Chapter 16: Radiation Protection and Safety in Radiotherapy

Set of 236 slides based on the chapter authored by P. Ortiz- Lopez, G. Rajan, and E.B. Podgorsak of the IAEA publication:
Radiation Oncology Physics: A Handbook for Teachers and Students

Objective:

To familiarize the student with the basic principles of radiation protection and safety in radiotherapy.

IAEA
International Atomic Energy Agency

Slide set prepared in 2006
by E.B. Podgorsak (Montreal, McGill University)
Comments to S. Vatnitsky:
dosimetry@iaea.org

CHAPTER 16. TABLE OF CONTENTS

CHAPTER 16. TABLE OF CONTENTS (continued)

16.1 INTRODUCTION

- Soon after Roentgen discovered x rays in 1895 and Becquerel discovered natural radioactivity in 1896 it became apparent that ionizing radiation was not only useful for the diagnosis and treatment of disease but was also harmful to human tissue through:
  - Direct clinical effects at very high doses.
  - Potential for delayed effects such as induction of malignancies.
  - Potential for genetic effects.

16.1 INTRODUCTION

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

16.1 INTRODUCTION

- Health care:
  - Disposable medical supplies sterilized by radiation are central in combating disease.
  - Radiology and nuclear medicine are a vital diagnostic tool
  - Radiotherapy is commonly used in treatment of cancer.
- Agriculture:
  - Irradiation is used to preserve foodstuff and reduce wastage.
  - Irradiation-based sterilization techniques are used to eradicate disease carrying insects and pests.
- Industry:
  - Industrial radiography is in routine use to examine welds.

16.2 RADIATION EFFECTS

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

16.2 RADIATION EFFECTS
16.2.1. Deterministic effects

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

16.2 RADIATION EFFECTS
16.2.1. Stochastic effects

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

16.2 RADIATION EFFECTS
16.2.1. Stochastic effects

- Stochastic effects may ensue if an irradiated cell is modified rather than killed, since modified cells may develop into a cancer after a prolonged delay.
- If a cell damaged by radiation exposure is a germ cell whose function is to transmit genetic information to progeny, it is conceivable that hereditary effects of various types may develop in the descendants of the exposed individual.
- The likelihood of stochastic effects is presumed to be proportional to the dose received without a dose threshold.

16.3 INTERNATIONAL CONCENSUS AND RADIATION SAFETY STANDARDS

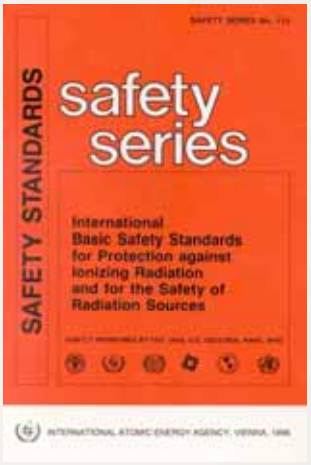
- Radiation safety standards are based on knowledge of radiation effects and on established principles of radiation protection.
- The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was set up by the United Nations in 1955 to compile, assess and disseminate information on:
  - Health effects of radiation.
  - Levels of radiation exposure due to various sources.

16.3 INTERNATIONAL CONCENSUS AND RADIATION SAFETY STANDARDS

- Purely scientific considerations are only part of the basis for decisions on protection and safety; an important component is also value judgment on the relative risks of different kinds and on the balancing of risks and benefits.
- General acceptance of risk is a matter of consensus and the international safety standards should provide a desirable international consensus for the purpose of radiation protection.

16.3 INTERNATIONAL CONCENSUS AND RADIATION SAFETY STANDARDS

- International consensus is basic to the IAEA radiation safety standards, which are prepared with the wide participation of and approval by its Member States as well as relevant international organizations.
- The current version of the safety standard was issued in 1996 and is entitled "International Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources", in short Basic Safety Standard (BSS).



16.4 TYPES OF RADIATION EXPOSURE

The BBS defines two types of exposures:

- Normal exposure results from certain industrial or medical practices and is of predictable magnitude albeit with some degree of uncertainty.
- Potential exposure is an unexpected but feasible exposure that can become actual exposure, if the unexpected situation does occur, for example, as a consequence of equipment failure, design problems or operating errors.

16.4 TYPES OF RADIATION EXPOSURE

The BBS specifies means for controlling normal and potential exposures:

- Normal exposures are controlled by restricting the dose delivered. For example, exposure of patients is controlled through delivering only the doses that are necessary to achieve the diagnostic or therapeutic objective.
- Potential exposures are controlled by optimizing the design of installations, equipment and operating procedures.

16.4 TYPES OF RADIATION EXPOSURE

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

16.4 TYPES OF RADIATION EXPOSURE

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION

16.5.1. Physical quantities

- Most of the requirements of the BBS are qualitative, yet they also establish quantitative limits and guidance levels.
- Radiation exposure originates from natural or man-made radionuclides or from special equipment producing ionizing radiation.
- The main physical quantities used in safety standards are the activity and the absorbed dose.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.1. Physical quantities

- The activity $A(t)$ of an amount of a radionuclide in a particular energy state at a given time is given as:

$$A(t) = \frac{dN}{dt} = \lambda N(t) = \frac{\ln 2}{t_{1/2}} N$$

  - λ is the decay constant of the radioactive nucleus
  - $N(t)$ is the number of radioactive nuclei at time t.
  - $t_{1/2}$ is the half-life of the radioactive nucleus.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.1. Physical quantities

- The SI unit of activity is 1 s^{-1} and its name is the becquerel (Bq), representing one nuclear transformation (disintegration or decay) per second, i.e., 1 Bq = 1 s^{-1}.
- The older unit of activity is the curie (Ci), representing 3.7×10^{10} s^{-1} (i.e., 1 Ci = 3.7×10^{10} Bq).
- The curie was initially defined as the activity of 1 gram of radium-226; however, refined measurements have shown that the activity of 1 g of Ra-226 is 0.988 Ci.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.1. Physical quantities

- The absorbed dose D is defined as:

$$D = \frac{d\bar{\varepsilon}}{dm}$$

  - $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm.

- The SI unit for absorbed dose is 1 J/kg and its name is the gray (Gy).
- The older unit of absorbed dose is the rad, representing 100 erg/g, i.e., 1 Gy = 100 cGy = 100 rad.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Organ dose)

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

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

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Equivalent dose)

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

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

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

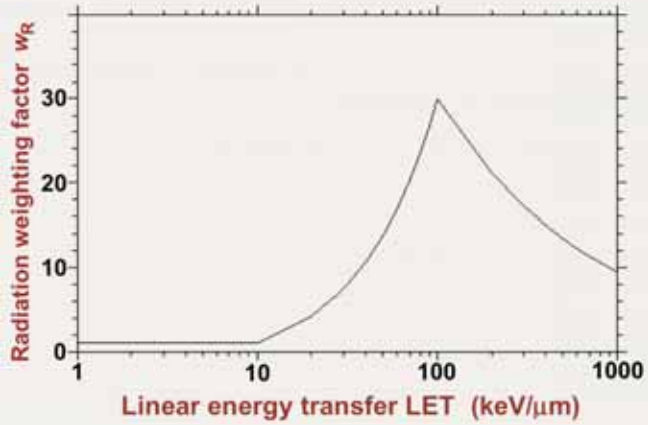
16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Equivalent dose)

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Equivalent dose)

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

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



16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Equivalent dose)

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

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Equivalent dose)

- The organ dose $D_{T,R}$ is a measure of the energy absorption per unit mass averaged over the organ.
- The equivalent dose H_T is a measure of the biological harm (detriment) to the organ or tissue T as a result of organ dose $D_{T,R}$.
- If an organ is irradiated by more than one type of radiation, the equivalent dose H_T is given by the sum:

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Effective dose)

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

$$E = \sum w_T H_T$$

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

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

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

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

- The effective dose then is:

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Effective dose)

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

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

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Committed dose)

- When radionuclides are taken into the body, the resulting dose is received throughout the period of time during which they remain in the body.
- The total dose delivered during this period of time is referred to as the committed dose and is calculated as a specified time integral of the rate of receipt of the dose.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.2. Radiation protection quantities (Collective dose)

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

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities

- The organ dose D_T, equivalent dose H_T and effective dose E are not directly measurable quantities and no standards are available to obtain traceable calibrations for radiation monitors using these quantities.
- The ICRU has defined a set of measurable operational quantities for radiation protection purposes:
  - Ambient dose equivalent (for area monitoring)
  - Directional dose equivalent (for area monitoring)
  - Personal dose equivalent (for personnel monitoring)

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities

- Two approximations are made to radiation fields for purposes of radiation protection:
  - In the expanded field the fluence, angular distribution and energy distribution have the same values throughout the volume of interest as in the actual field at the reference point.
  - In the expanded and aligned field the fluence and its energy distribution are the same as in the expanded field but the fluence is unidirectional.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities

- The operational quantities are defined either for strongly penetrating radiation or for weakly penetrating radiation:
- Weakly penetrating radiation:
  - Alpha particles
  - Beta particles with energies below 2 MeV
  - Photons with energies below 12 keV
- Strongly penetrating radiation:
  - Beta particles with energies above 2 MeV
  - Photons with energies above 12 keV
  - Neutrons

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities (ICRU sphere)

- For purposes of measurement of operational quantities a special sphere has been designed by the ICRU.
- The ICRU sphere is a reference phantom made of 30 cm diameter tissue equivalent material with a density of 1 g/cm^3.
- The composition of the ICRU sphere is as follows:
  - Oxygen 76.2%
  - Carbon 11.1%
  - Hydrogen 10.1%
  - Nitrogen 2.6%

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities (Ambient dose equivalent H*(*d*))

- The ambient dose equivalent $H^*(d)$ at a point in a radiation field is defined as the dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d in millimeters on the radius opposing the direction of the aligned field.
- The recommended value for d for penetrating radiation is 10 mm and the ambient dose equivalent is designated as $H^*(10)$.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities (Directional dose equivalent)

- The directional dose equivalent $H'(d, \Omega)$ at a point in a radiation field is defined as the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at depth d on a radius in a specified direction Ω.
- The directional dose equivalent is generally defined for area monitoring of weakly penetrating radiation:
  - The recommended depth of d = 0.07 mm.
  - Angle Ω is the angle between the beam direction and the radius of the ICRU sphere on which the depth d is defined.

16.5 QUANTITIES AND UNITS IN RADIATION PROTECTION
16.5.3. Operational quantities (Personal dose equivalent $H_p(d)$)

- The personal dose equivalent $H_p(d)$ is defined for both strongly and weakly penetrating radiations as the equivalent dose in soft tissue below a specified point on the body at an appropriate depth d:
  - d is 10 mm for penetrating radiation.
  - d is 0.07 mm for skin and 3 mm for the eye lens.
- The personal dose equivalent $H_p(10)$ from exposure to penetrating radiation during the year is the radiation quantity to be compared with the annual dose limits.

16.6 BASIC FRAMEWORK OF RADIATION PROTECTION

- The principles of radiation protection and safety upon which the radiation safety standards are based are those developed by the ICRP.
- A practice that entails exposure to radiation should only be adopted if it yields sufficient benefit to the exposed individuals or to society to outweigh the radiation detriment it causes or could cause. This means the practice must be justified.

16.6 BASIC FRAMEWORK OF RADIATION PROTECTION

- Individual doses due to the combination of exposures from all relevant practices should not exceed specified dose limits for occupational and public exposure.
- Dose limits are not applicable to medical exposures resulting from diagnostic procedures applied in diagnosis of disease or therapeutic procedures applied in treatment of disease.

16.6 BASIC FRAMEWORK OF RADIATION PROTECTION

- Radiation sources and installations should be provided with the best available protection and safety measures under the prevailing circumstances, so that;
  - The magnitudes and likelihood of exposures and the numbers of individuals exposed be as low as reasonably achievable (ALARA principle), economic and social factors being taken into account
  - The doses they deliver and the risk they entail be constrained which means the radiation protection and safety are optimized.

16.6 BASIC FRAMEWORK OF RADIATION PROTECTION

- In diagnostic medical exposure, optimization of protection is achieved by keeping the exposure of patients to the minimum necessary to achieve the diagnostic objective: optimized image quality and signal to noise ratio of the image.
- In therapeutic medical exposure, optimization is achieved by keeping exposure of normal tissue ALARA consistent with delivering the required dose to the planning target volume (PTV).

16.6 BASIC FRAMEWORK OF RADIATION PROTECTION

- Pregnant workers shall be protected so as to ensure that the embryo or foetus is afforded the same broad level of protection as required for members of the public.
- A safety culture should be inculcated that governs attitudes and behaviour in relation to the protection and safety of all individuals and organizations dealing with sources of radiation.

16.7 GOVERMENTAL REGULATION AND NATIONAL INFRASTRUCTURE

- Legal persons authorized to conduct practices that cause radiation exposure have the primary responsibility for applying the safety standards.
- Governments have the responsibility for enforcement of the safety standards, generally through a system that includes a regulatory authority.

16.7 GOVERMENTAL REGULATION AND NATIONAL INFRASTRUCTURE

- The authorization of a legal person to conduct a radiation related practice may take the form of a registration or license:
  - A registered legal person is called a registrant.
  - A licensed legal person is called a licensee.
- In comparison with registration, a license requires a more specific safety assessment.
- In the case of radiotherapy, the authorization usually takes the form of a license.

16.7 GOVERMENTAL REGULATION AND NATIONAL INFRASTRUCTURE

Summary of annual dose limits (BSS schedule II and ICRP 60)

Radiation quantity	Occupational exposure	Exposure to apprentices	Public exposure
Effective dose whole body (mSv)	**20**, averaged over 5 consecutive years (50 in single y)	**6**	**1**, averaged over 5 consecutive years (5 in single y)
Equivalent dose eye lens (mSv)	**150**	**50**	**15**
Equivalent dose hands, feet, skin (mSv)	**500**	**150**	**50**

16.8 SCOPE OF THE BASIC SAFETY STANDARDS

- Paragraph 1.3 of the BSS states that:

  "*The standards apply to practices, including any sources within the practices and interventions which are:*

  - *Carried out in a State that chooses to adopt the Standards or requests any of the Sponsoring Organizations to provide for the application of the Standards.*
  - *Undertaken by States with the assistance of the FAO, the IAEA, the ILO, the PAHO, or the WHO, in the light of relevant national rules and regulations.*
  - *Carried out by the IAEA or involve the use of materials, services, equipment, facilities, and non-published information made available by the IAEA or at its request or under its control…."*

16.9 RESPONSIBILITIES FOR IMPLEMENTATION OF BSS REQUIOREMENTS

- Paragraph 1.6 of the BSS states that:

  "*The principal parties having the main responsibilities for the application of the Standards shall be:*

  - *Registrants or licensees*
  - *Employers"*

- Paragraph 1.7 of the BSS states that:

  "*Other parties shall have subsidiary responsibilities for the application of the Standards:*

  - *Suppliers, workers, radiation protection officers*
  - *Medical practitioners, health professionals, qualified experts*
  - *Any other party to whom a principal party has delegated specific responsibilities."*

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- Radiation sources, including radioactive material, equipment and accessories, should be purchased only from authorized suppliers and should have a valid wipe test.
- Procedure for the purchase, installation, acceptance, commissioning, use , maintenance and quality control of such material should be developed with involvement of qualified experts, the quality assurance committee, and the radiation protection committee.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- Paragraph II.13 of the BSS (Appendix II) states that:

  "*Registrants and licensees, in specific cooperation with suppliers, shall ensure that:*

  - *The equipment conform to applicable standards of the IEC and the ISO or to equivalent national standards,*
  - *Performance specifications,operating and maintenance instructions as well as protection and safety instructions be provided in a major world language understandable to the users and in compliance with the relevant IEC and ISO standards with regard to 'accompanying documents'.*
  - *Where practicable, the operating terminology and operating values be displayed on operating consoles in a major world language."*

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- Paragraph II.15 of the BSS (Appendix II) states that:

  "*Registrants and licensees, in specific cooperation with suppliers, shall ensure that:*

  - *Radiation installations using radioactive sources be fail-safe in the sense that the source will be automatically shielded in the event of an interruption of power and will remain shielded until the beam control mechanism is reactivated from the control panel.*
  - *High energy radiotherapy equipment should:*
    - *Have at least two fail to safety systems for terminating the irradiation*
    - *Be provided with safety interlocks or other means designed to prevent the clinical use of the machine in conditions other than those selected at the control panel."*

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- The International Electrotechnical Commission (IEC) safety standards applicable to radiotherapy are:

  - IEC 601-2-1 for medical electron accelerators
  - IEC 60601-2-11 for external beam radiotherapy
  - IEC60601-2-17 for remote afterloading brachytherapy
  - IEC 601-2-8 for superficial therapy with x rays
  - IEC 60601-2-29 for therapy simulators
  - IEC62C/62083 for treatment planning systems
  - IEC 60601-1-4 for computer controlled or programmable medical systems

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- The IEC standards prescribe the tests to be carried out:
  - By the manufacturer for a given type of equipment
  - For site tests to be carried out at the hospital on every individual piece of equipment.
- The IEC distinguishes three types of tests:
  - Grade A refers to an analysis of the equipment design related to an IEC safety requirement.
  - Grade B refers to visual inspection or functional test or measurement.
  - Grade C refers to functional test or measurement which may involve interference with circuitry or the construction of the equipment.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- For external beam and high dose rate brachytherapy:
  - The equipment design should allow interruption of the irradiation from the control panel.
  - After the interruption resumption of irradiation should only be possible from the control panel.
- Machines incorporating radioactive sources:
  - Teletherapy machines and high dose rate brachytherapy machines should be provided with a device to return sources manually to the shielded position in the event of an emergency.
  - For Gamma Knives it should be possible to close the shielding door manually.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.1. Equipment

- Irradiation heads for external beam radiotherapy, source containers in brachytherapy and other devices containing radioactive sources should have a clear permanent sign indicating the existence of radioactive material (ISO 361 symbol).

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.2. Sealed sources

- Paragraph II.15 of the BBS (Appendix II) states that:
  - "*Radioactive sources for either teletherapy or brachytherapy shall be so constructed that they conform to the definition of a sealed source.*"
- A sealed source is defined in the BSS as radioactive material that is:
  - Permanently sealed in a capsule
    or
  - Closely bounded and in a solid form.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.2. Sealed sources

- The capsule or material of a sealed source shall be strong enough to maintain leak-tightness under:
  - Conditions of use and wear for which the source was designed.
  - Foreseeable mishap.
- Applicators for brachytherapy should be:
  - Those manufactured specifically for the source or
  - Those with which they are compatible.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.2. Sealed sources

- The use of radioactive sources after their manufacturer recommended working life should be continued only upon leak testing and with approval of the regulatory authority.
- The use of older teletherapy units containing cesium-137 and brachytherapy sources incorporating radium-226 or old cesium-137 in preloaded applicators is no longer justified.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.2. Sealed sources

- Preloaded applicators and sources should be replaced as soon as practicable with afterloading sources not containing radium-226.
- Sources using beta emitters should be provided with shielding of low atomic number materials to minimize bremsstrahlung production while in storage or while undergoing preparation for use.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

- As a general rule, the design of a radiotherapy facility needs to make provisions for safety systems or devices associated with the equipment and treatment room. This includes electrical wiring related to emergency off switches, safety interlocks and warning signals.
- An appropriate qualified expert should carry out the overall design of the facility including shielding calculations.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

- Radiation monitoring equipment should be available on the site in the vicinity of installations using sources of ionizing radiation.
- A radiation safety committee should oversee all installations using sources of ionizing radiation and the installation must possess appropriate licenses issued by a national regulatory authority.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

Appropriate data and methods for shielding calculations are presented in the following publications:

- (1982) ICRP Publication 33
- (1997) IEC Report 61859
- (1997) IPEM Report
- (1998) IAEA TECDOC-1040
- (2006) NCRP Report 151 update of NCRP Report 49.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

- Paragraph II.15 of the BBS (Appendix II) states that:

  "When appropriate, monitoring equipment be installed or be available to give warning of an unusual situation in the use of radiation generators and radionuclide therapy equipment".

- The area monitoring equipment consists of:
  - Radiation detectors running independently from the therapy machine and permanently installed in treatment rooms.
  - Portable radiation monitors located in easily accessible locations in the treatment control rooms for use in radiation emergencies.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

- Example of area monitoring equipment running independently from the therapy machine and permanently installed in a treatment room:
  - Permanently attached to the wall in the treatment room.
  - With a flashing light indicates the source is in ON position.
  - Sounds an audible alarm when the source is in ON position and the treatment room door is open.

- The permanently installed monitoring equipment usually consists of radiation detectors running independently from the therapy machine.
- These detectors respond to the presence of radiation in the treatment room with an audible warning signal but the signal is normally suppressed when the treatment room door is closed.

Manual brachytherapy

- Typical safety features for the storage and preparation of radioactive sealed sources for manual brachytherapy are:

(1) Room to be used only for source storage and preparation by designated and trained personnel.
(2) Room should be provide with a lockable door to control access and maintain source security.
(3) A radiation sign should be posted on the door.
(4) There should be shielded storage available for all sources.
(5) The source safe should have separate compartment for different source activities.

- Safety features for source storage and preparation (cont.):

(6) Workbench should be provided with an L block shielding with a lead glass viewing window.
(7) The source handling area should be well illuminated.
(8) Devices for handling sources (forcepts) should be available.
(9) Sources should be readily identifiable by sight.
(10) Working surface for source preparation should be smooth.
(11) The room should be equipped with a sink with a filter and trap.
(12) There should be a clear indication of the radiation level in room.
(13) Space should be available for storage of short half-life sources.
(14) Space should be available for source transport trolleys.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT
16.10.3. Safety in the design of facilities and ancillary equipment

- Patient treatment rooms for manual brachytherapy

- It is preferable that patient treatment rooms be for individual patients and adjacent to each other.
- Movable shielding should be provided for nurses and visitors.
- Prior to each treatment, movable shields should be placed close to the patient's bed in such a way that exposure of the nurses caring for the patient is minimized.
- The treatment room should contain a shielded storage container.
- An area monitor should be placed at the treatment room entrance so as to detect when a source or a patient is leaving the room area.

Remote control brachytherapy and external beam radiotherapy

- External beam radiotherapy and high dose rate (HDR) brachytherapy should be carried out in specially designed treatment rooms within the radiotherapy department. These rooms are often called treatment vaults or bunkers.
- The treatment room should be large enough to accommodate the treatment machine and allow the full range of motion of the treatment table and patient transport.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT
16.10.3. Safety in the design of facilities and ancillary equipment

- Access to the treatment (irradiation) room shall be furnished with a visible signal indicating whether the radiation source is on or off.
- A door interlock or other suitable means to prevent unauthorized access should be provided and a power fail safe area-monitor should be visible on entering the treatment room.

16.10 SAFETY IN THE DESIGN OF RADIATION EQUIPMENT

16.10.3. Safety in the design of facilities and ancillary equipment

- One or more emergency off switches should be conveniently placed inside the treatment room to allow interruption of the radiation from inside the room.
- The control panel should be installed in such a way that the operator will have a total overview and control of the access to the irradiation room at all times.
- Adequate systems, devices or other means should be provided to allow the operator to have a clear and full view of the patient during treatment.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- Between issuing a purchase order for radiation-emitting equipment and its eventual clinical use there are many important steps that must be followed carefully:
  - Installation and preliminary radiation survey.
  - Rigorous radiation survey and acceptance testing.
  - Commissioning.
  - Development of quality assurance and quality control procedures.
  - Introduction of maintenance and servicing procedures.
  - Start of clinical operation.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- The first act during radiation-producing equipment installation must be a preliminary radiation survey of the area immediately adjacent to the treatment room to verify that radiation levels under the most adverse conditions do not exceed levels estimated in the planning process and approved by the licensing body.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS,COMMISSIONING AND OPERATION

- After equipment installation and preliminary area survey, acceptance tests are conducted in order to verify that:
  - Equipment conforms to the technical specifications given by the manufacturer.
  - Equipment complies with the IEC safety requirements.
- The following generally applies:
  - It is assumed that the equipment belongs to the manufacturer until the acceptance process has been completed.
  - The acceptance tests are usually carried out by a manufacturer's representative in the presence of personnel representing the user (medical physicist) who will decide upon acceptance.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- The tests included in the acceptance protocol should:
  - Be specified in the purchasing conditions and contracts.
  - Clearly establish the responsibility of suppliers for resolving any non-conformity identified during acceptance testing.
- The grade B and grade C tests specified in the IEC standard for a particular machine can be used as guidance for preparing the test protocol.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- After acceptance and before starting clinical operation, commissioning is performed.
- During commissioning medical physicists:
  - Calibrate the radiation beam output.
  - Measure all data required for the clinical use of the machine, including all data to be used in treatment planning computers (TPSs).
  - Measure all data required for the specialized treatment techniques to be used on the equipment.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- An independent audit of the output calibration of the radiation beam should be carried out before starting the clinical operation.
- Quality control protocols must be operational on all radiation-emitting equipment used clinically. The equipment parameters should be tested:
  - Periodically under normal operating conditions.
  - After the radiation source has been installed or replaced.
  - After repairs or maintenance work are carried out on a treatment machine that have potential to alter the radiation output.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- Radiation-emitting equipment should be operated in accordance with the technical documents, ensuring satisfactory operation at all times in respect of both the tasks to be accomplished and radiation safety.
- The manufacturer's operating manual, and any additional procedures, should be approved in accordance with the quality assurance system by a national or international body that is responsible for type approval of radiation emitting devices.

16.11 SAFETY ASSOCIATED WITH INSTALLATION, ACCEPTANCE TESTS, COMMISSIONING AND OPERATION

- Sealed sources should undergo leak tests prior to first clinical use and at regular intervals thereafter, in conformity with ISO 9978.
- Leak tests should be capable of detecting the presence of 200 Bq of removable contamination from sealed source:
  - For manual brachytherapy souces the typical method is the direct wet wipe test.
  - For external beam radiotherapy and remote control brachytherapy the indirect wipe test method of the nearest accessible surface is to be used.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.1. Safe operation of external beam radiotherapy

- Safe operation of external beam treatment machines requires procedures for:
  - Wipe tests
  - Area surveys
  - Interlock checks
  - Emergency OFF buttons.
  - Last-person-out of the treatment room verification circuits.
  - Emergencies when source is stuck in the ON or partially ON position.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.1. Safe operation of external beam radiotherapy

- Safe operation of external beam treatment machines requires that the necessary survey equipment be available:
  - A radiation monitor of the Geiger-Mueller (GM) type
  - A radiation monitor, ionization chamber type, with scales from microsieverts onward.
  - Equipment for wipe tests, such as well counters and multi-channel analysers.
  - Personal alarm dosimeters, especially for emergency intervention.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

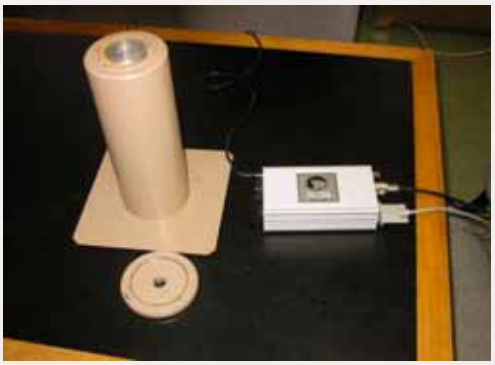
16.11.1. Safe operation of external beam radiotherapy

Radiation monitors:

Ionization chamber type

Geiger-Mueller type

Equipment for wipe tests, such as well counter and multi-channel analyser



16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.1. Safe operation of external beam radiotherapy

- The procedures for use of radiation survey instruments must recognize that some instruments will ‘lock up’ in a high radiation field and give erroneous readings.
- Hence, a measuring procedure should require a three step process:
  - Checking the battery.
  - Checking the monitor response with a check source.
  - Turning the meter on and starting to measure from outside the room in which the source is located (i.e., from lower to higher dose rate areas)

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- The source strength (in terms of air kerma rate) of each brachytherapy source should be determined individually before it is used clinically.
- It is essential that the unit of activity used for source calibration be the same as the unit of activity used in the brachytherapy treatment planning system (TPS).

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- The movements of the sources from the time they have left the safe until their return should be documented and signed by the person responsible for the move.
- A person should be in charge of accountability of the sources. This person should keep a record, with signatures, of the source order and issuance from and return to the safe.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- LDR and HDR sources have certain common operating procedures for safe use:
  - Source inventories should be carried out that show the location and current activity of each source at the facility.
  - Sources should never be left on preparation surfaces.
  - Leak tests with moist wipes need to be carried out and documented on a periodic basis.
  - For HDR units wipe tests are only performed on the afterloading drive assembly and transport containers.
  - Area surveys are to be carried out periodically around the source storage facilities for LDR and HDR sources.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Other conditions for safe use of LDR and HDR sources:
  - The storage facilities are to be marked to indicate that they contain radioactive material.
  - The person responsible for radiation safety in the event of an emergency should be clearly indicated.
  - The storage facilities are to be kept locked at all times.
  - After every brachytherapy treatment, the patient has to be monitored with a radiation survey meter so as to ensure that no activity remains in the patient.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Specific precautions to be observed during the cutting and handling of iridium-192 wire should include ensuring that:
  - Appropriate tools and equipment such as forcepts, cutting devices, magnifying glasses and good illumination of the work surface are available and used.
  - If iridium-192 wires are cut off for immediate use, a container to hold cul lengths should be provided and labeled.
  - Radioactive waste is collected and stored in adequate containers.
  - Surfaces and tools are properly decontaminated.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- The following information should be posted for brachytherapy treatments:
  - Identification of the patient.
  - Sources used.
  - Date and time of insertion and removal.
  - Nursing required.
  - Time allowance for nurses and visitors.
  - Concise instructions for unplanned source and applicator removal and for emergency.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Upon completion of treatment the licensee should ensure that all brachytherapy sources are removed from the patient, except in the case of permanent implants.
- The patient should be monitored with a portable detector to ensure that no source remains in or on the patient.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Linen, dressings, clothing and equipment should be kept within the room where the removal of sources takes place until all sources are accounted for and should be monitored with a radiation survey meter.
- Rubbish bins, soiled dressing bins and laundry baskets coming from a brachytherapy ward or other area where brachytherapy sources are employed should be monitored with a radiation survey meter.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Safe operation of manual brachytherapy:
  - The sources should be inspected visually for possible damage after each use by means of magnifying viewersand a leaded viewing window in a shielded work area.
  - A diagram should be provided at the source storage safe showing the exact location of each source within the safe.
  - When transporting the sources a mobile, shielded container is needed and the shortest possible route should be used.
  - Sources must be sterilized with great care to prevent damage.
  - A filter should be used to prevent loss of sources to the drainage system while cleaning in the sink.

16.11 SAFETY OF RADIATION-EMITTING EQUIPMENT

16.11.2. Safe operation of brachytherapy

- Safe operation of remote control afterloading brachytherapy:
  - Quality control of the afterloader including tests to be carried out at the beginning of each treatment day.
  - The couplings and transfer tubes need to be checked before each treatment to ensure that there is nothing to prevent source motion.
  - Remote afterloading equipment requires specific emergency procedures, which are especially critical in HDR brachytherapy.

16.12 SECURITY OF SOURCES

- Paragraph 2.34 of the BSS states that:
  - "Sources shall be kept secure, so as to prevent theft or damage and to prevent any unauthorized legal person from carrying out any of the actions specified in the General obligations for practices of the Standards by ensuring that:
    - (a) Control of a source not be relinquished without compliance with all relevant requirements specified in the registration or licence and without immediate communication to the Regulatory Authority…..of information regarding any decontrolled, lost, stolen or missing source.
    - (b) A source not be transferred unless the receiver possesses a valid authorization.
    - (c) A periodic inventory of movable sources be conducted at appropriate intervals to confirm that they are in their assigned locations and are secure."

16.12 SECURITY OF SOURCES

- The objective of source security is to ensure continuity in the control and accountability of each source at all times.
- Specific provisions shall be made for situations in which loss of control could lead to accidents, such as:
  - Storage of sources before the installation.
  - Temporary or permanent cessation in use.
  - Storage after decommissioning.
  - Brachytherapy sources remaining in the patient or lost in clothes, bed linen or treatment area.

16.12 SECURITY OF SOURCES

- Radiotherapy equipment should be equipped with safety systems capable of preventing their use by un-authorized personnel.
- A key should be required to energize the system, access to which should be restricted to authorized staff.
- Any loss of source should be reported immediately to the radiation protection officer, who will report it to the regulatory authority.

16.13 OCCUPATIONAL EXPOSURE

16.13.1. Responsibilities and conditions of service

- The parties responsible for protection against occupational exposure are not only the licensees but also the employers.
- In some cases the licensee and the employer are the same legal person, but in other cases they may be different.
  - For example, the employer of a maintenance engineer may be the maintenance company, while maintenance engineers work in many radiotherapy departments, each under a different license.

16.13 OCCUPATIONAL EXPOSURE

16.13.2. Use of dose constraints in radiotherapy

- Dose constraints can be used for optimizing protection in the planning stage for each radiation source.
- The BSS definition of the dose constraint is:
  - “For occupational exposures, dose constraint is a source related value of individual dose used to limit the range of options considered in the process of optimization.”
  - Since the dose constraints are source related, the source should be specified.

16.13 OCCUPATIONAL EXPOSURE

16.13.3. Investigation levels for staff exposure in radiotherapy

- Investigation levels are a tool used to provide a 'warning' on the need to:
  - Review procedures and performances
  - Investigate what is not working as expected
  - Take timely corrective action.
- In radiotherapy:
  - A suitable quantity for use as the investigation level is the monthly effective dose itself
  - The dose to the hands can be used as a quantity for the investigation level for staff in manual brachytherapy.

16.13 OCCUPATIONAL EXPOSURE

16.13.3. Investigation levels for staff exposure in radiotherapy

- Examples of investigation levels for various tasks:
  - For staff working only with accelerators or remote control brachytherapy, a monthly investigation level of 0.2 mSv effective dose.
  - For staff working with cobalt-60 external beam radiotherapy, brachytherapy nurses and persons inserting and removing manual brachytherapy sources, a monthly investigation level of 0.4 mSv effective dose.

16.13 OCCUPATIONAL EXPOSURE

16.13.4. Pregnant workers

- Paragraph I.16 of the BSS states that:

  "A female worker should, on becoming aware that she is pregnant, notify the employer in order that her working conditions may be modified if necessary."

- Paragraph I.17 of the BSS states that:

  "The notification of pregnancy shall not be considered a reason to exclude a female worker from work; however, the employer of a female worker who has notified pregnancy shall adapt the working conditions in respect to occupational exposure so as to ensure that the embryo or foetus is afforded the same broad level of protection as required for members of the public."

16.13 OCCUPATIONAL EXPOSURE

16.13.5. Classification of areas

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

16.13 OCCUPATIONAL EXPOSURE

16.13.5. Classification of areas

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

16.13 OCCUPATIONAL EXPOSURE

16.13.5. Classification of areas

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

16.13 OCCUPATIONAL EXPOSURE

16.13.6. Local rules and supervision

- The rules and procedures dealing with safe operation of external beam radiotherapy and brachytherapy include those needed for occupational protection.
- Management should ensure that:
  - Rules and procedures are known to those to whom they apply.
  - Rules and procedures are followed by assigning responsibilities for supervision of tasks.

16.13 OCCUPATIONAL EXPOSURE

16.13.7. Protective equipment and tools

- Paragraph I.28 of the BSS (Appendix I, Occupational exposure, Personal protective equipment) states that:
  - "*Employers… and licensees shall ensure that*
    (a) workers be provided with suitable and adequate personal protective equipment….."
- Section 16.10 describes in detail the protective devices and equipment required for external beam radiotherapy and brachytherapy.

16.13 OCCUPATIONAL EXPOSURE

16.13.8. Individual monitoring and exposure assessment

- The purpose of monitoring and exposure assessment is to gather and provide information on the actual exposure of workers and to confirm good working practices contributing to reassurance and motivation.
- The BSS requires individual monitoring for any worker who is normally employed in a controlled area and who may receive a significant occupational exposure.

16.13 OCCUPATIONAL EXPOSURE

16.13.8. Individual monitoring and exposure assessment

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

16.13 OCCUPATIONAL EXPOSURE

16.13.8. Individual monitoring and exposure assessment

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

16.13 OCCUPATIONAL EXPOSURE

16.13.8. Individual monitoring and exposure assessment

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

16.13 OCCUPATIONAL EXPOSURE

16.13.9. Monitoring the workplace

- The BSS requires licensees in cooperation with employers to develop programmes for monitoring the workplace.
- Initial monitoring:
  - Is to be conducted immediately after the installation of new radiotherapy equipment and after the replacement of a teletherapy source and remotely controlled brachytherapy sources.
  - Should include measurements of radiation leakage from equipment as well as area monitoring of occupied space around irradiation rooms.

16.13 OCCUPATIONAL EXPOSURE

16.13.9. Monitoring the workplace

- Monitoring is to be conducted in association with brachytherapy procedures:
  - Soon after implantation of the sources, a survey should be made of exposure rates in the vicinity of the patient.
  - After removal of the brachytherapy sources from a patient, a survey is to be performed to confirm removal from the patient and return to shielding of all sources.
  - The transport container should be surveyed before and after brachytherapy procedures.

16.13 OCCUPATIONAL EXPOSURE

16.13.9. Monitoring the workplace

- Monitoring of exposure levels should be conducted through the use of area monitors in teletherapy and HDR treatment rooms.
- Monitoring of the source storage and handling area is to be conducted with a survey meter immediately following the removal from and return to storage of brachytherapy sources.

16.13 OCCUPATIONAL EXPOSURE

16.13.9. Monitoring the workplace

- Monitoring of packages containing radioactive sources upon receipt by the licensee is to be carried out with survey meters.
- All survey meters used for workplace monitoring must be calibrated on a yearly basis and this calibration shall be traceable to a standards dosimetry laboratory.

16.13 OCCUPATIONAL EXPOSURE

16.13.10. Health surveillance

- Paragraph I.41 of the BSS (Appendix I) states that:

  "Employers… and licensees shall make arrangements for appropriate health surveillance in accordance with the rules established by the Regulatory Authority."

- The primary purpose of medical surveillance is to assess the initial and continuing fitness of employees for their intended tasks.

16.13 OCCUPATIONAL EXPOSURE

16.13.10. Health surveillance

- Health surveillance programmes shall be based on the general principles of occupational health.
- No specific health surveillance related to exposure to ionizing radiation is necessary for staff involved in the operation of a radiotherapy practice.

16.13 OCCUPATIONAL EXPOSURE

16.13.10. Health surveillance

- Only in case of heavily overexposed workers would special investigations involving biological dosimetry and further extended diagnostic and treatment procedures be necessary.
- Counseling should be available to workers:
  - Who are or may be pregnant.
  - Who have or may have been exposed substantially in excess of the dose limits.
  - Who are worried about their potential or actual radiation exposure.

16.13 OCCUPATIONAL EXPOSURE

16.13.11. Records

- Paragraph I.44 of the BSS (Appendix I) states that:

  "Employers… and licensees shall maintain exposure records for each worker."
- Employers and licensees shall provide for access by workers to information contained in their own exposure records, and give due care and attention to the maintenance of appropriate confidentiality of records.

16.13 OCCUPATIONAL EXPOSURE

16.13.11. Records

- The exposure record shall include the following:
  - Information on the general nature of work involving occupational exposure.
  - Information on the doses and data upon which dose assessments have been based.
  - When a worker is or has been occupationally exposed while in the employ of more than one employer.
  - Information on the dates of employment with each employer and the doses, exposures and intakes in each employment.
  - Records of any doses due to emergency interventions or accidents, which shall be distinguished from normal work doses.

16.14 MEDICAL EXPOSURE

- Requirements on justification and optimization of protection apply to medical exposure but not to dose limits.
- Dose constraints do not apply to the exposure of patients as part of their own diagnosis and treatment, but specific dose constraints shall be defined:
  - For non-occupational comforters.
  - For medical exposure of individuals exposed for medical research, if these individuals do not benefit directly from the exposure.

16.14 MEDICAL EXPOSURE

16.14.1. Responsibilities for medical exposure

Paragraph II.1 of the BSS (Appendix ii) states that:

"Registrants and licensees shall ensure that:

(a) *No patient be administered a diagnostic or therapeutic medical exposure unless prescribed by a medical practitioner.*

(b) *Medical practitioners be assigned the primary task and obligation of ensuring overall patient protection related to medical exposure.*

(c) *Properly trained medical and paramedical personnel be available for discharge of assigned tasks related to the conduct of the diagnostic or therapeutic procedure prescribed by the practitioner.*

(d) *For therapeutic uses of radiation the calibration, dosimetry and quality assurance requirements of the BSS be conducted by or under the supervision of a qualified medical physics expert."*

16.14 MEDICAL EXPOSURE

16.14.2. Justification of medical exposure

Paragraph II.4 of the BSS (Appendix II) states that:

"Medical exposures should be justified by weighting the diagnostic or therapeutic benefits they produce against the radiation detriment they might cause, taking into account the benefits and risks of available alternative techniques that do not involve medical exposure."

With respect to medical research, paragraph II.8 states that:

"The exposure of humans for medical research is deemed not to be justified unless it is:

(a) *In accordance with the provisions of the Helsinki Declaration.*

(b) *Subject to the advice of an Ethical Review Committee and to applicable national and local regulations.*

16.14 MEDICAL EXPOSURE

16.14.3. Optimization of exposure and protection of the patient

Paragraph II.18 of the BSS (Appendix II) states that:

"Registrants and licensees shall ensure that:

(a) *Exposure of normal tissue during radiotherapy be kept as low as reasonably achievable and organ shielding be used when feasible and appropriate.*

(b) *Radiotherapeutic procedures causing exposure of the abdomen or pelvis of women who are or may be pregnant be avoided unless there are strong clinical indications.*

(c) *Any therapeutic procedure for pregnant women be planned to deliver the minimum dose to any embryo or foetus."*

16.14 MEDICAL EXPOSURE

16.14.3. Optimization of exposure and protection of the patient

- The optimization of protection in the case of patients is complex and does not necessarily mean the reduction of doses to patients, as priority has to be given to the acquisition of:
  - Reliable diagnostic information.
  - Desired therapeutic effect.
- The risk of given diagnostic or therapeutic exposure must be weighted with the risk to the patient of not doing the procedure.

16.14 MEDICAL EXPOSURE

16.14.3. Optimization of exposure and protection of the patient

- With regard to the exposure of pregnant patients, the ICRP Publication 84 states:
  - *"Termination of pregnancy is an individual decision affected by many factors.*
  - *Foetal doses below 100 mGy (1 rad) should not be considered a reason for terminating a pregnancy.*
  - *At foetal doses above this level, there can be foetal damage, the magnitude and type of which is a function of dose and stage of pregnancy at the time of exposure."*

16.14 MEDICAL EXPOSURE

16.14.4. Calibration of radiotherapy sources and machines

Paragraph II.19 of the BSS (Appendix II) states that:

"Registrant and licensees shall ensure that:

(a) The calibration of sources used for medical exposure be traceable to a national or international standards laboratory.

(b) Radiotherapy equipment be calibrated in terms of radiation quality or energy and absorbed dose under specified conditions.

(c) Sealed sources used for brachytherapy be calibrated in terms of activity, reference air kerma rate in air or absorbed dose rate in a specified medium, at a specified distance, for a specified date.

(d) The calibrations be carried out at the time of commissioning a unit, after any maintenance that may affect the dosimetry and at regular intervals approved by the regulatory authority."

16.14 MEDICAL EXPOSURE

16.14.4. Calibration of radiotherapy sources and machines

- Sealed sources used for external beam radiotherapy and brachytherapy need to have a calibration certificate provided by the manufacturer, in accordance with ISO 1677 or its national equivalent standard.
- The licensee must implement a protocol for the calibration of radiation sources used for radiotherapy.
- It is advisable to use international protocols for calibration to avoid confusion and help prevent mistakes.

16.14 MEDICAL EXPOSURE

16.14.4. Calibration of radiotherapy sources and machines

- Calibration of new equipment and new radiation sources should be performed independently by at least two different qualified experts in radiotherapy physics using different dosimetry systems.
- The licensee should ensure that all teletherapy equipment outputs are compared at least once every two years in a national, regional, or international programme for independent dose verification.

16.14 MEDICAL EXPOSURE

16.14.4. Calibration of radiotherapy sources and machines

- One of the simplest mechanisms for independent verifications of external beam calibration or physical dosimetry is participation in the IAEA-WHO or similar thermoluminescence dosimetry postal dose quality audit.
- For new brachytherapy sources for which measurement varies by more than 5% from the manufacturer's certified activity or air kerma rate in air, the source shall not be used for patient treatment until the diference is resolved.

16.14 MEDICAL EXPOSURE

16.14.5. Clinical dosimetry

Paragraph II.20 of the BSS (Appendix II) states that:

"Registrants and licensees shall ensure that the following items be determined and documented:

(b) *For each patient treated with external beam radiotherapy equipment, the maximum and minimum absorbed doses to the planning target volume together with the absorbed dose to the dose prescription point…."*

(c) *In brachytherapy treatments performed with sealed sources, the absorbed doses at selected relevant points in each patient….*

(e) *In all radiotherapeutic treatments, the absorbed doses to relevant organs."*

16.14 MEDICAL EXPOSURE

16.14.6. Quality assurance for medical exposure

Paragraph II.22 of the BSS (Appendix II) states that:

"Registrants and licensees, in addition to applying the relevant requirements for quality assurance specified elsewhere in the BSS, shall establish a comprehensive quality assurance programme for medical exposures with the participation of appropriate qualified experts in the relevant fields, such as radio-physics or radiopharmacy, taking into account the principles established by the WHO and the PAHO."

16.14 MEDICAL EXPOSURE

16.14.6. Quality assurance for medical exposure

- The regulatory authority should encourage licensees to work with professional associations in the development of such programmes.
- The licensee should ensure that the programmes are updated on a regular basis.
- As the development of a national programme may not be feasible in many Member States, a well established and proven international or national programme may be followed.

16.14 MEDICAL EXPOSURE

16.14.6. Quality assurance for medical exposure

Paragraph II.23 of the BSS (Appendix II) states that:

"Quality assurance programmes for medical exposures shall include:

(a) *Measurements of the physical parameters of the radiation generators, imaging devices and irradiation installations at the time of commissioning and periodically thereafter.*

(b) *Verification of the appropriate physical and clinical factors used in patient diagnosis and treatment.*

(c) *Written record of relevant procedures and results.*

(d) *Verification of the appropriate calibration and conditions of operation of dosimetry and monitoring equipment.*

(e) *Regular and independent quality audit reviews.*

16.14 MEDICAL EXPOSURE

16.14.6. Quality assurance for medical exposure

- Following the acceptance of new radiotherapy equipment, sufficient data shall be measured at the commissioning to be used for clinical dosimetry and treatment planning:
  - The measured data shall be clearly documented in the workbook.
  - Before being issued for use in treatment planning, the documentation shall be independently verified, signed, and dated.
  - All dosimetry calibrations, clinical dosimetry data and methods of calculations for therapy equipment are to be reconfirmed at regular intervals.

16.14 MEDICAL EXPOSURE

16.14.6. Quality assurance for medical exposure

- A routine quality assurance programme is an integral component of modern radiotherapy practice; this programme should include:
  - Internal and external auditing
  - Continual improvement management practice.
- These principles should be linked to the radiation protection programme in order to strengthen safety while at the same time improving quality and efficiency.

16.14 MEDICAL EXPOSURE

16.14.7. Constraints for comforters and visitors

With regard to patients' comforters and visitors, paragraph II.27 of the BSS (Appendix II) recommends:

"Registrants and licensees shall constrain, to a level not exceeding that specified in Schedule II, paragraph II-9, any dose to:

- Individuals incurred knowingly while voluntarily helping in the care, support or comfort of patients undergoing medical diagnosis or treatment
- Visitors to patients who have received therapeutic amounts of radionuclides or who are being treated with brachytherapy sources."

16.14 MEDICAL EXPOSURE

16.14.7. Constraints for comforters and visitors

Schedule II, paragraph II-9 of the BSS states that:

"….of the dose of any such comforter or visitor of patients shall be constrained so that it is unlikely that his or her dose will exceed 5 mSv (500 mrem) during the period of a patient's diagnostic examination or treatment.

The dose to children visiting patients who have ingested radioactive materials should be similarly constrained to less than 1 mSv (100 mrem)."

16.14 MEDICAL EXPOSURE

16.14.8. Discharge of patients

- Paragraph II.28 of the BSS (Appendix II) states that:

  "In order to restrict the exposure of any members of the household of a patient who has undergone a therapeutic procedure with sealed or unsealed radionuclides and members of the public, such a patient shall not be discharged from hospital before the activity of radioactive substances in the body falls below the level specified in Schedule III, Table III-VI."

- Table III-VI in Schedule III of the BSS only includes the value of 1100 MBq as the maximum activity guidance level for iodine-131, other sources such as iodine-125 and paladium-103 are under consideration.

16.14 MEDICAL EXPOSURE

16.14.9. Investigation of accidental medical exposure

Paragraph II.29 of the BSS (Appendix II) states that:

"Registrants and licensees shall promptly investigate any of the following:

(a) *Any therapeutic treatment delivered to either the wrong patient or the wrong tissue, or using the wrong pharmaceutical, or with a dose or dose fractionation differing substantially from the values prescribed by the medical practitioner or which may lead to undue acute secondary effects……*

(c) *Any equipment failure, accident, error, mishap or other unusual occurrence with the potential for causing a patient exposure significantly different from that intended."*

16.14 MEDICAL EXPOSURE

16.14.9. Investigation of accidental medical exposure

Paragraph II.30 of the BSS (Appendix II) states that:

"Registrants and licensees shall, with respect to any investigation required under paragraph II.29:

(a) Calculate or estimate the doses received and their distribution within the patient.

(b) Indicate the corrective measures required to prevent recurrence of such an incident.

(c) Implement all corrective measures that are under their own responsibility.

(d) Submit to the Regulatory Authority a written report.

(e) Inform the patient and his or her doctor about the incident.

16.15 PUBLIC EXPOSURE

16.15.1. Responsibilities

- The licensee is responsible for controlling public exposure resulting from a radiotherapy practice.
- Public exposure is controlled by:
  - Proper shielding design
  - Ensuring that radiation sources are shielded and secured,
  - Ensuring that interlocks are functional,
  - Keys to the control area are secured to prevent unauthorized access or use.

16.15 PUBLIC EXPOSURE

16.15.2. Access control for visitors

- The licensee should make arrangements to:
  - Control access of members of the public to radiotherapy irradiation rooms.
  - To provide adequate information and instruction to members of the public before they enter a controlled area so as to ensure appropriate protection.
  - Members of the public entering a radiotherapy room must be accompanied by radiotherapy staff.

16.15 PUBLIC EXPOSURE

16.15.3. Radioactive waste and sources no longer in use

- The licensee should notify the regulatory authority and submit a plan for the transfer and disposal of sources if they are no longer in use.
- The licensee maintains responsibility for the sources until the time of their transfer to other appropriate licensee or to an authorized waste disposal facility.

16.15 PUBLIC EXPOSURE

16.15.3. Radioactive waste and sources no longer in use

- The licensee must notify the regulatory authority of any intention to transfer or decommission cobalt-60 teletherapy equipment prior to initiating any action.
- Depleted uranium used as shielding material shall also be treated as radioactive waste and should be disposed of appropriately.

16.15 PUBLIC EXPOSURE

16.15.4. Monitoring of public exposure

Paragraph III.13 of the BSS (Appendix III) states that:

"……and licensees shall, if appropriate:

(a) *Establish and carry out a monitoring programme sufficient to ensure that the requirements of the BSS regarding public exposure to sources of external irradiation be satisfied and to assess such exposure….*

(c) *Keep appropriate records of the results of the monitoring programmes…."*

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.1. Potential exposure and safety assessment

- Paragraph IV.3 of the BSS (Appendix IV) states that:

  "…licensees shall conduct a safety assessment, either generic or specific for the sources for which they are responsible…"

- The assessment is to be provided to the regulatory authority, according to the BSS principal requirements on authorization.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.2. Mitigation of consequences: emergency plans

- Based on the events identified by the safety assessment, the licensee shall elaborate mitigation measures embodied in a set of emergency procedures.
- The responsibilities shall be allocated and the relevant staff shall be trained in the mitigation measures, which shall be periodically rehearsed.
- The procedures shall identify the responsibilities of individuals and shall be concise, unambiguous and posted visibly in places where they could be needed.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.2. Mitigation of consequences: emergency plans

- For emergency situations there need to be emergency plans that are concise and easily followed, and these should be developed before the startup of a radiation treatment programme.
- The most frequent types of emergency situations are:
  - Lost source.
  - Stuck source.
  - Contamination.
  - Off-site accidents.
  - Patient accidental exposure.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.2. Mitigation of consequences: emergency plans

Emergency involving lost radioactive source:

- It is critical for this type of event that an up to date inventory exists so that the following can be determined:
  - Which source or sources are missing.
  - Type and activity of the missing sources.
  - Where the missing sources were last known to be and when.
  - Who last took possession of the missing sources.
- The area where the sources were last known to be should be closed to entry and exit until a radiation survey has been performed.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.2. Mitigation of consequences: emergency plans

Emergency involving a stuck source

- Emergency procedures need to be short, concise, unambiguous and, if necessary, illustrated with drawings without any explanation text.
- Emergency procedures need to be suitable for being read at first sight and followed.

Stuck source in external beam radiotherapy units:

- Emergency procedures for this event are to be posted at the treatment unit console:
  - The first step is to use the source driving mechanism to return the source to the shielded position.
  - If this is not immediately successful and there is a patient on the treatment table, the patient should be removed from the area and the area closed to further entry.
  - Emphasis should be placed on avoiding staff exposure to the primary beam.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS
16.16.2. Mitigation of consequences: emergency plans

Stuck source in remote control brachytherapy unit:

- Emergency procedures for this event should be posted at the treatment unit console:
  - Emergency container should be available in the treatment room.
  - The emergency container should be placed close to the patient and should be sufficiently large so that it can accept the entire applicator assembly containing the stuck sources.
  - An emergency kit containing long handled forceps for manipulation of the source transfer tubes and applicators should also be available in the treatment room.

Stuck source in remote control HDR brachytherapy unit:

- The following remark is given in the IAEA TECDOC 1040:

> *"High dose rate (HDR) brachytherapy is potentially a high risk technique and extreme accuracy and care are essential. The short response time required for emergency actions (Minutes) imposes the need for the presence of both a physician and physicist trained in emergency procedures during all applications."*

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS
16.16.2. Mitigation of consequences: emergency plans

Stuck source in remote control HDR brachytherapy unit:

- Manufacturers usually provide suggested emergency procedures for an event in which the source fails to return to the safe.
- The procedures assume that the physical integrity of the applicator is maintained.
- The procedures are specific to the actual model of the HDR unit but generally involve the same sequences.

Stuck source in remote control HDR brachytherapy unit:

- The generic sequence of emergency procedures is:
  - Observation of error message at the console.
  - Recovery from the console (pressing emergency off button).
  - Entry into the room with a portable radiation survey meter.
  - Monitoring radiation levels in the room.
  - Recovery from the afterloading unit (pressing emergency off).
  - Manual retraction of the source using a hand crank.
  - Patient and HDR unit survey to confirm source is in the safe.
  - Applicator removal and placement into emergency container.
  - Patient radiation survey and container radiation survey.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS
16.16.2. Mitigation of consequences: emergency plans

Emergency involving contamination:

- In radiotherapy departments where radium-226 brachytherapy sources and powder form cesium-137 sources have been replaced, there is a very low probability of having a contamination accident.
- In the event of a contamination accident it is important:
  - That the area be closed to further entry.
  - That all who were in the area remain there to be surveyed and decontaminated, if necessary.

16.16 POTENTIAL EXPOSURE AND EMMERGENCY PLANS

16.16.2. Mitigation of consequences: emergency plans

Emergency involving off-site accident:

- Off-site accidents with major consequences are rare but can happen through loss of security of teletherapy sources not in use.
- These accidents can cause large scale contamination or external irradiation only and require action by national and international intervening organizations.

16.17 GENERAL SHIELDING CALCULATIONS

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

16.17 GENERAL SHIELDING CALCULATIONS

Parameters: time, distance, and shielding are involved in shielding design, which consists of three steps:

1. Establishing a design value for the effective dose rate in the occupied area.
2. Estimating the radiation field in the occupied area, as if there were no shielding present.
3. Obtaining the attenuation factors that are necessary to reduce the dose value from the effective dose in step (2) to the effective dose in step (1).

16.17 GENERAL SHIELDING CALCULATIONS

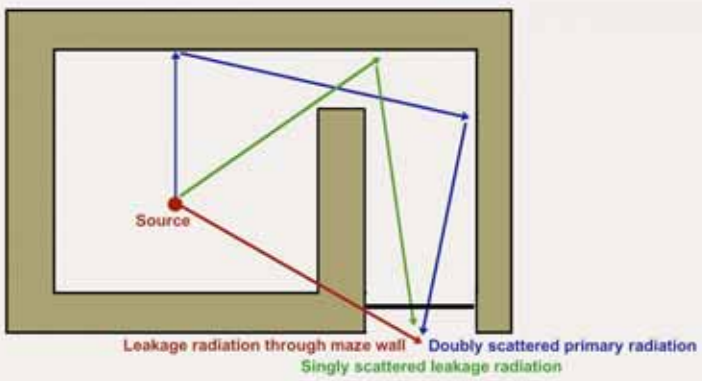
- In shielding design, it is convenient:
  - To keep heavily occupied areas as far away as possible from the treatment rooms.
  - To surround treatment rooms with no occupancy or low occupancy areas (e.g., roof with controlled access).
- Treatment rooms should be large enough for:
  - Easy patient transport in trolleys.
  - Ease of installation and servicing of equipment.

16.17 GENERAL SHIELDING CALCULATIONS

- Since there are major differences in the secondary radiation types and fluences produced by low versus high energy accelerators, the maze design is usually treated under two separate headings:
  - Low energy accelerators (10 MV and below): heavy motorized door is not necessary for shielding against scattered photons.
  - High energy accelerators (above 10 MV): in addition to scattered photons, neutrons also contribute to the dose at the maze entrance, so special doors that shield against neutrons are required.

16.17 GENERAL SHIELDING CALCULATIONS

- Design of the maze.



16.17 GENERAL SHIELDING CALCULATIONS

- Radiotherapy treatment room categories are:
  - Low and high energy linac treatment rooms.
  - Cobalt-60 teletherapy treatment rooms.
  - Superficial and orthovoltage x-ray treatment rooms.
  - High dose rate (HDR) brachytherapy treatment rooms.
  - Low dose rate (LDR) brachytherapy treatment rooms.
- Shielding requirements for each of these rooms follow similar rules and conventions; however, each of the rooms introduces a few of its own specific requirements and constraints.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.1. Step one: Design dose in occupied areas.

- The design effective dose rate *P* in Sv/a or Sv/week in a given occupied area is derived by constrained optimization with the condition that the individual effective doses from all relevant sources will be well below the prescribed effective dose limits for persons occupying the area to be shielded.
- Several conservative assumptions are made in the barrier thickness calculations, so that the actual effective doses received by occupational personnel are much lower than the calculated values.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.1. Step one: Design dose in occupied areas.

- The typical conservative assumptions in the calculations:
  - The attenuation of the radiation beam by the patient is usually not considered.
  - The maximum possible leakage is assumed.
  - The workload, as well as the use factors and occupancy factors, is overestimated.
  - An assumption is made that staff are always in the most exposed place of the occupied area.
  - For linacs producing both x rays and electrons an assumption is made that the linac always operates in the x-ray mode.
  - For dual energy linacs an assumption is made that the linac always runs in the higher energy mode.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.1. Step one: Design dose in occupied areas.

- Typical values for design effective dose rate *P* in occupied controlled areas adjacent to a radiotherapy treatment room:

	Effective dose rate *P*	
	Annual (mSv/a)	Weekly (mSv/week)
Occupational worker	10	0.2
Member of the public	0.5	0.01

16.17 GENERAL SHIELDING CALCULATIONS

16.17.2. Step two: Calculation of air kerma in air without shielding

- The following parameters are used for calculation of the effective dose in Gy/week or Gy/a at points of interest in the controlled area assuming that there is no shielding between the radiation source and the point of interest:
  - Primary radiation.
  - Scatter radiation.
  - Leakage radiation.
  - Machine workload *W*.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.2. Step two: Calculation of air kerma in air without shielding

- Primary radiation is the radiation directly emitted from the treatment machine through the collimator opening and striking the patient or a primary barrier of the treatment room (walls, ceiling or floor).
- Scatter radiation is the radiation produced by the scattering of the primary radiation beam from patient, collimators, beam shaping devices, air, treatment room wall, floor or ceiling.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.2. Step two: Calculation of air kerma in air without shielding

- Leakage radiation is the radiation that escapes through the shielded head of the therapy unit (for linacs the leakage radiation is only present when the beam is on; for cobalt units the leakage radiation is always present).
- Machine workload *W* is defined as the machine output in Gy per week or Gy per year at a well defined point (usually machine isocentre at 100 cm from the source) in the treatment room.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.2. Step two: Calculation of air kerma in air without shielding

- For a linac the machine workload consists of two components: clinical and physics
  - The clinical workload refers to the workload produced at the point of interest in the treatment room during the treatment of patients.
  - The physics workload results from the use of the linac for calibration, quality assurance, phantom measurements, servicing and maintenance.
  - The total linac workload is the sum of the clinical and physics workload:

$$W_{tot} = W_{clin} + W_{phys}$$

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

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

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- The primary barrier is irradiated directly by photons from the target or the source.
- The secondary barrier receives radiation resulting from:
  - Scatter of the primary beam by the patient and/or the surfaces of the treatment room that are hit by primary radiation.
  - Leakage radiation which originates in the x-ray target or radionuclide source and is transmitted through the shielded head of the therapy machine.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Primary radiation is limited in direction by the placement of the therapy machine in the treatment room and the maximum beam size.
- The width of the primary barrier is determined by calculating the size of the diagonal of the largest beam at the point of interest in the controlled areas and adding at least 30 cm to each side.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

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

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Two factors influence the barrier thickness calculation: use factor *U* and occupancy factor *T*:
  - The use factor *U* for the primary barrier is the fraction of the beam-on time during which the primary beam is directed toward a particular barrier.
  - The use factor U for secondary barriers always equals to 1, since secondary radiation is always present when the beam is on.
  - The occupancy factor *T* is a factor with which the workload is multiplied to account for the degree of occupancy of the area in question.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Use factor *U* (for primary barriers)
  - Floor 1
  - Walls 0.25
  - Ceiling 0.25
- Use factor *U* for all secondary barriers = 1
- Occupancy factor *T*
  - Offices, full occupancy areas 1
  - Adjacent treatment treatment room 0.5
  - Corridors, employee lounges 0.2
  - Waiting rooms 0.125

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- The barrier transmission factor *B* provides the fraction of the incident beam air kerma in air transmitted through a given thickness of shielding material.
- Primary, scatter and leakage barrier transmission factors B_{pri}, B_{scat}, and B_{leak}, respectively, are calculated and the required barrier thickness t_{bar} is then determined
  - Either using published graphs (recommended by the NCRP 49).
  - Or using tenth-value layer data (recommended by the NCRP 151).

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Shielding materials are materials used in primary and secondary barriers to provide shielding against primary, scatter and leakage radiation produced in a radiotherapy treatment room.
- The most common materials used for shielding of external beam and brachytherapy treatment facilities are:

  Ordinary concrete, high density (heavy concrete), steel, and lead.

- Common shielding materials for photons and neutrons:

	Density (g/cm^3)	Effective *Z*
• **Ordinary concrete**	**2.35**	**11**
• Heavy concrete	up to 5	26
• **Lead**	**11.3**	**82**
• Steel	7.8	26
• Polyethylene	0.95	-
• Earth	1.5	-
• Wood	-	-

16.17 GENERAL SHIELDING CALCULATIONS
16.17.3. Step three: Attenuation by shielding barriers

- Concrete (nominal density: 2.35 g/cm^3) is the most common shielding material for teletherapy treatment rooms (bunkers, vaults) including cobalt-60 installations, low energy linac rooms and high energy linac rooms.
- For high energy linac rooms, where neutrons are of concern, the shielding wall thickness in concrete is determined by x-ray shielding requirements rather than the neutron shielding requirements.

- Primary barriers are designed to attenuate the photon beam emanating from the treatment unit that is directly incident on the barrier:

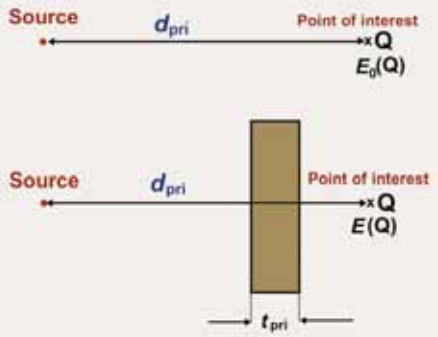
$$E = E_0 e^{-\mu x} = WUT\left(\frac{d_0}{d_{pri}}\right)^2 e^{-\mu x} \qquad E_0 = WUT\left(\frac{d_0}{d_{pri}}\right)^2$$

  - E_0 is the equivalent dose at point of interest a distance d_{pri} from the source and no primary barrier present.
  - E is the equivalent dose at point of interest a distance d_{pri} from the source and with the primary barrier of thickness t_{pri} present.

- The primary barrier is also expected to adequately attenuate the dose equivalent beyond the barrier that results from secondary products of the photon beam.
- For an adequate primary barrier the ratio of the equivalent dose E transmitted through the barrier to the shielding goal P should be equal to or less than one:

$$\frac{P}{E} = 1 \Rightarrow P = E = E_0 B_{pri} \Rightarrow B_{pri} = \frac{P}{E_0} = \frac{P}{WUT}\left(\frac{d_{pri}^2}{d_0}\right)^2$$

- Primary barrier transmission factor B_{pri}



$$E_0 = WUT\left(\frac{d_0}{d_{pri}}\right)^2$$

$$E(t) = E_0 e^{-\mu t} = WUT\left(\frac{d_0}{d_{pri}}\right)^2 e^{-\mu t}$$

$$B_{pri} = \frac{E}{E_0} = e^{-\mu t_{pri}} = e^{-\left(\frac{\ln 10}{TVL}\right)t_{pri}} = 10^{-\frac{t_{pri}}{TVL}} = 10^{-n} \Rightarrow n = -\log B_{pri} = \frac{t_{pri}}{TVL}$$

16.17 GENERAL SHIELDING CALCULATIONS
16.17.3. Step three: Attenuation by shielding barriers

- The thickness of the barrier can be determined using tenth-value layers based on the energy of the beam and the type of the shielding material.
- The required number n of TVLs is given by:

$$n = -\log B_{pri} = \frac{t_{pri}}{TVL}$$

- The barrier thickness is:

$$t_{pri} = (TVL)\log\frac{1}{B_{pri}} = (TVL)\ \log\frac{WUT}{P\ (d_{pri}^2 / d_0^2)}$$

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- To account for the spectral changes of a heterogeneous x-ray beam penetrating the barrier two tenth value layers are defined: TVL_1 (first TVL) and TVL_e (equilibrium TVL).
- The thickness of the primary barrier is estimated from:

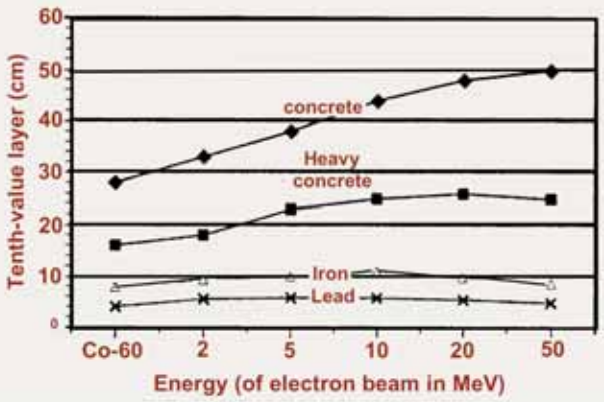
$$t_{pri} = TVL_1 + (n-1)TVL_e$$

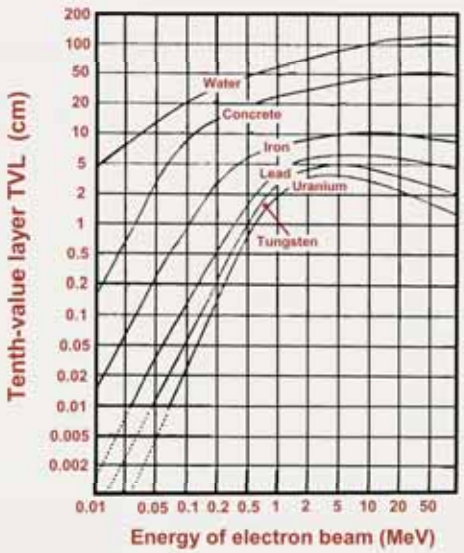
- In general, the primary barrier thickness is calculated for the perpendicularly incident beam and held constant over the whole barrier width.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Primary TVLs for various shielding materials:





The first tenth value layer TVL_1 and the equilibrium tenth value layer TVL_e in concrete and lead.

- **Shielding material: Concrete**

Photon energy (MV)	Co-60	4	6	10	18	25
TVL_1 (cm)	21	35	37	41	45	49
TVL_e (cm)	21	30	33	37	43	46

- **Shielding material: Lead**

Photon energy (MV)	Co-60	4	6	10	18	25
TVL_1 (cm)	4	5.7	5.7	5.7	5.7	5.7
TVL_e (cm)	4	5.7	5.7	5.7	5.7	5.7

16.17 GENERAL SHIELDING CALCULATIONS
16.17.3. Step three: Attenuation by shielding barriers

- The secondary barriers are designed to protect individuals beyond the treatment room from:
  - Leakage radiation from the machine head originating in the x-ray target or radionuclide source and transmitted through the head.
  - Radiation scattered from the patient.
  - Radiation scattered from the treatment room walls.
  - Secondary radiation including photoneutrons and neutron capture gamma rays produced in the machine head or in scattering throughout the treatment room.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- With regard to secondary barriers, photoneutrons and neutron capture gamma rays are of concern only for photon energies above 10 MeV and this only for thin barriers such as:
  - Doors in a treatment room maze.
  - Conduits for high voltage power to the machine.
  - Ducts for treatment room air conditioning and ventilation.

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Since leakage radiation and scatter radiation are of different energies, the secondary barrier requirements of each are calculated separately and compared to arrive at the final secondary barrier thickness:
  - If the thickness of the required barrier is about the same for each secondary component, one HVL is added to the larger of the two barrier thicknesses.
  - If the two barrier thicknesses differ by one TVL or more, the larger barrier thickness is used

- The leakage barrier transmission factor B_{leak} is, similarly to the primary barrier transmission factor B_{pri}, given as:

$$B_{leak} = \frac{P}{10^{-3} WT} \left(\frac{d_{leak}}{d_0} \right)^2$$

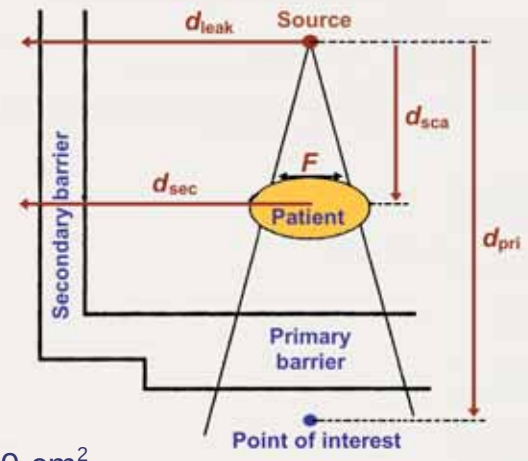
- The following assumptions govern the equation above:
  - 10^{-3} factor arises from the assumption that leakage radiation from the linac head is 0.1% or less of the useful beam.
  - The use factor is taken as 1, since the leakage radiation is always present when the beam is ON.
  - d_{leak} is measured from machine isocentre (d_0 = 1 m), assuming that the linac gantry angles used are, on average, symmetric.

- The scatter barrier transmission factor B_{scat} is given as:

$$B_{scat} = \frac{P}{aWT} \left(\frac{d_{sca}}{d_0} \right)^2 \left(\frac{d_{sec}}{d_0} \right)^2 \frac{20 \times 20 \text{ cm}^2}{F}$$

  - d_{sca} is the distance from the radiation source (x-ray target or radionuclide source) to the patient.
  - d_{sec} is the distance from the patient to the point of interest.
  - $a(\alpha)$ is the scatter fraction, i.e., fraction of the primary dose that scatters from the patient at a particular angle α.
  - F is the field size at the machine isocentre.

- Schematic diagram of d_{pri}, d_{leak}, d_{sca}, and d_{sec}.



$$B_{pri} = \frac{P}{WUT}\left(\frac{d_{pri}}{d_0}\right)^2$$

$$B_{leak} = \frac{P}{10^{-3}WT}\left(\frac{d_{leak}}{d_0}\right)^2$$

$$B_{scat} = \frac{P}{aWT}\left(\frac{d_{sca}}{d_0}\right)^2\left(\frac{d_{sec}}{d_0}\right)^2\frac{20\times 20\ \text{cm}^2}{F}$$

16.17 GENERAL SHIELDING CALCULATIONS
16.17.3. Step three: Attenuation by shielding barriers

- Scatter fraction for d_{sca} = 1 m, d_{sec} = 1 m, F = 20x20 cm^2.

Angle (degrees)	Scatter fraction a			
	6 MV	10 MV	18 MV	24 MV
10	1.04×10^{-2}	1.66×10^{-2}	1.42×10^{-2}	1.78×10^{-2}
20	6.73×10^{-3}	5.79×10^{-3}	5.39×10^{-3}	6.32×10^{-3}
30	2.77×10^{-3}	3.18×10^{-3}	2.53×10^{-3}	2.74×10^{-3}
45	1.39×10^{-3}	1.35×10^{-3}	8.64×10^{-4}	8.30×10^{-4}
60	8.24×10^{-4}	7.46×10^{-4}	4.24×10^{-4}	3.86×10^{-4}
90	4.26×10^{-4}	3.81×10^{-4}	1.89×10^{-4}	1.74×10^{-4}
135	3.00×10^{-4}	3.02×10^{-4}	1.24×10^{-4}	1.20×10^{-4}
150	2.87×10^{-4}	2.74×10^{-4}	1.20×10^{-4}	1.13×10^{-4}

NCRP #151, page 163

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Tenth-value layers (in centimeters) in concrete for patient-scattered radiation at various scattering angles.

Scatter angle (degrees)	Tenth-value layer TVL (cm)							
	Co-60	4 MV	6 MV	10 MV	15 MV	18 MV	20 MV	24 MV
15	22	30	34	39	42	44	46	49
30	21	25	26	28	31	32	33	36
45	20	22	23	25	26	27	27	29
60	19	21	21	22	23	23	24	24
90	15	17	17	18	18	19	19	19
135	13	14	15	15	15	15	15	16

NCRP #151, page 164

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

- Mean energy (in MeV) of patient-scattered radiation as a function of scatter angle and endpoint energy.

Endpoint energy (MV)	Scatter angle (degrees)							
	0	10	20	30	40	50	70	90
6	1.6	1.4	1.2	0.9	0.7	0.5	0.4	0.2
10	2.7	2.0	1.3	1.0	0.7	0.5	0.4	0.2
18	5.0	3.2	2.1	1.3	0.9	0.6	0.4	0.3
24	5.6	3.9	2.7	1.7	1.1	0.8	0.5	0.3

NCRP #151, page 166

16.17 GENERAL SHIELDING CALCULATIONS

16.17.3. Step three: Attenuation by shielding barriers

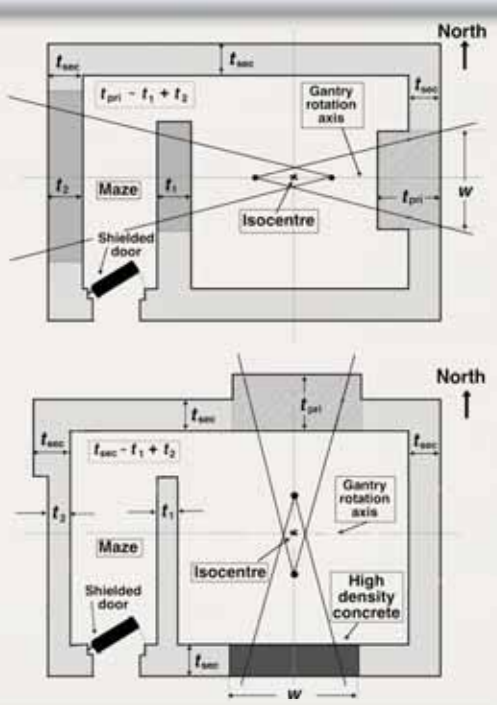
- The equation for B_{scat} assumes that the scatter fractions are normalized to those measured for a field size of 20x20 cm^2.
- The use factor for patient-scattered radiation is 1.
- The scattered radiation energy is significantly degraded from that of the primary beam and therefore data different from the primary beam attenuation data are used to compute the scatter barrier transmission factor.

16.18 TYPICAL LINAC INSTALLATION

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

16.18 TYPICAL LINAC INSTALLATION

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



16.18 TYPICAL LINAC INSTALLATION

16.18.1. Workload

- Linac workloads vary depending on initial assumptions.
- Typical conservative clinical workload W_{clin} assumptions:
  - 50 patients per working day.
  - 3.3 Gy delivered dose at the isocentre per patient.
  - 5 working days per week.
  - 52 working weeks per year.

$$W_{clin} = 3.3\ \frac{Gy}{pt} \times 50\ \frac{pt}{day} \times 5\ \frac{day}{week} \times 52\ \frac{week}{year} = 42\ 900\ \frac{Gy}{year}$$

16.18 TYPICAL LINAC INSTALLATION

16.18.1. Workload

- Typical physics workload W_{phys} includes use of linac for:
  - Calibration.
  - Quality assurance.
  - Phantom measurements.
  - Servicing and maintenance.
- A conservative estimate for W_{phys} is W_{phys} = 7100 Gy/year.
- Typical total linac workload is thus given as:

$$W_{tot} = W_{clin} + W_{phys} = 5 \times 10^4 \text{ Gy/year} = \sim 10^3 \text{ Gy/week}$$

16.18 TYPICAL LINAC INSTALLATION

16.18.2. Calculation of the primary barrier transmission factor

- The primary barrier transmission factor B_{pri} is given as:

$$B_{pri} = \frac{P}{E_0} = \frac{P}{WUT}\left(\frac{d_{pri}^2}{d_0}\right)^2$$

- The primary beam of an external beam unit should only be directed toward primary barriers with sufficient shielding.

16.18 TYPICAL LINAC INSTALLATION

16.18.2. Calculation of the primary barrier transmission factor

- Occasionally, part of the primary shielding is incorporated into the machine as a retractable or permanent beam stopper.
- The beam stopper is usually made of lead with a thickness adequate to attenuate the primary radiation beam to 0.1% of its original value (typically 3TVLs or about 10 HVLs) amounting to about 10 - 15 cm of lead for megavoltage photon beams.

16.18 TYPICAL LINAC INSTALLATION

16.18.2. Calculation of the primary barrier transmission factor

- Treatment machines equipped with beam stoppers are cumbersome with regard to patient setup on the machine.
- Beam stoppers minimize the required thickness of the primary barriers and are used in installations in which space constraints prevent the use of adequate primary barrier thickness.
- With the use of beam stoppers, the primary barrier wall thickness becomes close to (but cannot be less than) that required for secondary barriers.

16.18 TYPICAL LINAC INSTALLATION

16.18.3. Calculation of the scatter barrier transmission factor

- The scatter barrier transmission factor is determined from:

$$B_{scat} = \frac{P}{aWT}\left(\frac{d_{sca}}{d_0}\right)^2\left(\frac{d_{sec}}{d_0}\right)^2\frac{20\times 20}{F}$$

- The scatter factor *a* depends on photon energy and scattering angle. Its typical value for 90° scatter is 10^{-4} - 10^{-3}.
- The Compton scattering formula predicts a maximum energy of 0.511 MeV for 90° scatter and 0.255 MeV for 180° scatter.

16.18 TYPICAL LINAC INSTALLATION

16.18.4. Calculation of the leakage barrier transmission factor

- The leakage barrier transmission factor B_{leak} is:

$$B_{leak} = \frac{P}{10^{-3}WT}\left(\frac{d_{leak}}{d_0}\right)^2$$

- B_{leak} is calculated assuming a beam attenuation due to linac head shielding transmission of 0.1%.
- The energy of the leakage radiation is assumed to be the same as that of the primary radiation.

16.18 TYPICAL LINAC INSTALLATION

16.18.5. Determination of barrier thickness

- One can determine the required primary, leakage, and scatter barrier thickness for the calculated transmission factors B_{pri}, B_{leak}, and B_{scat}, respectively, using the broad beam transmission data from the following publications:
  - ICRP Publication 33
  - NCRP Report 49
  - NCRP Report 151

16.18 TYPICAL LINAC INSTALLATION

16.18.5. Determination of barrier thickness

- Ordinary concrete (nominal density: 2.35 g/cm^3) is the most common shielding material in megavoltage therapy installations.
- Typical shielding thickness of ordinary concrete to protect members of the public in areas next to bunkers housing megavoltage machines:

Radiation quality	Primary barrier (cm)	Secondary barrier (cm)
Cobalt-60	130	65
10 - 25 MV	240	120

16.18 TYPICAL LINAC INSTALLATION

16.18.5. Determination of barrier thickness

- Materials with higher density than concrete may be used to conserve space, since for megavoltage beams the required primary barrier thickness is inversely proportional to the density of the shielding material (Compton effect predominates).
- Replacing ordinary concrete with other materials will have serious financial implications and make the construction of the bunker significantly more expensive.

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.6. Consideration of neutron production in high-energy linac

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

16.18 TYPICAL LINAC INSTALLATION

16.18.7. Entrance door to a high-energy linac room

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

16.18 TYPICAL LINAC INSTALLATION

16.18.7. Entrance door to a high-energy linac room

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

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

- A radiation area sign (along with a visible red light) needs to be provided above the door to the treatment room, and preferably also on the control room door, to indicate a beam on condition.
- There should be audio communication with the patient and emergency switches inside the room to shut off the radiation in the event of an emergency.

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

- Ozone (O_3) is not directly related to radiation shielding concerns, however, it is a safety hazard for personnel.
- Electron beams are much more efficient producers of ozone than photon beams since it is the electron interaction with oxygen molecule that produces the ozone.
- The NCRP recommends that the concentration of ozone should not exceed 0.1 ppm for continuous exposure.

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

- Several of the new specialized techniques used in modern radiotherapy may affect the shielding design of teletherapy rooms. These are:
  - Intensity modulated radiotherapy procedures.
  - Stereotactic radiosurgery.
  - Tomotherapy.
  - Linac on robotic arm (CyberKnife).
  - Dedicated intraoperative electron beam machines.

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

Intensity modulated radiotherapy (IMRT):

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

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

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

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

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

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

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

- Tomotherapy is the newest method of dose delivery involving the principles of computed tomography imaging with 6 MV IMRT.
- The modern tomotherapy machine incorporates helical patient motion, a beam stopper, and efficient use of the rotating beam and will therefore generally fit into a standard linac bunker without major changes in required barrier thickness.

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

- Miniature linac mounted on robotic arm (CyberKnife) can in principle point the primary beam at all barrier walls, thus essentially all walls and the ceiling are considered primary barriers.
- Details of the range of solid angles over which the beam can be pointed should be examined when preparing a shielding plan.

16.18 TYPICAL LINAC INSTALLATION

16.18.8. Other considerations

Dedicated intraoperative radiotherapy machines:

- Mobile linacs that produce only electron beams are used in operating suites to obtain direct access to deep seated tumours.
- No special shielding is required because the machine:
  - Incorporates a beam stopper.
  - Runs at relatively low electron energy (typically 6 MeV).

16.19 SHIELDING DESIGN FOR BRACHYTHERAPY FACILITIES

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

16.19 SHIELDING DESIGN FOR BRACHYTHERAPY FACILITIES

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

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

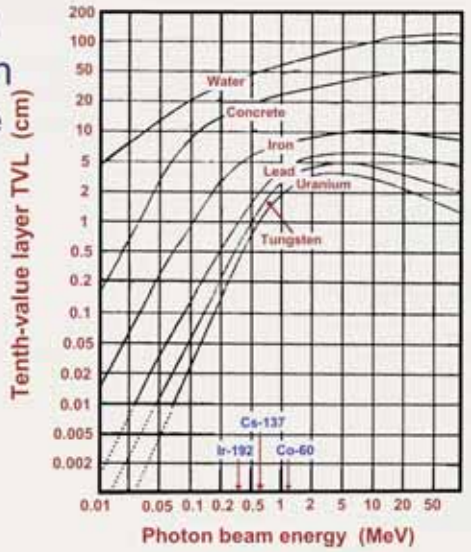
  - P is the design effective dose.
  - d_{pri} is the distance from the source to the point of interest.
  - W_{BT} is the brachytherapy workload in Gy.m^2/week
  - T is the occupancy factor

16.19 SHIELDING DESIGN FOR BRACHYTHERAPY FACILITIES

- From the known B_{pri} we calculate n, the number of TVLs, for a given gamma ray energy emitted by the brachytherapy source:

$$n = \log_{10}(1/B_{pri})$$

Radio-nuclide	Mean gamma energy (MeV)	Γ_{AKR} $\left(\frac{\mu Gy \cdot m^2}{GBq \cdot h}\right)$
Ir-192	0.38	111.0
Cs-137	0.662	77.3
Co-60	1.25	308.5



16.19 SHIELDING DESIGN FOR BRACHYTHERAPY FACILITIES

- Typical workload specification for a remote afterloading HDR iridium-192 (Ir-192) facility is determined as follows:
  - Maximum source activity: 370 GBq (10 Ci).
  - Maximum number of patients treated: 10/day.
  - Number of working days (treatment days) per week: 5 days/week.
  - Maximum treatment time per patient: 10 minutes (for 10 Ci source) per patient.
  - Air kerma rate constant for Ir-192: $\Gamma_{AKR} = 111\ \mu Gy \cdot m^2/(GBq \cdot h)$
  - Typical brachytherapy workload W_{BT} is:

$$W_{BT} = 10^4 \times 10 \times 5 \times 10 \times (1/60) \times 4.1\ \mu Gy \cdot m^2/week =$$
$$= 3.4 \times 10^5\ \mu Gy \cdot m^2/week$$

16.19 SHIELDING DESIGN FOR BRACHYTHERAPY FACILITIES

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