Stanford Radiation Oncology Residents' Physics Course
2009-2010

Radiation Protection

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ASTRO's 2007 Core Physics Curriculum for Radiation Oncology Residents

Learning Objectives

1. General concept of shielding, including exposures that are "as low as reasonably achievable" (ALARA), and federal regulations.

2. Units of personnel exposure, sources of radiation, (man-made and natural), and means of calculating and measuring exposure for compliance with regulations.

3. Components of a safety program, including NRC definitions and the role of a radiation safety committee.

Klein et al. IJROBP 68(5): 1276-1288, 2007.

ASTRO's 2007 Core Physics Curriculum for Radiation Oncology Residents (cont'd, p.2)

A. Radiation safety - Concepts and units

Radiation protection standards
- Definitions for radiation protection
- Quality factors [Dose equivalent]
- Effective dose equivalent

Types of radiation exposure
- Natural background radiation
- Man-made radiation

(NCRP) #91 Recommendations on Exposure Limits
- Protection regulations

Klein et al. IJROBP 68(5): 1276-1288, 2007.

ASTRO's 2007 Core Physics Curriculum for Radiation Oncology Residents (cont'd, p.3)

NRC definitions
- Medical event
- Authorized user
- NRC administrative requirements

Radiation safety program
- Radiation safety officer
- Radiation safety committee
- NRC regulatory requirements (including security)

Personnel monitoring

Klein et al. IJROBP 68(5): 1276-1288, 2007.

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B. Radiation shielding

Treatment Room Design

- Controlled/uncontrolled areas
- Types of barriers
- Factors in shielding calculations
- Workload (W)
- Use factor (U)
- Occupancy factor (T)
- Distance

Shielding calculations (including IMRT)

- Primary radiation barrier
- Scatter radiation barrier
- Leakage radiation barrier
- Neutron shielding for high-energy photon beams

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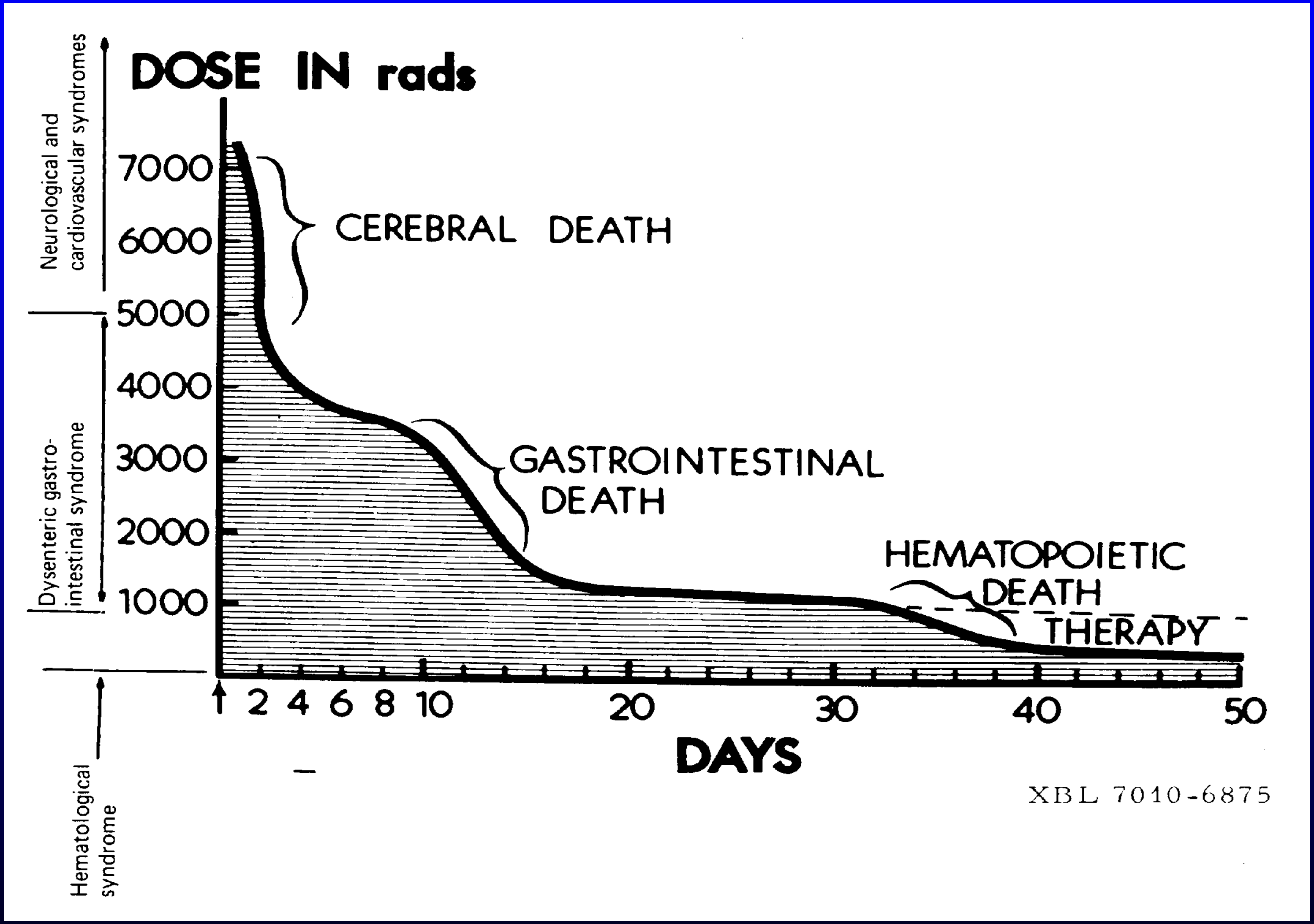
Sealed source storage (Brachytherapy)
Protection equipment and surveys

Operating principles of gas-filled detectors as radiation monitoring equipment
Ionization chambers (Cutie Pie), Geiger–Mueller counters, Neutron detectors

Additional shielding design issues
- Shielding requirements for conventional simulators, CT simulators
- High dose-rate (HDR) unit shielding (linac vault vs. dedicated bunker)
- Special procedure shielding (total body irradiation [TBI])

High-Level Radiation Effects

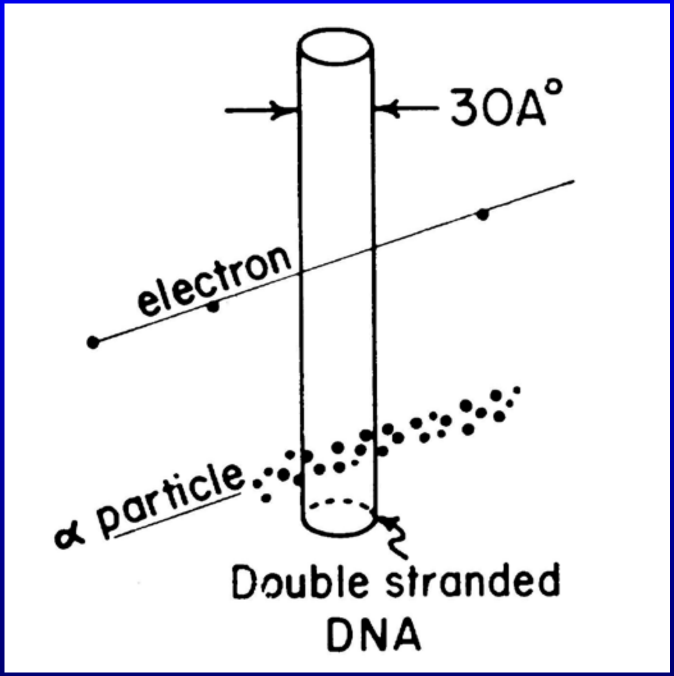


Low-Level Radiation Effects

(e.g. less than 10 cGy)

- Genetic Effects – radiation-induced gene mutations, chromosome breaks, and anomalies
- Neoplastic Diseases – leukemia, thyroid tumors, skin lesions
- Effect on Growth and Development – fetus and young children
- Effect on Life span – diminishing life span or premature aging
- Cataracts – opacification of lens

High-LET vs. Low-LET



Not all dose is biologically equivalent, e.g., densely-ionizing (high-LET) α particles deposit dose that is more biologically effective than dose from X-rays or electron beams (low-LET)

Equivalent Dose H

Special unit used in radiation protection

Sievert (Sv)

Equivalent Dose : $H[Sv] = D[Gy] \bullet W_R$

W_R is **Quality Factor (formerly Q)**

X-rays, electrons	$W_R = 1$
Protons	$W_R = 2$
Thermal neutrons	$W_R = 5$
Fast neutrons	$W_R = 20$
Alpha, pions	$W_R = 20$

Older Unit: $H[rem] = D[rad] \bullet Q$

Question

10 μSv is equal to ________ mrem.

A. 100
B. 10
C. 1
D. 0.1
E. 0.01

Effective Dose (E)

When irradiation is from radionuclides deposited in various tissues and organs, nonuniform or partial body exposures usually occurs.

Effective dose (E) is associated with the same probability of the occurrence of cancer and/or genetic effects as received by the whole body.

Quantities and Units for Radiation Measurement and Radiation Protection

Exposure X

↓

Absorbed Dose D

↓

Equivalent Dose H_T

↓

Effective Dose H_E

Effective Dose Equivalent

In addition, biological response to radiation varies based on tissue type. Therefore, dose equivalent is modified to **effective dose equivalent**, as defined by

$$E = \sum W_T \ H_T$$

Effective dose equivalent

Organ weight factor

Equivalent dose

$W_T = 0.01$	$W_T = 0.05$	$W_T = 0.12$	$W_T = 0.20$
Bone surface Skin	Bladder Breast Liver Esophagus Thyroid	Bone marrow Colon Lung Stomach	Gonads

W_T values from NCRP 116 – quoted from ICRP Publication 60 (1990)

Stochastic vs. non-stochastic

- Stochastic effect: probability increases with dose, but severity does not depend on magnitude of dose (“all or none” effect)

- Non-stochastic effect: somatic effect that increases in severity with increasing dose in an individual, owing to damage to increasing numbers of cells and tissues; also called deterministic effect.

Adapted from NCRP 91

Low-Level Radiation Effects

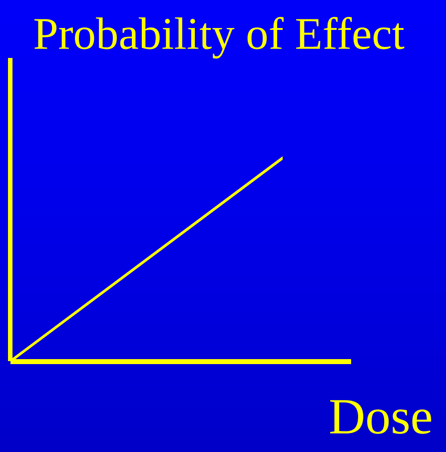
Stochastic effects

Carcinogenesis

Genetic effects

Birth defects

Example : leukaemogenesis



Non-stochastic, or deterministic effects

Increases in severity with increasing absorbed dose

Fibrosis

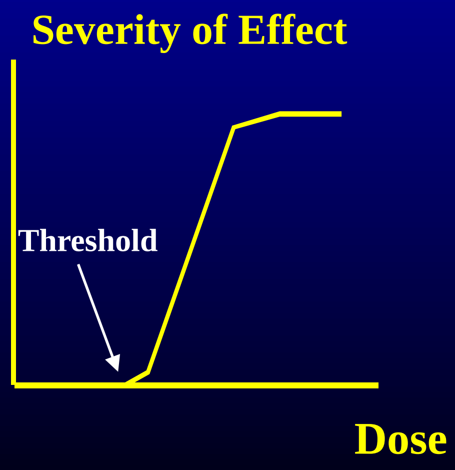
Organ atrophy

Lens opacification

Blood changes

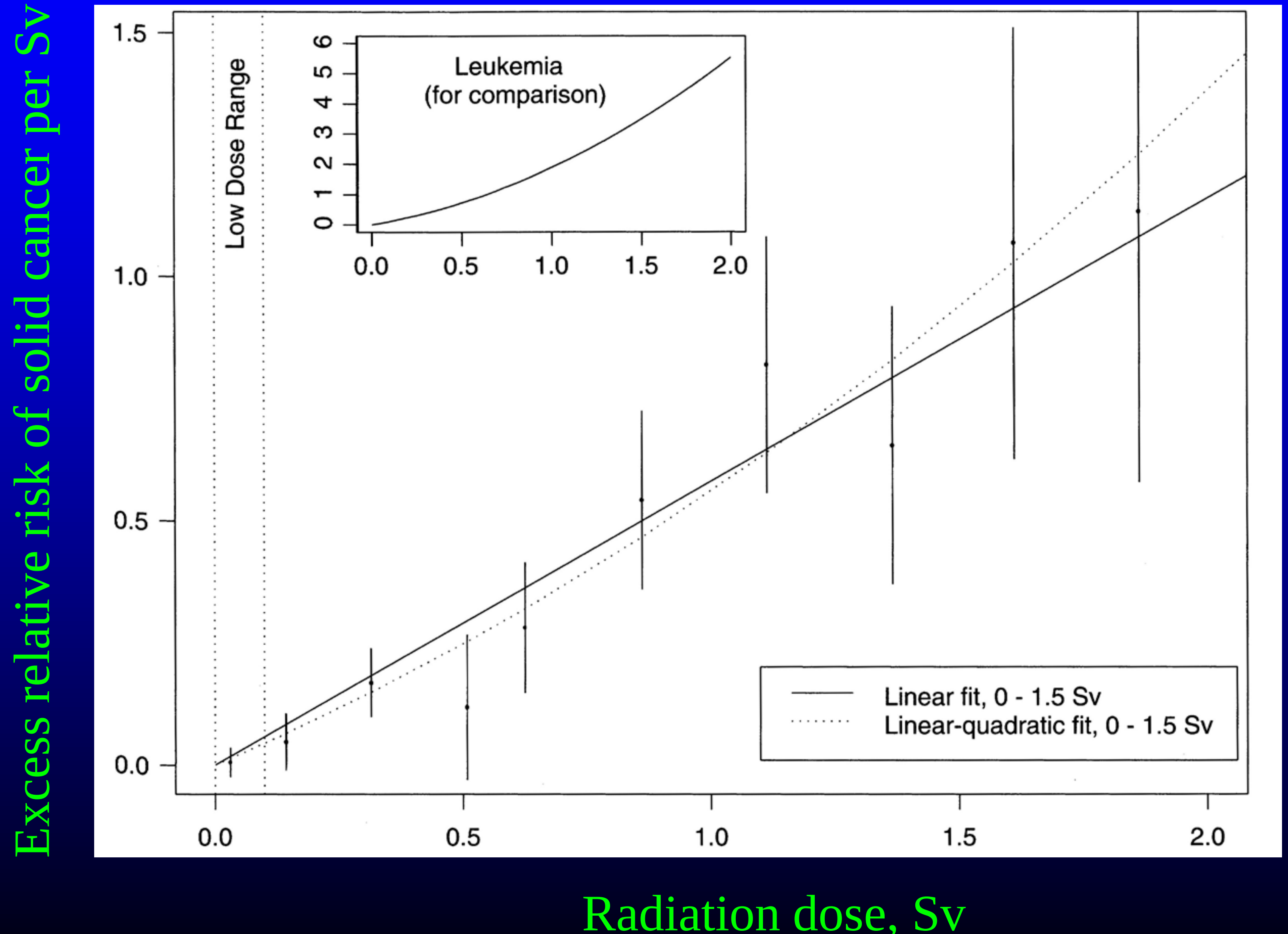
Decrease in sperm count

Examples : epilation, radiation sickness, erythema



Stochastic radiation risks

BEIR VII data on A-bomb survivors



Objectives of Radiation Protection

- **Stochastic effects:** To limit risk to a reasonable level in comparison with non-radiation risks* by adhering to dose limits below apparent practical thresholds

- **Non-stochastic effects:** To prevent, to the extent practicable, occurrence of severe radiation-induced deterministic effect

* ~ 10^{-4}/y occupational

Adapted from NCRP 91

Effective Dose Equivalent Limits

should conform to the "ALARA Principle":

Ensure that total societal detriment of radiation exposures from justified activities is…

<u>A</u>s <u>L</u>ow <u>A</u>s <u>R</u>easonably <u>A</u>chievable

…taking into account economic and social factors

Justifications and ALARA radiation exposure limits must also ensure that individuals or groups of individuals are not subjected to levels exceeding acceptable risk.

Principles of Radiation Protection

1. Any activity involving radiation exposure must be justified on the basis that expected benefits exceed predicted cost (i.e., risk)
2. Need to reduce total radiation detriment to as low as reasonably achievable (ALARA)
3. Need to apply individual dose limits to ensure that justification and ALARA do not result in exceeding levels of acceptable risk

Adapted from NCRP 91

Radiation Protection Standards

Proposed by national and international councils and agencies

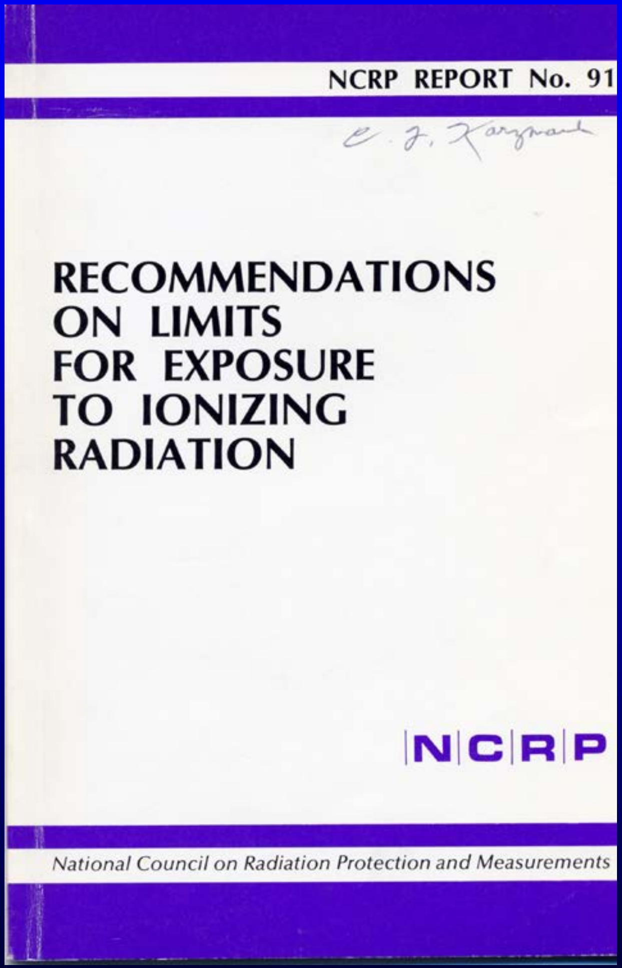
- National Council on Radiation Protection and Measurements (NCRP)
- International Commission on Radiological Protection (ICRP)
- International Atomic Energy Agency (IAEA)

<u>None</u> of these agencies has regulatory authority, even though IAEA is a United Nations Commission

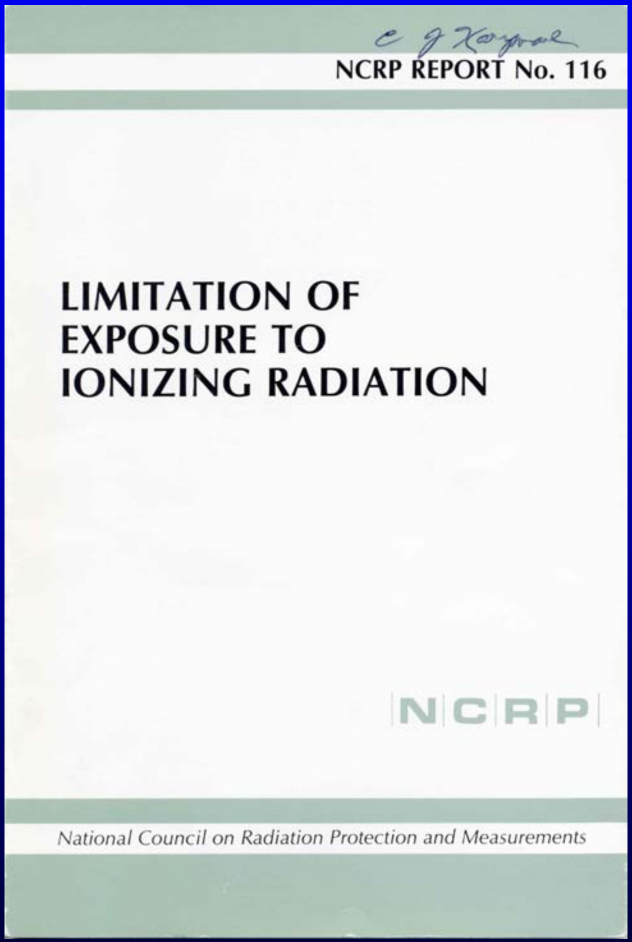
Regulatory Agencies

- Nuclear Regulatory Commission (NRC)
- State Department of Health
- Department of Transportation (U.S. DOT)
- FDA (radiopharmaceuticals)

NCRP Reports 91 and 116

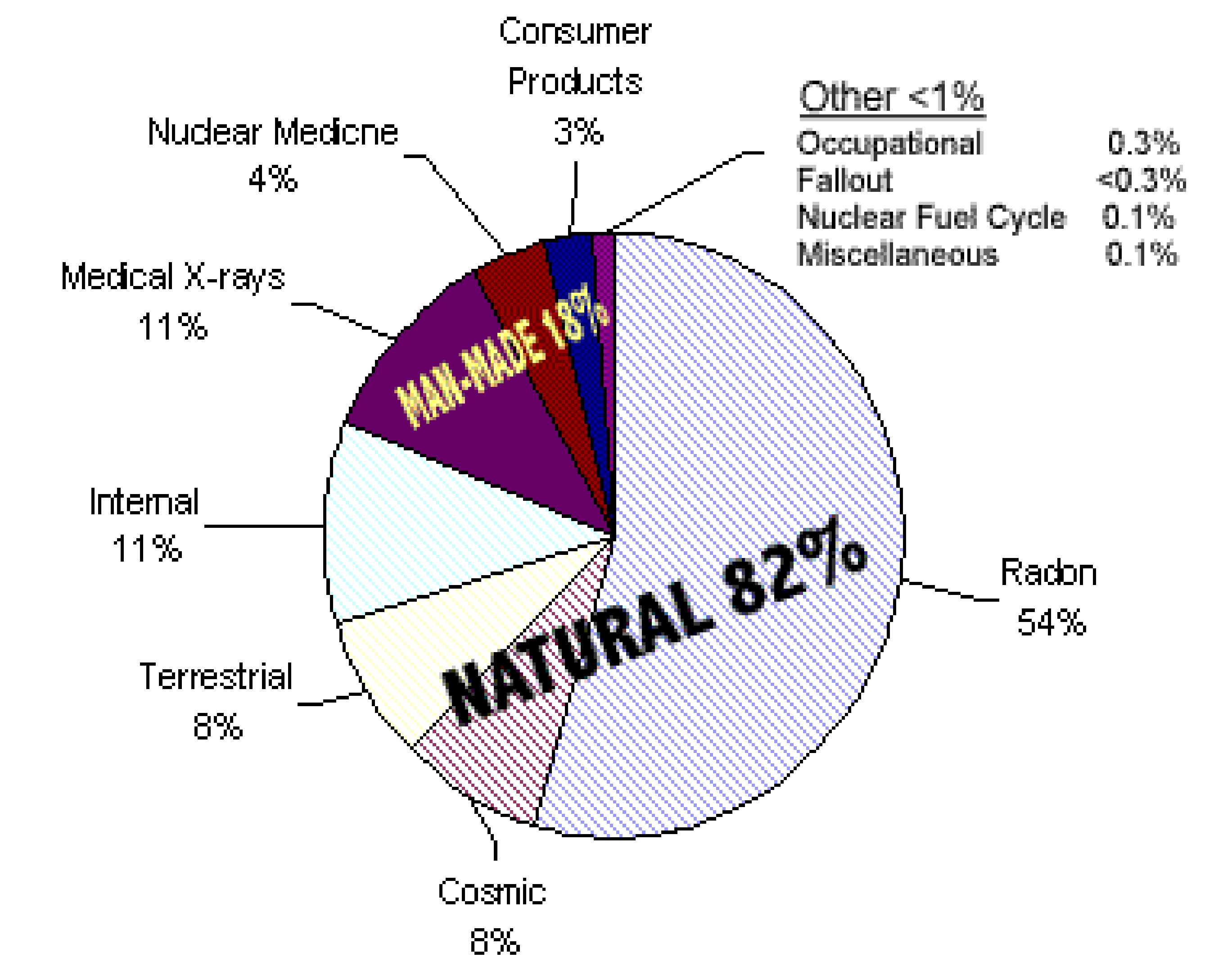


1987



1993

Background Radiation



Background Radiation – Effective Dose

- **Natural Background**
  Excluding radon: 100 mrem/year
  Including radon: 330 mrem/year

- **Medical**
  30 mrem (chest film)
  300 mrem (abdominal)

Question

The largest contribution to the radiation exposure of the U.S. population as a whole is from:

A. Radon in the home.

B. Medical x-rays.

C. Nuclear medicine procedures.

D. The nuclear power industry.

Question

The annual average natural background radiation dose to members of the public in the United States, excluding radon, is approximately _____ mrem

A. 10

B. 50

C. 100

D. 200

E. 400

Effective Dose Equivalent Risk Estimates

Nominal lifetime probability coefficients for stochastic effects

	Detriment			
Exposed Population	Fatal Cancer	Nonfatal Cancer	Severe genetic Effects	Total Detriment
	10^{-2} Sv^{-1}	10^{-2} Sv^{-1}	10^{-2} Sv^{-1}	10^{-2} Sv^{-1}
Adult Workers	4.0	0.8	0.8	5.6
Whole Population	5.0	1.0	1.3	7.3

NCRP Report No. 116 “Limitation of Exposure to Ionizing Radiation. 1993

Effective Dose Equivalent Limits

Summary of Annual Occupational and Public Dose Limits

A. Occupational exposures	
1. Effective dose limits	
a) Annual	50 mSv (5 rem)
b) Cumulative	10 mSv x age
2. Equivalent dose annual limits for tissues and organs	
a) lens of eye	150 mSv (15 rem)
b) skin, hands and feet	500 mSv (50 rem)
B. Public exposures (annual)	
1. Continuous or frequent	1 mSv (100 mrem)
2. Infrequent	5 mSv (500 mrem)
3. For tissues and organs	
a) lens of eye	15 mSv (1.5 rem)
b) skin, hands and feet	50 mSv (5 rem)
C. Embryo-fetus (monthly)	0.5 mSv (50 mrem)

NCRP Report No. 116 “Limitation of Exposure to Ionizing Radiation, 1993.

Dose Limits - Patient's Relatives/Visitors

- The dose limits for members of the public do not apply. However,
  - the dose must be constrained so that it is unlikely that an effective dose of 5 mSv will be exceeded during the diagnostic procedure or treatment
  - for children, the constraint should be 1 mSv

Effective Dose Equivalent Limits

Dose Limits for Pregnant Women

Annual Maximum Permissible Dose

50 mSv	**5 rem**	**Radiation Worker**
5 mSv *	**0.5 rem**	**Pregnant Radiation Worker**
1 mSv	**0.1 rem**	**General Public**

* NCRP Report No. 105, *Radiation Protection for Medical and Allied Health Personnel, (1989).*

Effective Dose Equivalent Limits

Negligible Individual Risk Level [NIRL] (NCRP 91)

Negligible Individual Dose [NID] (NCRP 116)

"a level of average annual excess risk of fatal health effects attributable to irradiation, below which further effort to reduce radiation exposure to the individual is unwarranted"

NID is 0.01 mSv = 1mrem

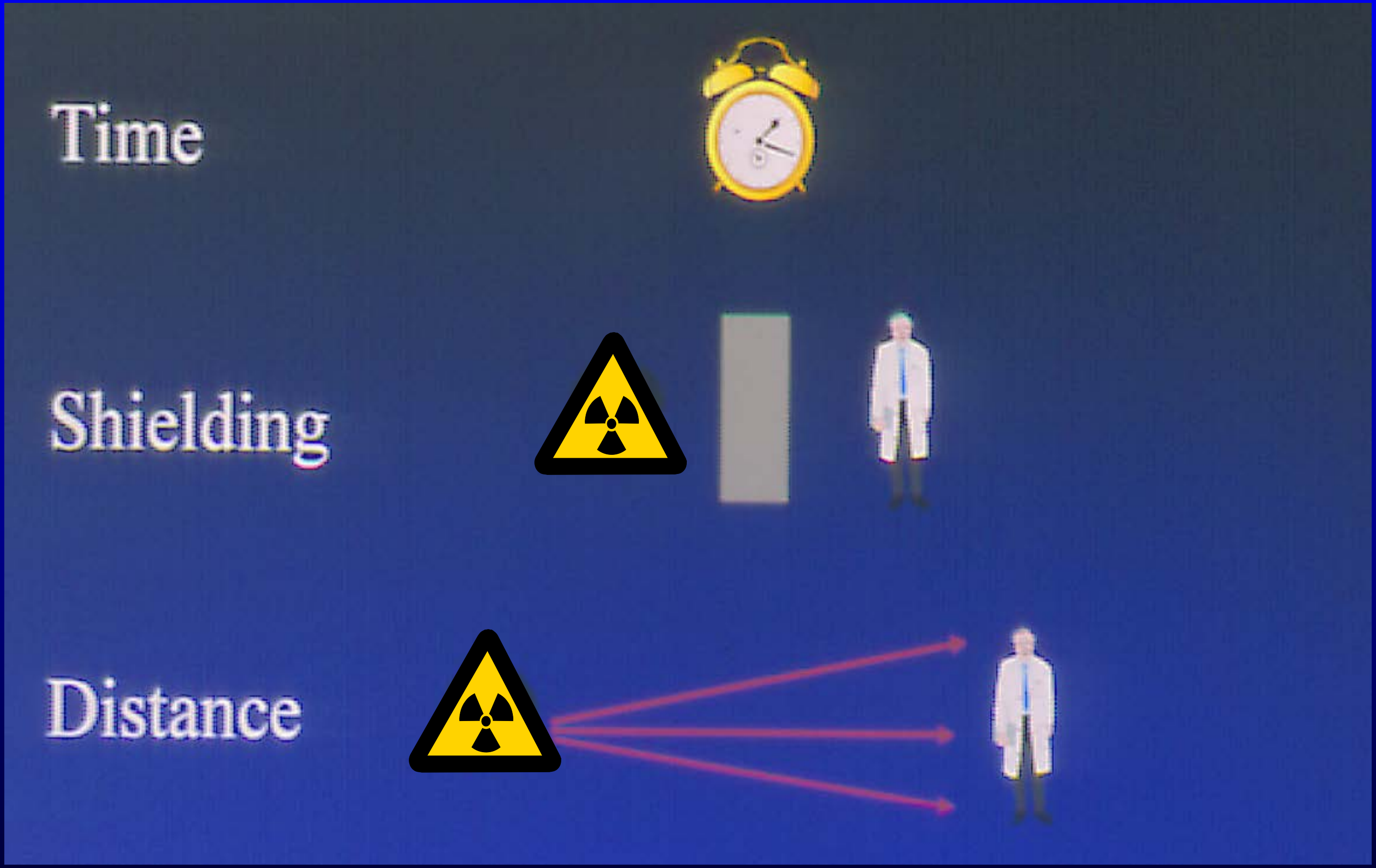
Current estimate of lifetime risk detriment from NID is $7x10^{-7}$

Structural Shielding Design

Three Principles of Radiation Protection

- Distance
- Time
- Shielding

Hazard Reduction Methods



Shielding

Shielding

- Use of high atomic number and high density materials eg. lead, concrete, steel
- Normal building materials e.g., brick, mortar, wallboard, can be either very poor shielding materials, or have quite variable and very unpredictable properties

Distance

Inverse square law

– radiation from a point source decreases by the square of the distance

Dose is proportional to $1/(\text{distance})^2$

i.e., twice the distance gives 1/4 the dose, but half the distance gives 4 times the dose

Structural Shielding Design

NCRP Reports 49 & 51, NCRP 151 update, Guidelines:

Controlled **(Radiation Workers - Area supervised by RSO)**

Permissible Limit: P = 100 mrem (1 mSv)/wk

Noncontrolled Areas **(General Public)**

Permissible Limit: P = 10 mrem (0.1 mSv) /wk

frequent exposure P = 2 mrem (0.02 mSv) /wk

Structural Shielding Design

Exposure Rate

"WUT" factor:

$$X = \frac{W \cdot U \cdot T}{\left(d / d_{ref} \right)^2} \cdot B$$

Workload **(W):**

10,000 to 100,000 MU/wk

Use Factor **(U):**

.25 for isocentric units

Occupancy Factor **(T):**

1, 1/4, 1/8, 1/16

Distance factor:

$$= \frac{d_{ref}^2}{d^2}$$

d is distance from radiation source to shielded area.

Radiation Shielding Requirements

Controlled areas (supervised by Radiation Safety Office)

Maximum dose equivalent: **1.0 mSv/week**

50.0 mSv/year

Noncontrolled areas (general public)

Maximum dose equivalent: **0.1 mSv/week**

5.0 mSv/year

Radiation shielding must be designed to reduce doses to these limits

→ Primary radiation, scattered radiation, leakage radiation

Primary Radiation Barrier

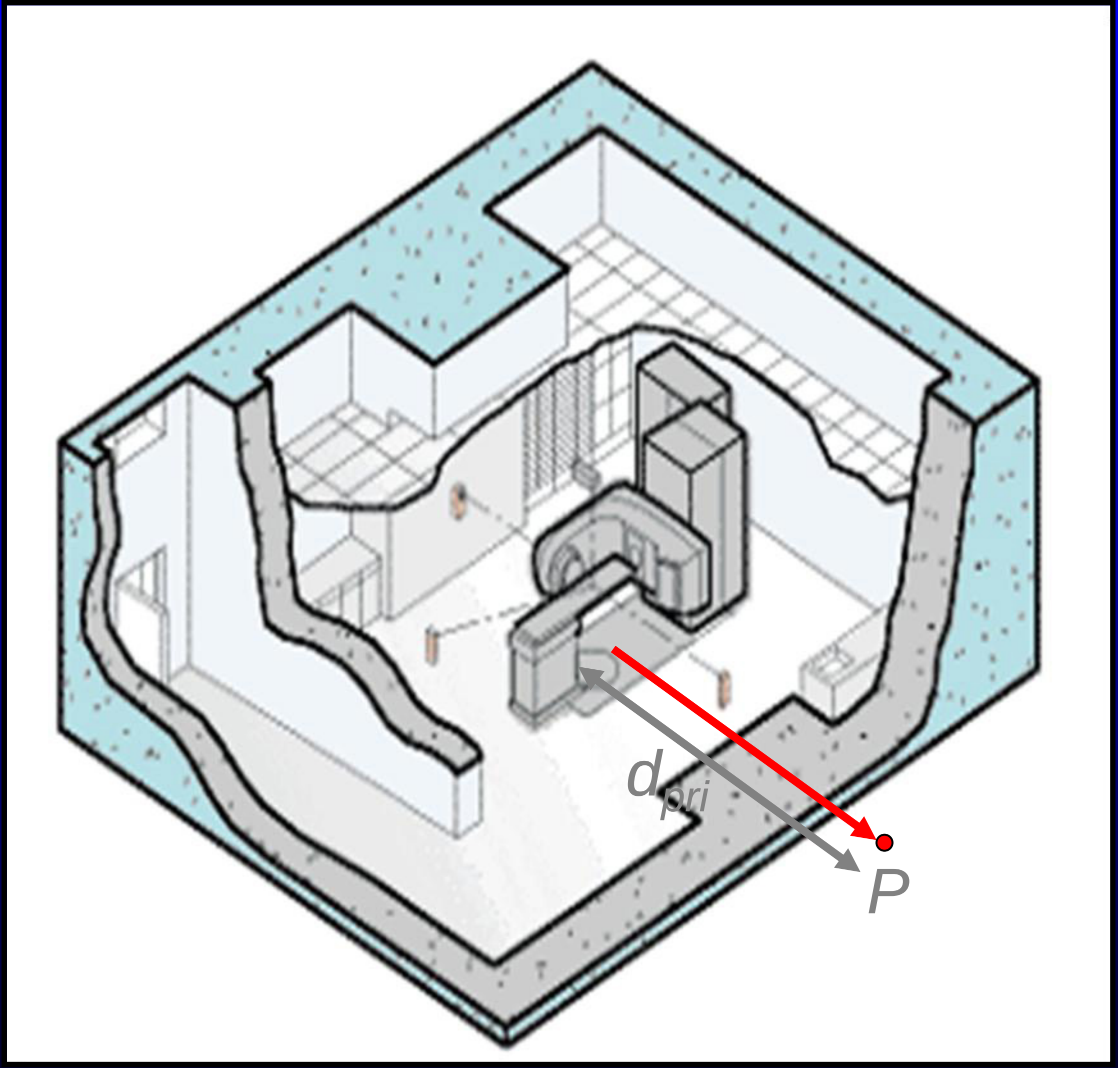
Maximum dose

Distance to protected area

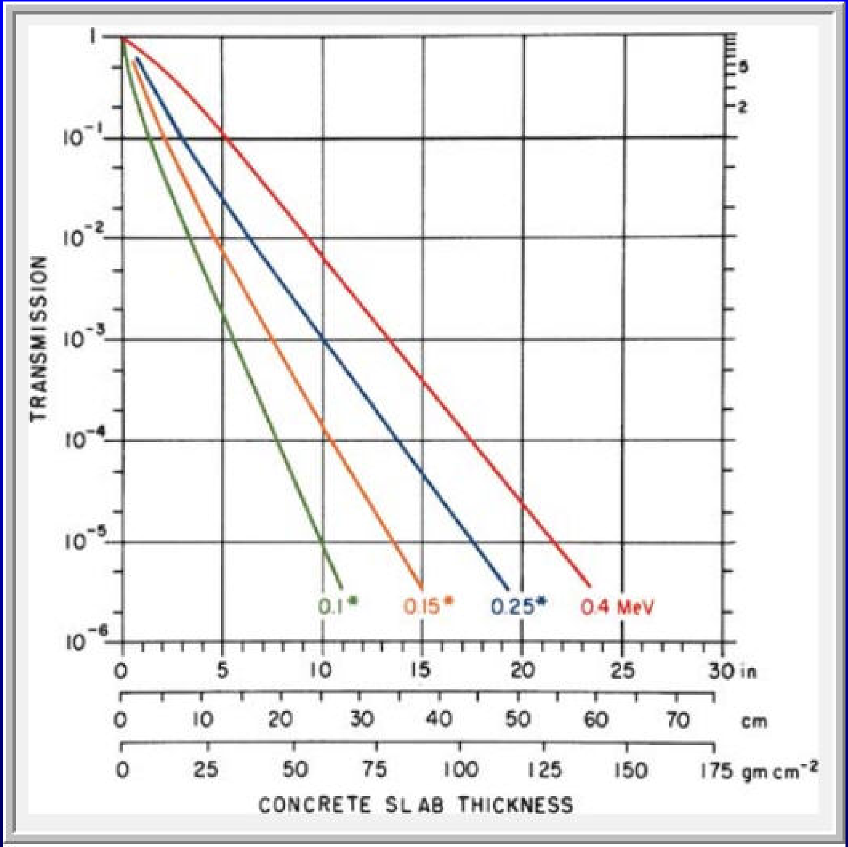
$$B_x = \frac{Pd_{pri}^2}{\underbrace{WUT}}$$

Effective dose with no shielding at d_{ref}

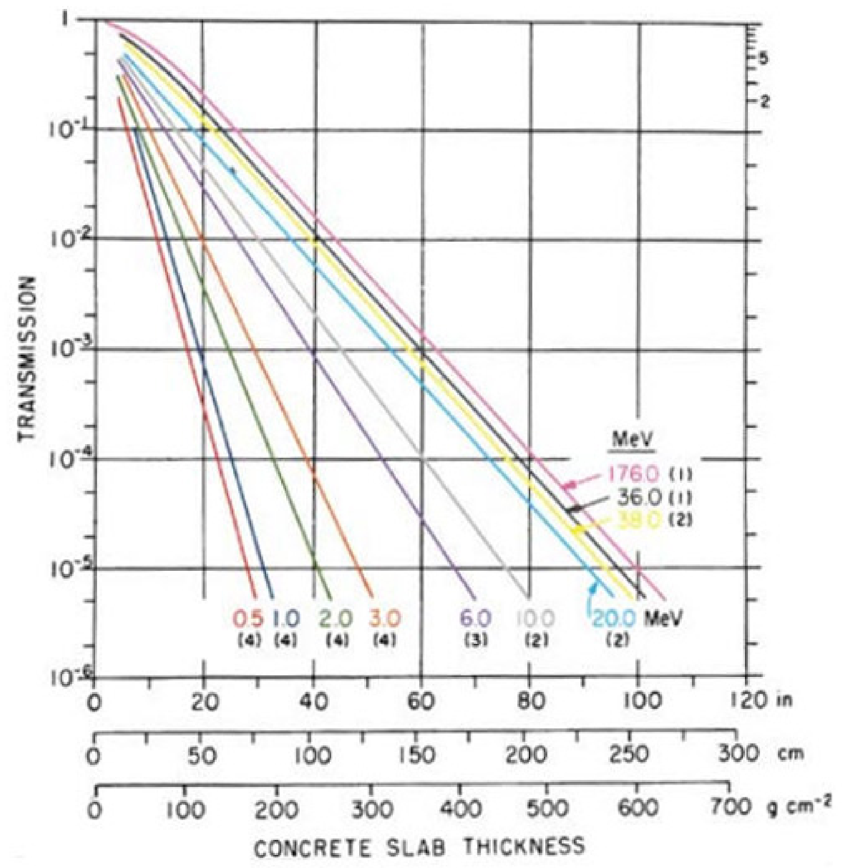
Required transmission factor



Broad-beam transmission



Broad-beam transmission, NCRP 51

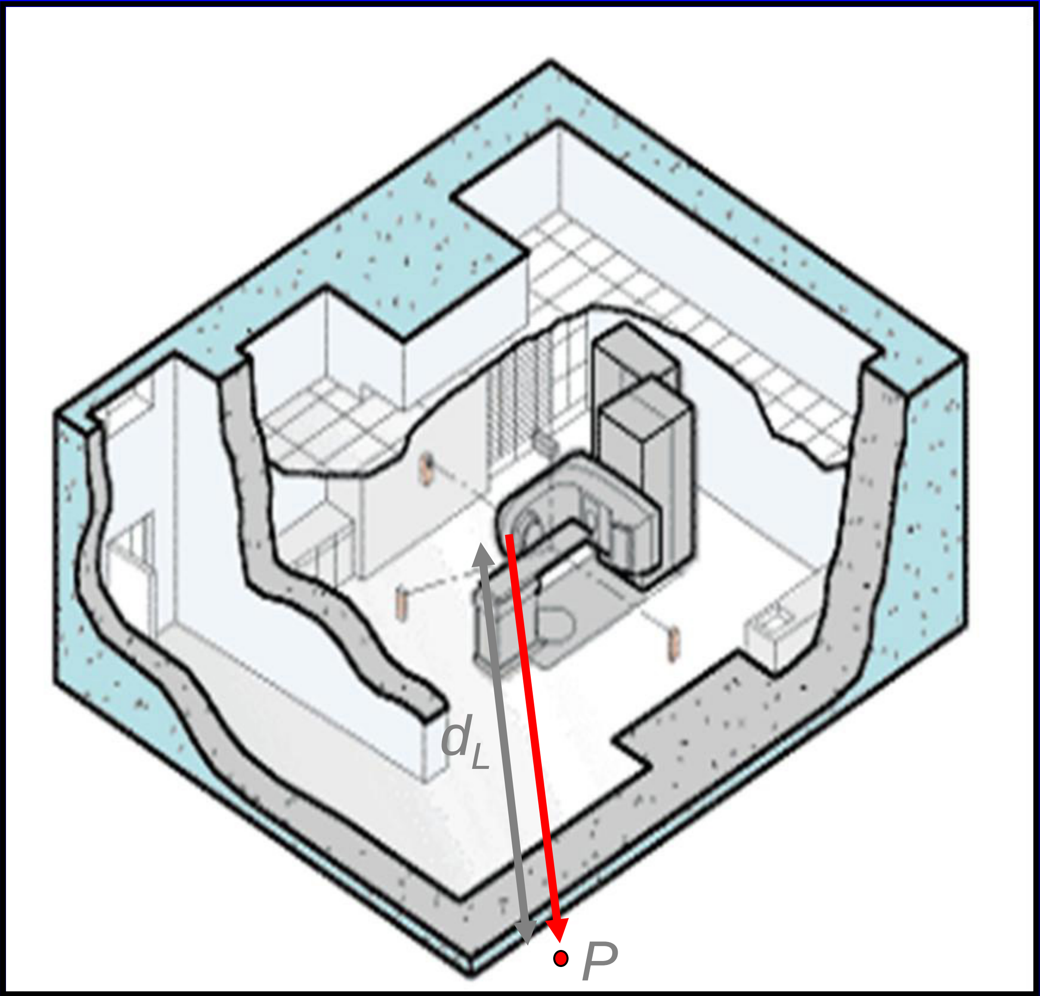


Broad-beam transmission, MV range NCRP 51

Leakage Radiation Barrier

$$B_L = \frac{Pd_L^2}{0.001WT}$$

0.1% leakage limit through source housing for megavoltage units



Bigger concern than scattered radiation (higher energy)

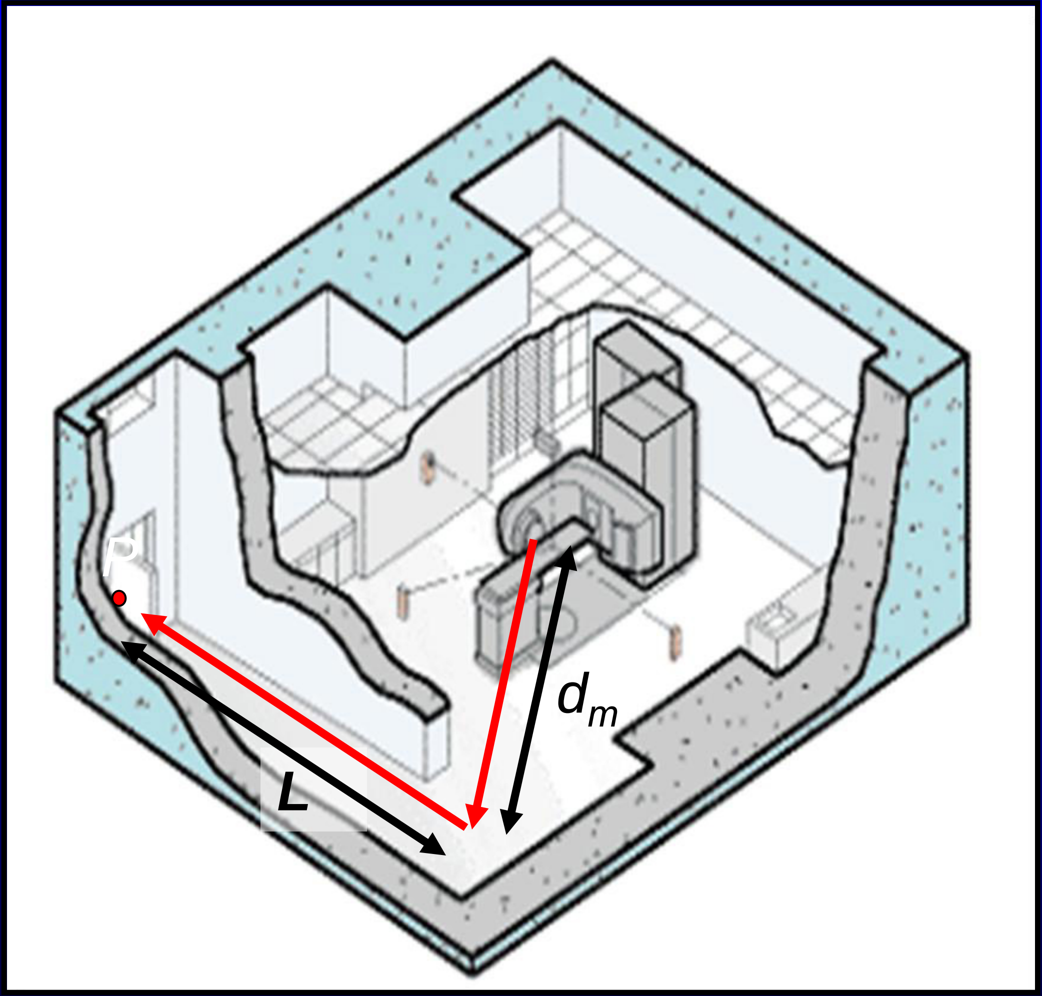
Door Shielding

Use maze room layout.
Repeatedly apply:

$$B_s = \frac{P}{\alpha WT}\,\frac{400}{F}\,\underset{(d_m)}{d_{sca}^2}\;\underset{(L)}{d_{sec}^2}$$

to trace photons from source to the door over multiple scattering interactions.

NCRP 151. Khan, Eq. (16.6)



F: Area of the beam in the plane of the scatterer (cm^2)
α: Scatter fraction; (θ, E)

Scattered radiation

Ratio, α, of Scattered to Incident Exposure[a], NCRP 151

Scattering Angle (From Central Ray)	***6 MV***	***10 MV***	***18 MV***
10°	1.0×10^{-2}	1.7×10^{-2}	1.4×10^{-2}
30°	2.8×10^{-3}	3.2×10^{-3}	2.5×10^{-3}
45°	1.4×10^{-3}	1.3×10^{-3}	8.6×10^{-3}
60°	8.2×10^{-4}	7.6×10^{-4}	4.2×10^{-4}
90°	4.2×10^{-4}	3.8×10^{-4}	1.9×10^{-4}
135°	3.0×10^{-4}	3.0×10^{-4}	1.2×10^{-4}

[a]Scattered radiation measured at 1 m from phantom when field area is 400 cm^2 at the phantom surface; incident exposure measured at center of field but without phantom.

Neutron Shielding

1. 10 MV and higher energy X-ray beams are contaminated with neutrons produced by photon/electron interactions within the accelerator head and/or shielding. These neutrons contribute dose as well as producing γ-rays by neutron capture when interacting with matter.

2. Primary and secondary wall shielding are sufficient to reduce neutron dose. Depending on the maze configuration, additional door shielding is sometimes required.

3. A few inches of a hydrogenous material (polyethylene) can be used to capture neutrons. In general however it is preferable to reduce scattered neutron flux than to shield against neutrons and capture-produced γ-rays.

Radiation Surveys

State requires qualified expert to perform survey before operation of a linear accelerator may begin.

Equipment

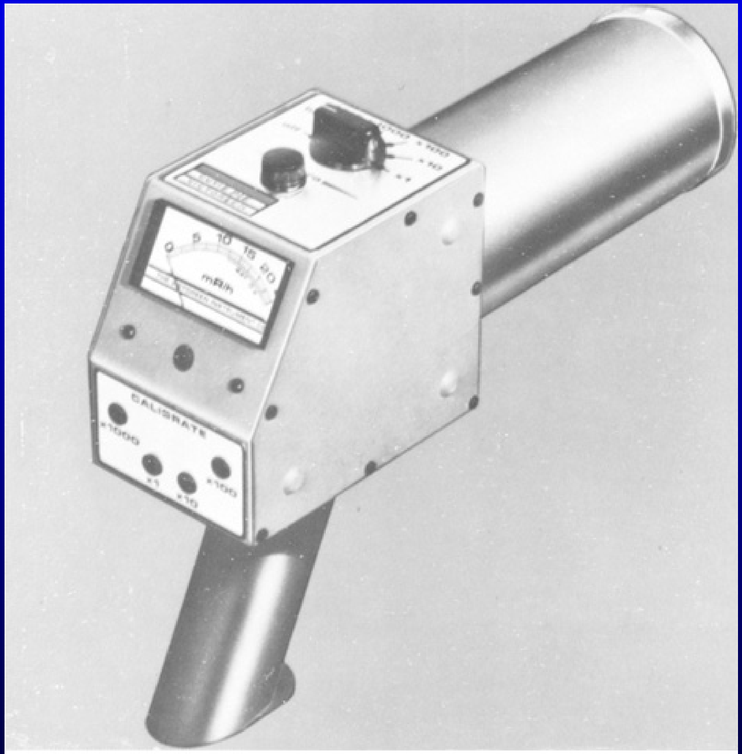
- Use film to locate radiation leaks through source housing
- Use ionization chamber to measure dose at 1 m from source in various directions of possible leakage.

Area

- Use ionization chamber to measure dose outside treatment room with phantom in treatment position.
- Incorporate estimates of W, U, T

Radiation Monitoring Instruments

Ionization Chambers



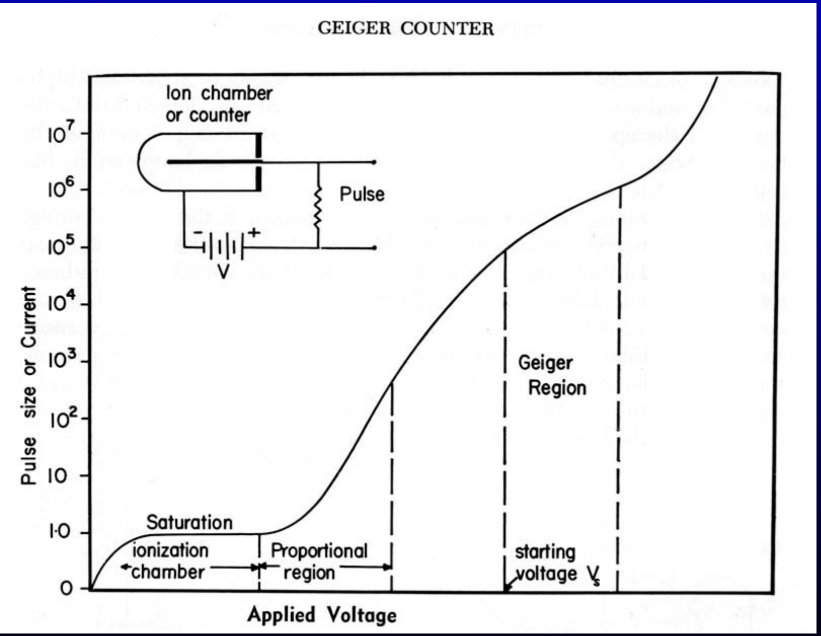
Used for low-level X-ray measurements. A photo appears in Fig. 16.4 of Khan

Large ionization chamber volume (~ 500 ml.). Called a “Cutie Pie”. Accurate even at low exposure rates (~0.1 mR/h = 1.0 μSv/h)

Calibrated using a γ-ray source of known activity.

Radiation Monitoring Instruments

Geiger-Müller Counters



Ionization chamber operated in Geiger region of the chamber response curve. Therefore a single event creates an “avalanche” of ionizations.

Useful for qualitative measurement of very low levels of radiation.

Radiation Monitoring Instruments

Neutron Counters

Activation detectors: contain materials e.g., gold foils that become radioactive upon neutron bombardment.
Examples – $^{31}P(n,p)^{31}Si$
$^{31}P(n,\gamma)^{32}P$

Moderated activation detectors: use hydrogenous material to convert neutrons to H atoms or protons. Counter can be calibrated as a remmeter, including quality factor W_R (ex. see photo).

Outside the treatment room, one typically uses two detectors: one sensitive to photons, and one to both photons and neutrons.

NRC Regulations; State Regulations for Radiation-Producing Machines [Linear Accelerators]

Teletherapy

- Radiation surveys
- Safety Instructions
- Dosimetry Equipment
- Calibration before Use
- Periodic spot checks
- Maintenance
- Five-year Inspection

General Safety Requirements

- Clear Indicators shall be provided at the control console and in the treatment room to show when the equipment is in operation
- Have at least two independent 'fail to safety' systems for terminating the irradiation. These could be:
  - two independent integrating in-beam dosemeters
  - two independent timers
  - integrating dosemeter and timer
- Each system shall be capable of terminating the exposure

Radioactive Materials License

NRC Regulations

License required for use of by-product material

Nuclear Regulatory Commission Regulations

The **USNRC** is a federal agency that controls use of all reactor-produced materials. They enact regulations recommended by the **International Commission on Radiological Protection (ICRP)**, the **National Council on Radiation Protection and Measurements (NCRP)**, and the **American Association of Physicists in Medicine (AAPM)**.

A license from the NRC (or the State, if in an “Agreement State”) is required for use of radioactive materials. A license is awarded after review of a substantial application.

Administrative Requirements

- **ALARA Program**
- **Radiation Safety Officer (RSO)**
- **Radiation Safety Committee**
- **Quality Management Program**

Technical Requirements

- **Dose calibrator**
- **Survey Instruments**
  - **Survey program**
  - **Regular calibration of instruments**
- **Source storage**
  - **Appropriate shielding**
  - **Leak test program**
- **Isolation of radioactive patients**
- **Radiation safety instructions**

Brachytherapy Source Storage

- Lockable storage room with signage
- Lead safes
- Sinks with filter or trap to prevent loss of sources
- Lead-lined carts for transport of sources

Brachytherapy Leak Testing

Periodic testing required by state regulations

Wipe tests measured in scintillation counter

Removable activity must be less than 0.005 μCi

PET Tracer Shielding and Storage

Need shielding for workers during:

1. Dose transport
2. Dose preparation and calibration
3. Injection and patient management

Need shielding of room to minimize:

dose to personnel outside hot lab

Need to account for radioactive waste (sharps, gloves)

Personnel Monitoring

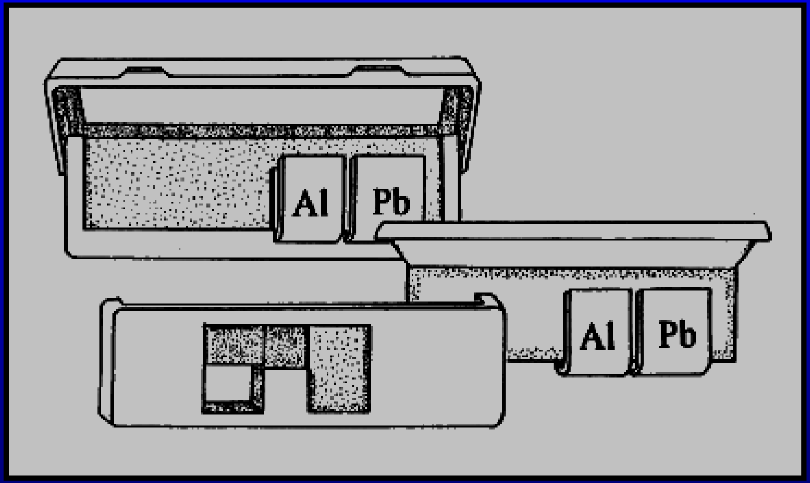
Film Badges

TLD badges

- Chest
- Hands

Pocket dosimeters

- More frequent monitoring during a particular procedure



General Safety Requirements

- Warning Signals and Signs

RADIATION

DO NOT ENTER

When

RED LIGHT

is on.

Shipping Labels

Transport Index (T.I.) [D.R. @ 1m]	Maximum exposure rate on container surface	Label Category
0	0 – 5 μSv/h 5 μSv/h – 0.5 mSv/h 0.5 mSv/h – 2 mSv/h 2 mSv/h – 10 mSv/h	White - I
0 - 1	0 – 5 μSv/h 5 μSv/h – 0.5 mSv/h 0.5 mSv/h – 2 mSv/h 2 mSv/h – 10 mSv/h	Yellow - II
2 - 10	0 – 5 μSv/h 5 μSv/h – 0.5 mSv/h 0.5 mSv/h – 2 mSv/h 2 mSv/h – 10 mSv/h	Yellow - III
>10	0 – 5 μSv/h 5 μSv/h – 0.5 mSv/h 0.5 mSv/h – 2 mSv/h 2 mSv/h – 10 mSv/h	Yellow - III Exclusive Provisions

Radiation Warning Signs

Condition	Posting
5 mrem (0.05 mSv) in 1 hour at 30 cm from the source or shield surface	Caution, Radiation Area
100 mrem (1 mSv) in 1 hour at 30 cm from the source or shield surface	Caution, High Radiation Area
500 rads (5 Gy) in 1 hour at 1 m from the source or shield	Grave Danger, Very High Radiation Area
Air concentration exceeding the Derived Air Concentration	Caution, Airborne Radioactivity Area
Use or storage of ten times the Quantities of Licensed Material Requiring Labelling	Caution, Radioactive Material

References

1. *The Physics of Radiation Therapy*, *4th Edition*, Faiz M. Khan (LippincottWilliams and Wilkins, Baltimore, 2010), chapter 16.
2. *Recommendations on Limits for Exposure to Ionizing Radiation*, NCRP Report 91 (1987).
3. *Limitations of Exposure to Ionizing Radiation*, NCRP Report 116, (1993).
4. *Health Risks from Exposure to Low Levels of Ionizing Radiation*, *BEIR VII Phase 2* (2007), National Academies Press.
5. *Structural shielding design and evaluation for megavoltage X- and gamma-ray radiotherapy facilities*, NCRP Report 151, (2005).

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