Chapter 15
Radiation Protection

Radiation Dosimetry I

Text: H.E Johns and J.R. Cunningham, The physics of radiology, 4th ed.
F.M. Khan, The Physics of Radiation Therapy, 4th ed., Chapter 16
http://www.utoledo.edu/med/depts/radther

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Introduction

- Radiation exposure standards were introduced as early as the start of the 20th century when the potential hazards of radiation were realized
- Limits on radiation exposure to public and radiation workers
- Radiation presents a risk to workers that is similar to other industrial hazards
- Radiation dose recommendations for occupational exposures have evolved as more information is gathered on the effects of radiation on humans

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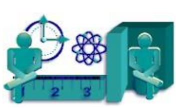
Main Principles of Radiation Protection

- **Time** – exposure is proportional to duration
- **Distance** – governed by the inverse square law
- **Shielding** – presence of protective barrier



Time Distance Shielding

- Minimize time and maximize distance and shielding

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Advisory bodies

- The International Commission on Radiological Protection (ICRP) issues reports which form the basis for many national protection guidelines
- In the United States, the National Council on Radiation Protection and Measurements (NCRP) functions as a primary standard-setting body through its separate publications
- Both are **advisory** bodies: collect and analyze data, and put forward recommendations on radiation protection
- Recommendations are utilized by regulatory groups to develop regulations

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Regulatory bodies

- The Nuclear Regulatory Commission (NRC) has **regulatory** powers in US, having control over the use of all reactor-produced materials (e.g., ^{60}Co and ^{192}Ir)
- The naturally occurring radioactive materials (e.g., radium and radon) and x-ray machines are regulated by individual states
- US NRC has agreement with states (called 'agreement states') that allows these states to enforce NRC regulations
- Many other federal agencies regulate different aspects of radiation protection pertaining to their specific program area (FDA, FEMA, OSHA, DOT, EPA, USPS)

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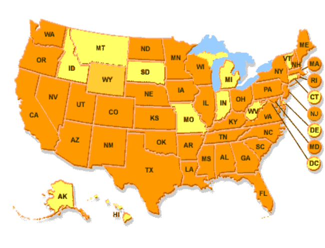
Regulations in individual states



https://scp.nrc.gov/asdirectory.html

- Oversight of naturally occurring radioactive materials and x-ray machines
- "Non-agreement states" are partially or fully regulated by the NRC
- "Agreement states" are self-regulating

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Example: DOT label

Label	Surface (mR/h)	At 1 m (mR/h)
White I	< 0.5	N/A
Yellow II	0.5 - 50	< 1
Yellow III	50 - 200	1 - 10

7 – hazard class for radioactive materials in DOT designation

Transport Index (TI) – reading in mR/h at 1 m must be indicated on DOT label
See 49 CFR 172.403 (CFR – Code of Federal Regulations)

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Dose Equivalent

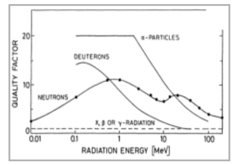

TABLE 16.1 Recommended Quality Factors

Radiation	*Quality Factor*
X-rays, γ rays, and electrons	1
Thermal neutrons	5
Neutrons, heavy particles	20

Data are from National Council on Radiation Protection and Measurements. Recommendations on Limits for Exposure to Ionizing Radiation. Report No. 91.

- The biologic effects of radiation depend not only on dose, but also on the type of radiation, the dosimetric quantity relevant to radiation protection is the dose equivalent H, defined as

$$H = D \cdot Q$$

$$[H] = Sv = J / kg$$

Old unit $[H] = rem = 10^{-2} J / kg$

- The Q-factor (unitless) value depends on RBE (related to LET) of the radiation

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Effective Dose Equivalent

- For a given uniform exposure
  - Received dose may differ markedly for various tissues
  - Tissues vary in sensitivity to radiation-induced effects
- The concept of effective dose equivalent has been adopted by the ICRP and the NCRP as "the sum of the weighted dose equivalents for irradiated tissues or organs"

$$H_E = \sum W_T H_T$$

↑ Based on risk estimates

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Risk Estimates

- The excess risk is estimated in terms of the probability to develop a *fatal cancer* in various organs of the body
  - Stochastic (no threshold) quantity
  - The severity of the effect does not depend on the dose
  - Risks of tumor induction are higher (e.g., since ~50% of breast cancers are curable the risk of induction is 2x)
- Estimates are based on effects at high doses (no data for dose equivalent < 100mSv)
- The average natural lifetime incidence of cancer in the United States is 42%

*39.5% based on 2015–2017 data

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Risk Estimates

TABLE 16.2 Recommended Values of the Weighting Factors W_T, for Calculating Effective Dose Equivalent and the Risk Coefficients from which they were Derived

Tissue (T)	*Risk Coefficient*	W_T
Gonads	40×10^{-4} Sv^{-1} (40×10^{-6} rem^{-1})	0.25
Breast	25×10^{-4} Sv^{-1} (25×10^{-6} rem^{-1})	0.15
Red bone marrow	20×10^{-4} Sv^{-1} (20×10^{-6} rem^{-1})	0.12
Lung	20×10^{-4} Sv^{-1} (20×10^{-6} rem^{-1})	0.12
Thyroid	5×10^{-4} Sv^{-1} (5×10^{-6} rem^{-1})	0.03
Bone surface	5×10^{-4} Sv^{-1} (5×10^{-6} rem^{-1})	0.03
Remainder	50×10^{-4} Sv^{-1} (50×10^{-6} rem^{-1})	0.30
Total	165×10^{-4} Sv^{-1} (165×10^{-6} rem^{-1})	1.00

From National Council on Radiation Protection and Measurements. *Recommendations on Limits for Exposure to Ionizing Radiation*. Report No. 91. Bethesda, MD: National Council on Radiation Protection and Measurements; 1987, with permission.
Values are from International Commission on Radiological Protection. *Recommendations of the International Commission on Radiological Protection*. Report No. 26. New York: Pergamon Press; 1977.

- The weighting factors are defined through corresponding risk coefficients normalized to the "total" value of 165×10^{-4} Sv^{-1}
- Genetic (hereditary effect) included in the "total" 40×10^{-4} Sv^{-1}

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Background Radiation

- The background radiation is contributed mainly by 3 sources: terrestrial radiation, cosmic radiation, and radiation from radioactive elements in our bodies
  - Terrestrial radiation varies based on surrounding materials, including buildings (granite rocks contain small amount of Uranium-238 producing radon)
  - Cosmic radiation levels change with elevation and latitude (~20% in going from equator to 50° latitude)
  - The internal irradiation arises mainly from ^{40}K in our body, which emits γ and β rays and decays with a half-life of 1.3×10^9 years

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Background Radiation

TABLE 16.3 Estimated Total Effective Dose-Equivalent Rate for a Member of the Population in the United States and Canada[a] from Various Sources of Natural Background Radiation

	Total Effective Dose Equivalent Rate (MSV/Y)[b]					
Source	*Lung*	*Gonads*	*Bone Surfaces*	*Bone Marrow*	*Other Tissues*	*Total*
W_T	0.12	0.25	0.03	0.12	0.48	1.0
Cosmic	0.03	0.07	0.008	0.03	0.13	0.27
Cosmogenic	0.001	0.002	—	0.004	0.003	0.01
Terrestrial	0.03	0.07	0.008	0.03	0.14	0.28
Inhaled	2.0	—	—	—	—	2.0
In the body	0.04	0.09	0.03	0.06	0.17	0.40
Rounded totals	2.1	0.23	0.05	0.12	0.44	3.0

[a]The effective dose-equivalent rates for Canada are approximately 20% lower for the terrestrial and inhaled components.
[b]1 mSv = 100 mrem.
From National Council on Radiation Protection and Measurements. *Exposure of the Population in the United States and Canada from Natural Background Radiation.* Report No. 94. Bethesda, MD: National Council on Radiation Protection and Measurements; 1987, with permission.

- The total effective dose equivalent for a member of the population in the US from various sources of natural background radiation is ~ 3.0 mSv/year (300 mrem/year)
- Actually 6.2mSv/year from //epa.gov

Background Radiation: Cosmic

- Elevation and latitude: the Earth's atmosphere and magnetic shield (strongest at the equator and weakest near the poles) protect us from cosmic radiation
  - People in Denver, Colorado, are exposed to slightly more cosmic radiation than those in Miami, Florida
  - A one-way flight across the country (New York to Los Angeles), we likely receive 2-5 mrem (0.02-0.05 mSv) of radiation. The radiation from two cross-country flights is about equal to that from a single chest x-ray
  - Solar events can raise radiation levels


Aurora borealis caused by a proton storm (Denali National Park, Alaska)

From https://www.epa.gov/radtown/cosmic-radiation

Occupational Dose Limits

- NCRP recommendations on exposure limits of radiation workers are based on the following criteria:
  - at low radiation levels the nonstochastic effects are essentially avoided
  - the predicted risk for stochastic effects should not be greater than the average risk of accidental death among workers in "safe" industries
  - the ALARA principle should be followed, for which the risks are kept "as low as reasonably achievable", taking into account social and economic factors
  - Negligible Individual Risk Level (NIRL) - a threshold below which efforts to reduce the risk further is not warranted

Occupational Dose Limits

TABLE 16.4 Annual Fatality Rates from Accidents in Different Occupations[a]

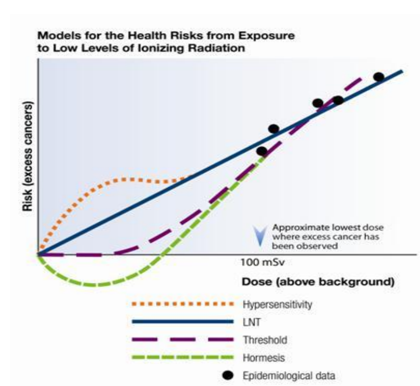
Occupation	*Number of Workers × 10^3*	*Annual Fatal Accident Rate (per 10,000 Workers)*
Trade	24,000	0.5
Manufacturing	19,900	0.6
Service	28,900	0.7
Government	15,900	0.9
Transportation and utilities	5,500	2.7
Construction	5,700	3.9
Agriculture	3,400	4.6
Mining, quarrying	1,000	6.0
All industries (U.S.)	104,300	1.1

[a]Certain occupations have higher annual fatal accident rates than those given here.
Reprinted from National Council on Radiation Protection and Measurements. *Recommendations on Limits for Exposure to Ionizing Radiation.* Report No. 91. Bethesda, MD: National Council on Radiation Protection and Measurements; 1987, with permission.
Data are from National Safety Council. *Accident Facts 1984.* Chicago: National Safety Council; 1985.

- "Safe" industries are defined as "having an associated annual fatality accident rate of 1 or less per 10,000 workers, or an average annual risk of ~10^{-4}
- The radiation industries show an average fatal accident rate of < 0.3 x10^{-4}, therefore the radiation industries compare favorably with the "safe" industries

Occupational Dose Limits

- Harmful effects of radiation are classified into two general categories:
  - Stochastic effects, with the severity of the effect independent of the dose
  - Nonstochastic: increases in severity with increasing absorbed dose, due to damage to increasing number of cells and tissues. Examples: radiation-induced degenerative changes such as organ atrophy, fibrosis, lens opacification, blood changes, etc.
  - Assumed linear-no threshold (LNT) model may overestimate the effect at low doses



Occupational Dose Limits

- Radiation workers are limited to an annual effective dose of 50 mSv (5 rem)
- The pregnant woman who is a radiation worker can be considered as an occupationally exposed individual, but the fetus cannot. The total dose-equivalent limit to an embryo-fetus is 5 mSv (0.5 rem), with the added recommendation that exposure to the fetus should not exceed 0.5 mSv (0.05 rem)in any 1 month
- Once a pregnancy is made known, the dose-equivalent limit of 0.5 mSv (0.05 rem) in any 1 month should be the guiding principle

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Effective Dose-Equivalent Limits

TABLE 16.5 Summary of Recommendations

A. Occupational exposures (annual)		
1. Effective dose-equivalent limit (stochastic effects)	50 mSv	(5 rem)
2. Dose-equivalent limits for tissues and organs (nonstochastic effects)		
a. Lens of eye	150 mSv	(15 rem)
b. All others (e.g., red bone marrow, breast, lung, gonads, skin, and extremities)	500 mSv	(50 rem)
3. Guidance: cumulative exposure	10 mSv × age	(1 rem × age in years)
B. Planned special occupational exposure, effective dose-equivalent limit	See section 15[a]	
C. Guidance for emergency occupational exposure	See section 16[a]	
D. Public exposures (annual)		
1. Effective dose-equivalent limit, continuous or frequent exposure	1 mSv	(0.1 rem)
2. Effective dose-equivalent limit, infrequent exposure	5 mSv	(0.5 rem)
3. Remedial action recommended when:		
a. Effective dose equivalent	>5 mSv	(>0.5 rem)
b. Exposure to radon and its decay products	>0.007 Jhm^{-3}	(>2 WLM)
4. Dose-equivalent limits for lens of eye, skin, and extremities	50 mSv	(5 rem)
E. Education and training exposures (annual)		
1. Effective dose equivalent	1 mSv	(0.1 rem)
2. Dose-equivalent limit for lens of eye, skin, and extremities	50 mSv	(5 rem)
F. Embryo-fetus exposures		
1. Total dose-equivalent limit	5 mSv	(0.5 rem)
2. Dose-equivalent limit in a month	0.5 mSv	(0.05 rem)
G. Negligible individual risk level (annual) effective dose equivalent per source or practice	0.01 mSv	(0.001 rem)

[a] In National Council on Radiation Protection and Measurements Report No. 91.
From National Council on Radiation Protection and Measurements. *Recommendations on Limits for Exposure to Ionizing Radiation*. Report No. 91. Bethesda, MD: National Council on Radiation Protection and Measurements; 1987, with permission.

Excluding background and exposures from personal medical care

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Structural Shielding Design

- NCRP provides radiation protection guidelines for the design of structural shielding for radiation installations (new and remodeled facilities):
  - Report No. 102 - Medical X-Ray, Electron Beam and Gamma-Ray Protection for Energies Up to 50 MeV (Equipment Design, Performance and Use) (supersedes NCRP Report 33)
  - Report No. 151 - Structural Shielding Design and Evaluation for Megavoltage X- and Gamma-Ray Radiotherapy Facilities (2005) (supersedes Reports 49 and 51)

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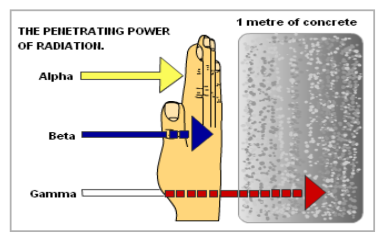
Structural Shielding Design



- The type of radiation and its energy determine the shielding required

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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
- The areas surrounding the room are designated as *controlled* or *noncontrolled*, depending on whether or not the exposure of persons in the area is under the supervision of a radiation protection supervisor
  - For the controlled areas the dose-equivalent limit is assumed to be 1 mSv/week or 50 mSv/year
  - For the noncontrolled areas the limit is 0.02 mSv/week or 1 mSv/year annual limit

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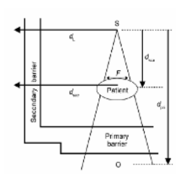
Structural Shielding Design

- Protection is required against three types of radiation: the primary radiation, the scattered radiation, and the leakage radiation through the source housing
- A barrier sufficient to attenuate the useful beam to the required degree is called the *primary* barrier
- The required barrier against stray radiation (leakage and scatter) is called the *secondary* barrier



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Primary Radiation Barrier Calculations

- Workload (W) expressed in rad/week at 1 m
  - For x-ray equipment operating below 500 kVp usually expressed in mA-minutes per week of beam “on” time
  - For MV machines usually stated as weekly dose delivered at 1 m from the source; can be estimated by multiplying the number of patients treated per week with the dose delivered per patient at 1 m
- Use Factor (U) - fraction of the operating time during which the radiation under consideration is directed toward a particular barrier

TABLE 16.6 Typical Use Factor for Primary Protective Barriers

Location	*Use Factor*
Floor	1
Walls	¼
Ceiling	¼–½, depending on equipment and techniques

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Primary Radiation Barrier Calculations

- Occupancy Factor (T) - fraction of the operating time during which the area of interest is occupied by the individual
- Distance (d) in meters from the radiation source to the area to be protected. Inverse square law is assumed for both the primary and stray radiation.

TABLE 16.7 Typical Occupancy Factors

Full occupancy ($T = 1$)
Work areas, offices, nurses' stations
Partial occupancy ($T = ¼$)
Corridors, restrooms, elevators with operators
Occasional occupancy ($T = ⅛ – 1/16$)
Waiting rooms, restrooms, stairways, unattended elevators, outside areas used only for pedestrians or vehicular traffic

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Primary Radiation Barrier Calculations

- For the maximum permissible dose equivalent for the area to be protected P (NCRP#151: 0.1 mSv/week for controlled and 0.02 mSv/week for noncontrolled area) the required transmission factor B is given by

$$B = \frac{P \cdot d^2}{WUT}$$

- Using broad-beam attenuation curves for the given energy beam, one can determine the barrier thickness required

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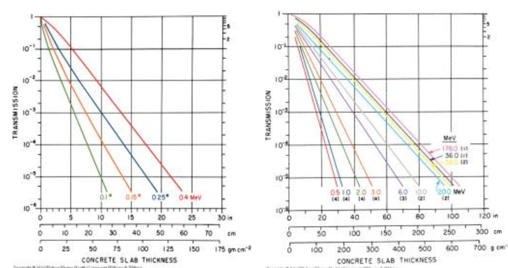
Broad-beam Attenuation Curves



- Concrete is cheap, but its density is fairly low 2.35 g/cm^3
- Lead or steel can be used for more compact barriers

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Secondary Radiation Barrier Calculations: Scatter

- The transmission factor to reduce scatter B_S:

$$B_S = \frac{P}{\alpha WT}\frac{400}{F} \cdot d^2 \cdot d'^2$$

- Here α is the ratio of scattered dose to incident dose, F is the area of the beam incident at the scatter, d' is the distance from the scatterer to the area of interest
- U=1 for secondary barriers

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Secondary Radiation Barrier Calculations: Scatter

TABLE 16.8 Ratio, α, of Scattered to Incident Exposure[a]

	γ Rays		*X-rays*
Scattering Angle (From Central Ray)	*^{60}Co*	*4 MV*	*6 MV*
15			9×10^{-3}
30	6.0×10^{-3}		7×10^{-3}
45	3.6×10^{-3}	2.7×10^{-3}	1.8×10^{-3}
60	2.3×10^{-3}		1.1×10^{-3}
90	0.9×10^{-3}		0.6×10^{-3}
135	0.6×10^{-3}		0.4×10^{-3}

[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.
From National Council on Radiation Protection and Measurements. *Medical X-ray and Gamma-ray Protection for Energies up to 10 MeV. Structural Shielding Design and Evaluation.* Report No. 34. Washington, DC: National Council on Radiation Protection and Measurements; 1970, with permission.
Data also are available in National Council on Radiation Protection and Measurements. *Radiation Protection Design and Guidelines for 0.1–100 MeV Particle Accelerator Facilities.* Report No. 51. Washington, DC: National Council on Radiation Protection and Measurements; 1977.

- For MV beams α is usually assumed to be 0.1% for 90^o scatter

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Secondary Radiation Barrier Calculations: Leakage

- The transmission factor for the leakage barrier for therapy units, above 500kVp, B_L:

$$B_L = \frac{P \cdot d^2}{0.001WT}$$

- The quality of leakage radiation is approximately the same as that of the primary beam
- For MV installations the leakage barrier usually far exceeds that required for scatter radiation

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Door Shielding

- Unless a maze entranceway is provided, the door must provide shielding equivalent to the wall surrounding the door
- For MV installations, a door that provides direct access to the treatment room will have to be extremely heavy
- The function of the maze is to prevent direct incidence of radiation at the door. With a proper maze design, the door is exposed mainly to the multiply scattered radiation of significantly reduced intensity and energy

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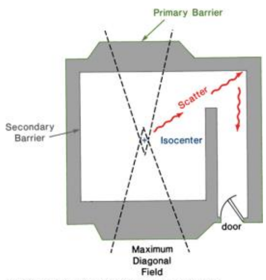
Door Shielding



- The door shielding can be calculated by tracing the path of the scattered radiation from the patient to the door and repeatedly applying equation for B_S
- In a properly designed maze the required shielding turns out to be less than 6 mm of lead

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Shielding Against Neutrons

- For x-ray beams with energy >10MV, photonuclear interactions (γ,n) result in neutron contamination
- In the 16- to 25-MV x-ray therapy mode the neutron dose equivalent along CA is ~0.5% of the x-ray dose and falls off to ~0.1% outside the field
- When thermal neutrons are absorbed by the nuclei of atoms within the shielding door, energetic γ radiations (neutron-capture γ rays) are produced, their energy is up to 8MV
- In general, a longer maze (>5 m) is desirable in reducing the neutron fluence at the door
- A few inches of a hydrogenous material such as polyethylene can be added to the door to thermalize the neutrons and reduce the neutron dose

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Protection Against Brachytherapy Sources

- Governed by NCRP report 40
- Storage: lead-lined safes with adequate shielding, ventilation for radium source storage
- Source preparation: usage of lead L-block for handling applicators
- Source transportation in lead containers or leaded carts
- Leak testing of sealed sources (e.g., check radium source for radon leaks); periodicity is specified by NRC or state regulations

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Radiation Protection Surveys

- After the installation of radiation equipment, a qualified expert must carry out a radiation protection survey of the installation
- The survey includes
  - Equipment survey to check equipment specifications and inter-locks related to radiation safety
  - Area survey as evaluation of potential radiation exposure to individuals in the surrounding environment
- Since low levels of radiation are measured, the instrument must be sensitive enough to measure such low levels

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Radiation Monitoring Instruments

- The detectors most often used for surveys are ionization chambers and Geiger counters

A Cutie Pie survey meter, Victoreen

- *Ion chamber survey meter*: large volume (~600 cc), sensitivity ~mR/hr
- Usually calibrated with γ-ray beam of brachytherapy sources (Cs or Ra)
- For linac installations additional calibration corrections may be required (energy response, linearity, T-P, angular dependence)

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Radiation Monitoring Instruments

- *Geiger-Müller counter* (G-M tube) is much more sensitive than ionization chamber due to gas multiplication
- Can detect individual particles

- Not a dose-measuring device; useful for preliminary surveys to detect the presence of radiation, ionization chambers are recommended for quantitative measurement
- Because of their inherently slow recovery time they can never record more than 1 count/machine pulse, significantly underestimating radiation levels for linacs

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Radiation Monitoring Instruments

- *Neutron detector* is typically used independently of x-ray detector to survey outside of the treatment room

A portable neutron rem counter 'Rascal' (Eberline)

- Detection principles:
  - In hydrogenous materials neutrons produce hydrogen recoils (protons) that can be detected by ionization measurements, proportional counters, scintillation counters, cloud chambers, or photographic emulsions.
  - Activation detectors: detected by their induced nuclear reactions in certain materials
- Neutron count rate in mrem/hr

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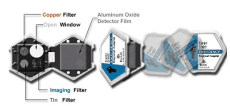
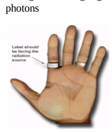
Personnel Monitoring



Al_2O_3:C badges by Landauer. Plastic case has cutaway portion to permit entry of β- particles; small metallic filters help distinguish among higher energy photons

- Personnel monitoring must be used in controlled areas for occupationally exposed individuals
- Cumulative radiation monitoring is performed with film, TL (thermally stimulated), and OSL (optically stimulated luminescence) dosimeter badges
- Since the badge is mostly used to monitor the whole body exposure, it should be worn on the chest or abdomen
- Special badges may also be used to measure exposure to specific parts of the body (e.g., hands) if higher exposures are expected during particular procedures



Ring badge dosimeter, LiF TLD

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Acute Radiation Effects

Annual limit for radiation workers → 5-10

Exposure (rem, x10mSv)	Health Effect	Time to Onset (without treatment)
5-10	changes in blood chemistry	
50	nausea	hours
55	fatigue	
70	vomiting	
75	hair loss	2-3 weeks
90	diarrhea	
100	hemorrhage	
400	possible death	within 2 months
1,000	destruction of intestinal lining	
	internal bleeding	
	and death	1-2 weeks
2,000	damage to central nervous system	
	loss of consciousness;	minutes
	and death	hours to days

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Summary

- Basic principles: time-distance-shielding
- Regulated by NRC, states, DOT, etc.
- Effective dose equivalent and risk estimates
- Structural shielding design
  - Primary, scatter, leakage
  - Controlled vs. noncontrolled areas
- Radiation protection monitoring

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