

Physics Review Course Radiation Protection in Radiotherapy

Arthur Boyer, Ph.D.

It is well known that radiation can be applied as a useful form of medicine, and that it can also induce harmful biological effects. Medical physicists have a legal as well as moral responsibility to see that radiation is used in a manner that is safe for the general public as well as radiation workers. National and international bodies have developed guidelines and standards for radiation protection. These bodies include:

Slide 2

The National Council on Radiation Protection and Measurements (NCRP). The NCRP is an independent group of scientists in the United States chartered by Congress to study radiation protection so as to develop recommendations in concert with other international bodies. The NCRP has published over 170 reports with 15 reports on radiation in medicine since 2000.

The International Commission on Radiological Protection (ICRP). This is an independent group of scientists formed in 1928. It reviews the scientific literature on radiation protection issues and makes recommendations through publications including three in the last five years related to external beam therapy.

The International Atomic Energy Agency (IAEA). The IAEA works out of Geneva, Switzerland and has promulgated radiation protection guidelines used internationally, specifically the 2011 Basic Safety Standards or radiation protection.

Other international organizations concerned with basic safety Standards for protection against ionizing radiation and for the safety of radiation sources (see list and web links below).

1. Identify three national or international bodies that provide guidelines for radiation protection standards.

International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources

- International Atomic Energy Agency (IAEA)
https://rpop.iaea.org/RPOP/RPoP/Content/InformationFor/HealthProfessionals/2_Radiotherapy/index.htm
- World Health Organisation (WHO)
http://www.who.int/ionizing_radiation/about/med_exposure/en/index.html
- Pan American Health Organization (PAHO)
http://www.paho.org/hq/index.php?option=com_content&view=category&layout=blog&id=1162&Itemid=599
- the International Labour Organisation (ILO)
<http://www.ilo.org/global/topics/safety-and-health-at-work/lang--en/index.htm>
- the Food and Agriculture Organisation of the United Nations (FAO)
http://www.fao.org/index_en.htm
- the Nuclear Energy Agency of the Organisation for Economic Co-operation and Development (OECD/NEA).
<http://www.oecd-nea.org/rp/>

U. S. Regulatory Agencies

- Nuclear Regulatory Commission (NRC)
<http://www.nrc.gov/>

The Nuclear Regulatory Commission (NRC) exercises legislated control over the use of all radioactive products of nuclear reactors and radionuclides for medical uses produce by accelerators.



- Department of Transportation (DOT)
Regulates transportation of radioactive materials

State Regulatory Agencies

Each state then has its own regulatory body, usually in the Department of Health of the state, that licenses the use of naturally occurring radioactive isotopes such as radium and radon, and radiation producing machines used in diagnostic and therapeutic medicine. NRC relinquishes to “Agreement States” portions of its regulatory authority to license and regulate



By product materials (radioisotopes); source materials (uranium and thorium); and certain quantities of special nuclear materials. The state regulations dealing with radiation protection are found in the state legal codes.

Radiation Protection Quantities and Units of Measure

Specialized units of measure are used in the radiation protection standards. These units and the concepts behind them were developed by the bodies listed above to provide a meaningful framework for radiation protection practices and standards that accounts for the various biological and technical peculiarities of radiation protection. One must start with the purely physical units of exposure and dose.

Exposure, X

Briefly, exposure is defined by the ionization of air by radiation. The SI unit for exposure is C/kg and the special unit for exposure is the Röntgen, defined as $1R = 2.58 \times 10^{-4} \text{ C/kg}$.

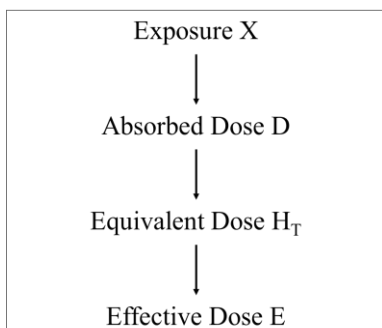
Dose, D

The unit of measure of absorbed dose is the Gray defined as $1\text{Gy} = 1 \text{ J/kg}$, that is the absorption of 1 Joule of energy by 1 kg of material. The old unit of dose is the rad defined as $1\text{rad} = 100 \text{ erg/gm} = 10^{-2} \text{ J/kg}$

The conversion of exposure to dose for x-ray energies below 3MeV is well known.

$$D = X \times f$$

Where f depends on radiation energy and the target material, eg. for soft tissue, 100 keV, 1 Röntgen gives 9.5 mGy (0.95 rad) absorbed dose. Because the conversion factor from Röntgens to rads is so close to unity, for radiation protection purposes they are often set to be equal.



Slide 3

2. Identify two regulatory agencies and their roles in medical radiological practice.

Slide 4

Exposure X

- defined as the amount of *ionization* created in air
- only defined for air, and x- and gamma radiation
- measured as Coulomb/kg
- (old unit) Roentgen R = $2.58 \times 10^{-4} \text{ C/kg air}$

Absorbed Dose D

- the amount of energy deposited per unit mass in any target material
- applies to any radiation
- measured in Gray (Gy) = 1 Joule/kg
- (old unit) 1 rad = 0.01 Gy

3. Gy is equal to _____.

- a. 1 rad
- b. 10 rad
- c. 100 rad
- d. 1 kilo-rad

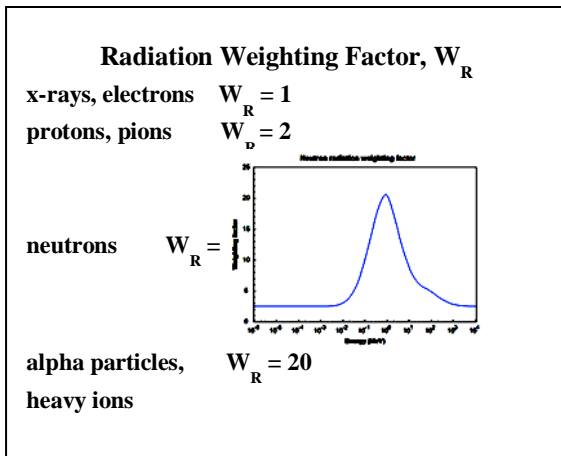
Equivalent Dose, H_T

It has been found that neutrons and energetic ions are more damaging by virtue of their high linear energy transfer. To account for such biological effects, a quantity called the equivalent dose (represented by H_T by convention) is defined as the absorbed dose averaged over a specified organ or tissue volume multiplied by a radiation weighting factor,

$$H_T [Sv] = D [Gy]W_R$$

where W_R is defined as a quality factor or radiation weighting factor unique to the type of radiation employed. The unit of equivalent dose is J/kg and has been given the special name the Sievert [Sv]. The Equivalent Dose replaces the unit of Dose Equivalent whose units were the rem ($H[rem] = D[rad] \cdot Q$). The radiation weighting factor is unitless.

The radiation weighting factor is related to RBE and simplified for radiation protection purposes. The current recommendations are from ICRP Publ 103 (2007).



Effective Dose, E

Effective Dose accounts for differences in organ sensitivity when different tissues/organs receive different absorbed doses. E is defined as the sum

$$E[Sv] = \sum_T \{ H_T[Sv] \times W_T \}$$

Slide 5

4. 1 SV is equal to _____ rem.
a) 100 b) 10 c) 1 d) .1

5. The unit for Equivalent Dose, H_T , is expressed in
a) Sievert b) Gray c) rad d) roentgen

6. Define the Radiation Weighting Factor in the context of radiation protection and estimate the equivalent dose received by a person exposed to 1 rad of ^{60}Co gamma rays.
Estimate the equivalent dose received by a person exposed to 0.1 rad of ^{252}Cf neutrons.

Slide 6

7. 1 Sv is equal to
a) 1 rem
b) 100 rad
c) 100 rem
d) none of the above

Slide 7

8. 10 μ Sv is equal to _____ mrem.
a) 100
b) 10
c) 1
d) 0.1

Slide 8

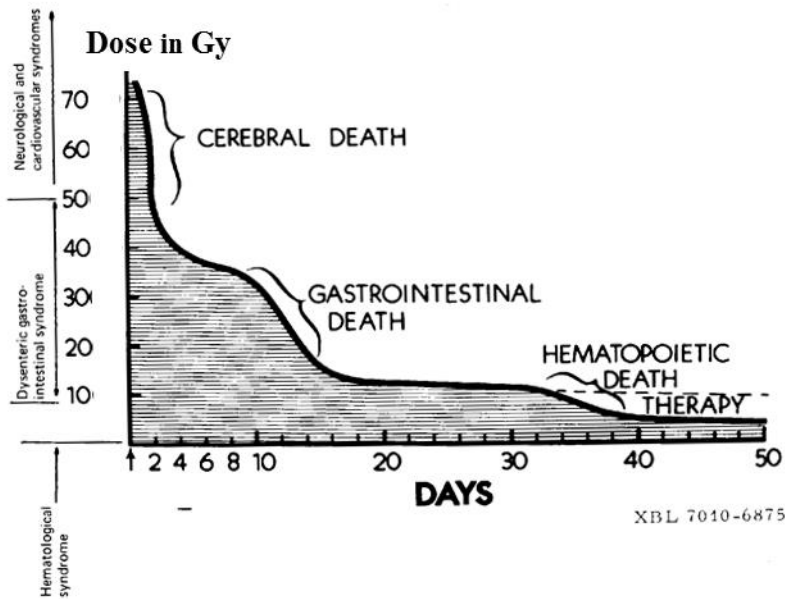
where W_T is a weighting factor for tissue T and H_T is the equivalent dose received by the tissue T. Values recommended in ICRP in Publ 103 (2007) are given in the table below.

Weighting Factors for Tissues			
$W_T = 0.01$	$W_T = 0.04$	$W_T = 0.08$	$W_T = 0.12$
Bone Surface	Bladder	Gonads	Bone marrow
Brain	Esophagus		Colon
Salivary glands	Liver		Lung
Skin	Thyroid		Stomach
			Breast
			13 others

Note that the weighting factors, W_T , when summed over all individual organs add up to 1.00

Radiobiology

Considerable analysis has been made of the deleterious effects of radiation in order to establish standards for radiation protection. These analyses have considered the biological effects of low levels of radiation and the associated relative risks. The graph below shows effects of whole body irradiation to unfractionated doses above 5 Gy.



Low-Level Radiation Effects

The following table lists some of the biological effects of low doses of radiation less than 0.5Gy.

9. 1 mrem is equal to _____ mSv
 a) 0.001
 b) 0.01
 c) 0.1
 d) 1.0

Slide 9

10. Dose equivalent (H) and absorbed dose (D) are numerically the same (Yes / No).

11. Under what conditions is it appropriate to set 1 R = 1 rad = 1 rem?

12. Match organs to tissue weighting factors, W_T

a) Gonads	i) 0.04
b) Red bone marrow	ii) 0.08
c) Thyroid	iii) 0.12
d) Lung	

Slide 10

13. The radiation risk to an organ depends not only on the equivalent dose to the organ but also on the type of tissue involved (Yes / No)

Slide 11

- 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

Slide 12

Dose Effects

Dose effects have been divided into two types:

Stochastic Effects

“all or none” effects whose probability increases with dose

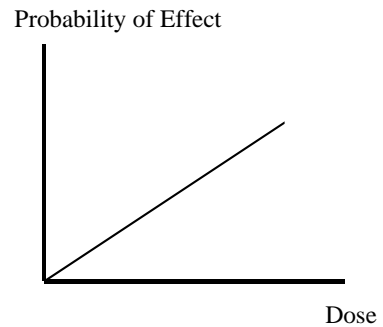
- Carcinogenesis
- Genetic Effects
- Birth Defects

Tissue Reactions

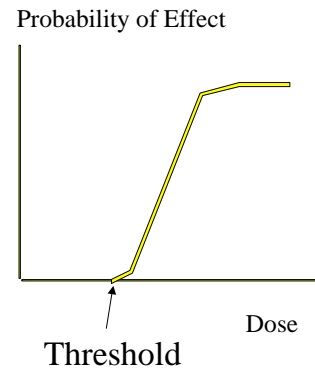
Increases in severity with increasing absorbed dose

- Fibrosis

Deterministic effects (now called Tissue Reactions) are not considered in protection limits because the exposures are assumed to be below the thresholds for observing these effects. The stochastic effect probabilities have not been demonstrated to be linear down to zero dose. A stochastic linear risk is assumed for the purposes of radiation protection but not for the purposes of risk assessment.



Stochastic Effects



Tissue Reactions

Projected threshold estimates of the acute absorbed doses for 1% incidences of morbidity and mortality involving adult human organs and tissues after whole body gamma ray exposures.

Organ/tissue effect	Time to develop	Absorbed dose (Gy) ^e
Morbidity:		
Temporary sterility	Testes 3–9 weeks	0.1 ^{a,b}
Permanent sterility	Testes 3 weeks	6 ^{a,b}
Permanent sterility	Ovaries < 1week	3 ^{a,b}
Depression of blood-forming process	Bone marrow 3–7 days	0.5 ^{a,b}
Main phase of skin reddening	Skin (large areas) 1–4 weeks	<3–6 ^b
Skin burns	Skin (large areas) 2–3 weeks	5–10 ^b
Temporary hair loss	Skin 2–3 weeks	4 ^b
Cataract (visual impairment)	Eye Several years	1.5 ^{a,c}
Mortality:		
Bone marrow syndrome:		
– without medical care	Bone marrow 30–60 days	1 ^b
– with good medical care	Bone marrow 30–60 days	2–3 ^{b,d}
Gastro-intestinal syndrome:		
– without medical care	Small intestine 6–9 days	6 ^d
– with good medical care	Small intestine 6–9 days	>6 ^{b,c,d}
Pneumonitis	Lung 1–7 months	6 ^{b,c,d}

^aICRP (1984). ^bUNSCEAR (1988). ^cEdwards and Lloyd (1996). ^dScott and Hahn (1989), Scott (1993).
^eMost values rounded to the nearest Gy; ranges indicate area dependence for skin and differing medical support for bone marrow.

Slide 13

Background Radiation

The risks associated with radiation must be considered in light of the naturally occurring background radiation. Decaying radioactive isotopes are an inherent component of the rock, soil, air, and water around us. High-energy cosmic radiation originating in the sun and outer space constantly bombards the earth. Even the minerals in our own body contain a small proportion of radioactive isotopes that contribute to the annual effective dose (AED). Estimates of the background radiation vary depending on how the averages from the various sources are taken, but the following table from NCRP Rpt No. 160 (doses as of 2006), gives approximate values per exposed individual compared with estimates of medical exposures.

Slide 14

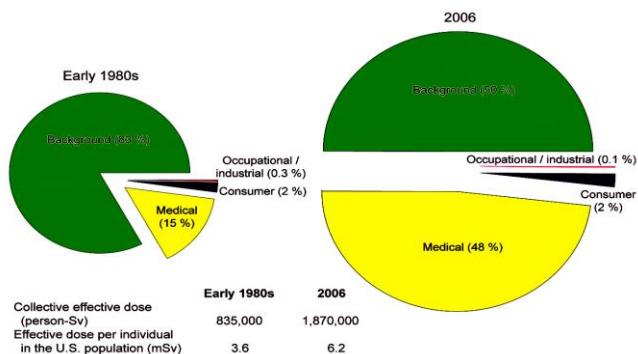
Natural Background

Excluding radon: 0.83 mSv/y
Including radon: 3.11 mSv/y

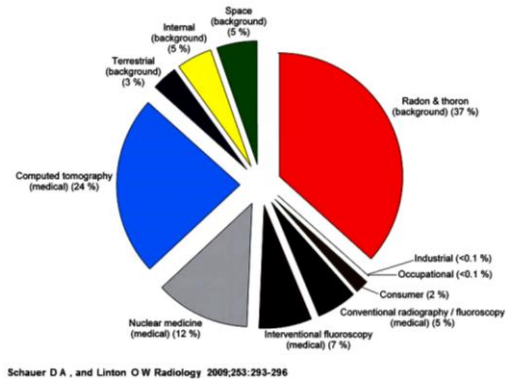
Medical

All Medical: 3.00 mSv/y
CT: 1.47 mSv/y
Nucl Med: 0.77 mSv/y
Int. Fluoro.: 0.43 mSv/y
Conventional: 0.33mSv/y

Slide 15



Slide 16



Slide 17

14. The annual average natural background radiation dose to members of the public in the United States including radon is approximately ____ mrem.

- a) 10
- b) 50
- c) 300
- d) 200

Slide 18

15. 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.

Radiation Risk

There is a measurable incidence of cancer of about 3000 cases in the lifetime of 10,000 individuals in a population that is not exposed to radiation as part of their occupation. It is presumed that these presentations are caused by the natural background as well as other environmental factors common to radiation workers and the general population. Exposures to radiation from man-made sources are always in addition to the background exposure values. Therefore there is some risk associated with these exposures of increasing the number of individuals in a population of radiation workers that will suffer from a fatal cancer, a nonfatal cancer, or some genetic defect appearing in the two generations following that of the exposed person. Studies of populations that have been exposed to man-made radiation, such as survivors of the Japanese atomic bomb attacks, radium dial painters, and scientists working with accelerators in the early twentieth century, have been used to estimate the increase in stochastic effects such as fatal or nonfatal cancers and genetic defects over the rate observed in a population exposed only to natural radiation sources per unit of exposure expressed in effective dose units (Sv). These studies have resulted in estimates of a quantity called “risk” that is used to evaluate levels of radiation exposure expressed in annual effective dose equivalent units. The value of “risk” has been revised several times, as the estimates of dose received by the historical populations has been refined. The following table gives one recent estimate of annual risk coefficients.

Exposed Population	Nominal probability coefficients for stochastic effects Detriment (10^{-2}Sv^{-1})		
	All Cancer	Heritable Effects	Total Detriment
Whole	5.5	0.2	5.7
Adult	4.1	0.1	4.2

Slide 19

16. A whole body dose of 5 mSv/yr for 20 years would increase an adult radiation worker’s risk of dying from cancer by approximately __%

A. 0.02
 B. 0.4
 C. 5
 D. 10

Using the NCRP risk estimate for a radiation worker for fatal cancer of 4.1×10^{-2} per Sv per year,
 $0.041 \text{ Sv}^{-1} \text{ yr}^{-1} \times 0.005 \text{ Sv} \times 20 \text{ yr} = 0.0004$
 $= 0.4\%$

17. The annual effective dose equivalent limit (in mSv) for radiation workers is

a) 20
 b) 50
 c) 150
 d) 1 000

18. Assuming a risk coefficient for inducing a fatal cancer of $4.1 \times 10^{-2} \text{ Sv}^{-1} \text{ yr}^{-1}$, calculate the annual risk for a radiation worker who receives the annual effective dose equivalent limit.

Maximum Permissible Dose Equivalent is 50 mSv

On average, industrial records show that the about 1 fatal accident occurs annually per 10,000 workers in non-radiation industries, a risk factor of 10^{-4} . The following table illustrates how radiation safety limits were calculated to provide a risk to radiation workers equivalent to workers in other industries.

Table 2. Current Standards and Associated Estimates of Risk (NCRP Report Number 116, 1993)

Category	Annual Limit	Recommended Risk Coefficient	Estimated Risk at the Annual Limit
Occupational annual whole-body limit for stochastic effects	5 rem (stochastic)	$4 \geq 10^{-4} \text{ rem}^{-1}$ (for fatal cancer)	2 in 1,000 per year
		$8 \geq 10^{-5} \text{ rem}^{-1}$ (for severe genetic effects)	4 in 10,000 per year
Occupational lifetime limit	1 rem \geq age (years)	—	3 in 100 at age 70
Occupational annual limit for deterministic effects	15 rem to lens of eye 50 rem to any other organ or tissue system	—	no risk if limits not exceeded
Public annual whole body limit for continuous exposure	100 mrem	$5 \geq 10^{-4} \text{ rem}^{-1}$ (for fatal cancer)	1 in 10,000 per year
		$1 \geq 10^{-4} \text{ rem}^{-1}$ (for severe genetic effects)	1 in 100,000 per year

Maximum Permissible Dose Equivalents

Radiological protection is concerned with controlling exposures to ionizing radiation so that tissue reactions are prevented and the risk of stochastic effects is limited to acceptable levels. Considering the relative risk factors in various industries as well as the natural occurrence of malignancies in non-radiation workers, the NCRP and ICRP have recommended that radiation workers and the general public be limited to an annual effective dose equivalent in the table below:

Effective Dose Equivalent Limits.

Summary of Annual Occupational and Public Dose Limits

	^a NCRP	^b ICRP
A. Occupational exposures		
1. Effective dose limits		
a) Annual	50 mSv (5 rem)	20 mSv (5 year avg)
b) Cumulative	10 mSv x age	-----
2. Equivalent dose annual limits for tissues and organs		
a) lens of eye	150 mSv (15 rem)	20 mSv (5 year avg)
b) skin, hands and feet	500 mSv (50 rem)	500 mSv
B. Public exposures (annual)		
1. Continuous or frequent	1 mSv (100 mrem)	1 mSv
2. Infrequent	5 mSv (500 mrem)	-----
3. For tissues and organs		
a) lens of eye	15 mSv (1.5 rem)	15 mSv
b) skin, hands and feet	50 mSv (5 rem)	50 mSv
C. Embryo-fetus	0.5 mSv (50 mrem)	1 mSv

^a

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

^b

ICRP Publication 103, The 2007 Recommendations of the International Commission on Radiological Protection, 2007

^c

ICRP PUBLICATION 118, ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs – Threshold Doses for Tissue Reactions in a Radiation Protection Context

Slide 20

19. The annual effective dose limit to the public, in the case of continuous exposure is

- a) 1 /10th of the occupational worker limit
- b) 1/50th of the occupational worker limit
- c) 1/100th of the occupational worker limit
- d) same as the occupational worker limit.

Slide 21

20. The NCRP annual effective dose limit to public (in mSv) , in the case of infrequent exposure is

- a) 1
- b) 5
- c) 50
- d) 0

These are the maximum values persons may receive in any one year. They do not represent an annual credit for receiving exposures, any remainder of which is carried over from year to year. More recent analyses by the ICRP have produced the following dose limits.

ICRP 2007 & 2011	
Occupational	
Annual Effective Dose	20 mSv/yr (avg over 5 years)
Annual Equivalent Dose	
Lens of Eye,	20 mSv/yr
Skin, etc	500 mSv/yr

Slide 22

The ALARA Principle

The NCRP and the ICRP have developed a principle that requires that radiation exposure be reduced to as low as reasonably achievable below the regulatory limits through a process of optimization. This phrase “as low as radiation reasonable achievable” is the basis for the acronym formulated by the USNRC. The vast majority of all workers receive less than one-tenth of the regulatory limit. The spirit of the recommendations is to design facilities and procedures in which radionuclides and radiation-producing machinery can be used such that annual personnel exposure be “as low as reasonable achievable”.

Slide 23

21. Radiation protection procedures should be optimized so that the doses received, the number of people exposed and the likelihood of incurring exposures are as low as reasonably achievable, taking the economic and social factors into account (Yes / No)

Dose Limits for Pregnant Women

Because the fetus is susceptible to radiation damage that can lead to birth defects including reduction of mental acuity (see table below), there are specific

Slide 24

Summary of Fetal Dose Effects					
Period of Fetal Development	Gestation Age (days)	Effect	Dose (mSv)	Probability	Comments
preimplantation	0 - 8	death of fetus	100	1% - 2%	none if fetus survives
embryonic	8 - 56	organ malformation (small head size) carcinogenesis	100 500 14% / 1000 mSv	threshold 40%	single dose
early fetal	56 - 105	small head size and mental retardation carcinogenesis and sterility	120 40% / 1000mSv 1000	threshold	
mid-fetal	105-175	growth retardation severe mental retardation carcinogenesis	500 650	threshold threshold	lower in this period
late fetal	175 - term	lifetime carcinogenesis	14% / 1000 mSv		single dose

From AAPM Report No 50 “Fetal Dose from Radiotherapy with Photon Beams”

recommendations for both the pregnant worker and the pregnant general public. The total annual dose equivalent recommendation for a occupationally exposed pregnant worker is 5 mSv (500 mrem). It is recommended that any exposure be spread out over the pregnancy such that the fetal exposure not exceed 0.5 mSv (50 mrem) in any one month. Nevertheless, the ALARA principle should be applied carefully in the case of pregnancies. A radiation worker should make their pregnancy known to their employer immediately so that special considerations can be made by their Radiation Safety Officer to limit any possible exposure to 0.5 mSv in any month. This may include reassigning pregnant technologists working at a ^{60}Co teletherapy unit to work at a linear accelerator or restricting the handling of brachytherapy sources. For a non-occupationally exposed pregnant woman, the annual fetal dose limit is 100 mrem, the same as the annual general public dose limit.

Negligible Individual Risk Level

The various radiation protection bodies had defined an annual effective dose equivalent value called the negligible individual risk level or NIRL. The NIRL value is an annual effective dose equivalent of 0.01 mSv (1 mrem). This corresponds to an annual risk of 10^{-7} or a lifetime risk (a lifetime calculated for 70 years) of 0.7×10^{-5} . The NCRP identified the NIRL as a point beyond which further efforts or reduce radiation exposure to individuals is unwarranted.

Slide 25

Principles of Radiation Protection

Given that one knows the maximum permissible effective dose equivalent goals, how can they be achieved? The three cardinal principles of radiation protection are:

Slide 26

- **Minimize Time**
- **Maximize Distance**
- **Maximize Shielding**

These principles are to be used by a Radiation Safety Officer to develop policies and procedures to be communicated to and followed by radiation workers in a radiation workplace. They are also the guiding

principles for the methodology for designing radiation therapy facilities.

Radiation shielding design methodologies are discussed in another lecture.

The workplace is divided into *controlled* areas:

- radiation warning signage required
- radiation workers are under the supervision of a RSO
- personnel exposures are monitored
- weekly limit of 1 mSv based on an effective dose of 50 mSv/y.

and *noncontrolled* areas:

- radiation warning signs are not required
- freely accessible to the general public
- MPE = 10 mrem/wk (infrequent exposure) or
= 2 mrem/wk (ALARA)

A person who occasionally enters a controlled area is not required to wear a film badge if the potential effective dose is less than 1 mSv/y. Who should wear individual dosimeters is generally part of written institutional policy developed by a Radiation Safety Committee and administered by a Radiation Safety Officer. Regulatory and liability concerns should be addressed by these policies.

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.

Dual interlocks shall be provided on all doors to the treatment room such that opening a door will interrupt the treatment. It should only be possible to resume treatment from the control console.

Have at least two independent 'fail to safety' systems for terminating the irradiation. These could be:

- two independent integrating in-beam dosimeters
- two independent timers
- integrating dosimeter and timer

Each system shall be capable of terminating the exposure.

As nearly as practicable, the exposure be limited to the area being examined or treated by using collimating devices aligned with the radiation beam.

Slide 27

Slide 28

Slide 29

Exposure rates outside the examination or treatment area due to radiation leakage or scattering be kept as low as reasonably achievable.

Radiation Warning Signs

Condition	Posting
5 mrem in 1 hour at 30 cm from the source or shield surface	Caution, Radiation Area
100 mrem in 1 hour at 30 cm from the source or shield surface	Caution, High Radiation Area
500 rads 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

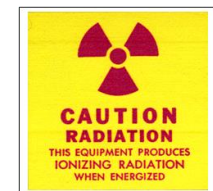
Slide 30



Slide 31



Slide 32



Radiation Protection for Brachytherapy

Radiation protection standards for radioactive sources are expressed in units of activity.

- Curie (Ci) = 3.7×10^{10} dis/sec
- Becquerel (Bq) = 1.0 dis/sec 1 mCi = 37 MBq

The NRC (or the Department of Health in Agreement States) licenses facilities to acquire, store and use sealed and unsealed radioactive sources for therapeutic medicine. Among the requirements for licensees are the following:

Slide 33

22. One Curie is equal to _____ disintegrations per second.

A. 3.7×10^7
 B. 3.7×10^{10}
 C. 2.7×10^{-8}
 D. 2.7×10^{-11}
 E. 1.4×10^6

1. A documented inventory must be kept of sources as they are removed and returned to the radioactive storage facility.
2. Upon implanting and removing sealed sources from a patient the licensee shall make a radiation survey of the patient and the OR or patient's room to confirm that all sources are accounted for.
3. The dose rate in the uncontrolled areas surrounding a patient's room shall not exceed 2 mrem/hr
4. All personnel caring for the patient while they are implanted must receive safety instructions.

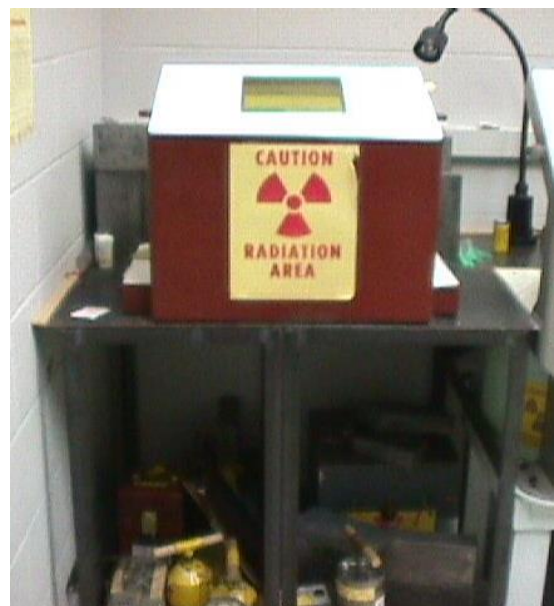
In order to meet these obligations a licensee must have an isotope laboratory for storage, source preparation, source transportation, and leak testing. In addition the licensee must be prepared to conduct radiation protection surveys.

Radioactive Isotope Laboratory

A radioactive isotope laboratory consists of a lockable room with enough space perform the operations of preparing sources for use, cleaning sources after use, source inventory and maintenance, and storage of transportation carts. The room should be clearly indicated with exterior and interior signage. A source preparation area should be surfaced with stainless steel and should contain lead safes for the storage of brachytherapy sources. An L-block with a lead glass viewing window should be located conveniently near the safes. The work area should contain drawers and cabinets to store long forceps for handling the sources.

A reentrant well air ionization chamber and associated electrometer should be in the same area to provide for source calibration checks. In addition, a scintillation-well counter should be available (if not in the laboratory) to carry out leak testing. If radium is to be used (a rarity these days), the room must be ventilated by a direct filtered exhaust to the outdoors. The room must be equipped with a sink for cleaning sources after they are used. The sink must be fitted with a trap or filter adequate to prevent accidentally washing a radioactive source into the public sewer system. Storage

Slide 34



Slide 35

drawers and cabinets must be near the sink and preparation area to store applicators and gadgets.

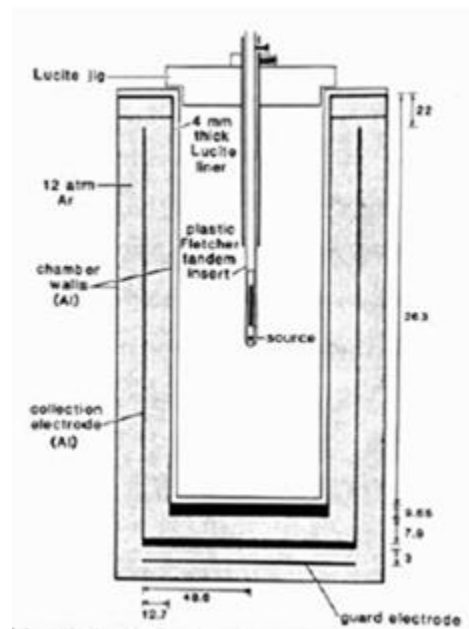
Desk space should be available for record keeping and document preparation. A computer networked to a server could be used for source inventory, calibration, and billing. A GM area monitor should be installed to monitor radiation levels while the sources are being handled. Space must be allowed to store lead-lined carts and wheeled pigs for transporting the sources to the OR and back.

Administration of ^{131}I and ^{32}P

Because they are not used in sealed sources, ^{131}I (with a half-life of 8 days) and ^{32}P (with a half-life of 14.3 days) present special radiation hazards. When ^{131}I is administered, isotope unbound by the thyroid is excreted in the urine. ^{131}I emits both a gamma ray and a beta particle, so it is both an external and internal radiation hazard. ^{32}P is less of a hazard since it is a pure beta emitter. However, when it is injected into a cancer patient's abdomen or thorax, spillage can occur to contaminate the area. If responsibility is taken for ^{131}I administration, additional special procedures must be developed, documented and put in place. These include:

1. Facilities to collect and store contaminated linens and food trays contaminated with patient's secretions
2. Procedures to address the patient vomiting within the first 24 hours of administration
3. Room decontamination after the patient is discharged
4. Radiation safety instruction for the patient upon discharge to keep the radiation dose to household members and the public as low as reasonably achievable.

A routine thyroid bioassay of all personnel involved in the administration and care of the patient.



Signs

Federal and state licensing bodies require that signs be posted at locations where radioactive material and radiation-producing machines are in use or are being stored. The sign required for a given location depends on the amount of radioactivity or on the level or radiation that can be produced.

The International Standards Organization (ISO) and IAEA have recommended an additional warning sign to be placed inside teletherapy units or high dose rate afterloaders that contain high activity radioactive sources. The IAEA initiated the development of this symbol in late 2000 out of concern that people might try to disassemble such devices, unwittingly thinking the metal might be valuable as scrap. The symbol is meant to warn them of the danger of imminent harm after they break into a device and urge them to flee before they expose themselves and others to potentially harmful contamination.

Signs are also required by the Federal Department of Transportation on packages being shipped that contain radioactive materials. When shipping radioactive material through the public transportation system, radioactive materials are controlled by the Department of Transportation (DOT) in the United States. Placard requirements are as follows:

Transport Index	Maximum radiation level at any point on the external surface	Label category
0	0 – 5 $\mu\text{Sv/h}$	White - I
0-1	5 $\mu\text{Sv/h}$ - 0.5 mSv/h	Yellow - II
2-10	0.5 mSv/h - 2 mSv/h	Yellow - III
>10	2 mSv/h - 10 mSv/h	Yellow – III Exclusive provisions

Slide 36



Slide 37



Leak Testing

Slide 38

- Periodic testing required
- Wipe tests measured in scintillation counter
- Removable activity less than 0.005 microCi (185 Bq)

Therapy Misadministration

Slide 39

Therapy events (misadministrations) are defined by state regulations. Typical definitions of a misadministration in therapy are:

- (A) the event involves the wrong individual, wrong type of radiation, wrong energy, or wrong treatment site;
- (B) the treatment consists of three or fewer fractions and the calculated total administered dose differs from the total prescribed dose by more than 10% of the total prescribed dose; or
- (C) the calculated total administered dose differs from the total prescribed dose by more than 20% of the total prescribed dose

Reports of therapy events (misadministrations).

Slide 40

In the event of a therapy event, a radiation machine registrant is required to do the following:

- (A) notify the agency by telephone no later than 24 hours after discovery of the event.
- (B) notify the referring physician and the patient of the event no later than 24 hours after its discovery.
- (C) submit a written report to the agency within 15 days after the discovery of the event. Individual Radiation Safety Committees may define recordable events that are not reported to the State at lower levels as part of a Continuous Quality Improvement program.

Personnel Monitors

The RSO is responsible for administering a personnel monitoring program in their facility. The duties of the RSO in this capacity are shown in the table below

Slide 41

Duties of a Radiation Safety Officer in Regards to Personnel Monitoring

- Establish a system to ensure that monitors are worn and returned in a timely manner, including:
 - Advise on who and when individuals should be monitored
 - Advise on where and how personnel monitoring devices shall be worn
- Enforce the use of personnel monitoring devices
- Interpret the results of personnel monitoring
- Advise the staff of their personnel monitoring and bioassay results
- Investigate doses exceeding trigger levels as to cause
- Provide annual written reports to supervised staff

Radioactive Materials License

To control the receipt, possession, use, and transfer of sources of radiation by the licensee so the total dose to an individual, including doses resulting from all sources of radiation other than background radiation, does not exceed the standards for protection against radiation.

Slide 42

TREC Form 12-1
02/04



Page 1 of 6

Department of State Health Services

RADIOACTIVE MATERIAL LICENSE

Pursuant to the Texas Radiation Control Act and Texas Department of State Health Services (Agency) regulations on radiation, and in reliance on statements and representations hereinafter made by the licensee, a license is hereby issued authorizing the licensee to receive, possess and transfer radioactive material listed below, and to use such radioactive material for the purposes and at the places designated below. This license is subject to all applicable rules, regulations and orders of the Agency now or hereafter in effect and to any conditions specified below.

ICRP Publication 112: Preventing Accidental Exposures from New External Beam Radiation Therapy

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. General Technologies

(198) This section is a summary of the main safety issues identified retrospectively in Sections 2 and 4 on lessons from accidental exposure and near-misses, as well as an anticipative identification of safety implications of new technologies given in Section 3 and on systematic prospective safety assessments explained in Section 5.

(199) The following conclusion for conventional radiation therapy from ICRP Publication 86 (ICRP, 2000) is equally applicable, and even more relevant and important, for new technologies: ‘purchasing new equipment without a concomitant effort on education and training and on a programme of quality assurance is dangerous’.

(200) Increasingly complex new technologies require a safety strategy that combines:

- Initiatives from manufacturers to incorporate, in their equipment, effective safety interlocks, alerts and warnings, self-test capabilities, and easy-to-understand user interfaces in a language comprehensible by the user. International standards must be adhered to in order to ensure compatibility between equipment from different manufacturers. All these safety measures are applicable to hardware as well as software.
- Revisiting training at three levels: (1) generic training on the in-depth understanding of the science involved in the new technology at both clinical and physical levels, (2) specific training in the equipment and techniques to be used, and (3) ‘hands-on’ training to obtain the necessary competence before being allowed to use the new techniques in the clinical environment.
- Risk-informed approaches for selecting and developing quality control tests and checks,

through the application of prospective methods of risk assessment, to be performed in co-operation with manufacturers.

6.2 Justification of and smooth transition to new technologies

(201) The decision to embark upon a new technology for radiation therapy should be based on a thorough evaluation of expected benefits, rather than being driven by the technology itself. It would be unreasonable to use costly, time-consuming, and labour-intensive techniques for treatments for which the same results could be obtained with conventional, less sophisticated techniques which can be used with confidence and safety.

(202) During technology upgrades, a smooth, step-by-step approach should be followed; for example, moving from conventional to conformal therapy with MLCs through 3D treatment planning to finally arrive at IMRT. Failure to adopt a gradual approach may not only lead to a waste of resources but may also increase the likelihood of accidental exposures.

6.3 Changes in processes and workload

(203) The considerable changes in processes, procedures, tasks, and allocation of staff entailed in the introduction of a new technology need to be planned, commissioned, and quality controlled on a regular basis. The full potential impact of these changes should be assessed.

6.4 Availability and dedication of trained staff

(204) Major safety issues in the introduction of new technologies include the danger of underestimating staff resources, and

replacing proper training with a short briefing or demonstration from which important safety implications of new techniques cannot be fully appreciated.

(205) Certain tasks, such as complex treatment planning and pretreatment verification for IMRT, require a substantial increase in resource allocation. The re-assessment of staff requirements, in terms of training and number of professionals, is essential when moving to new technologies.

(206) To prevent shortages of staff with key roles in safety, such as radiation oncologists, medical physicists, and technologists, governments should make provisions for an appropriate system of education and training (in the country or abroad) and have in place a process of certification. In particular, medical physicists, whose activities have a major impact on avoiding catastrophic accidental exposures (e.g. calibration, dosimetry, and physical aspects of quality control), should be integrated as health professionals, and plans should be developed to retain staff who are essential to safety.

(207) Technologists should be involved, together with radiation oncologists and medical physicists, in the decision processes, because technical solutions to monitor patient set-up will become ever more widely available (e.g. image-guided radiation therapy or adaptive radiotherapy).

6.5 Responsibilities of manufacturers and users for safety

(208) Hospital administrators, heads of radiation therapy departments, and staff should remain cognisant of the fact that the primary responsibility for the safe application of new and existing treatment strategies remains with the user. This responsibility includes investigating discrepancies in dose measurements for beam calibration before applying the beam to patient treatments.

(209) Manufacturers should be aware of their responsibility for delivering the correct equipment with the correct calibration files and accompanying documents. They also have a responsibility for

supplying correct information and advice, upon request, from the hospital staff. In particular, they should have policies and procedures in place for assisting users to clarify questions on discrepancies in absorbed dose. They should also identify any limitations in performance of their equipment, and pathways which may lead to the misuse of their equipment.

(210) Manufacturers should collect updated information on safety-related operational experience, and disseminate this information rapidly to users (e.g. as safety information bulletins). This dissemination is particularly critical during the introduction of new techniques and technologies, and especially for problems that appear rarely. For example, serious problems may occur when certain conditions happen to coincide; such a coincidence may not be identified during commissioning and subsequent quality control tests.

(211) Programmes for purchasing, acceptance testing, and commissioning should not only address treatment machines but also increasingly complex TPSs, RTISs, imaging equipment used for radiation therapy, software, procedures, and entire clinical processes.

(212) Professional bodies and international organisations should develop codes of practice, and protocols for calibration of specific beam conditions found in new technologies, such as small field size and the absence of charged particle equilibrium.

(213) There is a need to recommission devices and processes after equipment modifications, and software upgrades and updates.

6.6. Dose escalation

(214) Tumour dose escalation requires a reduction of geometrical margins in order to avoid an increase in the probability of complications in normal tissue. Such a reduction is only feasible with an improvement in dose conformality, accompanied by effective immobilisation with accurate and precise patient positioning based on image guidance. Dose escalation also requires a clear understanding of the overall positioning accuracy achievable in clinical practice as a prerequisite to safe margin reduction. Without these features, tumour dose escalation could lead to severe patient complications.

6.7. Radiation doses from increased use of imaging

(215) When making increased use of imaging for simulation, verification, and correction of patient set-up during the course of treatment delivery, an assessment of the additional radiation doses from imaging is necessary for integration of these doses into treatment planning and delivery.

6.8. Omnipresence of computers

(216) Equipment instructions and human–machine communication should be understandable by the users. Procedures should be in place to deal with situations created by computer crashes, which may cause a loss of data integrity. These procedures should include a systematic verification of data integrity after a computer crash during data processing or data transfer.

(217) When introducing an RTIS, it is necessary to develop procedures and to plan commissioning and ‘probing’ periods to confirm that such a system can be used safely.

6.9. Tests that are no longer effective

(218) When conventional tests and checks are not applicable or not effective for new technologies, the safety philosophy should aim to find measures to maintain the required level of safety. This requirement may lead to the design of new tests or the modification and validation of the old tests. Conscious efforts are required in this regard to avoid compromising safety.

6.10. Consistency in prescription

(219) Protocols for prescription, reporting, and recording, such as those included in ICRU reports, should be kept updated to reflect and accommodate new technologies. Such protocols should be adopted at a national level with the help of professional bodies.

6.11. Co-ordinates, reference marks, and tattoos

(220) Procedures for virtual simulation, and their implications for the whole treatment chain, should be introduced with sufficient training to ensure that the staff are familiar with them and aware of all the critical aspects. A consistent co-ordinate system is required for the whole process from virtual simulation through treatment planning to delivery.

6.12. Handling of images

(221) Written instructions should be visibly posted and followed by the imaging staff who perform the imaging for radiation therapy treatment planning and delivery. These instructions should include procedures for verifying left and right in critical images (e.g. by using fiducial markers), for recording image orientation with respect to the patient, and for ensuring consistency through the whole process from prescription to delivery.

(222) Procedures are also required for selecting the correct images and correct regions of interest, and for deriving electron density from CT, giving specific attention to possible image artifacts and potential geometric distortion.

6.13. Uniformity and clarity in data transfer approaches

(223) When several methods and different protocols for data transfer are used for treating patients in a given department, the patient categories to which the different protocols are applicable should be clearly defined and communicated, including details about which planning system and which data transfer method is applicable.

6.14. Safe interdisciplinary communication

(224) Communication should follow a stated structure regarding content and format, and include formal recording of safety critical issues. Unambiguous communication is essential, especially considering the complexity of radiotherapy and the multidisciplinary nature of the healthcare environment.

6.15. Maintenance, repairs, and notification of the physicist

(225) Procedures to notify a physicist of maintenance or repair activities have been identified as crucial in conventional technology. However, they are even more necessary with new complex technologies, in which modifications, software updates, adjustments, and calibration files can be introduced into the computer dialogue between the various devices, and these might go undetected in the absence of formal notification.

6.16. Prospective safety assessment for selecting quality control checks

(226) The programme of checks should be rationalised and simplified, with the help of manufacturers, by designing proper alerts and warnings, self-test routines especially related to software, easy-to-understand user interfaces, and internal safety interlocks. These measures should be augmented by training in the proper and cautious use of the equipment.

(227) Increased complexity requires a strategy to choose quality control checks based on selective, risk-informed approaches to identify and prioritise tests. In co-operation with manufacturers, mechanisms should be

found to perform prospective safety assessments when a new product, technology, or technique is being introduced.

(228) Timely and effective sharing of operational experience is crucial when introducing new techniques and technologies. This could be achieved by organised and structured sharing mechanisms; for example, through the creation of moderated electronic networks and by the early establishment of panels of experts.

6.17. Safety culture

(229) Hospital administrators and heads of radiation therapy departments should provide a work environment that encourages 'working with awareness', facilitates concentration, and avoids distraction. They should monitor compliance with procedures of the quality control programme, not only for the initial treatment plan but also for treatment modifications.

Physics Review course (Answers to practice questions)

1. Identify three national or international bodies that provide guidelines for radiation protection standards.

NCRP, ICRP, IAEA

2. Identify two regulatory agencies and their role in Medical Radiological Practice

NRC : regulates the use of by-product materials (reactor produced materials) e.g. brachytherapy sources, radiotherapy equipment incorporating radioactive sources (e.g. HDR brachytherapy equipment), Co-60 units etc.

State agencies for other radiation equipment (linacs, Kilovoltage machines, PET scanners etc.)

DOT (for the transport of radioactive materials)

3. Gy is equal to 100 rads (c)

4. 1 Sv = 100 rem (a)

5. The unit for Dose equivalent, H, is expressed in Sievert (a)

6. Define Quality factor in the context of radiation protection and estimate the dose equivalent received by a person exposed to 1 rad of ^{60}Co gamma rays and 0.1 rad of ^{252}Cf neutrons.

Radiation Weighting Factor is a measure of the biological effectiveness (harm) of the radiation in question.

A dose of 1 rad of ^{60}Co corresponds to a dose equivalent of a rem (1 cSv).

A dose of 0.1 rad of ^{252}Cf neutrons corresponds to a DE of about 2 rem (2cSv)

7. 1 Sv = 100 rem (c)

8. 10 μSv is equal to 1000 μrem (=1 mrem) (c)

9. 1 mrem is equal to 1/100 mSv = 0.01 mSv. (b)

10. Dose equivalent and absorbed dose are numerically the same: No

11. Under what conditions is it appropriate to set $1 \text{ R} = 1 \text{ rad} = 1 \text{ rem}$?

For radiation protection purposes (where accuracy of the order of 30 % is reasonable), one can set, for photons and beta radiation, $1 \text{ R} = 1 \text{ rad} = 1 \text{ rem}$.

12. Match organs to tissue weighting factors, W_T

- a) Gonads (0.08) b) Red bone marrow (0.12)
c) Thyroid (0.04) d) Lung (0.12)

13. The radiation risk to an organ depends not only on the equivalent dose to the organ but also on the type of tissue involved : Yes

14. The annual average natural background radiation dose to members of the public in the United States excluding radon is approximately 100 mrem/yr. Radon adds approximately 200 mrem/yr.

15. The average AED received from natural background (in mSv) is about 2-3 (b)

16. A whole body dose of 5 mSv/yr for 20 years would increase a radiation worker's risk of dying from cancer by approximately: 0.4 % (b)

17. The annual effective dose limit (AEDL) (i.e. the whole body dose), as per recent NCRP recommendations (in mSv), is 50 mSv (b)

18. Assuming a risk coefficient for inducing a fatal cancer of $4 \times 10^{-2} \text{ Sv}^{-1}$, calculate the annual risk for a radiation worker who receives the annual effective dose equivalent limit (50 mSv):
Annual risk = $4 \times 10^{-2} \text{ Sv}^{-1} \text{ yr}^{-1} \times 50 \times 10^{-3} \text{ Sv} \times 1 \text{ yr} = 0.2\%$

19. The annual effective dose limit to public, in case of continuous exposure was set by the NRC in 1991 to be 1/50th of the occupational worker limit.

20. The annual effective dose limit to public (in mSv) , in case of infrequent exposure is: (b) 5

21. Radiation protection procedures should be optimized so that the doses received, the number of people exposed and the likelihood of incurring exposures are as low as reasonably achievable, taking the economic and social factors into account : Yes

22. One Curie is equal to 3.7×10^{10} disintegrations per second.

General Instructional Objectives:

After attending this lecture and studying the handout, the attendee will be able to:

1. Use the system of units special to radiation safety.
2. Apply dose limits required for radiation workers and the general public.
3. Devise applications of principles of radiation safety described by national and international advisory bodies to the implementation of regulations required by state health departments or the NRC.
4. Appreciate the scope of radiation safety procedures required to deliver external beam and brachytherapy radiation medicine.
5. Describe the requirements for a radiation safety program in a medical setting.

Acknowledgement

The author acknowledges and thanks Kenneth Kase for providing updates and clarifications for this lecture.