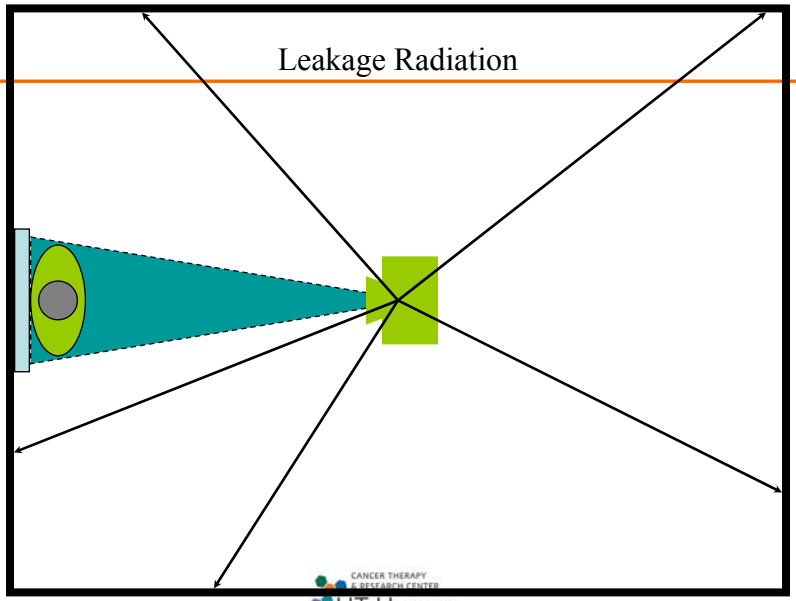
Primary Radiation



Scatter Radiation



Leakage Radiation



Shielding Barriers

- Two types of barriers are considered in shielding of radio-therapy installations: primary and secondary.
  - Primary barriers are the portion of the treatment room walls and ceiling that may be irradiated directly by the primary beam which originates in the x-ray target or radionuclide source.
  - Secondary barriers are all portions of the treatment room walls, floor and ceiling that cannot be irradiated directly by the primary beam. These barriers must provide shielding against two types of radiation: scattered radiation produced by the primary beam and leakage radiation transmitted through the head of the machine.

Shielding Barriers

- The primary barrier is irradiated directly by photons from the target or the source
- The primary barrier receives radiation resulting from:
  - Primary beam in the direction the LINAC is pointed

Shielding Barriers

- Secondary radiation is emitted in all directions and covers all of the treatment room surfaces.
- An adequately designed primary barrier will be more than sufficient as a barrier for all sources of secondary radiation.
- If the secondary barrier of a high energy linac installation is made of concrete, then the barrier will adequately absorb all photo-neutrons and neutron capture gamma rays, because of the relatively high hydrogen content of the concrete.

Workload (W)

- **Workload**: the maximum amount of dose that the machine will expect to produce at reference point in one week
  - These can be estimated or use published data
  - NCRP for “busy departments”
    - 1000 Gy/week in 0.5 to 10 MV range (NCRP 49)
    - 500 Gy/week above 10 MV (NCRP 51)

Use Factor (U)

Use factor: how often the beam is pointing in a particular direction

- Primary barriers only
- 25% for each wall and ceiling recommended by NCRP in the 1970s
- Special procedures need to be considered, e.g. IMRT, TBI

Use Factor (U)

TABLE 3—*Use factors for primary protective barriers*[a]

[To be used only if specific values for a given installation are not available.]

	Radiographic Installations	Therapy Installations
Floor	1	1
Walls	1/4	1/4
Ceiling	—[b]	—[c]

[a] The use factor for secondary protective barriers is usually 1.

[b] The shielding requirements for the ceiling of a radiographic installation are determined by the secondary barrier requirements rather than by the use factor which is generally extremely low.

[c] The use factor for the ceiling of a therapy installation depends on the type of equipment and techniques used, but usually is not more than 1/4.

Occupancy Factors (T)

Occupancy Level	Type of Area	T (Occupancy Factor)
Full	work areas, offices, labs, nurses stations, living quarters, children's play areas	1
Partial	corridors, restrooms, unattended parking lots	1/4
Occasional	waiting rooms, toilets, stairways, elevators, closets	1/16

Primary Barrier Transmission

- Calculation of primary barrier transmission
  - Transmission needed to provide desired protection level

$$B_x = \frac{P\, d_{pri}^{\,2}}{WUT}$$

Primary Barrier Transmission

- B_x is the barrier transmission needed
- P is the dose/week required outside barrier at protection point
- d_{pri} is the distance in meters from the target to the protection point, usually 1 ft (.305 m) from the outside of the barrier
- W is the workload
- U is the use factor
- T is the occupancy factor

Secondary Barrier Transmission

- Calculation of secondary barrier transmission
  - Three components: primary barrier scatter, head leakage, patient scatter
  - It is the current standard of practice to ignore the primary barrier scatter
  - For **energies above 10 MV**, the patient scattered radiation has low penetration compared to the head leakage and it is ignored (no need to calc patient scatter)

Head Leakage Transmission

– Barrier transmission for head leakage:
U = 1

$$B_l = \frac{1000\ P\ d_{sec}^2}{WT}$$

Leakage Transmission

– The factor of 1000 is used because the shielding of medical accelerators attenuates the radiation by at least this much. The manufacturer's specifications should be checked because it can be several times lower
– P is the dose/week required outside the barrier at the protection point
– d_{sec} is the distance (m) from the target to the protection point. There is a special case for horizontally mounted wave guides. The barrier behind the accelerator, in this case, is primarily subjected to leakage from the gun area. For this situation one uses the distance from the gun to the protection point.
– T is the occupancy factor. This will not necessarily be the same as for the primary barrier

Barrier for Patient Scatter

- Barrier transmission for patient scatter

$$B_p = \frac{400\, P\, d_{sca}^2\, d_{sec}^2}{\alpha W T F}$$

Barrier for Patient Scatter

- B_p is the barrier transmission needed
- P is the dose/week required at the protection point
- d_{sec} is the distance (m) from the scattering surface to the protection point
- d_{sca} is the distance (m) from the target to the patient
- F is the field size at the patient (cm^2)
- W is the workload
- T is the occupancy factor
- a is the ratio of scattered radiation intensity at 1 m to the primary radiation intensity at 1 m. This is called the scatter-primary ratio

Scatter-Primary Ratio (a)

Table 2-1 Scatter-primary ratio (a) at one meter from a human-size phantom for a size 400 cm^2 at the phantom, target to phantom distance of one meter

Scattering angle (deg)	*6 MV** *a*	*10 MV†* *a*
30	0.007	0.0030
45	0.0018	0.0010
60	0.0011	0.0005
90	0.0006	0.0003
135	0.0004	0.0002

*From NCRP Report No. 49.

†From Weise and Jost (1983).

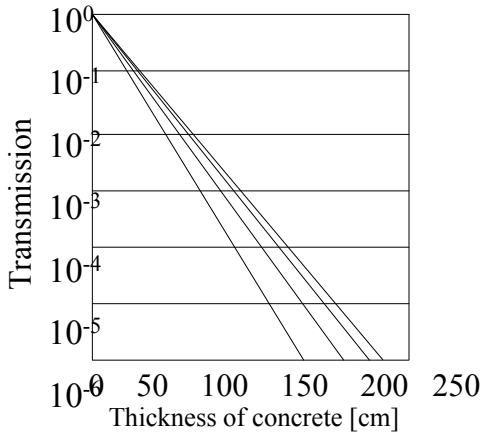
Rule of Thumb

- Rule of thumb in use when leakage and scatter used to determine barrier thickness: **if the thicknesses < 3 HVL, use the larger and add 1 HVL; if the difference equal to or > 3 HVL, use the thicker one.**

Barrier Thickness for Primary Beam

- To determine the Barrier thickness (S) for primary beam use:
  - Published transmission curve for barrier material and nominal energy, or
  - Published tenth-value layer data for barrier material and nominal energy

Thickness



Transmission through concrete, ρ = 2.35 g/cc, of x-rays produced at 4-10 MV. Based on NCRP Report 51 (27).

Published Tenth-Value Layer Data

Table 2-4 Tenth value layers in ordinary concrete, steel, and lead*

Electron energy (MeV)	Shield material	TVL_1 (m)	TVL_e (m)
6	concrete	0.35	0.35
	steel	0.099	0.099
	lead	0.055	0.057
10	concrete	0.41	0.39
	steel	0.104	0.104
	lead	0.057	0.056
15	concrete	0.46	0.43
	steel	0.108	0.108
18	concrete	0.47	0.43
	steel	0.108	0.108
20	concrete	0.48	0.44
	steel	0.108	0.109
24	concrete	0.51	0.46
	steel	0.109	0.109

*Adapted from figures E.12, E.13, and E.14 of NCRP Report No. 51 (NCRP 1977).

The number (n) of TVLs required for the shield can be obtained from equation 2-5 using the value of the barrier transmission factor (B_x).

Published Tenth-Value Layer Data

- Read material thickness directly off of transmission curve for appropriate energy
- Calculate thickness based on TVL data
  - For fixed TVL value

    $n = \log_{10}(1/B_x)$;

    $S = n\ TVL$
  - For TVL_1 and TVL_e

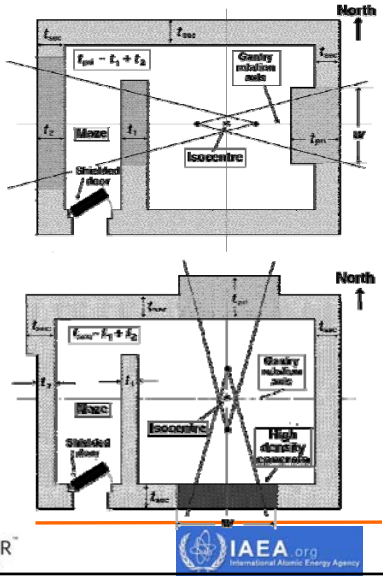
    $S = TVL_1 + (n-1)\ TVL_e$

LINAC Vault Design

- The main components of a typical linac installation are:
  - Treatment room
  - Entrance maze
  - Control room
- The maze connects the treatment room with the control room, which houses the operational controls of the linac.
- The treatment room and maze together are called the linac bunker or vault.

LINAC Vault Design

- Typical floor plan for a high-energy linac bunker.
- The thickness of the primary and secondary barriers is determined through:
  - First determining the transmission factors for a given barrier.
  - Then determining the barrier thickness required to achieve the calculated transmission.



Neutron Production

- In high-energy linac installations (above 10 MV), neutrons are produced by:
  - X ray - neutron (X,n) reactions.
  - Electron - neutron (e,n) reactions.
- The neutron contamination is produced by high energy photons and electrons incident on the target, primary collimator, beam flattening filter, collimator jaws, beam accessories, air and patient.

Neutron Production

- The cross section for (X,n) reactions is at least an order of magnitude larger than that for (e,n) reactions at the same energy; hence neutrons produced by the linac x-ray mode rather than the electron modes are of primary concern.
- The neutron contamination can be a direct or indirect hazard for patients in the treatment room and individuals in areas surrounding the linac bunker.

Neutron Production

- In the indirect hazard, neutrons can activate other elements (neutron activation), which remain radioactive and will contribute to the radiation exposure of radiotherapy staff entering the treatment room after a high energy photon beam treatment.
- The radionuclides from activated components of a linac are generally short lived (of the order of seconds to a few minutes).

Neutron Production

- The principal radionuclides produced through (n,γ) reactions in a high energy linac room are:
  - Aluminum-28 in the treatment table (half-life: 2.3 m)
  - Antimony-122 in lead shielding in the linac head (half-life: 2.6 h)
- Because of the short half-lives of the radioactive products, the dose equivalent rates in treatment rooms decay to background levels within 2 days, so there is no appreciable buildup of activity over the long term.

Neutron Production

- To minimize the staff dose resulting from radioactivation of the treatment equipment and room the following recommendations are in effect (NCRP 151, page 91):
  - All IMRT treatments should be delivered with low x-ray energies, such as 6 MV rather than 18 MV in dual energy linacs.
  - Equipment should be designed without the use of aluminum and other materials that have high neutron capture cross section.
  - Physics and QA measurements with high energy x-ray beams should be carried out at the end of the day to allow overnight decay of the activated products.

Neutron Production

- As far as the direct neutron hazard is concerned, the concrete primary and secondary barriers designed to protect against photon dose are quite adequate to protect against electrons and contamination neutrons.
- However, doors into high energy treatment rooms and ventilation ducts as well as large conduits piercing the treatment room barriers must be adequately shaped and constructed, so as to minimize the neutron hazard.

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Neutron Production

- An additional radioactivity problem to the neutron activation is the direct activation of elements in (x,n) reactions, such as oxygen-15 (half-life: 2 minutes) and nitrogen-13 (half-life: 10 minutes).
- The radioactivity in the treatment room air is removed by efficient room ventilation, which also handles the removal of ozone and noxious gases produced by photon interactions with air.
- Typically, there are 5 - 8 exchanges of air per hour in a high energy linac room.

Entrance Door: High-energy LINAC

- The door of a high-energy linac installation may require shielding against x rays and neutrons scattered through the maze toward the linac control area.
- Scattered high energy neutrons are more of a problem than low energy scattered photons.
- The door shielding in high-energy rooms is usually dominated by the neutron capture gamma ray and photoneutron requirements.

Entrance Door: High-energy LINAC

- Neutrons are thermalized and absorbed with a layer of about 12 cm of borated polyethylene (BPE) in the door.
- BPE (5% by weight) is only slightly less effective in fast neutron shielding, but is much more effective for thermal neutrons compared with polyethylene without boron.
- BPE is followed by about 2.5 cm of lead to absorb the gamma rays produced by neutron capture reactions (n, γ) in boron nuclei.

Additional Considerations

Intensity modulated radiotherapy (IMRT):

- The net result of the IMRT is that the absorbed dose is delivered from many directions around the patient with as much as 10 times the standard beam-ON time.
- The fluence on the primary barriers is similar to the conventional treatment regimen, but the leakage radiation on the secondary barriers may be much larger.

Additional Considerations

- The increase in monitor units (MU) required by the IMRT does not significantly increase the workload for the primary barrier or for the scatter barrier, thus the primary and scatter barrier thicknesses will be the same for conventional or the IMRT use.
- The contribution to the leakage workload, on the other hand, is significantly larger by a factor called the IMRT factor C_{IMRT}.

$$C_{IMRT} = \frac{MU_{IMRT}}{MU_{conv}}$$

Additional Considerations

- In comparison with conventional treatments, the increased leakage workload for the IMRT is compensated by:
  - Larger patient set-up times.
  - Use of lower energy x rays (typically: 6 MV) for IMRT treatments.
  - Conservative design of treatment rooms for conventional radiotherapy.
- It is thus generally accepted that a new linac to be used for the IMRT can be installed in a bunker designed conservatively for conventional radiotherapy with the same machine.

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Additional Considerations

- Radiation skyshine
  - Because of the advantage in shielding design, vaults are typically constructed without occupied space above them.
  - Some of these vaults are designed with little shielding in the ceilings. Also, in order to create a more pleasant atmosphere, some facilities have an atrium or skylight located in the secondary barrier portion of the ceiling
  - Skyshine is radiation that is scattered by the atmosphere to points at ground level.

Simulator Room Shielding

- Techniques for simulator shielding are similar to the techniques for linacs
- Some exceptions: the ceiling is shielded if the space above is occupied, lead-backed gypsum board is used in the walls, shielding is provided to a height of 7 feet above the floor, the door is wood with a lead core, and a viewing window made of leaded glass is provided so that the sim operator can see the patient

Brachytherapy Room Shielding

- HDR brachytherapy treatment rooms are designed with similar constraints as the linac and teletherapy rooms with one major difference:
- In HDR brachytherapy rooms, all walls are primary barriers, since:
  - Source can be positioned anywhere in the room.
  - Radiation is emitted isotropically and uncollimated from the source.

Brachytherapy Room Shielding

- The primary barrier transmission factor B_{pri} for an HDR brachytherapy machine is calculated similarly to the external beam therapy case except that the use factor U = 1.

$$B_{pri} = \frac{P\, d_{pri}^2}{W_{BT} T}$$

  - P is the design effective dose.
  - d_{pri} is the distance from the source to the point of interest.
  - W_{BT} is the brachytherapy workload in Gy.m^2/week
  - T is the occupancy factor

Brachytherapy Room Shielding

- Attenuation of the radiation beam in the patient is not accounted for when calculating the required primary barrier thickness.
- Although the treatment time increases because of the source decay, the product (activity x time) remains the same and hence the barrier thickness is determined for the maximum source activity and its corresponding treatment time.

Personal Radiation Monitoring

- Those radiotherapy professionals most likely to require individual monitoring are:
  - Radiation oncologists
  - Qualified experts in radiotherapy physics (medical physicists)
  - Radiotherapy technologists
  - Source handlers
  - Radiation protection officers
  - Maintenance staff
  - Nursing or any other staff spending time with patients who contain radioactive sources.

Personal Radiation Monitoring

- Monitoring includes:
  - Measuring and determining the equivalent dose
  - Interpretation of monitoring results
  - Assessment of measured results
- Individual external doses can be determined by using individual monitoring devices (TLD or film badges) worn on the front of the upper torso and an assumption is made that the whole body is uniformly exposed.

Personal Radiation Monitoring

- In a radiotherapy department the personal dosimeters should be exchanged at regular intervals not exceeding 3 months.
- The reports should become available no later than within 3 months after the exchange.
- If a dosimeter is lost, the licensee shall perform and document an assessment of the dose the individual received and add it to the worker's dose record.

NRC Regulations

- License is required from the NRC for possession or use of byproduct materials
- Administrative Requirements:
  - ALARA Program
  - Radiation Safety Officer (RSO)
  - Quality Management Program
- Unintended Deviation:
  - Recordable Event
    - Weekly dose: >15% of prescribed dose (teletherapy)/10% (brachy)
  - Misadministration
    - Wrong patient, SRS dose >10%
    - Teletherapy dose: weekly dose >30%, total dose >20%