МІНІСТЕРСТВО ОСВІТИ І НАУКИ УКРАЇНИ
ДЕРЖАВНИЙ УНІВЕРСИТЕТ "ЖИТОМИРСЬКА ПОЛІТЕХНІКА"

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Radiobiology and Radioecology
(англійська мова за професійним спрямуванням)

НАВЧАЛЬНИЙ ПОСІБНИК

Рекомендовано Вченою Радою
Державного університету "Житомирська політехніка"
як навчальний посібник для студентів спеціальності
183 «Технології захисту навколишнього середовища»
(Протокол № 4 від 26.06.2020 р.)

Державний університет «Житомирська політехніка»

2020

УДК 577.34+504(075)
Р 15

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Р 15 "Radiobiology and Radioecology" (англійська мова за професійним спрямуванням): навч. посіб. для ауд. та самост. роботи студ. спец. 183 «Технології захисту навколишнього середовища» освіт.-кваліфік. рівня «бакалавр»./ Л.Ф. Могельницька, І.С. Ковальчук, С.В. Суховецька, В.А. Шадура. – Житомир : Державний університет «Житомирська політехніка», 2020. – 230 с. – (Серія "Англійська мова").

ISBN 978-966-683-545-4

Навчальний посібник " Radiobiology and Radioecology" призначений для студентів гірничо-екологічного факультету, які володіють основами лексичного та граматичного мінімумів, базовими знаннями в галузі радіобіології та радіоекології і бажають вдосконалити володіння професійною та загальнотехнічною термінологією, навчитись перекладати і реферувати тексти за фахом, сформувати навички професійно-спрямованого мовлення.

УДК 577.34+504(075)

ISBN 978-966-683-545-4

ПЕРЕДМОВА

Навчальний посібник “Radiobiology and Radioecology” призначений для аудиторної та самостійної роботи студентів спеціальності 183 «Технології захисту навколишнього середовища» освітньо-кваліфікаційного рівня «бакалавр». Посібник пропонується для аудиторної та самостійної роботи студентів 3-4 курсів. Головною метою посібника є підготовка студентів до читання професійно орієнтованої літератури; удосконалення навичок усного мовлення і формування навичок групового спілкування у формі дискусії із загальнодоступних та поглиблених екологічних проблем у межах знань студентів зазначеної спеціальності; засвоєння необхідного лексичного мінімуму, який має сприяти здійсненню професійної комунікації та діяльності; розуміння основних проблем радіоекології.

Посібник орієнтовано на підготовленого адресата – студента, що володіє певними уміннями в межах інструментальних та професійних компетенцій, базовими знаннями в галузі радіоекології.

Посібник складається з 2 розділів: Basic Course, який включає 8 уроків; розділ «Additional Reading» складається з 2 уроків та завдань для тестового контролю опрацьованого матеріалу. Структура основних 8 уроків стереотипна та призначена для введення фактичного та мовного матеріалу заняття. Кожен урок містить найважливіші терміни по темі, питання для обговорення професійної тематики іноземною мовою, додаткові навчальні тексти.

Уроки з розділу «Additional Reading» призначені для поглиблення та узагальнення матеріалу. Текстовий матеріал підібраний з урахуванням повторюваності основної фахової термінології.

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PART I

1. The development of radiation protection

1. Historical perspective. *1.1 Early applications of ionising radiation in medicine. 1.2 Early radiation protection. 1.3 The development of radiation safety standards. 1.4 The application of radionuclides to imaging.* **2. Standards and legislation for protection against ionising radiations.** *2.1 Review of evidence on biological effects of radiation .2.2 Implementation of radiation protection standards. 2.3 Medical radiation exposure.* **3. Public perception of ionising radiation. 4. Non-ionising radiations.** *4.1 Optical radiations. 4.2 Electromagnetic fields. 4.3. Ultrasound. 4.4 Standards and guidance for non-ionising radiations.*

1 Historical perspective

1.1. Early applications of ionising radiation in medicine

The potential for the application of ionising radiations in medicine was realized almost as soon as Wilhelm Roentgen discovered X-rays in 1895. Roentgen determined the basic properties of X-rays, such as their ability to penetrate light materials and the dependence of absorption on density, within a few weeks of his discovery. He also found that X-rays affected photographic plates, and six weeks after his initial discovery he used X-rays to form an image of his wife's hand, the first radiograph. The use of X-rays for medical diagnosis developed rapidly and many radiological techniques were applied within the first year of Roentgen's discovery. Fluorescent screens were used to enhance radiographic images, and in 1897 W. B. Cannon at Harvard reported a study of 'Movements of the stomach by means of Roentgen X-rays', the first fluoroscopic examination. Radiology departments were established to aid diagnosis in most major hospitals in the last few years of the nineteenth century. During this period clinicians tried to use X-rays for treatment of a variety of conditions including lupus, ringworm, tuberculosis, epithelioma, port-wine stain, and cancer. The first proven cure of a cancer patient by X-ray treatment was as early as 1899 by Tage Sjorgen in Sweden.

Roentgen's discovery stimulated the interest of other scientists working in related fields and in 1896 Henri Becquerel discovered radioactivity when he found that uranium salts gave off penetrating radiation which blackened photographic film. Understanding of the nature of the radiations emitted was developing gradually over succeeding years. Many scientists contributed to this, of which Marie Curie made some of

the most significant discoveries, establishing that radiation was emitted by compounds containing the elements uranium thorium, and radium, and in 1898 separating radium which became widely used for therapy.

Choose the proper meaning of the word in *bold.*

1. The potential for the application of ionising radiations in medicine was ***realized*** almost as soon as Wilhelm Roentgen discovered X-rays in 1895.

1) become fully aware of (something) as a fact; understand clearly
2) cause to happen
3) achieve (something desired or anticipated); fulfil
4) make (a profit) from a transaction 5) convert (an asset) into cash

2. The use of X-rays for medical diagnosis ***developed*** rapidly and many radiological techniques were applied within the first year of Roentgen's discovery.

1) grow or cause to grow and become more mature, advanced, or elaborate
2) become more economically and socially advanced
3) start to exist, experience, or possess
4) treat (a photographic film) with chemicals to make a visible image

1.2. Early radiation protection

As the use of X-rays became widespread, evidence that radiation might be harmful began to accumulate. Skin burns and dermatitis were reported among scientists and medical practitioners working with X-rays and the Roentgen Society set up a Committee of Inquiry to look into 'the alleged injurious effects of Roentgen rays' in March 1898. Radiation protection facilities for most early workers were rudimentary or non-existent and a number of reports of hazards from overexposure to radiation appeared during the period 1897-1907. It became apparent that there was a need for measures to protect operators and patients from unnecessary exposure. During the early years of the twentieth century many protective devices, such as shielding around X-ray tubes, aprons and gloves containing lead, mobile lead screens, and lead protection in walls, began to be used by some workers, and in 1915 the Roentgen Society produced recommendations for the use of X-ray operators. These measures marked the beginning of formal radiation protection. Box 1.1 lists some of the events in the evolution of radiation protection.

Choose the proper meaning of the word in *bold.*

3. It became apparent that there was a need for ***measures*** to protect operators and patients from unnecessary exposure.
1) quantity 2) means , step 3) cadence 4) tune

1.3. The development of radiation safety standards

X-rays were used extensively during the First World War and many cases of leukaemia and aplastic anaemia were reported among operators and radiologists. These effects emphasized the need for radiation protection and criteria for limiting exposure to ionising radiations were proposed by various groups and individuals. The British X-ray and Radium Protection Committee (BXRPC) published formal recommendations on radiation protection measures in 1921. For diagnostic radiology these included shielding of X-ray tubes with 2 mm of lead, use of rubber gloves providing protection equivalent to 0.5 mm of lead, and provision of a shielded enclosure for the operator. For radium therapy the use of forceps when handling radioactive sources and the use of lead-lined boxes for transporting sources were recommended. It was also in 1921 that the BXRPC suggested the first tolerance dose of X-rays equivalent to one-tenth of the erythema dose per month. This was the first attempt to introduce a formal dose restriction.

In 1925 the International Commission on Radiological Units and Measurements (ICRU) was set up at the First International Congress of Radiology in London. The aim of the ICRU is the development of a framework of scientific concepts relevant to the assessment of radiation for its safe and effective use. It recommends radiation quantities and units, measuring procedures, and numerical values for physical data. In 1928 the International Commission on X-ray and Radium Protection was established to consider radiation protection problems and issue recommendations on safety measures and practices. This was later to become the International Committee on Radiological Protection (ICRP). Once the roentgen had been established as the unit of exposure, radiation doses could be quantified and limits set for exposure. Techniques were required to measure doses received by radiation workers so that limits could be applied successfully. The National Physical Laboratory (NPL) in Britain set up a radiation dose-monitoring service for their employees in 1937 using dental X-ray film, and this was extended to hospitals in 1942. In 1948 the BXRPC recommended use of photographic film or condensers for assessment of doses for radiation workers, together with regular medical examinations including blood counts.

Box 1.1 Events in the first 100 years of ionising radiation protection

1896 Grubbe's published paper describing X-ray dermatitis of the hands
1897 Roentgen Society founded
1911 Adoption of international radium standard and Curie as unit of activity
1915 Roentgen Society (London) recommends X-ray protection measures
1920 American Roentgen Ray Society founded
1923 BXRPC presents first radiation protection rules
1925 First International Congress of Radiology (London) establishes ICRU
1925 Tolerance dose of 0.01 skin erythema per month proposed (about 50 mSv per month)
1926 Dutch Board of Health adopts first regulatory exposure limit (1 skin erythema dose per 90000 working hours)
1928 International Committee on X-ray and Radium Protection established, later to become the ICRP
1928 ICRU adopts roentgen as unit of exposure
1929 ACXRP formed, which becomes the NCRP in 1946
1931 ACXRP proposes body dose limit of 0.2 R per day (about 2 mSv per day)
1933 Irene Curie discovers that artificial radionuclides can be produced when elements are bombarded with particle radiations
1934 ICXRP proposes 'safe threshold' exposure of 0.2 R per day
1934 ACXRP recommends separate dose limit for hands of 5 R per day (about 50 mSv)
1937 National Physical Laboratory (NPL) set up first radiation monitoring service
1941 ACXRP recommends maximum body burden of radium of 0.1 μ Ci
1942 Start of Manhattan project with first reactor at University of Chicago
1942 Concept of maximum permissible dose for inhaled radioactivity introduced, together with rem (roentgen equivalent man)

1947 First UK Radioactive Substances Act implemented
1948 NCRP lowers maximum permissible dose (MPD) for workers to 0.3 R per week
1949 ICRP recommends 0.3 R per week MPD for low linear energy transfer (LET) radiation and highlights potential risks from leukaemia, malignancy, genetic effects, superficial injury, and cataract
1953 ICRU introduces concept of absorbed dose
1953 ICRP introduces maximum permissible concentration for 90 radionuclides
1954 Atomic Energy Act allows private commercial companies to use radioactive materials under licence in the USA
1955 ICRP rejects concept of 'safe threshold' and recommends MPD set to reduce exposure to 'lowest possible level'
1955 UNSCEAR established
1955 NCRP recommends occupational MPD of 5 R (50 mSv) per year
1957 IAEA set up by General Assembly of United Nations with remit relating to use of radioactive materials

The first attempt to establish restrictions on intake of a radionuclide was made after radium poisoning that was recognized among luminous dial painters who frequently died from leucopenia or bone tumours during

the 1930s. A maximum body burden of 0.1 μg of radium was proposed in 1941.

During the early 1950s committees were set up by the ICRP to consider the permissible doses from external and internal radiation, protection against X-rays and high-energy radiation, and handling and disposal of radioactive materials. In 1954 the NCRP made the statement: 'exposure to radiation should be kept at the lowest practicable level in all cases'. This concept was subsequently adopted by the ICRP who stated that all radiation doses should be kept 'as low as reasonably practicable', the ALARP principle. For general radiation safety, a Code of Practice for the Protection of Persons Exposed to Ionising Radiations was issued to National Health Service (NHS) hospitals in the UK in 1957. Ionising radiation safety continued through voluntary implementation of codes of practice until the 1980s.

Box 1.1 (continued)

1957 Windscale accident in UK in which cloud of radioactive iodine released
1958 First UNSCEAR report on exposure sources and biological hazards
1958 ICRP recommends MPD of 50 mSv per year
1958 Oxford survey of childhood malignancies suggests link with fetal exposure
1959 ICRP states that doses should be 'as low as practicable' and recommends limitation of genetically significant dose to population
1960 Adrian Committee publishes results of survey of doses from medical exposures
1962 First remote afterloading brachytherapy machine built in Sweden
1968 FDA regulates X-ray equipment in US

1970 NRPB formed from amalgamation of Radiological Protection Service (formed 1953) and division of UK AEA
1972 Initial report by BEIR Committee
1973 ICRP adopts concept of 'as low as reasonably achievable' (Report 22) 1975 ABCC replaced by RERF to continue studies of Japanese A-bomb survivors
1977 ICRP adopts 'effective dose equivalent' terminology and introduces principles which become 'justification, optimisation, and dose limitation' (Report 26)
1978 UK MARS regulations require certification of those prescribing radiopharmaceuticals through ARSAC
1979 Three Mile Island accident on 28th March
1980 Euratom Directive 80/836 sets out radiation safety requirements for workers and public, including limit of 500 mSv per year for extremities
1980 Society for Radiological Protection and Hospital Physicists Association set up schemes for certification of radiation protection practitioners
1984 Euratom Directive 84/466 sets out requirements for medical exposures
1985 First Ionising Radiations Regulations implemented in the UK
1986 Dosimetry System 1986 (DS86) developed by RERF for A-bomb survivors
1986 Chernobyl accident on 26th April
1986 NRPB publishes results of survey of patient doses in English hospitals
1989 NRPB proposes reference doses for common radiological examinations
1989 RCR issues guidelines on making best use of a Department of Radiology
1990 BEIR V report provides new estimates of risks from ionising radiation
1991 IAEA report on health effects from the Chernobyl accident
1991 ICRP proposes major revision of practices, reduction in occupational dose limit to 20 mSv, and adopts effective dose terminology (Report 60)
1994 FDA issues guidance relating to risk of skin erythema from fluoroscopy
1996 IAEA publishes international BSS for ionising radiation
1997 IPEM, CoR, and NRPB issue recommended standards for performance testing of X-ray equipment in the UK
1998 Euratom Directive 97/43 issues revised guidance on medical exposures

1. Choose the correct word and fill in the blanks.

radiation/ radioactive/ radioactivity

- Radiation medicine studies the effects of ionizing _____.
- Radiation ecology investigates ways of _____ substances migration.
- The level of _____ is estimated by various methods of radiometry.

emit/ emission

- Radioactivity is the process of elementary particles' _____.
- γ-radiation_____ when a nucleus of a radioactive isotope is in the excited state.

- When the isotope U-238 _____ α-particles it changes into thorium-234.

apply/ application

- _____ of ionizing radiation in medicine started after X-rays discovery.
- Clinicians _____ different radiological techniques.

measure(s)/ measurement

- Scientists recommend certain X-ray protection_____.
- Dosimetry is a _____ of energy of ionizing radiation in an object.

protect/ protection/ protective

- Radiation _____ is one of the main trends of Radiobiology.
- Take this medicine regularly; it will _____ you against a return of the illness.
- Chemical pollutants destroy the _____ layer of ozone in Earth' atmosphere.

2. Match the synonyms.

1) intake	a) irradiation
2) exposure	b) absorb
3) accumulation	c) defence
4) emit	d) contamination
5) penetrate	e) release
6) protection	f) examine
7) survey	g) permeate
8) pollution	h) neoplasm
9) cancer	i) storage

3. Give official Ukrainian equivalents to the following: ICRU, ICRP, code of (good) practice.

4. Match the terms and the definitions.

1) radioactivity	a)emission of corpuscular or electromagnetic radiations consequent to nuclear disintegration; it is a natural property of all chemical elements of atomic number above 83 and can be induced in all other known elements;

2) ionizing radiation	b)corpuscular or electromagnetic radiation capable of producing ionization, directly or indirectly, in its passage through matter;
3) radioecology	c)study of the environmental effects of radioactive contaminants;
4) nuclide	d)a species of an atom characterized by the charge, mass, number and quantum state of its nucleus; capable to exist for a measurable lifetime (usually more than 10−10 sec.);
5) pollution	e)the act or process of polluting or the state of being polluted, especially the contamination of soil, water or the atmosphere by the discharge of harmful substances.

5. Choose three correct variants.

Ionizing radiation is characterized by:

a. the ability to penetrate light materials;
b. the dependence of absorption on density;
c. the ability to affect photographic plates;
d. the ability to deaden a sound;
e. the ability to evaporate.

X-ray can cause:

a. deafness;
b. skin erythema;
c. bone fractures;
d. leukaemia;
e. anemia gravis

Measures for limiting radiation exposure among workers:

a. shielded enclosure;
b. zinc screens;
c. forceps;
d. apron;
e. high temperatures;
f. low temperatures.

1.4. The application of radionuclides to imaging

Shortly after the USA entered the Second World War, President Roosevelt approved the programme to construct an atomic bomb (Manhattan Project). The first reactor was built at the University of Chicago and this provided experience in the production of radionuclides.

After the war, radionuclides were made available to qualified physicians outside the Manhattan Project. ^{131}I was employed in the treatment of thyroid cancer and to image the thyroid gland using a point-by-point counting technique! Subsequently, large sodium iodide crystals became available and were used by Hal Anger to construct the first scintillation gamma camera in 1957. A method for enabling hospitals to obtain a supply of ^{99m}Tc, a radionuclide with a short half-life ideal for imaging applications, became available in 1961 with the manufacture of a generator containing ^{99}Mo. These two developments led to the beginning of radionuclide imaging and the founding of nuclear medicine.

Formal regulation by national governments of the use of radionuclides began in about 1950. The first Radioactive Substances Act dealing with holding, use, and disposal of radioactive material came into force in the UK in 1948. The Atomic Energy Act regulating the use of reactor-produced radionuclides in the United States was enacted in 1954.

Choose the proper meaning of the word in *bold.*

This was the first attempt to ***introduce*** a formal dose restriction.	1) bring (something, especially a product, measure, or concept) into use or operation for the first time; 2) make (someone) known by name to another in person, especially formally; 3) insert or bring into something; 4) occur at the start of
These two ***developments*** led to the beginning of radionuclide imaging and the founding of nuclear medicine.	1) a specified state of growth or advancement; 2) a new and refined product or idea; 3) the process of starting to experience or suffer from an ailment or feeling; 4) the process of treating photographic film with chemicals to make a visible image

2. Standards and legislation for protection against ionising radiations

2.1. Review of evidence on biological effects of radiation

Evidence has been accumulated slowly to document the harmful effects of ionising radiations. Threshold doses were determined for skin erythema and other so-called 'deterministic' effect (§3.3). However, the question of most importance in occupational use of ionising radiation concerns the risk from exposure to very low levels of radiation dose

received over long periods of time. The dropping of a ^{235}U bomb on Hiroshima and a ^{239}Pu bomb on Nagasaki exposed an immense number of individuals to substantial whole-body doses of radiation. The United Nations Scientific Committee on the Effects of Radiation (UNSCEAR) was set up in 1955 to study evidence on the effects of radiation exposure. The United States National Research Council (USNRC) commissioned a study of survivors of the atomic bombs and other groups who had been either accidentally exposed to large doses of radiation or routinely exposed over many years and the results were published in 1972 in the Biological Effects of Ionising Radiation (BEIR) report. Reports by the BEIR, III (1980), IV (1988) and V (1990) together with ones from UNSCEAR collated evidence on effects of long-term exposure to low levels of ionising radiation. The knowledge gained from the study of radiation effects is used by ICRP to recommend standards that will prevent deterministic effects and limit the risk of radiation-induced cancer and genetic effects. The current recommendations of the ICRP issued in 1991 are based largely on the BEIR V report, which included data on the health of the Japanese survivors for a period of over 40 years after the atomic bombs were dropped. The standards for individuals working with radiation are designed to provide an occupational risk that is lower than that found in areas of work normally considered as 'safe' industries.

2.2. Implementation of radiation protection standards

Organizations such as the ICRU and ICRP are independent bodies composed of specialists from a wide range of related disciplines, whose aims are to put forward recommendations based on international consensus. They have no affiliation to national governments and have no legal authority to enforce the recommendations they make. National governments have responsibility for implementation of radiation protection programmes, taking account of social, political, and economic considerations. National radiological protection bodies such as the National Radiological Protection Board (NRPB) in the UK and the National Council on Radiation Protection and Measurements (NCRP) in the USA provide guidance on implementation of recommendations made by the ICRP and may advise on and contribute to the development of national legislation.

Legislation in the European Economic Community is drawn up to fulfill requirements laid down in Euratom Directives (§5.2). These set out safety standards to minimize divergence between the national legislation of member states, although each is allowed to decide how the regulations

should be incorporated into their national legal framework. Regulations are supplemented by the approved codes of practice which give guidance on general requirements set out in the legislation. Failure to comply with an approved code of practice is held to be the proof of a contravention of a requirement of the code unless a defendant can show that compliance was achieved in another equally appropriate way. Guidance notes accompany legislation and set out opinions on good practice in particular applications. Government bodies may issue guidance notes as opinions on good practice in specific activities; professional bodies may also be a source of guidance for their particular field. Guidance notes do not in themselves have legal force, but because of their origin and the experience of the individuals involved in their production, they are in practice persuasive documents in lower courts and are useful in establishing reasonable standards prevailing in a particular industry.

1. Find the only one word in the text with the closest meaning to the following.

1. Proof, demonstration, witness.
2. To get, tj obtain, to receive.
3. Occasionally, by chance, at random.
4. Connection, joining, attachment.
5. Variance, contradiction, discrepancy.
6. To complement, to add, to elaborate.
7. Violation, breach, offence.
8. To claim, to assert, to affirm.
9. To go with, to escort, to follow.
10. To create, to make, to form.
11. Extreme, greatest, supreme.
12. Anxiety, worry, trouble.

2. Form the word-combinations from the text by adding one word from the box.

Reasonable, independent, particular, related, approved, radiobiological, national, legal, general
Bodies, standards, disciplines, applications, protection, code, framework, legislation, requirements

3. Make as many word-combinations as you can, combining the words from ex2.

4. Make your own sentences using the terms from ex 1-4.

2.3. Medical radiation exposure

Concerns about the potential harmful consequences of medical exposures were raised in 1957 by UNSCEAR, who stated that 'the medical use of radiation is clearly of the utmost value in prevention, diagnosis, investigation and treatment of human disease, but the possible effects of irradiation of individuals requires examination'. The main concern at this time was the potential risk of genetic defects in future generations from irradiation of the gonads. Some evaluations of radiation levels from medical exposures were made during the 1950s. The Adrian Committee reported results of a UK survey in 1960, which found that 21 million medical examinations were performed each year, with an associated mean genetically significant dose (GSD) to the population of 0.123 mGy. A survey carried out by the NRPB in the early 1980s showed that the number of medical examinations had risen to 30 million per year and the ' GSD was 0.120 mGy. Meanwhile, a study in Oxford by Alice Stewart reported in 1958 suggested that the level of childhood malignancies was higher among individuals whose mothers were X-rayed during pregnancy. This finding, coupled with results of further studies, led to the restrictions on fetal exposures. The Adrian Committee expressed concern about the variation in doses at different hospitals in their 1960 report and recommended strategies for dose reduction, many of which are still applicable today. The variations were highlighted by an NRPB survey report in 1986 and, based on these results, reference doses were recommended in 1989 which could be utilized by hospitals in evaluating local practice. This principle has subsequently been taken up in a Euratom Directive in the form of diagnostic reference levels which are now embodied in legislative requirements of European countries.

5. Choose the proper meaning of the word in *bold.*

The question of most importance in occupational use of ionising radiation concerns the risk from ***exposure*** to very low levels of radiation dose received over long periods of time.	1) the state of having no protection from something harmful 2) the revelation of something secret, especially something embarrassing or damaging 3) the publicizing of information or an event 4) the direction in which a building faces

3. Public perception of ionising radiation

Deaths of radiation workers aroused concern in the early part of the century. The destructive potential of atomic weapons with the grim aftermath of the bombs dropped on Japan left an indelible image in the minds of the developed world. Following on from its destructive beginnings, the peaceful use of nuclear power has been dogged by bad press linked to the arms race and concern about potential hazards around nuclear establishments. Nuclear accidents at Windscale (1957), Three Mile Island (1979), and Chernobyl (1986) have reinforced public awareness of the dangers from radiation. The tendency to a lack of openness has contributed to public distrust and uncertainty. Public outcry over atomic weapons tests and the potential hazards during the 1950s was dismissed in early reports of BEIR and UNSCEAR, which regarded the risks as small. During the 1970s reports on a high incidence of leukaemia among veterans proved that risks had been underestimated. Errors in radiotherapy treatments delivered to patients in the 1980s and 1990s have raised public concern about hospital applications.

With this background, it is hardly surprising that radiation conjures up alarm and distrust in the public mind. Public concern rose because radiation is unfamiliar and its effects are poorly understood. In addition, radiation has a number of other 'fright factors' which further help to trigger public anxiety. The risks are imposed rather than being a matter of individual choice and are seen as involuntary, inescapable, and unequally distributed. They also cause hidden damage and many years after exposure it may lead to cancer. Moreover, there is a particular danger to small children or pregnant women and a risk of damage to future generations.

All these factors arouse public concern about radiation exposure. The public impression of the danger is often disproportionate to the measurable harm. This tends to be a large discrepancy between the perception of the size of the risk and values estimated from the available data. For example, people are usually surprised to learn that the atomic bombs dropped on Japan caused less than 500 deaths from cancer among about 50 000 exposed survivors. This is less than 5% of all deaths from cancer even in that highly exposed population, and only 1% of all deaths.

In order to retain the confidence of the general public, openness is required about the risks from radiation and a proper emphasis on justification and optimisation of medical procedures involving radiation is necessary.

Choose the proper meaning of the word in bold.

1. Deaths of radiation workers aroused ***concern*** in the early part of the century.

1) anxiety 2) relation 3) gadget 4) business

2. The destructive potential of atomic weapons with the grim aftermath of the bombs dropped on Japan left an ***indelible*** image in the minds of the developed world.

1) indefinite 2) incredible 3) ineffaceable 4) insufficient

3. Errors in radiotherapy treatments delivered to patients in the 1980s and 1990s have raised public concern about hospital ***applications***.

1) request 2) use 3) diligence 4) attention

4. With this background, it is hardly surprising that radiation ***conjures up*** alarm and distrust in the public mind.

1) call up 2) beseech 3) ring up 4) get up

5. They also ***cause*** hidden damage and many years after exposure it may lead to cancer.

1) course 2) notice 3) lose 4) produce

4. Non-ionising radiations

Electromagnetic radiation photons can be divided into two categories: those that have sufficient energy to produce ionisation (X-rays and γ-rays) and those with energies less than 12 eV which are referred to as non- ionising radiations (NIRs). The spectrum of electromagnetic radiation, together with some applications of the different parts in medicine and elsewhere, is shown in Box 1.2. Non-ionising electromagnetic radiations can be divided into optical radiations and electromagnetic fields, and the energy/wavelength/frequency ranges to which these correspond are shown in Box 1.2. Other forms of NIR are high-frequency mechanical waves or ultrasound waves, which can be propagated through the body and the energy absorbed by tissue.

NIRs usually interact with tissue through the generation of heat. The hazards depend on the ability to penetrate the human body and the absorption characteristics of different tissues (Box 1.3). There is much uncertainty about the severity of the effects of both acute and chronic exposure to various types of NIRs. Questions raised in relation to each type of NIR are different because of the variation in properties with wavelength. Public concern about NIR has been the greatest about the longer wavelength radiations defined as electromagnetic fields (Box 1.2), which include microwaves and radiofrequency radiations. However, the greatest risk to public health probably arises from natural ultraviolet radiation (Box 1.3).

4.1. Optical radiations

The optical radiations are centered on visible light; photons having higher energies are termed ultraviolet radiation and those with lower energies infrared radiation. Intensities of optical radiations decline according to an inverse square law with distance from a point source and the radiations are capable of being focused on and interact with matter in a similar way to visible light.

Ultraviolet phototherapy has been used for many years to treat a variety of conditions. Treatment of psoriasis has been carried out since the 1920s, but only during the latter part of the twentieth century were attempts made to optimize treatment and establish accurate dosimetry. The first laser was produced in 1960 by Mainman. The potential value of lasers in medicine with the high-intensity beam, which could be coupled into an optical fiber and delivered to the treatment site, was realized immediately and by 1964 lasers were being employed as a microsurgical tool.

Damage from optical radiations is largely confined to eye and skin. Despite having insufficient energy to ionise atoms, single photons of ultraviolet radiation can damage tissue through disruption of bonds within DNA molecules and give a long-term risk of cancer. This must be born in mind when determining allowable exposures. Visible light and infrared light only produce damage through high-intensity multi-photon interactions. For radiation protection, a distinction is made between lasers and noncoherent sources. The biological effects induced are essentially the same for both, but lasers are capable of producing higher irradiances and can heat localized volumes of tissue to a high enough temperature to produce rapid physical change.

4.2. Electromagnetic fields

The term 'electromagnetic fields' describes a wide range of lower energy electromagnetic waves (Box 1.2). The wavelengths range from 1mm up to thousands of kilometers. The term 'fields' is used because of the need to consider effects of the electric and magnetic components separately, as well as their different interactions. Radiofrequency (RF) electromagnetic fields are used in medicine to heat tissue to aid healing, with shortwave diathermy (27 MHz) being applied widely by physiotherapists and in a few centers oncologists are using microwave heating (e.g. 912 MHz) to treat tumors by hyperthermia. High static electromagnetic fields with RF pulses are used in magnetic resonance

imaging (MRI) and hazards of these must also be considered. Radio-frequency radiations are used extensively in communications and the potential for electromagnetic interference with electro-medical equipment has to be born in mind.

Energy densities of long-wavelength electromagnetic fields vary in a non-uniform manner at distances from sources at which operators might typically be working because of interference effects between emissions from different parts of a source. RF radiations present the greatest perceived risk of any non-ionising radiation, although studies so far performed do not provide statistical evidence of long-term effects at levels encountered in occupational exposure.

4.3. Ultrasound

Ultrasound became an established technique for medical imaging in the middle of the twentieth century. The risks from diagnostic ultrasound are generally agreed to be much lower than for X-rays and there have been no adverse effects observed following the routine diagnostic exposure of children *in utero* over a period of 50 years. Higher intensity ultrasound has been used for applications in physiotherapy, lithotripsy, and surgery. Due to its safe record, the establishment of recommended limits on intensity levels has been slow, but these are now being introduced.

4.4. Standards and guidance for non-ionising radiations

The earliest recommendations for exposure limitation for NIRs were made in the 1950s and 1960s for microwave and RF radiations produced by military radar and communication equipment. Recommendations relating to laser eye protection were made in the 1970s. The growing importance of all forms of NIRs led to the setting up of the International Non-Ionising Radiation Committee (INIRC) at an International Radiation Protection Association (IRPA) congress in 1977 to develop guidance for NIR protection programmes. The committee produced guidelines on limitation to exposure from ultrasound, lasers, and optical radiations in 1982 and for low-frequency electromagnetic fields in 1984 and 1987. The INIRC became independent from the IRPA in 1992 and was renamed the International Commission on Non-Ionising Radiation Protection (ICNIRP). The IC-NIRP works with the World Health Organization (WHO) to assess health effects of NIRs and to develop international guidelines on limits to exposure and protection measures, which are science based and independent. The American Conference of

Governmental Industrial Hygienists (ACGIH) set threshold limit values relating to exposure across the whole electromagnetic spectrum in 1992, which are revised annually and have been influential in the development of recommendations by the ICNIRP. The NRPB makes recommendations and the Medical Devices Agency issues guidance on NIRs relating to the UK. The American National Standards Institution publishes guidance on recommended practices in the USA.

The practical implementation of health-based exposure standards requires inputs from bodies responsible for the development of standards for measurement, product design, NIR emission, and safety, such as the International Electrotechnical Commission (IEC), the International Organization for Standardization (ISO), and the Commission Internationale de l'Eclairage [Illumination] (CIE). The ICNIRP guidelines are concerned with the basic principles of protection and it is the responsibility of national governments to implement the appropriate radiation protection programmes. The United States Radiation Control Health and Safety Act 1968 administers emission standards for ionising and non-ionising radiations for many types of equipment through the Food and Drug Administration (FDA). There is currently little legislation relating directly to NIRs in Europe. This gap is expected to be addressed by adoption of requirements of the CEC Directive on Physical Agents, which covers occupational protection from non-ionising radiations. A draft proposal was published in 1994 but its final form is still under debate. Lack of specific legislation does not disclaim the user from responsibility or immunity from prosecution. Good practice must be adopted, usually in accordance with accepted standards, recommendations, and guidelines.

Box 1.2 The electromagnetic spectrum

Radiations in different parts of the electromagnetic spectrum can be defined in terms of energy (E), wavelength (λ), of frequency (*f*). Conventionally, ionising radiations are described in terms of photon energy in electron volts (eV) [1 eV = 1.6×10^{-19} joules], optical radiations are described by the wavelength, and electromagnetic fields are characterized in terms of the radiation frequency. The relationship between these quantities are given by:

$E = hf$ where h is the Planck constant = 6.626×10^{-34} J s
and $c = f\lambda$ where c is the velocity of light = 3×10^{8} m s^{-1}

The parts into which the spectrum is divided and some applications in medicine (italics) and in other areas are in the table. The values of energy, wavelength, and frequency given for optical radiations and electromagnetic fields mark the boundaries between radiation subgroups, but those included for ionising radiations are linked to applications.

Radiation		Energy	Wavelength	Frequency	Applications
Ionising radiations	X-rays and γ-rays	15 MeV 150 keV 15 keV	80 fm 8 pm 80 pm	4 ZHz 40 EHz 4 EHz	Linac radiotherapy Brachtherapy Nuclear medicine Diagnostic radiology
Optical radiations		12.4 eV	100 nm	3 PHz	Corneal surgery lasers
Ultraviolet (UV)	UVC	4.43 eV	280 nm	1.07 PHz	Sterilization
	UVB UVA	3.94 eV	315 nm	952 THz	UVB phototherapy PUVA/sunbeds
Visible	Visible	3.10 eV	400 nm	750 THz	Neonate phototherapy Ophthalmic leasers
Infrared (IR)		1.59 eV	780 mn	385 THz	Surgical and therapy lasers Physiotherapy heat lamps Nd: YAG surgical laser
Near IR	IRA	886 meV	1.4 μm	214 THz	
Fair IR	IRS	413 meV	3 μm	100 THz	Thermographic imaging CO_2 surgical laser
Electromagnetic fields	EHF	1.24 meV	1 mm	300 GHz	MW telecommunications
Microwaves	SHF	124 μeV	10 mm	30 GHz	Microware radiometry Radar/satellite links
	UHF	12.4 μeV	100 mm	3 GHz	Mobile phones/MW ovens Microwave hyperthermia
	VHF	1.24 μeV	1 m	300 MHz	TV transmitters Emergency service radios
	HF	124 neV	10 m	30 MHz	Therapeutic diathermy MRI RF pulses
Radiofrequency (RF)	MF	12.4 neV	100 m	3 MHz	
Shortwave	LF	1.24 neV	1 km	300 kHz	Surgical diathermy AM radio
Mediumwave Longwave	VLF	124 peV	10 km	30 kHz	Shop/airport security Visual display units
	Voice-F	12.4 peV	100 km	3 kHz	Television sets
	ELF	1.24 peV	1000 km	300 Hz	Induction heaters
	Static	124 feV	10000 km	30 Hz	Electricity supply
				0 Hz	Power lines MRI magnetic field

HF, high frequency; MF, medium frequency; LF, low frequency; E, extremely; S, super; U, ultra; V, very; MW, microwave; FM, frequency modulated; AM, amplitude modulated; MRI, magnetic resonance imaging.

Box 1.3 Biological effects of different electromagnetic radiations			
Radiation		Energy, wavelength, frequency	Biological effects
Ionising radiations	X-rays and γ-rays	> 12 eV	Skin erythema, cataract, sterility Death From acute high doses *Cancer in radiosensitive organs, Genetic effects*
Optical radiations			
	UVC	100 nm	Skin-Erythema, increased pigmentation
		280 nm	Eye-Photokeratitis (inflammation of cornea) Skin-Erythema, increased pigmentation *Skin cancer*
Ultraviolet (UV)	UVB	315 nm	Eye-Photokeratitis cataract Photosensitive skin reactions
	UVA	400 nm	Skin-Erythema, increased pigmentation *Skin photo-ageing, Skin cancer* Eye-Photokeratitis and thermal retinal injury
Visible	Visible	780 nm	Eye-Thermal retinal injury
	IRA	1.4 μm	Eye-Thermal retinal injury, thermal cataract Skin burn
Infrared	IRB	3 μm	Eye-Corneal burn, cataract Skin burn
	IRC	1 μm	Eye-Corneal burn, cataract Heating of body surface
Electromagnetic fields	Microwaves	300 GHz	Heating of body surface
		1 GHz	Heating with penetration depth of 10 mm Raised body temperature
		<100 kHz	Accumulation of charge of body surface Disturbance of nerve and muscle responses
	Static	0 Hz	Magnetic field – vertigo/nausea Electric field – charge on body surface
Long-term effects are given in italics			

1. Give the definition of electromagnetic fields.

2. Decode the abbreviations.

MRI, RF, NIRs, INIRC, IRPA, IC-NIRP, WHO, ACGIH, NRPB, IEC, ISO, CIE, FDA

3. Connect the notions and comment on the chart.

ionizing radiations photon energy optical radiations

wavelength electromagnetic fields

radiation frequency

4. Complete the following sentences.

- RF electromagnetic fields are used in …
- RF radiations are used in …
- Ultrasound is used in …

5. Make a Noun out of a given Verb/Adjective by suffixation. Restore the context where these words are used.

Implement, safe, require, responsible, protect, assess, equip, guide, apply, emit, legislate, evident, frequent, expose.

6. Render the following text.

Радіоекологія, або радіаційна екологія, — це розділ радіобіології, який виник на стику з екологією. Іноді її вважають розділом екології. Останнім часом виділяють, навіть, як окрему науку.

Радіоекологія вивчає концентрації та міграцію радіоактивних речовин у навколишньому середовищі та вплив їхнього іонізуючого випромінювання на живі організми та їх угруповання.

Прерогативою радіоекології, як правило, є зовсім незначні потужності хронічного опромінення організмів іонізуючим випромінюванням за рахунок радіаційного фону, а також за рахунок забруднення біосфери штучними радіонуклідами. Проте багато рослин і тварин здатні нагромаджувати в життєво важливих органах значну кількість радіоактивних речовин, внаслідок чого можливе істотне внутрішнє опромінення організму.

Control points to Chapter 1

1) First application of ionising radiation.
2) Radiation protection facilities and first safety standards.
3) Founding of nuclear medicine. Medical exposures.
4) Biological effects of radiation.
5) Radiation protection standards and legislation.
6) Public concern about radiation exposure.
7) Types of non-ionising radiation.
8) Recommendations for NIRs protection.

Science vocabulary

1. **lupus [ˈlu:pəs]** вовчак, туберкульоз шкіри
2. **ringworm [ˈriŋwɜ:m]** грибкове захворювання шкіри, стригучий лишай.
3. **tuberculosis [[tju:bɜ:kjuˈlousis]]** туберкульоз
4. **epithelioma** епітеліома
5. **port-wine stain** капілярна гемангіома
6. **uranium (U) [juəˈreɪnɪəm]** уран
7. **thorium (Th) [Θɔ:riem]** торій
8. **dermatitis** запалення шкіри, дерматит
9. **rudimentary** елементарний, недорозвинений, зародковий, рудиментарний
10. **erythema** еритема
11. **fetal** ембріональний, зародковий
12. **scintillation gamma camera** сцинтиляційна гамма-камера
13. **code of practice** процесуальний кодекс
14. **gonad** гонада статева залоза
15. **genetically significant dose (GSD)** генетично значуща доза
16. **inverse-square law** закон зворотних квадратів, закон Кулона
17. **radiofrequency (RF)** радіочастота
18. **magnetic resonance imaging (MRI)** магнітно-резонансне зображення
19. **diathermy [ˈdaiəθə:mi]** діатермія
20. **velocity [viˈlɔsəti]** швидкість
21. **linac radiotherapy** лінійна радіотерапія
22. **brachytherapy** брахітерапія, близько променева терапія
23. **cornea [ˈkɔ:niə]** рогівка ока; **(~ al)** рогівковий
24. **X-rays** рентгенівське випромінювання

2. Types of radiation

1. Artificial Radioactive Isotopes. *1.1. Fission. 1.2.1. Activation Analysis. 1.2.2. Natural Radiation.* **2. Natural Radiation.** *2.1. Cosmic Radiation. 2.2. Natural Gamma Radiation. Natural Radioactive sources. 2.3. Distribution of Natural Radioactivity. 2.4. Internal Radioactivity (sources inside the body).*

1. Artificial Radioactive Isotopes

In 1934, Irene Joliot Curie (Marie Curie's daughter) and her husband, Frederic Joliot, succeeded in making a radioactive isotope that does not occur in nature. They bombarded an aluminum plate with α-particles from a natural radioactive source, and when they removed the α-particle source, it appeared that the aluminum plate emitted radiation with a half-life of approximately 3 minutes. The explanation was that the bombardment had resulted in a nuclear reaction. The α-particle penetrated the aluminum nucleus and changed it into phosphorus and was responsible for the observed radiation. Its designation is P-30.

This nuclear reaction is written as follows:

$$^{27}AI + \alpha \rightarrow {}^{30}P + n.$$

The neutron emitted can be observed as long as the bombardment takes place, but disappears immediately when the α-source is removed. However, the phosphorus isotope is radioactive and emits a positron with energy of 3.24 MeV (which can easily be measured) and a half-life of 2.50 minutes.

1. Choose the correct word and fill in the blanks.

contribute/ contribution

- I.J. Curie's _____ in the development of Radioecology is considerable.
- Fresh air and exercise _____to good health.
- In the 20th century nuclear power _____only 17% of the electricity production.

concentrate/concentration

- Scientists _____ their interest on the development of radiation protection
- The_____ of ^{222}Rn in outside air varies widely depending on the geographical location.
- The _____ of radioactive products is high in igneous and sedimentary rocks.

depend/ dependence/ dependent

- The radiation level inside the house _____ on the material this house is built of.
- There is a direct _____ between nuclear tests performed in the atmosphere and radiation pollution.
- A lot of countries are _____ on the nuclear power use.

2. Match the synonyms.

1) contribute	a) differ
2) vary	b) decline
3) decrease	c) promote
4) limit	d) grow
5) increase	e) investigation
6) artificial	f) man-made
7) examination	g) kind
8) species	i) constraint

3. Form the opposites from the given words:

-indoor
-outside
-external

4. Match the terms and the definitions.

1) risk	a) a situation involving exposure to danger;
2) rate	b) a measure, quantity, or frequency, typically one measured against some other quantity or measure;
3) artificial	c) something made or produced by human beings rather than occurring naturally, typically as a copy of something natural;

4) background radiation	d) naturally occurring radiation emitted by soil, groundwater, building materials, radioactive substances in the body and cosmic rays from outer space;
5) chemical element	e) each of more than one hundred substances that cannot be chemically interconverted or broken down into simpler substances and are primary constituents of matter; it is distinguished by its atomic number, i.e., the number of protons in the nuclei of its atoms;
6) isotopes	f) each of two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties; in particular, a radioactive form of an element…

1.1. Fission

After Chadwicks' discovery of the neutron in 1932, a large research effort was started in order to make and identify the isotopes formed when neutrons penetrate various atomic nuclei. In 1938, it was observed that one of the largest atoms, uranium, disintegrates in a dramatic way. This unstable nucleus splits into two large fragments. This reaction is called *fission*.

The splitting of a heavy atomic nucleus, such as U-235, occurs because of intrinsic instabilities. The nucleus can exist in a variety of energy states and there are numerous pathways by which the nucleus emits energy and creates new products. More than 200 fission products from uranium are known. The products formed can be divided into two groups, one "heavy" group with an atomic weight of about 140 units and one "light" group with an atomic weight of 90.

A large amount of energy is released in fission. Most of the energy is released directly during the process of fission but a small amount is released at a later stage by those fission products that are radioactive. Most fission products have short half-lives. From an environmental point of view, Cs-137 and Sr-90 are the most important fission products of U-235. They each have a half-life of about 30 years, which is important with regard to storage and disposal of these products. The fission process leads

to three different types of radioactive isotopes: *fission products, transuranic elements, and activation products.*

1.2. Activation Analysis

The activation of certain materials by neutron irradiation is used as an elegant analytical method for identifying chemical species. When a compound is irradiated with neutrons, many elements are activated and become radioactive. The radioactivity can be measured easily and the properties of the radiation can be used to identify an element. Thus, it is possible to observe the presence of tiny amounts of an element that would be undetectable by other analytical methods.

An archeologist can also obtain important information from activation analysis in order to determine the properties of old coins, pieces of ceramic pots, and other relicts. The method has the advantage that it does not destroy the sample.

Criminologists use activation analyses in the solution of criminal cases. For example, activation analysis showed that the hair of Napoleon contained arsenic. This raises the possibility that he was murdered. Indeed the arsenic could have been introduced intentionally but it also may have come from his environment. At that time, arsenic was used in wall coverings and could have been picked up by touch or given off into the atmosphere.

It is also interesting that determining the composition of the moon was assisted by activation analyses. Rocks, brought back to Earth by the astronauts, were bombarded by neutrons, forming radioactive products. The subsequent radioactive emissions were then used to identify elements in the moon rocks.

Choose the proper meaning of the word in *bold.*

1. In 1934, Irene Joliot Curie (Marie Curie's daughter) and her husband, Frederic Joliot, ***succeeded*** in making a radioactive isotope that does not occur in nature.
1) achieve the desired aim or result
2) attain fame, wealth, or social status
3) take over a throne, office, or other position
4) become the new rightful holder of an office, title, or property
5) come after and take the place of

2. They bombarded an aluminum plate with α-particles from a natural radioactive ***source***.

1) a place, person, or thing from which something originates or can be obtained
2) a spring or fountain head from which a river or stream issues
3) a person who provides information
4) a book or document used to provide evidence in research
3. In 1938, it was observed that one of the largest atoms, uranium, disintegrates in a ***dramatic*** way.
1) of or relating to drama or the performance or study of drama the dramatic arts
2) (of an event or circumstance) sudden and striking
3) exciting or impressive
4) (of a person or their behavior) intending or intended to create an effect; theatrical
4. The nucleus can exist in a variety of energy ***states***.
1) the structure, form, or constitution of something
2) position in life or society; estate
3) a sovereign political power or community
4) involving ceremony or concerned with a ceremonious occasion
5. Criminologists use activation analyses in the ***solution*** of criminal cases.
1) a means of solving a problem or dealing with a difficult situation
2) the correct answer to a puzzle
3) (solutions) products or services designed to meet a particular need
4) a liquid mixture in which the minor component (the solute) is uniformly distributed within the major component (the solvent)
5) the process or state of being dissolved in a solvent

2. Natural Radiation

People live surrounded by natural radioactive sources. There are radioactive isotopes in our bodies, houses, air, and water and in the ground as well. In this Chapter, natural radiation will be discussed in more detail, in particular, how much natural radiation people are exposed to every day.

Common sources of radiation are presented in Figure 2.1. The annual doses vary from one area to another but are more or less equal to those shown in the figure.

Choose the proper meaning of the word in *bold.*

1. Common sources of radiation are ***presented*** in Figure 2.1.
1) give or award formally or ceremonially
2) formally introduce (someone) to someone else
3) introduce or announce the various items of (a television or radio show) as a participant
4) exhibit (a particular state or appearance) to others

2.1. Cosmic Radiation

Annual dose = 0.3 to 0.6 mSv

The atmosphere is continuously exposed to particles from outer space. A stream of particles consisting of protons (about 85%), α-particles (about 13%), and a small fraction of larger particles hit the outer atmosphere. Some of the particles have very large energies when hitting the atmosphere (up to 10^{14} MeV). When the particles interact with the atoms in the atmosphere their energy gradually decreases and a number of *new* high energy particles are formed.

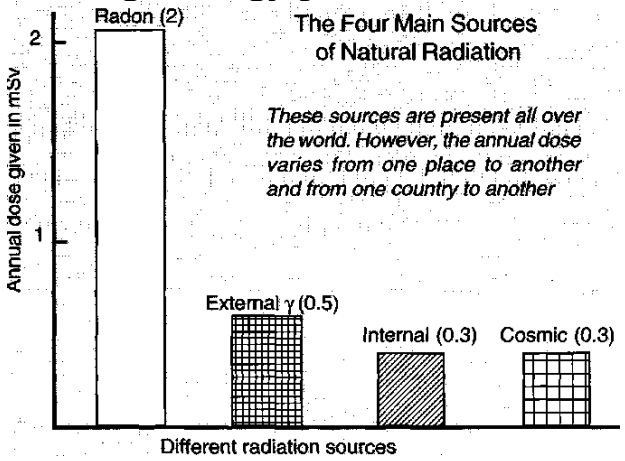


FIG 2.1.

Natural radiation sources and their annual doses. The particular dose levels given are for Scandinavia. The annual doses are given in mSv.

When cosmic radiation reaches both the inner atmosphere and the ground, it is accompanied by γ-radiation, neutrons and various other small particles. Moreover, some new radioactive isotopes are formed. The more important of these, *cosmogenic radionuclides,* are H-3 (tritium), Be-7, C-14 and Na-22.

Besides the radiation from space, which is rather constant, cosmic radiation contains particles and electromagnetic radiation from the sun. The radiation from the sun is variable due to sunspot activity (which has a period of about 11 years). The energies of these solar particles are small, contributing only a tiny fraction of the total dose from cosmic radiation.

The contribution of neutrons that accompany cosmic radiation increases with height above sea level. This influences the dose since

neutrons have a radiation weighting factor of 5 to 20, resulting in an annual dose at sea level of approximately 0.3 mSv. For those living 1,500-2,000 meters (5,000-6,000 feet) above sea level, the annual dose is approximately doubled. If you climb up to 5,000 meters (15,000 feet) the radiation is ten times higher than at sea level, mainly due to the increased neutron contribution.

The amount of cosmic radiation varies somewhat with latitude. Particles from space have an electric charge and the motion of these charged particles is influenced by the magnetic field around the Earth. For tropical areas this interaction is the largest, deflecting the particles while they are still high up in the atmosphere. In polar regions, the path of the particles more closely follows the magnetic field lines, allowing them to penetrate deeper into the atmosphere, which results in larger doses near the poles of the Earth. Another effect, due to the excitations of the atmospheric molecules, is the beautiful northern and southern lights *(aurora borealis* and *aurora australis).*

The variation in cosmic radiation with the height above sea level can easily be observed when flying. This means that air crews with a large number of flying hours receive an extra annual dose. Scientists in Germany supported by the "Gesellschaft fur Strahlenforschung" placed dosimeters inside airplanes in order to measure the amount of γ-and neutron radiation. From their observations it was calculated that, for an annual flying time of 600 hours at about 10,000 meters (30,000 feet), the extra dose is 3 mSv. For the height of 18,000 meters (55,000 feet), the dose rate is about 0.15 mSv per hour. If, for example, you use the above data for your own air travels, you will find that a trip between Europe and US yields an extra dose of about 0.03 to 0.04 mSv.

Choose the proper meaning of the word in *bold.*

2. When cosmic radiation ***reaches*** both the inner atmosphere and the ground, it is accompanied by γ-radiation, neutrons and various other small particles.

1) stretch out an arm in a specified direction in order to touch or grasp something
2) arrive at; get as far as
3) succeed in achieving
4) make contact with (someone) by telephone or other means

2.2. Natural Gamma Radiation. Natural Radioactive sources

Annual dose = 0.5 mSv

Gamma-radiation, emitted by radioactive isotopes in building materials and the around, produces an annual dose of about 0.5 mSv. In certain areas the γ-radiation can be much larger, particularly in areas where the ground contains thorium and radium. Let us consider, in more detail, the sources of γ-radiation.

A long time ago, when the earth was created, a number of radioactive elements were formed. Some of these isotopes have very long half-lives, billions of years, and so they persist today. Since radioactive isotopes are unstable, disintegration eventually occurs, resulting in a different type of atom. This continues until a stable (non-radioactive) isotope is formed. Because most of the natural radioactive isotopes are heavy (found in the fifth row or higher in the periodic table), more than one disintegration is necessary before a stable atom is reached. This radioactive series is called a *radioactive family.* It is not unusual for the number of disintegrations comprising a series to be around 11 to 14. The two most important radioactive series today are the *uranium-radium-series* and the *thorium-series.* There are two other series, but they have almost disappeared from the Earth because they have much shorter half-lives. The four possible series are given in Table 2. 1.

TABLE 2.1. *The radioactive series*

Name	**Start**	**End**	**Half-life**
Uranium-radium	U-238	Pb-206	4.47×10^9 year
Neptunium	Np-237	Bi-209	$2{,}14 \times 1O^6$ year
Uranium-actinium	U-235	Pb-207	7.038×10^8 year
Thorium	Th-232	Pb-208	1.405×10^{10} year

The first radioisotope in the thorium-series has a half-life of $1.4 \cdot 10^{10}$ years. This is why there is still a lot of thorium in the ground. On the other hand, neptunium with its short half-life has disappeared. However, it can be produced in the laboratory. Thus, all four radioactive series are well understood. The starting element in the uranium-actinium series has a half-

life of $7.038 \cdot 10^8$ years. This is short compared to the age of the Earth (5 billion years or about 7 half-lives), and, therefore, the content of U-235 is only 0.71 % of the uranium isotopes.

In addition to these radioactive series, there are a number of other radioactive isotopes. The most important is K-40 with a half-life of 1.27 billion years. This half-life is shorter than the age of the Earth and only a few percent of the original K-40 remains today. The half-lives given in Table 2.1. indicate that the natural radioactivity has decreased considerably since the formation of the Earth. This is of interest when speculating about the origin of life and discussing the possible effects of radiation when the Earth was younger.

Choose the proper meaning of the word in *bold.*

3. The half-lives given in Table 2.1. ***indicate*** that the natural radioactivity has decreased considerably since the formation of the Earth.

1) point out; show
2) mention indirectly or briefly
3) direct attention to (someone or something) by means of a gesture
4) suggest as a desirable or necessary course of action

2.3. Distribution of natural radioactivity

Natural radioactivity varies from place to place. With regard to doses from external γ-radiation, the most significant contributions come from the elements in the uranium-radium-series, the thorium-series and K-40.

In order to give a quantitative measure for the presence of radioactive elements, the number of becquerel per kilogram (Bq/kg) can be obtained for different types of rock and soil. Of course, this varies from place to place.

TABLE 2.2. *The concentration of isotopes (given in Bq/kg) in some species of rock and soil*

Species of rock/soil	**Ra-226**	**Th-232**	**K-40**
Granite	20-120	20-80	600-1800
Thorium and uranium rich granite	100-500	40-350	1200-1800
Gneiss	20-120	20-80	600-1800
Sandstone	5-60	4-40	300-1500
Limestone	5-20	1-10	30-150

Slate	10-120	8-60	600-1800
Shale (from cambrium)	120-600	8-40	1000-1800
Shale (lower ordovicium)	600-4500	8-40	1000-1800
Shale rich soil	100-1000	20-80	600-1000
Moraine soil	20-80	20-80	900-1300
Clay	20-120	25-80	600-1300

Table 2.2 gives the concentrations of Ra-226, Th-232 and K-40 in different species of rock found in Scandinavia. It appears that certain types of shale exhibit concentrations of Ra-226 up to 4,500 Bq/kg. The concentration of Th-232 also varies considerably from one mineral to another. In certain areas of the world, such as India, Brazil and Iran, the thorium concentration in the soil can be 10 to 100 times above the average.

Potassium is everywhere. It is in soil, plants, animals, and humans. The element potassium makes up 2.4 percent by weight of all elements. But, the abundance of the radioactive isotope K-40 is only 0.0118%.

Notice in Table 2-2 that the variation of K-40 between different types of rock is much smaller than that for radium and thorium. K-40 emits both a β-particle and a γ-ray.

Each isotope contributes a different amount to the total external γ-dose: approximately 40% from K-40, 40% from Th-232 and about 20% from Ra-226.

When inside houses and buildings, people are shielded from much of the radiation coming from outside. But since the building materials also contain radioactive elements, the dose generally does not go down. More often it goes up. Since the concentration of radioactive isotopes varies from one region to another, it is also true that the radioactivity in building materials, such as concrete, depends on where it is made.

In houses made of wood, the γ-radiation in the ground floor is approximately the same as that outdoors. This is because most of the radiation comes from the masonry materials in the cellar and the ground just outside. Wood materials contain less radioactivity than rocks and soil and the radiation level decreases as you go to higher floors. In houses made of concrete, the indoor radiation level will be like that of outdoors if the concrete is made from materials found locally. But it is not unusual for the concrete or cinder blocks to contribute to an increase in the radiation level over that found outdoors.

In Sweden, a number of houses were built using uranium rich shale. Because these houses have a radiation level that is unacceptable, construction using this type of building material was stopped in 1979. Houses made of red brick very often have a high radiation level, mainly because of the content of K-40. Brick houses are more common in cities than in the country; consequently, people living in cities tend to be exposed to more radiation than those living in the countryside.

Examples of the radiation level inside different types of houses in the same area are given in Figure 2.2. These data are for more than 2000 houses in Southern Norway. For different types of houses, the radiation level may vary by factor 2. The lowest levels were found for wood houses. Living in an average wood house for one year would result in a whole body dose of 0.87 mGy (for this type of radiation the weighting factor is 1 and the biological effective dose is the same, 0.87 mSv) from external γ-radiation and cosmic radiation.

1. Complete each sentence by choosing from the following:

Exist, determines, consists, contains

1. A field guide is a book that … descriptions of organisms grouped in different ways.
2. A compound is a substance that … of two or more elements that have combined in a chemical reaction.
3. A large number of radionuclide … emitting nuclear particles with a range of path lengths from nanometers to millimeters.
4. This study … the quantitative as well as the qualitative influence of modeling of inelastic nuclear interactions on ion therapy.

2. Find antonyms to these words in the text:

Stable
Radioactive
Similar
Seldom
Extraordinary
Unusual

3. Match the antonyms:

1. Balance a) unnecessary

2. Disorder	b) avoidable
3. Visible	c) unavailable
4. Irreplaceable	d) rational
5. Necessary	e) inefficient
6. Unavoidable	f) complete
7. Available	g) imbalance
8. Irrational	h) invisible
9. Efficient	i) replaceable
10. Incomplete	j) order

4. Make word-combinations with these words.

Annual doses inside homes

(*due to the natural occurrence of γ-emitters + cosmic radiation*)

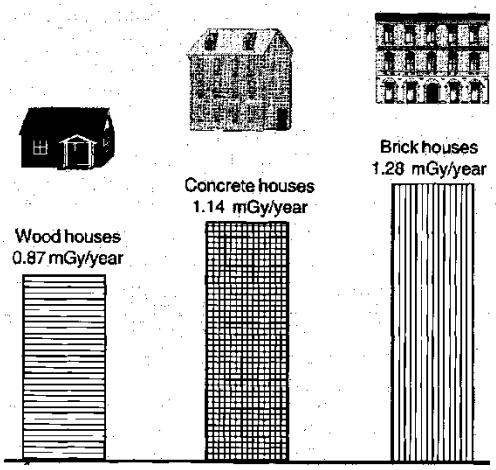


FIG 2.2.

Here is an example which shows that the annual dose depends on the house a person lives in. Approximately 2000 dwellings are included in this study. The value given for each type of dwelling is a combination of cosmic radiation and γ-radiation from sources external to the human body. The dose rate is given in mGy per year. Since this is mainly low LET-radiation, the dose rate would be the same in mSv. The houses in this examination are in Southern Norway, but similar results are likely in other areas.

It appears from the figure that, if you move from one house to another, you will also change your radiation milieu, your background dose either increasing or decreasing. Consequently, if small environmental doses, either natural or artificial, are of some concern, it would be of interest to have information about the sources that contribute to annual dose. The external γ-radiation dose (coming from sources external to the human body) varies within large limits from place to place, and even from one house to another house in the same area.

Choose the proper meaning of the word in *bold.*

4) It ***appears*** that certain types of shale exhibit concentrations of Ra-226 up to 4,500 Bq/kg.

1) come into sight; become visible or noticeable, especially without apparent cause
2) arrive at a place
3) perform publicly in a film, play, etc.
4) seem; give the impression of being [with infinitive]

2.4. Internal Radioactivity (sources inside the body)

Annual dose = 0.3 – 0.4 mSv

The food we eat contains radioactive isotopes and our bodies will therefore contain small amounts of radioactivity. The most important isotope is K-40. The daily consumption of potassium is approximately 2.5 gram. From this you can calculate that each day you eat about 75 Bq of K-40. Potassium is present in all cells making up soft tissue. The potassium content per kilogram body weight will vary according to sex and age (see Figure 2.3). The dose due to K-40 will of course also vary in a similar way. Muscular young men receive a larger dose than older people and men receive a larger dose than women.

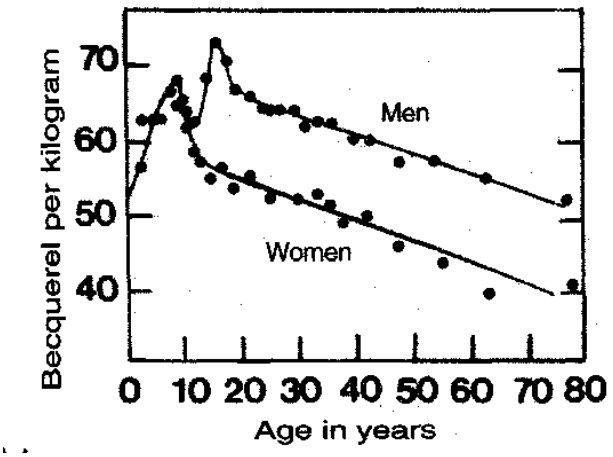


FIG 2.3.

The concentration of potassium (in Becquerel per kilogram from K-40) varies with age and sex. The abundance of the K-40 isotope is 0.0118%.

Two other naturally occurring radioactive isotopes of concern are C-14 and polonium (Po-210).

C-14 is formed in the atmosphere when neutrons react with nitrogen. C-14 is taken up by plants in the form of carbon dioxide, CO_2.

Polonium is one of the decay products in the uranium-series and results from the decay of the noble gas radon (see Figure 3.2.). After emitting two β-particles, Po-210 is formed. This isotope is α-particle emitter and, if ingested or inhaled, it delivers a relatively large local dose. When taken up by the body, 10% of the isotope is deposited in the liver, 10% in the kidneys, and 10% in, the spleen. The remaining 70% is uniformly distributed throughout the body.

Radon

Annual dose =1-3 mSv

Radon is a noble gas formed when radium disintegrates. Since radon is a gas, it readily becomes a part of the atmosphere. The half-life is rather short (3.82 days) and its four subsequent decay products (also with short half-lives) add large natural doses to the public environment. Some areas are high in radon because local concentrations of uranium are high. Radon measurements in dwellings, together with mathematical models, have been used to estimate the annual dose to the public. The calculations indicate that the radon dose to the people in Scandinavia, as well as to the average US citizen, is about 2 mSv per year. In other countries, like Denmark and Iceland, the doses are much smaller. In mines and other structures in the mountains (hydroelectric power stations and military installations), the radon concentrations may be large. People working at such places receive larger doses.

Several possibilities exist for the release of radon into houses. The main sources are the rock or soil on which the house is built, as well as the water supply. The rock formations under a house always contain some radium and the radon gas can penetrate into the house through cracks in the floor and walls of the basement. The water supply from wells, in particular in regions with radium-rich granite, contains high radon concentrations. When the water is the carrier, radon gas is readily released.

So, we have presented the four main natural radiation sources that give all of us a radiation dose from the time of conception until we die. The combined annual dose is around 2-3 mSv throughout the world, with a variation range of at least a factor of 10.

The most variable source is radon, varying between widely different extremes. Another important aspect of the radiation emitted by radon is that a large fraction consists of α-particles. Because α-particles produce a high density of ionizations along the track (high LET radiation) and because the emitter is localized in the lungs, the effective dose from this source (given in Sv) is much larger than the actual dose (given in Gy).

Members of the public often seem to ignore natural doses of radiation but they are very concerned about smaller doses from anthropogenic sources such as nuclear accidents (Chernobyl, Three Mile Island, etc.) and radioactive waste products from the nuclear industry. In order to carry out epidemiological studies on small doses, the natural background doses are very important. The natural background not only produces about half

billion ionizations in your body per second, it does so continuously from "cradle to grave".

1. Make a list of chemical elements used in this chapter. Restore the context they are used in.

potassium, polonium, carbon dioxide, nitrogen, radon, uranium, radium

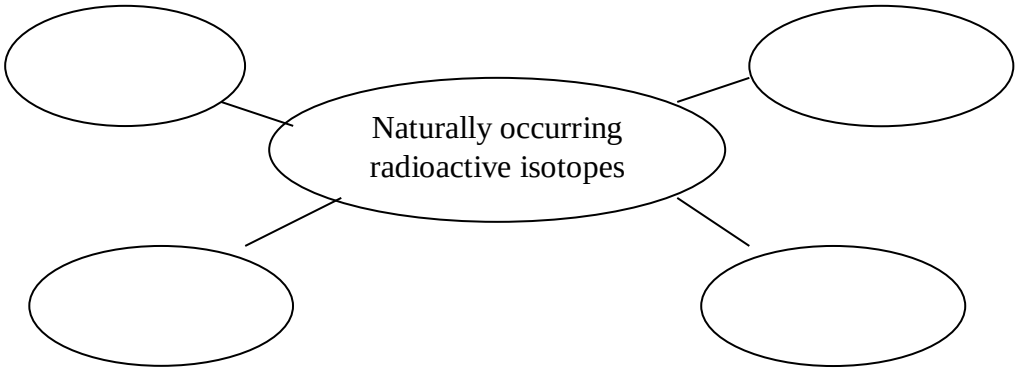
2. Say the following in Ukrainian:

mSv, Bq, K-40, Po-210, C-14, Th-232, Ra-226, CO_2, Sv, Gy

3. Complete the definitions:

- C-14 is …
- Polonium is …
- Radon is …
- The four main natural radiation sources are … (name them).
- Anthropogenic radiation sources are … (name them).

4. Complete the scheme:



5. Give Ukrainian equivalents to the following words and word combinations:

to contain, amount, consumption, vary, decay, emitting, to deposit, to distribute, to disintegrate, measurement, annual dose, natural background dose.

6. Choose the proper meaning of the word in *bold.*

5) Potassium is present in all cells making up ***soft*** tissue.

1) easy to mould, cut, compress, or fold; not hard or firm to the touch

2) having a pleasing quality involving a subtle effect or contrast rather than sharp definition

3) sympathetic, lenient, or compassionate, especially to a degree perceived as excessive; not strict
4) (of radiation) having little penetrating power

7. Render the following:

Всі існуючі радіонукліди ділять на два класи — *природні радіонукліди* і *штучні радіонукліди*. На теперішній час з відомих 1950 радіонуклідів (радіоактивних ізотопів) — 70 природних, що належать до 25 радіоактивних елементів і деяких нерадіоактивних елементів, до складу яких входять радіоактивні ізотопи. Основним джерелом надходження природних радіонуклідів в біосферу є земна кора. Значна частина може надходити з водою і певна частка - з атмосфери.

Відомі також 1880 штучних радіонуклідів, які утворюються в умовах штучних ядерних реакціях розпаду деяких елементів, а також одержують при бомбардуванні нерадіоактивних елементів потоком високоенергетичних частинок. Для переважної більшості відомих елементів одержані радіоактивні ізотопи, кількість яких для деяких, як, наприклад для цезію, вимірюється десятками. Джерелами надходження штучних радіонуклідів в біосферу є атомні вибухи і ядерні реактори. Безперечно, у цих ситуаціях виникають далеко не всі відомі штучні радіонукліди, а лише декілька сотень. При цьому переважна більшість їх є короткоживучими і внесок у дозу опромінення об'єктів біосфери формують практично декілька десятків радіонуклідів.

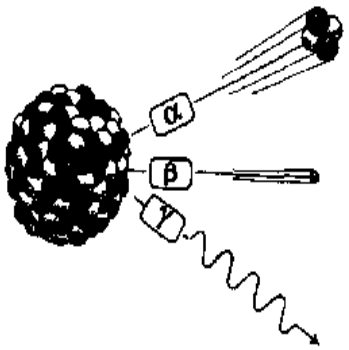
Control points to Charter 2

1) The discovery of radioactive isotope.
2) Disintegration of an atom. Types of radioactive isotopes.
3) Activation Analysis as a method to identify an element.
4) Natural radioactive source: Cosmic Radiation.
5) Natural Gamma radiation. External radioactivity.
6) Internal Radioactivity. Polonium. Radon.
7) The importance of the natural background doses.

Science vocabulary

1. **natural radiation background** природний радіаційний фон
2. **isotop** ізотоп
3. **transuranium element** трансурановий елемент
4. **fission** розщеплення, поділ
5. **cesium** цезій

6. **gamma rays** гамма-промені
7. **quantum** квант
8. **fallout** радіоактивні опади
9. **ampere** ампер
10. **excitation of electron** збудження електрону
11. **neutron** нейтрон
12. **positron** позитрон
13. **meson** мезон
14**. quantum state** квантовий стан
15. **bismuth** вісмут
16. **half-life period** період напіврозпаду
17. **neutrino** нейтрино
18. **isobar** ізобар
19. **isometric state** ізометричний стан
20. **corpuscular** корпускулярний, атомний
21. **tungsten** вольфрам
22. **scattering** розсіювання
23. **sparse-ionizing-radiation** розсіяне іонізуюче випромінювання
24. **LET (linear energy transfer)** лінійна передача енергії
25. **dense-ionizing radiation** щільно іонізуюча радіація
26. **deuteron** дейтрон
27. **exposure dose** експозиційна доза
28. **absorbed dose** поглинена доза
29. **dose rate** потужність дози опромінення.
30. **binding energy** енергія зв’язку
31. **coulomb** кулон
32. **intrinsic instability** внутрішня нестабільність
33. **activation product** продукт активування
34. **slate** сланець
35. **gneiss** гнейс
36. **sandstone** пісковик
37.**masonry** кам'яна (цегляна) кладка
38. **cinder** шлак; окалина
39. **effective dose** ефективна доза



3. What is Radioactivity?

1. Ionizing radiation. 2. Radioactive elements. 3. The nature of radioactivity. 4. Alpha radiation. 5. Beta and Gamma radiation. 6. What is an isotope? 7. The radiation series. 8. The energy of radiation. *8.1 Description of radioactive sources. 8.2. Alpha (α) radiation. 8.3. Beta (β) radiation. 8.4. Gamma (γ) radiation.* **9. The penetration of radiation. 10. Ionization. Excitation.**

1. Ionizing radiation

Living organisms as well as non-living objects of the environment are affected by set of various factors of the physical nature including radiation (visible light, ultraviolet, infra-red, magnetic fields, radio-waves of various ranges). Ionizing radiation of natural radioactive elements and isotopes as well as space radiation also acts.

The common name for both radiation from x-ray machines and radioactive sources is *ionizing radiation*. The name indicates that the radiation has sufficient energy to ionize atoms and molecules. Ionization takes place when an electron is removed from its position in the atom or molecule. Since a molecule usually has no net charge to begin with, the loss of a negative electron leaves behind a positive ion. The electron can then end up on another molecule which then becomes a negative ion. The creation of positive and negative ions in matter is the sign of radiation, allowing us to detect and categorize it. Ionizing radiation is distinct from low energy radiations which include ultraviolet, visible, infrared, microwaves and radio waves that produce effects, for the most part, of a different nature.

Choose the proper meaning of the word in *bold* .

1. The creation of positive and negative ions in ***matter*** is the sign of radiation, allowing us to detect and categorize it.

1) physical substance in general, as distinct from mind and spirit written or printed material
2) a subject or situation under consideration
3) something which is to be tried or proved in court; a case
4) (matters) the present state of affairs

2. Radioactive Elements

The atomic structure of most elements contains a nucleus that is stable. Under normal conditions, these elements remain unchanged indefinitely. They are *not* radioactive. Radioactive elements, in contrast, contain a nucleus that is unstable. The unstable nucleus is actually in an excited state that can not be sustained indefinitely; it must relax, or *decay*, to a more stable configuration. Decay occurs spontaneously and transforms the nucleus from a high energy configuration to one that is lower in energy. This can only happen if the nucleus gives off energy. The energy emitted by the relaxing nucleus is radiation. All radioactive elements have unstable nuclei; that is what makes them radioactive.

Thus, the radioactivity is considered as a spontaneous or artificial transformation of atomic nucleus of unstable isotopes from the basic state into other isotope of this or other element that is accompanied by energy emission.

3. The Nature of Radiation

The energy emitted by an unstable nucleus comes packaged in very specific forms. In the years that followed the discovery of radioactivity, determining the kind of radiation emitted from radioactive compounds was of great interest. It was found that these radiations consisted of three types called: alpha (α), beta (β) and gamma (γ) radiations after the first three letters in the Greek alphabet (see Figure 3.1).

The nuclear emission transforms the element into either a new element or a different isotope of the same element. A given radioactive nucleus does this just once. The process is called *decay or disintegration.*

The law of radioactive decay asserts that the identical portion of available nucleus disintegrates per unit time. The measure of the number of disintegrations per unit time is called the decay rate. The decay rate is proportional to the number of radioactive atoms present.

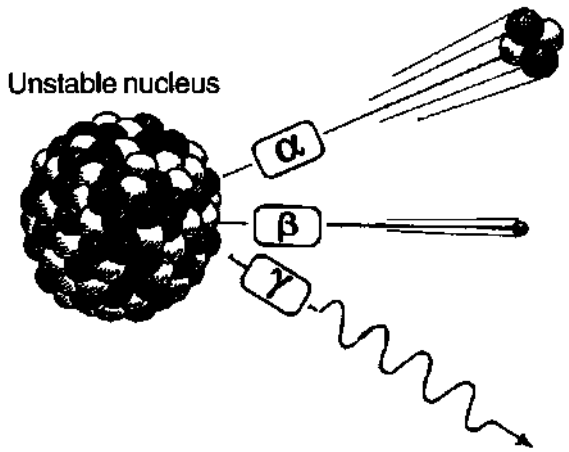


FIG 3-1.

A radioactive atom possesses an unstable nucleus. This means that radioactive atoms will emit radiation sooner or later and convert into a more stable state. The types of radiation that

may be emitted are called alpha (α), beta (β) and gamma (γ) radiation.

The evidence for the three types of radiation comes from an experiment in which the radiation from radioactive compounds was passed through a magnetic field. γ-rays passed through the field without disturbance, whereas the two other types were deflected from a straight line. Because it was known at that time that charged particles are deflected when they pass through a magnetic field, the conclusion was evident: γ-rays have no charge while α- and β-radiations consist of charged particles. The α-particles, deflected in one direction are positive whereas the β-particles, deflected in the opposite direction, are negative.

4. Alpha radiation

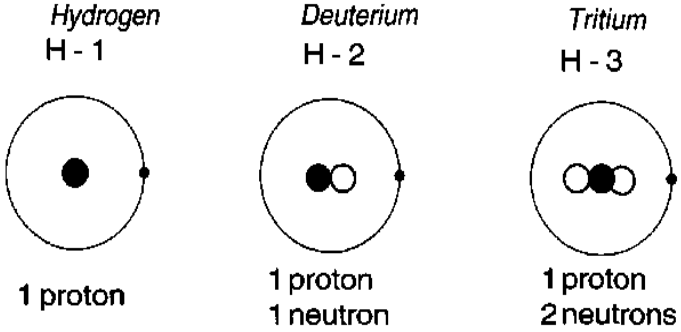
In 1903, Ernest Rutherford (a New Zealander who worked in Cambridge, England most of his life) performed a simple and elegant experiment showing that the α-particle is the nucleus of the helium atom. Rutherford positioned one glass tube inside a second glass tube. The inner tube contained a radioactive source that emitted α-particles. The outer tube contained a vacuum and at each end there was an electrode. The α-particles passed through a thin window, picking up two electrons on the way, and entered the outer tube as a gas. When Rutherford turned on the high voltage between the electrodes, the tube emitted light at very specific wavelengths (specific colors). He compared wavelengths of this light with the wavelengths of light produced by a similar tube that he had filled with helium gas. The colors of the light were identical. Rutherford concluded that α-particle is simply the nucleus of a helium atom and that when the α-particles reach the outermost tube they have picked up two electrons to become helium atoms.

5. Beta and gamma radiation

Experiments have shown that the β-particle is a fast moving electron, whereas γ-radiation is an electromagnetic wave. Other examples of electromagnetic radiation are ultraviolet (UV), visible light, infrared and radio waves. Electromagnetic radiation is characterized by its wavelength or frequency. The wavelength is the distance from one wave peak to the next and the frequency is the number of waves passing a given point per second. Through quantum mechanics it is known that particles can be described as waves and vice versa. Thus, γ-rays and other electromagnetic radiation are sometimes described as particles and are called *photons.*

6. What is an isotope?

In several places throughout this book isotopes are mentioned. Some isotopes are unstable and, therefore, radioactive while others are stable, and thus nonradioactive. What is an isotope? An element can exist in several versions that are chemically equivalent but have different atomic weights. The atomic weight of an element can be changed by altering the number of neutrons in the nucleus.



This is illustrated above for the most common of the elements, hydrogen.

The nucleus of an atom consists of protons and neutrons (called nucleons). The number of protons determines the element and the number of nucleons determines the atomic weight. Isotopes are atoms with the same number of protons, but with different numbers of neutrons.

Isotopes are written using the symbol for the element, such as H for hydrogen, O for oxygen, and U for uranium. Furthermore, the nucleon number is used to separate the isotopes. For example the three hydrogen isotopes are written as H-1, H-2 and H-3 (you will often see the isotopes written as ^{1}H, ^{2}H and ^{3}H).

Since the hydrogen isotopes are so well known, they have attained their own names. H-2 is called deuterium and H-3 is called tritium. When tritium disintegrates, it emits β-particle with an average energy of only 5.68 keV and maximum energy of 18.6 keV (1 keV equals 1000 electron volts of energy).

In nature, 99.985% of hydrogen is the H-1 isotope. In ordinary water, only one out of 7000 atoms is deuterium. Due to nuclear processes in the atmosphere there are small amounts of tritium. Tritium is widely used in research.

Potassium is another example of an element that has radioactive isotopes. Potassium consists of 93.10% K-39, 6.88% K-41 and 0.0118% of the radioactive isotope K-40. The latter isotope is present because it has a very long half-life of 1.27 billion years. The Earth's crust contains a lot of potassium. In spite of the small fraction of K-40, the radiation from this isotope is quite important. All living organisms contain some radioactive potassium. For example a human being contains, on average, about 60 Bq/kg body weight of K-40.

7. The Radioactive Series

A radioactive atom is unstable and will eventually eject a particle and/or a photon to attain a more stable state. Certain atoms are still unstable even if radiation has been emitted. Uranium is a typical example shown in Figure 3.2.

Type of radiation	Isotope	Half-life	
α	○ Uranium-238	4.47	billion years
β	○ Thorium-234	24.1	days
β	○Protactinium-234	1.17	minutes
α	○Uranium-234	245,000	years
α	○Thorium-230	77,000	years
α	○Radium-226	1600	years
α	● Radon-222	3.82	days
α	● Polonium-218	3.05	minutes
β	● Lead-214	26.8	minutes
β	● Bismuth-214	19.8	minutes
α	○ Poionium-214	0.164	milliseconds
β	○ Lead-210	22.3	years
β	○ Bismuth-210	5.01	days
α	○Polonium-210	138.4	days
	○ Lead-206	Stable	

FIG 3-2.

Uranium-radium-series. The start of the series is U-238 and the end point is Pb-206. The first isotope has the longest half-life, 4.47 billion years. Radon and the radon decay are encircled (notice the short half-lives).

The chemical symbol for uranium is U. The start of this decay series is the isotope U-238 or ^{238}U. When this isotope emits α-particle, it is changed into thorium-234.

Th-234 is also unstable and it emits β-particle, forming a new decay product, protactinium-234. The new product is still not stable and the decay processes continue step by step until Pb-206 is reached. Altogether, 14 disintegrations take place before U-238 ends up as a stable lead isotope (the whole series is shown in Figure 3.2). A series of unstable atoms where one atom changes into another is called a *radioactive family* or simply a *radioactive series.* Altogether, there are 4 naturally occurring radioactive families on Earth. Two of these have almost disappeared and only the uranium-radium series and thorium series are still active.

A radioactive source consists of a large number of unstable atoms. For example, one gram of the iodine isotope I-131 consists of $4.6 \cdot 10^{21}$ atoms. All these atoms will sooner or later emit radiation, but these emissions do not take place simultaneously. It is a statistical process, with one atom decaying every now and then. When one half of the atoms have decayed the source has gone through what is called one "half-life". Not all atoms have decayed after two half-lives, ¼ of the unstable atoms remain.

This uranium-radium series has been present from the beginning of the Earth. The first step in this series has a very long half-life of almost 5 billion years, the present age of the Earth. Thus, we are only now into the second half-life of the uranium-radium series. The two radioactive series that have almost disappeared have done so because the half-lives are much shorter.

1. Match the verbs with their meanings.

1) To alter	a) to produce and discharge sth (especially gas or radiation)
2) To process	b) to force or throw sth out in a violent or sudden way
3) To emit	c) to perform series of mechanical or chemical operations on sth In order to change or preserve it.
4) To eject	d)to change in a character or composition in comparatively Small but significant way

2. Insert the appropriate verb.

1. The salmon is quickly … after harvest to preserve the flavor.
2. Even the best cars … carbon dioxide.
3. Lumps of viscous lava were … from the volcano.
4. Our outward appearance … as we get older.

3. Match the terms with their Ukrainian equivalents.

1) Potassium	a) актиній
2) Thorium	b) калій
3) Hydrogen	c) свинець
4) Tritium	d) кисень
5) Bismuth	e)торій
6) Oxygen	f) водень
7) Actinium	g) тритій
8) Lead	h) вісмут

8. The Energy of the Radiation

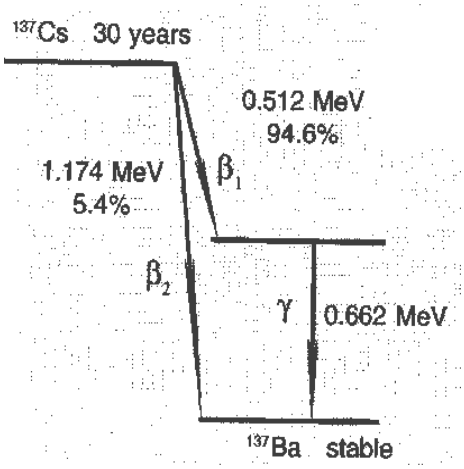
In order to detect radioactivity and to evaluate the biological effect of the radiation it is important to have information about the energy as well as the type of radiation emitted. The unit used for energy is the *electron volt* (abbreviated eV). By definition, an *electron volt is the energy attained by an electron when it is accelerated through a voltage gap of 1 volt.* The product of voltage and the electron charge (given in Coulombs, C) gives the relation between electron volt and a unit of energy, the joule (J):

$$\mathbf{1\ eV = 1\ V \cdot 1.6 \cdot 10^{-19}\ C = 1.6 \cdot 10^{-19}\ J.}$$

The electron volt is a very small unit. The energy usually set free by disintegration varies from a few thousand electron volts (keV) to approximately 6 million electron volts (MeV).

8.1. Description of a Radioactive Source

How is a radioactive source described? The intensity of the source depends on the number of atoms that disintegrate per second (i.e. the number of becquerels). Other parameters are: *type of radiation, half-life (*the *half-life period is the time during which the quantity of atoms of a radioactive isotope decreases twice),* and *energy of the radiation.* All these parameters can be given by a *decay scheme.* For example, the radioactive isotope Cs-137, which is the most important radioactive waste product from a nuclear reactor, has the decay scheme given in Figure 3.3.



A decay scheme is another way physicists use to convey information. The scheme tells us about the types of radiation emitted, the energy involved, half-life, etc. This type of information is necessary in calculating radiation doses and risks.

FIG. 3-3.

A scheme for the disintegration of Cs-137. The state of the nucleus is given by horizontal lines. The atomic number increases left-to-right, Cs is 55 and Ba is 56. The vertical scale is the energy of the nucleus, given in MeV. The vertical distances between the lines indicate the energy difference. This energy is set free by disintegration, appearing as β-particle or γ-ray.

The decay scheme shows that Cs-137 is transformed into the stable barium isotope Ba-137. This can take place via two different routes:

1.In 94.6% of the disintegrations a β-particle is emitted with an energy of 0.512 MeV (10^6 eV), followed immediately by a γ-ray with an energy of 0.662 MeV.

2. In 5.4% of the disintegrations the stable barium isotope is reached directly by emitting only a β-particle, with energy of 1.174 MeV.

The decay scheme also shows that the half-life of Cs-137 is 30 years. In addition, one might guess that Cs-137 can be observed by measuring the emitted γ-rays. γ-rays are easy to detect because they are very *penetrating.*

8.2. Alpha Radiation

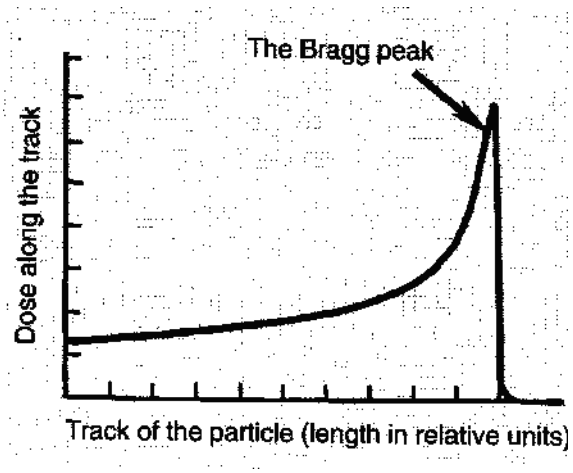
The energy of α-particle, when it is emitted by a nucleus, is usually a few MeV. Some of the properties which are characteristic of α-particles are:

• The α-particles from one particular radioactive source have the same energy. For example α- particles from U-238 always have a starting energy of 4.19 MeV.

• When α-particle passes through a material, it rapidly loses energy through numerous collisions with the electrons that make up the atoms and molecules. Because the collisions produce ionizations, a high density of

ions is deposited in the material tracing out a linear track. The energy of the α-particle is ultimately dissipated by this large number of low energy interactions and it stops at the end of the track.

The energy deposited per unit length of the track is called the *linear energy transfer* (abbreviated LET). An example is given in Figure 3.4. The range of α-particle from a radioactive source is very short in animal tissue and in air the range is only a few centimeters. As it can be seen from Figure 3.4 the energy loss along the track is not constant but gradually increases toward the end of the track.



The use of heavy particle beams offers potential advantages in cancer therapy. If the "Bragg peak" lands on the tumor, the tumor dose is larger than the dose to the surrounding healthy tissue. The goal is to maximize damage to the tumor while minimizing damage to healthy tissue.

FIG. 3-4.

The energy deposition along the track of α *-particle***.**

8.3. Beta Radiation

The energy of a β-particle (a fast electron or positron - the latter is a positively charged electron) is usually much smaller than the energy of α-particles. Furthermore, the energy of the β-particles varies from one disintegration to another; β-particle emission from a source is described by a spectrum of energies. Usually, the maximum energy is given in the decay schemes such as that shown earlier in Figure 3.3.

Let us consider this in more detail. In disintegration the nucleus changes from one energy state to another. This change is given as a well defined energy gap. However, the β-particles do not all have the same energy. The explanation is that, together with the β-particle, a tiny neutrally charged particle is emitted. This particle was called a *neutrino* by the Italian physicist Enrico Fermi. (The term neutrino means "the small

neutral particle".) The sum of the energies of the electron and the neutrino is equal to the energy gap in the decay scheme.

The **rule of thumb** determines the average β-particle energy: *The β-particle energy for a source varies from zero up to maximum. The average energy is approximately 1/3 of the maximum energy.*

β-particles are stopped by collisions with electrons in materials in a process similar to the way α-particles are stopped. According to the rule of thumb one can say that β -particle with energy 1 MeV will have a range in water or soft tissue of 0.5 cm. The β-particles from Cs-137 have an average energy of 0.2 MeV. If these particles hit the skin, the penetration into the body would be less than 1 mm. However, if a sufficient number of these β-particles hit the skin, it will be burned.

1. Describe a radioactive source.

2. Give the opposites of the following words from the extract:
disintegrate, increase, left, advantage, maximize, direct

3. Give the definition:

- The half life period is …
- A decay scheme is …
- The linear energy transfer is …
- A position is …
- A neutrino is …
- Quanta or photons are …

4. Say the following in English:
Cs-137, Ba-137, U-238 , Co-60

5. Complete the following sentences:

- Cs-137 is transformed into the stable barium isotope Ba-137 via two different routes: …
- The properties characteristic of α-particles are: …
- … are very penetrating.
- … is usually a few MeV.
- … is usually much smaller than the energy of α-particles.
- … is equal to the energy gap in the decay scheme.

6. Give Ukrainian equivalents to the words and word combinations:

radioactive source, half-life, decay scheme, disintegration, emit, particles, penetrate, deposit, collision.

8.4. Gamma Radiation

The energy of a γ-ray is given by the expression:

$$E = h\nu$$

where *h* is a fundamental constant known as Planck's constant and ν is the frequency of the radiation wave. The radiation can be considered to consist of small energy packages called quanta or photons. The energy of the γ-ray ranges from 0.1 to l.5 MeV. The cesium isotope Cs-137 emits γ-rays with energy of 0.662 MeV. The cobalt isotope Co-60 emits two quanta with energies of 1.17 and 1.33 MeV.

Gamma-rays and x-rays are absorbed differently from α-particles. When γ-rays penetrate a material, the intensity of the radiation (I) decreases according to an exponential formula:

$$I(x) = I_o \cdot e^{-\mu x}$$

where *x* is the depth in the material and μ is the absorption coefficient (μ describes how the radiation decreases per unit length for each type of material). The absorption coefficient has three different components. This is because three processes are involved: *photoelectric effect, Compton scattering* (inelastic scattering) *and pair production.*

Photoelectric effect is a process in which a photon interacts with a bound electron. The photon itself disappears, transferring all its energy to the electron and thereby imparting kinetic energy to the electron. This is the most important absorption process for radiation with energy less than about 100 keV (which is the type of radiation used in medical diagnostics). The photoelectric effect varies dramatically with the electron density of the absorbing medium. Thus material that contains atoms with high atomic numbers, e.g., the calcium in bone, gives strong absorption due to the photoelectric effect.

Compton scattering is a process in which a photon collides with a bound electron and where the photon energy is considerably greater than the electron binding energy (see Figure 3.5).

After the interaction, the photon continues in a new direction with reduced energy and the electron attains enough energy to leave the atom. We call this electron a *secondary electron.* The Compton process is the most important absorption process for photons with energies from about 100 keV to approximately 10 MeV (the type of radiation mainly used for radiation therapy).

Pair production is a process in which the energy of the photon is used to produce a positron-electron pair. The photon energy must be above 1.02 MeV, the threshold energy for forming two electrons. The process takes place near the atomic nucleus and is the most significant absorption mechanism when the photon energy is above about 10 MeV.

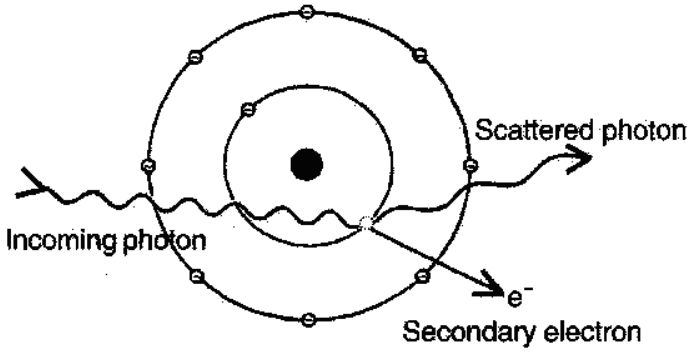


FIG. 3-5.

The drawing describes the process. The incoming photon interacts with an electron and the result is that the photon is scattered and its energy is reduced. The electron is ejected and becomes a "secondary electron".

Choose the proper meaning of the word in ***bold.***

2. When γ-rays ***penetrate*** a material, the intensity of the radiation (I) decreases according to an exponential formula.

1) go into or through (something), especially with force or effort
2) gain access to (an organization, place, or system), especially when this is difficult to do
3) be fully understood or realized by someone
4) succeed in understanding or gaining insight into (something complex or mysterious)

9. The Penetration of Radiation

When using a gun, the penetration by the bullet depends on the energy of the bullet as well as the composition of the target. For example, a pellet from an air gun will be stopped by a few millimeters of wood but a

bullet from a high powered rifle will pass through many millimeters of steel. It is similar with ionizing radiation. There are large differences in penetrating ability depending on the type of radiation (α-, β- or γ-radiation).

Alpha-particles from radioactive sources have energies up to 6 or 7 MeV with a range in air of only a few cm. In condensed matter the range is much shorter; α-particles will not even penetrate clothing. As long as the α-particle source is outside the body, there is no danger. If, however, the source is inside the body, all the energy is deposited in the body. It is mainly the heavy elements such as uranium, radon and plutonium which are α-emitters.

Beta-particles with energy of 1 MeV have a range in soft tissue of approximately 5 mm. The majority of β-particles have energy far less than 1 MeV. Consequently, almost all β-particles coming from sources in the environment are stopped by clothing.

Gamma radiation has the ability to penetrate tissue and even concrete. For example, 50% of the γ-rays from Cs-137, with energies of 0.662 MeV will penetrate a water layer of about 9 cm. We call this a *half-value layer*. Five half-value layers (less than 0.5 meter of water) will reduce the radiation by 97%. γ-radiation is easy to measure, whether the source is outside or inside the body. Consequently, isotopes emitting γ-radiation are used in medical diagnoses.

X-rays and γ-rays will easily penetrate into the human body. This property is utilized when x- and γ-rays are used for diagnostic purposes, α- and β-particles, on the other hand, lose their energy within a short distance and cannot penetrate into the body. Because of these penetration properties, γ-radiation is easy to observe whereas α-and β-radiation are more difficult to detect. Thus, special instruments are often needed in order to observe α-and β-rays. The following conclusions can be drawn:

- If a radioactive source is on the ground, such as in a rock, the α- and β-radiation will be stopped by air and clothes. Only γ-rays would penetrate into the body and deliver a radiation dose.
- When a radioactive source is **inside** the body, it is a different situation. α-and β-particles are completely absorbed within a short distance in the tissues, whereas only a certain fraction of the γ-radiation is absorbed. The rest of the γ-radiation escapes and can be observed with counters outside the body. Consequently, if you eat food containing radioactive compounds, they can be easily measured if γ-rays are emitted.

It is possible then to measure the radioactivity that is inside animals and humans who have eaten food containing Cs-137 contaminated, for example, due to fallout from nuclear tests or nuclear accidents. For adults, approximately 50% of the γ-radiation escapes the body and the other half is absorbed by the body. Other important isotopes such as Sr-90 (strontium) and Pu-239 (plutonium) are very difficult to observe since they only emit β-particles and α-particles.

Choose the proper meaning of the word in *bold.*

3. When using a gun, the penetration by the bullet depends on the energy of the bullet as well as the ***composition*** of the target.

1) the nature of something's ingredients or constituents; the way in which a whole or mixture is made up
2) a creative work, especially a poem or piece of music
3) the preparation of text for printing by setting up characters or by establishing its style and appearance electronically
4) a legal agreement to pay a sum in lieu of a larger debt or other obligation

4. In condensed matter the ***range*** is much shorter; α-particles will not even penetrate clothing.

1) the area of variation between upper and lower limits on a particular scale
2) the scope of a person's knowledge or abilities
3) a set of different things of the same general type the area offers a wide range of activities for the tourist
4) the direction or position in which something lies

5. Only γ-rays would penetrate into the body and ***deliver*** a radiation dose.

1) bring and hand over to the proper recipient or address
2) provide (something promised or expected)
3) launch or aim
4) save, rescue, or set someone or something free from

10. Ionization. Excitation.

Ionizing radiation is the more precise name for all types of radiation with energy large enough to ionize a molecule (below, M = molecule). Included under this designation are types of radiation from radioactive sources (α-, β- and γ-rays), x-rays, short wave length UV, particles from accelerators, particles from outer space, and neutrons.

Most atoms and molecules have ionization energy of 10eV and more. Certain molecules in liquids and in the solid state may have ionization energy as low as 6 eV. This means that UV-radiation with a wavelength below approximately 200 nm (6.2 eV) may cause ionization. Radiation with energy of 1 MeV has enough energy to yield about 150,000 ionizations if all the energy deposited produces ions.

The electron which is ejected from the molecule in an ionization process is called a secondary electron. Secondary electrons with the starting energy of 100 eV or more make their own tracks and will ionize and excite other molecules. These electrons are called delta rays.

Ionizing radiations do not only ionize but can also excite molecules. Excitations are also produced by long wavelength UV and visible light (called *non-ionizing* radiation). An excitation occurs when the molecule attains extra energy. This is done by increasing the vibrational, rotational, or electronic energies of the molecule. These excited states have short life times (less than milliseconds) and sometimes relax back to the ground state by emitting light. Light emission from an excited molecule, called fluorescence and phosphorescence, is a property that is used to measure and characterize ionizing radiation.

Excited and **ionized** molecules are very reactive and have short life times. These reactive products represent the starting point for all radiobiological effects, such as cancer. The biological effect increases with the number of ions and excited molecules formed.

1. Choose the correct word and fill in the blanks.

effect/affect

1. Different types of radiation _____ the environment and all living organisms in it.
2. Radioactive irradiation of living organisms can induce different radioecological _____.

act/action/active/activity/actively

3. In the atmosphere ozone gas _____ like a shield, protecting the Earth from dangerous ultraviolet rays.
4. The _____ or strength of a source is measured in Becquerels.
5. The _____ of ionizing radiation on human health is considered to be harmful.

6. The problem of occupational overexposure was _____ discussed by Roentgen Society during the early years of the 20th century.
7. The most chemically _____ element is the halogen known as fluorine.

nature/natural/naturally

8. There are _____ and man-made radionuclides.

9. Three _____ occurred radioactive series are the uranium, the actinium, and the thorium series.
10. General biological _____of this phenomenon is well studied.

move/movement

11. After the accident at nuclear power plant the situation was changing unpredictably as well as the direction of _____ of radioactive clouds.

12. Wind _____ clouds from place where they originate to the place where they drop precipitation.

2. Match the synonyms.

1) exposure	a) resolve
2) determine	b) illumination
3) distinct	c) separate
4) remove	d) happen
5) occur	e) withdraw

3. Match the opposites.

1) artificial	a) later
2) sooner	b) tense
3) negative	c) natural
4) outer	d) positive
5) relax	e) inner

4. Form opposites from the following using different prefixes:

charged, stable, available, visible, ionizing, normal, usual, acceptable.

5. Choose correct variants.

The types of electromagnetic radiation are:

- *γ-radiation*
- *β-radiation*
- *visible light*
- *infra-red radiation*
- *radio waves*

6. Render the following:

Радіоактивний ізотоп, або радіоізотоп, - це нестійкий ізотоп, що розпадається.

Радіоактивний елемент — це хімічний елемент, всі ізотопи якого радіоактивні.

Радіоактивна речовина - це речовина, до складу якої входить радіоактивний ізотоп.

Радіонуклід, або радіоактивний нуклід, - це нестійкий, такий, що розпадається, нуклід.

Control points to Charter 3

1) What is ionizing radiation?
2) Radioactivity.
3) The law of radioactive decay.
4) α-particles and Alpha radiation.
5) What is the difference between Beta and Gamma radiation?
6) What is an isotope?
7) Radioactive series; half-lives of radioactive series.
8) The unit for radiation energy. Radioactive source.
9) Alpha radiation. LET.
10) Beta radiation. The rule of thumb.
11) Gamma radiation. Photoelectric effect. Compton scattering. Pair production.
12) Penetration of radiation (α-particles, β-particles, γ-particles).
13) What is the difference between ionization and excitation?

Science vocabulary

1. **disintegration** розпадання; подрібнення на складові частини
2. **atomic weight** атомна маса
3. **nucleon** нуклон
4. **attain** досягати
5. **deuterium** дейтерій, важкий водень

6. **eject** вивергати; викидати
7. **radioactive series** радіоактивний ряд
8. **penetrate** проникати всередину
9. **dissipate** розсіювати(ся)
10. **radioactive decay** радіоактивний розпад
11**. trace out** креслити, накреслювати
12**. linear track** лінійний трек
13**. energy gap** перепад енергії; енергетичний інтервал
14. **tiny** дуже маленький, крихітний
15. **rule of thumb** практичний метод; емпіричне правило
16. **collision** зіткнення
17**. quantum (a)** квант
18. **photoelectric effect** фотоелектричний ефект
19. **inelastic scattering** непружне розсіювання
20. **pair production** утворення (електронно-позитронних) пар
21**. impart** надавати; передавати
22**. secondary electron** вторинний електрон
23. **pellet** кулька
24. **half-value layer** шар половинного послаблення (іонізуючого випромінювання**)**
25. **nm (nanometre)** нанометр
26. **fluorescence** флуоресценція, свічення
27. **phosphorescence** фосфоресценція, свічення
28. **tritium** тритій

4. Activity and Dose (gray, becquerel, sievert)

1. Activity in Becquerel. 2. Specific Activity. 3. Radiation Dose. *3.1. Dose Units and their History.* **4. Equivalent Dose. 5. Effective Equivalent Dose. 6. Other Dose Units. 7. Dose Measurements.**

1. Activity in Becquerel

When an atom disintegrates, radiation is emitted. If the rate of disintegrations is large, a radioactive source is considered to have a high activity.

The unit for the activity of a radioactive source was named after Becquerel (abbreviated Bq) and is defined as:

1 Bq - 1 disintegration per sec.

In a number of countries, the old unit, the curie (abbreviated Ci and named after Marie Curie) is still used. The curie-unit was defined as the *activity in one gram of radium.* The number of disintegrations per second in one gram of radium is 37 billion. The relation between the curie and the becquerel is given by:

$$\mathbf{1\ Ci = 3.7\ \ 10^{10}\ Bq}$$

The accepted practice is to give the activity of a radioactive source in becquerel. This is because Bq is the unit chosen for the system of international units (SI units). But one problem is that the numbers in becquerel are always very large. The opposite holds true when a source is given in curies. For example, when talking about radioactivity in food products, 3,700 Bq per kilogram of meat is a large number. The same activity given in Ci is a really small number, 0.0000001 curie per kilogram.

Most people are used to measuring the amount of a substance in kilograms or liters, not in becquerels or curies. Using the best balances in the world one can accurately measure down to about one microgram of substance (10^{-6} gram). By using our knowledge of radioactive detection, amounts more than a million times smaller than this can be measured.

Radioactive sources as small as 10 Bq to 100 Bq can be readily measured; this corresponds to only about 10^{-14} gram.

Choose the proper meaning of the word in *bold.*

1. The ***relation*** between the curie and the becquerel is given by:

$$\mathbf{1\ Ci = 3.7\ \ 10^{10}\ Bq}$$

1) the way in which two or more people or things are connected
2) the way in which two or more people or groups feel about and behave towards each other
3) a person who is connected by blood or marriage; a relative
4) the action of telling a story

2. Specific Activity

Specific activity is the activity per mass or volume unit. For example, the radioactivity in meat is given as Bq/kg. For liquids the specific activity is given in Bq/l and for air and gases the activity is given as Bq/m^3.

In the case of fallout from a nuclear test or accident, the activity on surfaces can be given either as Bq/m^2 or as Ci/km^2. Both are used to describe radioactive pollution. The conversion between them is:

$$\mathbf{1\ Ci/km^2 = 37{,}000\ Bq/m^2}$$

A great deal of information must be considered to calculate radiation doses and risk factors associated with these specific activities. The information must include the specific activity along with the various types of isotopes, their energies, physical and biological half-lives and methods of entry into the body. After considering all of these factors and calculating the dose, a determination of medical risk can be calculated.

Choose the proper meaning of the word in *bold.*

The information must include the specific activity along with the various types of isotopes, their energies, physical and biological half-lives and methods of ***entry*** into the body.

1) an act of going or coming in

2) an item written or printed in a diary, list, account book, or reference book

3) a person or thing competing in a race or competition

4) the forward part of a ship's hull below the waterline

3. Radiation Dose

A strong radioactive source represents no risk as long as it is isolated from populated environments. It is only when people are exposed to radiation that a radiation dose is delivered.

It is very important to distinguish between the activity of a radioactive source (measured in becquerels) and the radiation dose which may result from the source. The radiation dose depends on the location of the source with regard to those exposed. Furthermore, the radiation dose depends upon the type of radiation, such as whether it is α-, β- or γ-rays and the energy of the radiation.

Although people can neither see nor feel radiation, it is known that radiation deposits energy in the molecules of the body. The energy is transferred in small quantities for each interaction between the radiation and a molecule and there are usually many such interactions. For anything that is irradiated, the temperature rises. Additional radiation increases the temperature further. The temperature increase occurs because the radiation energy is transformed into heat. Even though it is generally very difficult to detect the rise in temperature, the realization that heat is generated by radiation is a key element in understanding the concept of *radiation dose.*

Choose the proper meaning of the word in *bold.*

3. It is very important to ***distinguish*** between the activity of a radioactive source (measured in becquerels) and the radiation dose which may result from the source.

1) recognize or treat (someone or something) as different

2) manage to discern (something barely perceptible)

3) (distinguish oneself) make oneself worthy of respect by one's behaviour or achievements

4) recognize or point out a difference

4. Although people can neither see nor feel radiation, it is known that radiation ***deposits*** energy in the molecules of the body.

1) [with obj. and usu. with adverbial of place] put or set down (something or someone) in a specific place

2) (of water, the wind, or other natural agency) lay down (matter) gradually as a layer or covering

3) [with obj.] place (something) somewhere for safekeeping

4) pay (a sum of money) into a bank or building society account

3.1. Dose Units and Their History

In the course of 100 years of dealing with ionizing radiation, several different dose units have been used. Some of these units are still used in different countries. It is useful, therefore, to consider some of these units and to see the relations between the old units and the gray unit (Gy).

Radiation dose measures the amount of energy deposited in an irradiated compound

1 Gy = 1 joule absorbed energy per kg

- ***Skin erythema dose***

It was discovered early that radiation exposure resulted in reddening of the skin. For a long period this reddening was used to quantify the radiation. This was called the *skin erythema dose.* This unit was quite uncertain since the reddening of the skin varied from one person to another. Another drawback was that the reddening appeared some time *after* the exposure.

In the case of ultraviolet radiation, this dose unit (along with the attending uncertainties) is still in use. The smallest UV-dose resulting in the reddening of the skin is called **MED,** which is an abbreviation of *minimum erythema dose.*

- ***The roentgen unit***

People who worked with radiation circa 1920 began searching for a more precise dose unit and in 1928, the *roentgen unit* (abbreviated R) was adopted. This unit can not be used for the dose itself since it is actually a measure of radiation exposure, i.e. the ionization of air molecules.

An exposure of 1 R means the amount of x- or γ-radiation that results in 2.58 10^{-4} coulomb per kg of ions generated in air.

To calculate the radiation dose (in Gy) from an exposure of 1 R depends on the energy of the x- or γ-radiation and the composition of the

irradiated material. For example, if soft tissue is exposed to γ-radiation of 1 R, the radiation dose will be approximately 9.3 milligray (mGy).

- ***The rad unit***

In 1953, the dose unit *rad* was developed. This is an abbreviation for *radiation absorbed dose* and is defined as:

The amount of radiation which yields an energy absorption of 100 erg per gram (i.e. 10^{-2} joule per kg).

The rad unit is still used in several countries.

1 gray = 100 rad

Choose the proper meaning of the word in *bold.*

5. People who worked with radiation circa 1920 began searching for a more precise dose unit and in 1928, the *roentgen unit* (abbreviated R) was ***adopted***.

1) legally take (another's child) and bring it up as one's own
2) choose to take up or follow (an idea, method, or course of action)
3) take on or assume (an attitude or position)
4) formally approve or accept (a report or suggestion)

1. Choose the correct word and fill in the blanks. Change the form if it is necessary.

disintegrate/disintegration

1. Radioactivity is the spontaneous _____ of atomic nuclei.
2. The number of atoms that _____ per second at any instant is directly proportional to the number of radioactive atoms actually present in the sample at that instant.

define/definition/definite

1. Natural radioactive background for a _____ country is more or less constant.
2. There are two _____ of oxygen effect.
3. Radioecology can be _____ as the study of the environmental effects of radioactive contaminants.

detect/detection/detective/detector

1. Gamma radiation _____ can be used for the _____ of radioactivity in everyday life such exposure on airplanes or from contaminated products.
2. Gamma radiation sources could be _____.
3. Various _____ devices are used to measure different types of radiation.

specify/specific/specification

1. Soil samples at different depths were taken to determine their radionuclide _____ activities and activity ratios.
2. The instruction _____ how the medicine is to be taken.
3. The equipment will be manufactured to proper _____.

consider/considerable/consideration

1. Becquerel was a _____ man in the scientific world.
2. Such natural radiation background is _____ to be high.
3. The workers were exposed to a _____ higher dose of radiation as compared with recommended tolerance dose.
4. Safety is the most important _____ in radio medicine.

2. Match the terms and the definitions.

1) specific activity	the energy absorbed from exposure to radiation;
2) radiation dose	to induce or undergo nuclear fission, as by bombardment with fast particles;
3) disintegrate	1997 the amount of radioactivity - or the decay rate - of a particular radionuclide per unit mass of the radionuclide;
4) skin erythema dose	1998 that amount of energy from ionizing radiations absorbed per unit mass of matter;
5) absorbed dose	1999 the amount of radiation which, when applied to the skin, causes temporary reddening;
6) roentgen unit (R)	2000 the minimum amount of UVB (ultra violet burns)that produces redness 24 hours after exposure. It is defined as the threshold dose that may produce sunburn;
7) minimum erythema dose (MED)	2001 a unit of dose of electromagnetic radiation equal to the dose that will

	produce in air a charge of 0.258 × 10-3 coulomb on all ions of one sign, when all the electrons of both signs liberated in a volume of air of mass one kilogram are stopped completely.

4. Equivalent Dose

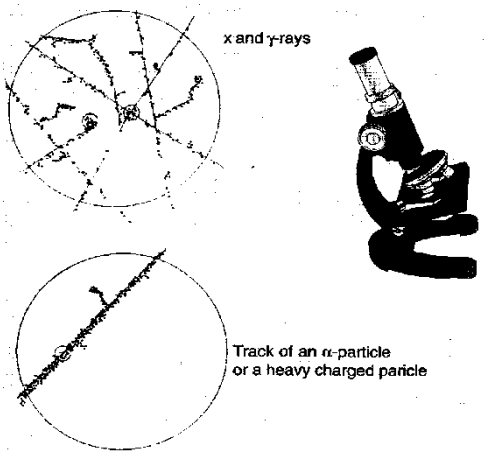
The equivalent dose is a dose of irradiation of a living organism by mixed or unknown types of ionizing radiation which biological efficiency is equivalent to the unit of absorbed dose.

When a biological system is exposed to ionizing radiation, molecules are ionized and excited. For a particular material, all types of radiation yield the same kinds of damaged molecules. However, there are differences with regard to the distribution of ionized and excited molecules along the track of a particle or photon.

Consider a very powerful microscope that makes it possible to "see" the molecules in a system. If a microscope is used when the system is exposed to radiation, differences will be observed in the distribution of ionizations produced by the radiation (see Figure 4.1). X-rays, β-particles and γ-rays strike the molecules rather sporadically - as indicated in the upper part of Figure 4.1. The small dark dots represent ionized molecules. For α-particles the situation is different. The ionizations are deposited along a single linear track. The molecules in the center of the track (the track core) are ionized, or hit. Sparse ionization along the γ-ray track is due to a low *linear energy transfer* (LET) while the dense ionization of the α-particle is due to high LET.

Even though the number of ionized molecules, and consequently the energy deposition, within the two circles is the same ((*the absorbed dose is a total quantity of ionizing radiation energy which* the absorbed dose *is absorbed by object of irradiation)* is the same), the distribution of the energy deposition (i.e., the LET) is different.

The biological effect depends upon the LET of the radiation, i.e., the distribution of the absorbed energy in other words the transfer of energy of ionizing radiation on the all length of path of a particle or a photon.



Ionizations from different types of radiation as seen in a very powerful microscope

FIG 4-1.

The Figure indicates how the distribution of absorbed energy in a system (for example an animal cell) might look after different types of radiation have passed through. The upper circle (field of view) contains tracks produced by x- and γ-ray absorption and the lower circle contains the track of α-particle. Each dot represents an ionized molecule. The number of dots within the two circles is the same, indicating the same radiation dose. However, note that the distribution of dots (ionizations) is quite different. The top is an example of low LET (linear energy transfer) and the bottom is an example of high LET.

For biological effects, such as cell death, cancer induction, and genetic damage, the effect is larger when the radiation energy is deposited within a small region. This is calculated by introducing a *radiation weighting factor (w_R).*

W_R is related to the relative efficiency of the radiation in producing a biological effect, and is given relative to high energy x-rays and γ-rays where w_R is set equal to 1. For α-particles, neutrons and other particles, w_R is larger than 1. This indicates that most biological effects depend on the spatial distribution of energy along the track (i.e. the LET or Linear Energy Transfer). In radiation protection, a w_R of 20 is currently used for α-particles where as for neutrons the factor varies from 5 to 20, depending upon their energy.

When the physical dose, measured in gray, is multiplied by w_R, the biological effective dose is calculated. This product is called the equivalent dose. The unit for equivalent dose is the sievert (abbreviated Sv), named after the Swedish scientist R.M. Sievert.

$$\mathbf{H = w_R \cdot D}$$

H is the equivalent dose in Sv and D is the dose in Gy.

In order to evaluate the biological effect of radiation we apply the sievert. The crux of the matter is the value of w_R. A number of experiments have been performed with the aim of getting more information on w_R. This parameter is frequently of crucial importance.

1. Insert the nouns from paragraph 4 into the following sentences. Use the hints given.

Irradiation, distribution, protection, deposition, situation, response, condition.

a) Variations in dose is kept minimal inside the target volume, aiming at a homogeneous
_____b_____ of dose.
b) Cells that fail to divide successfully after ___d_____can also undergo apoptosis in this stage.
c) Subsequent experiments showed that the adaptive ___p____ to low doses requires a certain minimal dose before it becomes active.
d) The range of energy d_____ is no more than a few micrometers.
e) A single laser shot can be applied in any other radiobiological experiment performed with laser-driven proton beams, with the only _____t___that the initial proton spectrum has to be at least roughly known.
f) The _____n is very different in radiological screening programmes for early diagnosis of specific diseases such as cancer.
g) In any case, radiation ___t_____ for the patient is afforded through the application of the principles of justification and optimization.

2. Translate these sentences into Ukrainian.

3. Form the verbs out of these nouns replacing the jumbled letters.

a) to dresopn
b) to tondsiburte
c) to daiterari
d) to tasuite
e) to tcorpect
f) to tinociden
g) to sepodit

4. Use these verbs in the sentences of your own.

5. Effective Equivalent Dose

In some cases, only a part of the body is irradiated. For example, mainly the lungs are involved in the case of radon and radon decay products. Different organs and types of tissue have different sensitivities with regard to what is termed the *late effects* of radiation. Late effects are biological responses that are only observed after a substantial amount of time has passed, often years. Induction of cancer is a late effect. In order to compare the risk for late effects of different types of radiation, the so-called *effective dose* is used.

If one part of the body (e.g., the lungs) receives a radiation dose, it represents a risk for a particularly damaging effect (e.g., lung cancer). If the same dose is given to another organ it represents a different risk factor.

It is possible to calculate a dose given to the whole body that yields the same risk as that from the much larger dose given to one particular organ.

This calculated dose is called *the effective dose* (often shortened to simply *the dose)* and is designated *E.* It is defined in the following way:

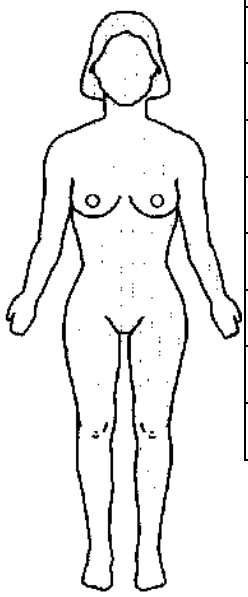
$$E = w_1H_1 + w_2H_2 + \ldots\ldots\ldots\ldots$$

where w_1 represents a weighting factor for organ 1 and H_1 is the equivalent dose (given in Sv) for organ number 1. The weighting factor represents the sensitivity of a particular organ and Table 4.1 gives the different weighting factors suggested for radiation protection work by the ICRP. Equivalent dose and effective equivalent dose have a meaning only when considering late effects such as cancer and leukemia.

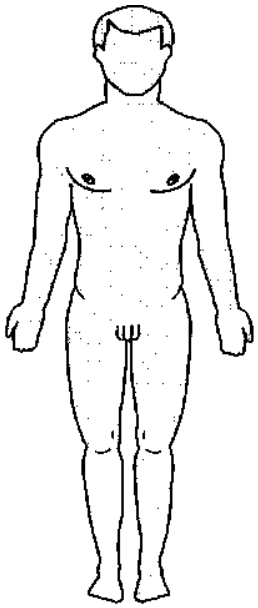
TABLE 4-1.

Tissue weighting factors used in radiation protection work

Organ	**Weighting factor**
Gonads	0.20
Bone marrow (red)	0.12
Lungs	0.12
Stomach	0.12



Colon	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Thyroid gland	0.05
Esophagus	0.05
Bone surfaces	0.01
Skin	0.01
The rest	0.05
TOTAL	1.00



6. Other Dose Units

In addition to the units already defined, there are a number of other concepts used in radiation protection and these, unfortunately, are frequently a source of confusion. Radiation biologists are interested in the mechanisms that result in the observable macroscopic effects on biological systems, whereas radiation protection authorities are interested in guidelines for large population groups. Here is a brief overview of the concepts used when working in radiation protection.

- **Collective dose**

The collective dose is the sum of all individual doses in a group of people. It can be obtained by the product of the average individual dose with the number of people in the group. For the collective dose the unit used is person-sievert (person-Sv). For some reasons the use of collective dose is questionable in risk analyses. Nevertheless, it is used by authorities for risk analysis in many countries.

- **Committed equivalent dose**

When a radioactive compound enters the body, the activity will decrease with time, due both to physical decay and to biological clearance, as noted earlier. The decrease varies from one radioactive compound to another. Accumulated dose over a certain period of time, usually 50 years, is called the committed equivalent dose.

7. Dose Measurements

The strength of a radioactive source (in Bq) and the energy of the emission (in eV) can be measured. This is, however, not a dose measurement.

The radiation dose is the energy deposited in the irradiated compound. If the radiation hits a human being, the dose is defined as the energy deposited in the human body. The amount of energy deposited is almost always different from the amount of energy coming from the source. Deposited energy determines dose.

Counters observe particles or photons sequentially. In dose measurements, the concern is not with the individual particles or photons but with the total energy absorbed in the exposed materials (e.g., tissue). It is difficult to observe energy absorption in tissue. Two of the problems are:

1. An exposure to one roentgen (1.0 R) of x- or y-radiation results in a radiation dose to soft tissue of approximately 9.3 mGy. The precision can be no better since the roentgen unit is based on the radiation absorption in air, whereas doses to a biological system (soft tissue or bone) are based on the energy absorbed in that system.

The absorption increases with the electron density of the exposed material and is therefore larger in bone compared with soft tissue. Furthermore, the energy absorption increases with decreasing radiation energy. Since these properties *are not* the same for air, soft tissue and bone, the doses delivered by a 1 R exposure are different.

2. When the radiation strikes a body, the dose changes with depth (i.e., the distance the radiation traverses in the body). This is illustrated in Figure 4.2 for different types of x-rays as well as a beam of charged particles (C-12 ions).

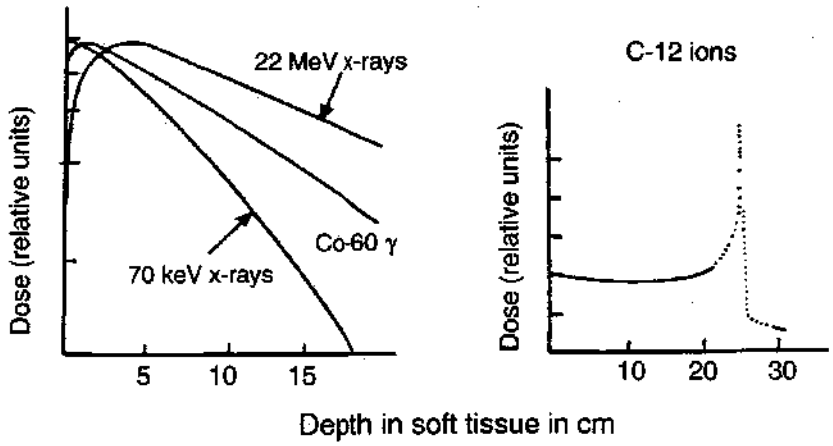


FIG 4-2.

Depth dose curves for soft tissue. The dose is measured from the surface of the skin. On the left are data for x- and γ-rays as indicated. To the right is shown the dose curve for high energy charged particles. In this example carbon atoms, with all 6 orbital electrons stripped away, were used. The energy of the carbon ions when they hit the soft tissue is 5,688 MeV.

In order to use radiation for cancer treatment it is important to have knowledge of these depth dose curves. As you can see from Figure 4.2, the region for maximum dose can be changed by changing the x-ray energy. For tumors positioned deeper than 6 cm into the tissue, x-rays with energy of more than 20 MeV should be used. The goal is to give a high killing dose to the tumor while minimizing the dose to the surrounding healthy tissue.

As you can see, the charged particle radiation has a striking depth dose relationship (Figure 4.2). The dose peaks at the end of the track (called the Bragg peak). The Bragg peak occurs at a depth which depends on the energy of the particles. This type of radiation has been used for cancer treatment. It requires large accelerators and it is, therefore, quite expensive. The depth dose curve shown in Figure 4.2 was obtained with a research accelerator at the Lawrence Berkeley Laboratory in the 1960s; it is no longer in operation.

The **"dose rate"** is usually given when describing the intensity of the radiation being absorbed by the target, i.e. the radiation dose per unit time. The total dose is then obtained by a simple multiplication of the dose rate by exposed time.

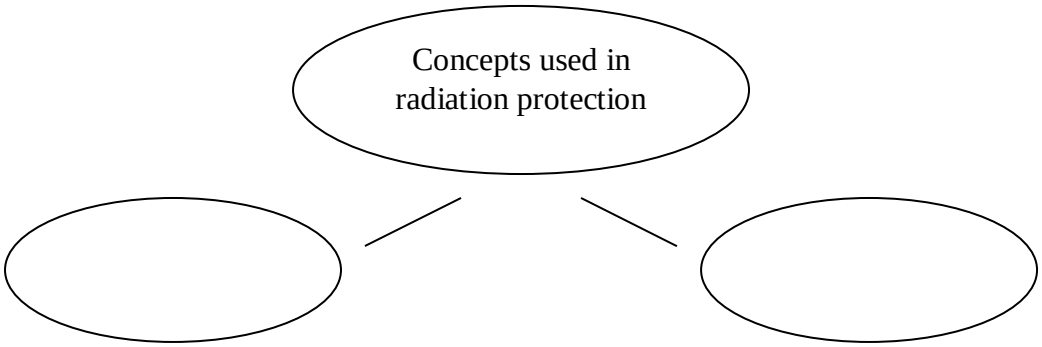
In order to measure the dose to soft tissue exposed to γ-radiation, the walls of the instrument as well as the compound in the sensitive volume (usually a gas) must have a composition that has absorption similar to soft

tissue. The observed ion current is then proportional to the dose rate. The sensitive volume must be small when the dose rate is large and vice versa.

Thermoluminescence dosimeters (TLD) are frequently used for dose measurements. TLDs are well suited for different types of radiation as well as for large and small doses and dose rates. If LiF-crystals are used, x- and γ-rays yield a response which is proportional to the dose to soft tissue. If crystals with calcium are used, the response is proportional to the bone tissue dose.

Since the TLD crystals are small, they are well-suited for measurement of doses to patients. They can be placed on and in the body.

1. Complete the scheme and comment on it:



2. Give the definition:

- The collective dose is …
- The committed equivalent dose is …
- The radiation dose is …
- The dose rate is …

3. Decode the following shortenings:

MeV, R, mGy, eV, TLD

4. Insert the necessary word: increase / decrease, measure / measurement, expose / exposure, absorb / absorption:

1. When a radioactive compound enters the body, the activity will _____ with time.
2. The strength of a radioactive source (in Bq) and the energy of the emission (in eV) can be _____.
3. In dose _____, the concern is not with the individual particles or photons but with the total energy _____ in the exposed materials (e.g., tissue).

4. _____ to one roentgen (1.0 R) of x- or y-radiation results in a radiation dose to soft tissue of approximately 9.3 mGy.
5. The roentgen unit is based on the radiation _____ in air.
6. The radiation absorption _____ with the electron density of the exposed material.
7. TLDs are frequently used for dose _____.

5. Render the following:

Потужність поглиненої дози іонізуючого випромінювання (потужність дози випромінювання) P_{abs} - це відношення приросту поглиненої дози (dD) за інтервал часу (dt) до цього інтервалу часу.

Еквівалентна доза в органі або тканині ($H_т$) - це величина, яка визначається як добуток поглиненої дози (D_T) в окремому органі або тканині (T) та радіаційного зважуючого фактору (w_R).

Радіаційний зважуючий фактор (коефіцієнт якості) w_R - коефіцієнт, що враховує відносну біологічну ефективність різних видів іонізуючого випромінювання. Використовується винятково при розрахунку ефективної та еквівалентної доз.

Ефективна доза (E) - сума добутків еквівалентних доз $H_т$ в окремих органах і тканинах на відповідні тканинні зважуючі фактори $w_{T.}$.

Тканинний зважуючий фактор - коефіцієнт, який відображає відносну імовірність стохастичних ефектів в тканині (органі). Сума всіх зважуючих факторів по всіх органах дорівнює одиниці.

Колективна ефективна (еквівалентна) доза—це сума індивідуальних ефективних (еквівалентних) доз опромінення певної групи населення за певний період часу або сума добутків середньогрупових ефективних доз на число осіб у відповідних групах, що утворюють колектив, для якого вона розраховується.

Control points to Charter 4

1) What are the units for the activity of a radioactive source?
2) What is *specific activity*?
3) The concept of *radiation dose*.
4) Skin erythema dose.
5) The roentgen unit.
6) The rad unit.

7) What is *equivalent dose*? LET.
8) *Absorbed dose*. Biological effect.
9) What is radiation weighting factor?
10) Late effects. The effective dose.
11) Radiation dose. The concern in dose measurements.
12) The Bragg peak.
13) Dose rate.

Science vocabulary

1. **radioactive detection** виявлення радіоактивності
2. **specific activity** питома активність
3. **medical risk** медичний ризик
4. **reddening** почервоніння
5. **drawback** хиба; вада; дефект
6. **uncertainty** невпевненість, невизначеність
7. **circa** приблизно
8. **sporadically** нерегулярно, випадково
9. **dissipate** розсіювати(ся)
10. **dot** крапка, цяточка
11. **field of view** поле зору
12. **radiation weighting factor** коефіцієнт зважування на іонізуюче випромінювання
13. **spatial** просторовий
14. **crux** утруднення; важке питання
15. **late effect** віддалений ефект
16. **risk factor** фактор ризику
17. **yield** призводити до, давати результат
18. **strip** знімати, позбавляти
19. **dose rate** потужність дози опромінення
20. **equivalent dose** еквівалентна доза
21. **effective dose** ефективна доза
22. **collective dose** колективна доза
23. **committed equivalent dose** поглинута еквівалентна доза
24. t**issue weighting factors** коефіцієнт зважування на тканину
25. **effective equivalent dose** еквівалентна ефективна доза

5. Radiation and the Environment

1. Radiation. *1.1. Radiation Dose. 1.2. Type of Radiation. 1.3. The Amount of Pollution. 1.4. The form of Dispersion of the Release.* **2. Use of Radiation in Society. 3. Radioactivity in the Ocean. 4. Plutonium and Chemical Compounds.** *4.1. Plutonium and the Environment.* **5. Remedial Action.**

1. Radiation

Radiation, both natural background and man-made, forms a part of our environment which must be considered as both a benefit and a risk. In order to judge radiation a number of things must be taken into account, such as:

1.1. Radiation Dose

When a situation occurs with radioactive pollution, it is important to get accurate information about the radiation doses that are involved. It would be a waste of resources to immediately implement countermeasures if the doses involved are smaller than the variations in natural background radiation.

To date no general agreements have been reached with regard to the dose levels where actions should be taken. For example, in the case of radon, the recommendations from WHO (World Health Organization) are that 800 Bq/m^3 should be considered as an action level. The equivalent dose involved would be approximately 20 mSv per year.

1.2. Type of radiation

In order to perform dose calculations and estimate health risks, it is important to have information on the radiation source (e.g., the isotopes involved). As pointed out in previous chapters, there is a clear distinction between γ-emitting isotopes and those which emit α- and β-particles.

Choose the proper meaning of the word in *bold.*

1. In order ***to perform*** dose calculations and estimate health risks, it is important to have information on the radiation source.

1) carry out, accomplish, or fulfil (an action, task, or function)

2) work, function, or do something well or to a specified standard

3) present (a form of entertainment) to an audience

4) entertain an audience, typically by acting, singing, or dancing on stage

1.3. The amount of pollution

The amount of radioactive material released to the environment should be given in Bq (or in Ci) and not in volume or weight since a large release in weight may contain small amounts of radioactivity and vice versa.

In the example of the Chernobyl accident a large fallout of Cs-137 resulted, both to areas around the reactor as well as far away. In Scandinavia, areas were found with fallout of 100 kBq/m^2. However, the total release of Cs-137 was in fact only a few kilograms. Here, a small amount of material produced an easily measurable amount of radioactivity at a great distance from the accident.

Choose the proper meaning of the word in *bold.*

2. Here, a small amount of material produced an ***easily*** measurable amount of radioactivity at a great distance from the accident.

1) without difficulty or effort
2) more quickly or frequently than is usual
3) without doubt
4) very probably

1. Choose the correct word and fill in the blanks. Change the form if it is necessary.

benefit/beneficial

1. When a medicine's _____ outweigh its known risks, health care professionals consider it safe enough to approve.
2. X-rays and gamma rays are employed in a number of _____ applications, including medicine.

implement/implementation

1. The decision making framework to optimise _____ of forest countermeasures in the long term after the ChNPP accident is described in the article.

2. The need to _____ countermeasures for the protection of the population requires that decision makers balance the large economic costs that those actions could involve.

produce/production/productivity

1. Every nation that possesses a nuclear power plant _____ plutonium, which can be used to build atomic bombs.

2. The primary military use of nuclear reactors is the _____ of material for nuclear weapons.
3. Workers have boosted _____ by 30 per cent.
4. To _____ a sustained chain reaction rather than a nuclear explosion, a reactor must not pack its fissionable atoms too closely together.

scatter/scattering

1. The blue color of the sky is caused by _____ the of sunlight off the molecules of the atmosphere.

2. It was observed that alpha particles from radioactive decays occasionally _____ at angles greater than 90°.

local/locality/localization

1. Migration can regulate the _____ density of animals**.**
2. All measures were taken to _____ the spread of radioactivity.
3. The process of economic _____ is the opposite to economic globalization.

accident/accidental/accidently

1. In Spring 1986, the world's worst nuclear power _____ occurred at the Chernobyl Nuclear Power Plant.
2. The damage might have been _____.
3. The gun went off _____.

exist/existence/existence

1. The _____ of radiation was discovered in 1896 by Henri Becquerel.
2. Radiation _____ in three primary types - Alpha, Beta, Gamma.
3. The technique has been _____ for some years.

disperse/dispersion

1. The smoke _____ into the sky.
2. Deposition patterns of radioactive particles depended highly on the _____ parameters, the particle sizes, and the occurrence of rainfall.

1.4. The form and dispersion of the release

It is important to have information on the form of the release; whether it is in the solid state, liquid state, or gaseous state. It is also important to know the dispersion or scatter characteristics in some detail in order to localize so-called "hot" areas. Consider two examples which demonstrate the differences with regard to transport and dispersion of radioactivity:

• ***The Chernobyl accident***

This accident caused a large release of radioactivity that reached a height of several thousand meters and was then transported by the wind systems. The fallout was mainly determined by precipitation in the areas where the radioactive "cloud" passed by. After fallout, the different radioactive isotopes still have possibilities for further dispersion via the water systems and plant uptake. This means that the isotopes reached the food chain and gave a large segment of the population an extra dose.

• ***The submarine Komsomolets***

In 1989, the Russian submarine Komsomolets sank in the North Atlantic to a depth of 1,680 meters. It contained a reactor, fission products, and nuclear war heads. The dispersion of radioactivity from this accident is so far not measurable and extra doses to the public are almost nonexistent. Because plutonium is not dissolved easily in water, even as it is released in the future, its dispersion will be very small.

2. Match the terms and the definitions.

1) benefit	a) the state of matter in which materials are not fluid but retain their boundaries without support, the atoms or molecules occupying fixed positions with respect to each other and unable to move freely;

2) accident	b) an action taken to counteract a danger or threat;
3) countermeasure	c) radioactive particles that are carried into the atmosphere after a nuclear explosion and gradually fall back as dust or in precipitation;
4) fallout	d) an advantage or profit gained from something;
5) equivalent dose	e) an unfortunate incident that happens unexpectedly and unintentionally, typically resulting in damage or injury;
6) uptake	f) an estimate of the biological effect of a dose of ionizing radiation, calculated by multiplying the dose received by a factor depending on the type of radiation. It is measured in sieverts;
7) solid state	g) the taking in or absorption of a substance by a living organism or bodily organ;
8) liquid state	h) the state in which a substance exhibits a characteristic readiness to flow with little or no tendency to disperse and relatively high incompressibility;
9) gaseous state	i) the state of matter distinguished from the solid and liquid states by: relatively low density and viscosity; relatively great expansion and contraction with changes in pressure and temperature; the ability to diffuse readily; and the spontaneous tendency to become distributed uniformly throughout any container;

Choose the proper meaning of the word in *bold.*

3. ***Consider*** two examples which demonstrate the differences with regard to transport and dispersion of radioactivity.

1) think carefully about (something), typically before making a decision
2) think about and be drawn towards (a course of action)
3) regard (someone or something) as having a specified quality
4) take (something) into account when making a judgement
5) look attentively at

4. The fallout was mainly ***determined*** by precipitation in the areas where the radioactive "cloud" passed by.

1) cause (something) to occur in a particular way or to have a particular nature

2) ascertain or establish exactly by research or calculation

3) specify the value, position, or form of (a mathematical or geometrical object) uniquely

4) firmly decide

5) bring or come to an end

5. Because plutonium is not dissolved easily in water, even as it is ***released*** in the future, its dispersion will be very small.

1) allow or enable to escape from confinement; set free

2) allow (something) to move, act, or flow freely

remove restrictions or obligations from (someone or something) so that they become available for other activity

3) remove (part of a machine or appliance) from a fixed position, allowing something else to move or function

4) allow (something) to return to its resting position by ceasing to put pressure on it

5) allow (information) to be generally available

2. Use of Radiation in Society

Human activities include the use of radiation. Some of these activities may involve a high probability for pollution. If the risk is high, the activity should be stopped. Again, the benefits must be compared with the risks.

Most people would agree that radioactive isotopes used in medical diagnoses and research involve minor pollution problems. However, the large radioactive sources used in therapy and in other activities have resulted in some radiation accidents with fatal outcomes. It is, therefore, necessary to train workers and to implement proper safety routines. This is particularly true within the nuclear power industry where the use of uranium involves risks for the release of radioactive isotopes from the mining of the ore to the final disposal of the waste. Under normal operating conditions, only negligible amounts of radioactivity are released from a power reactor. The public has concerns with waste disposal and the relatively low risk of accidents.

Choose the proper meaning of the word in *bold.*

1. Again, the ***benefits*** must be compared with the risks.

1) an advantage or profit gained from something

2) a payment made by the state or an insurance scheme to someone entitled to receive it

3) an event such as a concert or game, intended to raise money for a particular player or charity

2. The public has concerns with ***waste*** disposal and the relatively low risk of accidents.

1) an act or instance of using or expending something carelessly, extravagantly, or to no purpose

2) the gradual loss or diminution of something

3) unwanted or unusable material, substances, or by-products

4) (usu. wastes) a large area of barren, typically uninhabited land

5) damage to an estate caused by an act or by neglect, especially by a life tenant

3. Radioactivity in the Ocean

Over the years there have been releases of man-made radioactive isotopes into the oceans. This is mainly due to fallout from the nuclear tests performed in the atmosphere and releases from the reprocessing plants in Sellafield, England and La Hague in France. There have also been some releases of low and medium level radioactive waste from research reactors and nuclear powered ships. Studies have been carried out in order to map the pollution and to measure the activity in sea water, in marine organisms and in sediments.

It is important to realize that the oceans contain natural radioactive isotopes such as K-40, U-238 and Ra-226. The radioactivity in sea water has an average concentration of 12.5 Bq per liter. K-40 is responsible for 96% of this activity. The man-made pollution from nuclear tests and other releases has, on average, resulted in an increase of 1 Bq per liter.

By model calculations and measurements, it is possible to see how man-made releases follow the ocean currents. The release of Cs-137 from the reprocessing plants in Sellafield in England can be observed in the

West-Spitzbergen current after 4 to 6 years and in the East-Greenland current after 6 to 8 years.

Plutonium is usually bound to sediments and inorganic materials and the dispersion is restricted to a few km from the place of release.

Choose the proper meaning of the word in *bold.*

3. It is important to realize that the oceans ***contain*** natural radioactive isotopes such as K-40, U-238 and Ra-226.

1) have or hold (someone or something) within
2) be made up of (a number of things)
3)(of a number) be divisible by (a factor) without a remainder
4) control or restrain (oneself or a feeling)
5) prevent (a severe problem) from spreading or intensifying

4. K-40 is ***responsible*** for 96% of this activity.

1) having an obligation to do something, or having control over or care for someone, as part of one's job or role
2) (responsible to) having to report to (a superior) and be answerable to them for one's actions
3) being the primary cause of something and so able to be blamed or credited for it
4) morally accountable for one's behavior
5) (of a job or position) involving important duties, independent decision-making, or control over others
6) capable of being trusted

5. By model calculations and measurements, it is possible to see how man-made releases follow the ocean ***currents***.

1) a body of water or air moving in a definite direction
2) a flow of electricity which results from the ordered directional movement of electrically charged particles
3) a quantity representing the rate of flow of electric charge
4) the general tendency or course of events or opinion

4. Plutonium and Chemical Compounds

Throughout this book an attempt has been made to point out that radiation is of significance to our health. The emphasis, so far, has been

placed on detrimental effects, but the positive attributes of radiation and radioactivity have also been discussed. Because of the negative effects, radioactive isotopes have been called poisonous or toxic. The toxicity is related to the types of radiations emitted.

The nuclear power industry is the largest source of radioactive isotopes but plays only a minor role in delivering radiation doses to humans. The medical uses of radiation along with natural background radiation deliver the largest doses.

A number of chemical compounds are dispersed to the environment accidentally or sometimes deliberately. Some of these compounds are very hard to break down. It is, therefore, difficult to rank the toxicity of the different compounds. One of the major problems is the shape of the dose-effect curves at small doses. Environmental problems created by chemical compounds that are *not* radioactive are often similar to those that are radioactive.

Plutonium has sometimes been classified as the most dangerous element in the world. If plutonium is concentrated into one lump, large enough to become critical, it represents a serious threat. The fact is that, when plutonium is thinly dispersed around the globe, it is not dangerous.

Pu-239 emits α-particles. This means that plutonium does not represent any radiation problem when it is outside the body. The range of α-particles in air is only a few cm. In tissue the range is only a few cells but the ionization density is high, a characteristic of high-LET radiation. Plutonium can enter the body via two routes:

- ***Consumption of food.***

The plutonium received in food will mainly be excreted from the body. The uptake from the intestine into the blood stream is small. Consequently, the plutonium in food is of minor importance.

- ***Inhalation.***

Inhalation of air containing plutonium can lead to plutonium in the lungs and the bronchial tubes. How this isotope is distributed in the respiratory tract and the rest of the body is a function of the size of the particulates and their chemical state. Some of the plutonium will remain in the respiratory tract with a short half-life, some with a long half-life. The more water-soluble the plutonium compound, the more of the isotope that will dissolve in lung fluids and be taken up by the circulating blood. Of that which is taken up by the blood, 45% will be deposited in bone with a biological half-life of 100 years and 45% in the liver where it will have a

half-life of 40 years. A very small percentage is taken up by the gonads where it will remain indefinitely.

The conclusion is that it is inhaled plutonium that delivers damage to the body. The most important long-term effect is the risk of cancer (cancer of the lungs, liver and bone). Experiments have been carried out with dogs, rats and rabbits that have breathed air containing plutonium. The doses involved were very large and resulted in lung cancer.

These small animal experiments gave the very important finding that the latent period depends on the dose. The smaller is the dose, the longer the latent period. If (from these experiments) the *dose-latent period curve* is extrapolated down to a dose region that may occur in a human population exposed to a plutonium accident, the latent period would be significantly longer than the life expectancy of a human.

Choose the proper meaning of the word in *bold.*

1. The emphasis, so far, has been placed on detrimental effects, but the positive ***attributes*** of radiation and radioactivity have also been discussed.

1) a quality or feature regarded as a characteristic or inherent part of someone or something

2) a material object recognized as symbolic of a person

3) a piece of information which determines the properties of a field or tag in a database

4) an attributive adjective or noun

5) a real property which a statistical analysis is attempting to describe

2. If plutonium is concentrated into one lump, large enough to become ***critical***, it represents a serious threat.

1) expressing adverse or disapproving comments or judgements

2) involving the objective analysis and evaluation of an issue in order to form a judgement

3) (of a situation or problem) having the potential to become disastrous; at a point of crisis

4) having a decisive or crucial importance in the success or failure of something

5) relating to or denoting a point of transition from one state to another

3. This ***means*** that plutonium does not represent any radiation problem when it is outside the body.

1) intend to convey or refer to (a particular thing); signify

2) (of a word) have (something) as its signification in the same language or its equivalent in another language

3) genuinely intend to express (something)

4) be of a specified degree of importance to (someone)
5) intend (something) to occur or be the case
6) have as a consequence or result
7) necessarily or usually entail or involve

4.1. Plutonium and the environment

In the Chernobyl accident there was a release of plutonium with fallout that was concentrated in a region within 30 km of the reactor. Under weather conditions with strong winds, this plutonium dust could be picked up into the air and consequently, present a radiation risk.

Another source for plutonium pollution comes from the many nuclear tests performed in the atmosphere in the 1960s. A certain fraction of the plutonium was not fissioned and resulted in fallout that is assumed to be about 6 tons altogether. If we assume that this plutonium is distributed evenly around the world, over land and sea, this amount of plutonium represents a pollution of approximately 26 Bq/m^2. Since most of the atmospheric tests were performed on the northern hemisphere, the plutonium pollution in that hemisphere may be up to 50 Bq/m^2.

With regard to plutonium, the following can be concluded:

1. Plutonium dispersed into the environment represents a relatively small or nonexistent health problem.
2. Plutonium material *gathered in a lump* that can be made critical is extremely dangerous.
3. Plutonium used in reactors can be an important energy resource that does not contribute greenhouse gases to the environment.

5. Remedial Action

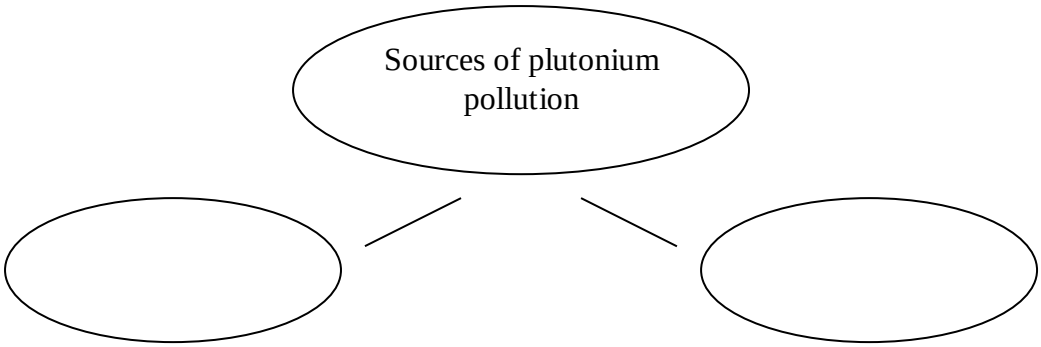
In some countries, resources and monies are available for environmental actions. It is important to judge the different proposals for action carefully in order to use resources in the best way. A cost-benefit analysis should always be made.

In the case of radiation, large amounts of money have been spent to reduce the radioactivity in meat. It is known that animals feeding on grass or lichen in polluted areas will take up this activity. For example, Cs-137 was taken up by sheep and reindeer after the Chernobyl accident. The radioactivity reached (in some parts of Scandinavia) several thousand becquerel per kilogram (for the reindeer it was measured up to 100,000 Bq/kg).

Since the biological half-life for Cs-137 in sheep is of the order of 3 weeks, it is possible to feed the animals for a few weeks on nonradioactive food before slaughtering. Considerable amounts of money have been spent in these feeding actions. The radioactivity in the meat was reduced and a threshold limit of 600 Bq/kg was set for selling the meat.

A critical question was not addressed. What is the cost-benefit of this remedial action? The authorities thought the benefits justified the cost, but from a radiobiology point of view, this was a waste of money. The extra radiation doses involved were already very small, even without any remedial action. The only argument that favors this remedial action is a psychological one. People were given the impression that authorities took action in behalf of their safety.

1. Complete the scheme:



2. Guess what it is:

- a substance in an atmosphere that absorbs and emits radiation within the thermal infrared range;
- emission of a particular substance into the air, water, soil, etc.;
- fine powder made from a particular substance;
- the action or process of making land, water, air, etc. dirty and not safe or suitable to use;
- a change made to a nonconforming product or service to address the deficiency, it can also refer to restoration of a landscape from industrial activity;
- a systematic process for calculating and comparing advantages and prices of a project, decision or government policy.

(*remedial action, plutonium pollution, release of plutonium, cost-benefit analysis, plutonium dust, greenhouse gas*)

3. Choose the proper meaning of the word in ***bold.***

4. It is known that animals feeding on grass or lichen in polluted areas will ***take up*** this activity.

1) If you take up an activity or a subject, you become interested in it and spend time doing it, either as a hobby or as a career.
2) If you take up a question, problem, or cause, you act on it or discuss how you are going to act on it.
3) If you take up a job, you begin to work at it.
4) If you take up an offer or a challenge, you accept it.
5) If something takes up a particular amount of time, space, or effort, it uses that amount.
6) If you take up a particular position, you get into a particular place in relation to something else.
7) If you take up something such as a task or a story, you begin doing it after it has been interrupted or after someone else has begun it.

5. The only ***argument*** that favors this remedial action is a psychological one.

1) an exchange of diverging or opposite views, typically a heated or angry one
2) a reason or set of reasons given in support of an idea, action or theory
3) an independent variable associated with a function or proposition and determining its value.
4) another term for amplitude

4. Render the following:

Основною одиницею в радіобіології і радіоекології є доза опромінення - міра енергії іонізуючого випромінювання, яка передана речовині, або міра біологічних ефектів іонізуючого випромінювання в тілі людини, його органах і тканинах.

Опромінення - пе вплив на людину чи будь-який об'єкт іонізуючого випромінювання.

Зовнішнє опромінення - опромінення тіла людини чи будь-якого живого об'єкту джерелами іонізуючих випромінювань, які знаходяться поза ним.

Внутрішнє опромінення - опромінення тіла людини чи будь-якого живого об'єкту, окремих органів та тканин від джерел іонізуючих випромінювань, що знаходяться в самому об'єкті.

5. Match the following words to make the word-combinations from the text.

Long-term	doses
Environmental	waste

Medical	organisms
Radioactive	problems
Serious	use
Marine	materials
Inorganic	threat
Radiation	effect

6. Form as many word-combinations as you can.

7. Find the synonyms to the following, using the adjectives from ex.1 :

Emission
Curative
Lasting
Dangerous
Not natural
Aquatic
Severe
Ecological

8. Describe the radioactivity in the ocean using the words from ex. 3.

Control points to Charter 5

1) What parameters should be taken into account to judge radiation? Speak of them.
2) Nuclear accidents.
3) Human activities and the use of radiation.
4) Natural isotopes and man-made releases in the ocean.
5) Plutonium compounds (plutonium in food; inhalation).
6) Plutonium in the environment.
7) Remedial action.

Science vocabulary

1. **countermeasure** протидія
2. **routine** заведений порядок, певний режим

3. **detrimental** шкідливий, збитковий
4. **deliberately** навмисне, свідомо
5. **extrapolate** екстраполювати
6. **hemisphere** півкуля
7. **dispersion** розкидання, розсіювання
8. **lichen** лишай, лишайник
9. **reindeer** північний олень
10. **slaughtering** забій (худоби)
11. **latent period** інкубаційний період
12. **in behalf of** для (заради) когось

6. Cellular Response to Radiation

1. Fate of Irradiated Cells. *1.1. Division Delay. 1.2. Interphase Death. 1.3. Reproductive Failure.* **2. Survival Curves for Mammalian Cells. 3. Descriptions of "Shouldered" Survival Curves. 4. Survival Curves and Repair.** *4.1. Sublethal Damage (SLD).4.2. Potentially Lethal Damage (PLD).*

As early as 11 years after the discovery of radiation, radiation injuries were reported in occupationally exposed persons. One of the first reported cases of radiation damage involved a physician who had lost his hair because he had allowed another physician to repeatedly use x-rays to "see" inside his skull! Reports of radiation injuries led to observation and investigation of the biologic effects of radiation. By studying responses such as skin erythema and hair loss, scientists proposed basic postulates concerning the responses of different cell populations to radiation. It was not until the 1920s, however, that techniques were developed to study individual cells and their response to radiation. The ingenuity and imagination of these early investigators in developing these techniques is striking; many techniques used today are based on these early investigations.

There are many ways to study the responses of cells to radiation, both in vivo (in the living organism) and in vitro (in glassware). Tissue culture (growing of animal and human cells in a bottle or tube by providing nutrients) is an extremely useful in vitro tool for studying the response of single cell types to radiation because vasculature and other physiologic factors present in the living organism do not contribute to the response.

Studies may be performed on asynchronous populations of cells; that is, the population being studied contains cells in all four phases of the cell cycle (G_1, S, G_2, and M). Other studies are performed on synchronous populations, necessitating techniques that place all cells in a given phase of the cell cycle at a given time. Dividing populations of cells in the body are asynchronous; therefore, the first method more nearly simulates the in vivo situation. The second method permits observation of the response of cells in each phase of the cell cycle.

One of the classic studies in radiation biology involved the construction of the first survival curve for mammalian cells by Puck and Marcus. These investigators grew HeLa cells (derived from human

carcinoma of the cervix) in tissue culture and kept them alive for many generations. In fact, the first culture was started in 1956, and today it is possible to purchase HeLa cells from biologic supply companies. Puck and Marcus exposed the cells to various doses of radiation and observed the ability of the cells to reproduce. Other investigators (Withers; McCulloch and Till) have developed techniques to construct cell survival curves using in vivo systems, such as the skin and hemopoietic systems.

Because the response of the individual cell cannot be observed in all systems in vivo, this chapter will deal with responses that have been observed in vitro and in appropriate in vivo systems.

Choose the proper meaning of the word in *bold.*

1. By studying ***responses*** such as skin erythema and hair loss, scientists proposed basic postulates concerning the responses of different cell populations to radiation.
   1) a verbal or written answer
   2) an answer to a question in a test, questionnaire, etc.
   3) a reaction to something
   4) an excitation of a nerve impulse caused by a change or event
   5) the way in which a mechanical or electrical device responds to a stimulus or stimuli

1. Fate of irradiated cells

One of three things can happen to a cell after irradiation:

1. It can be delayed from going through division; appropriately, the term used to define this response is *division delay*.
2. It can die before it divides, during interphase. This response is also appropriately named *interphase death*.
3. It can die when attempting mitosis; this response is termed *reproductive failure*.

Division delay occurs in both nonlethally and lethally damaged cells. Interphase death and reproductive failure, which, by definition, occur only in lethally damaged cells, represent two fundamentally different modes of cell death.

1.1. Division Delay

This cellular response to radiation involves mitosis. In dividing asynchronous populations of cells, a certain proportion of cells will be in mitosis at any one time. The ratio of the number of cells in mitosis at any one time to the total number of cells in the population is termed the *mitotic index.* If this ratio is plotted on graph paper, with mitotic index plotted on the *y* axis and time plotted on the *x* axis, the mitotic index remains relatively constant — as some cells are completing mitosis, others are entering prophase, maintaining the mitotic index at a status quo.

Irradiation of the population disturbs this ratio of mitotic to non-mitotic cells (Fig 6-1). Cells in mitosis at the time of irradiation complete division, but those about to enter division are delayed in G_2. The mitotic index, therefore, decreases for a period of time as some cells are stopped from proceeding through mitosis at their appointed time. If the dose is low enough, these cells recover from this delay and proceed through mitosis — resulting in an increased number of cells in mitosis, appropriately termed *mitotic overshoot.* During this time, cells entering mitosis consist of two classes: those normally progressing through mitosis and that were not delayed by irradiation and those that were delayed by irradiation. This cellular response to radiation is termed division or *mitotic* delay.

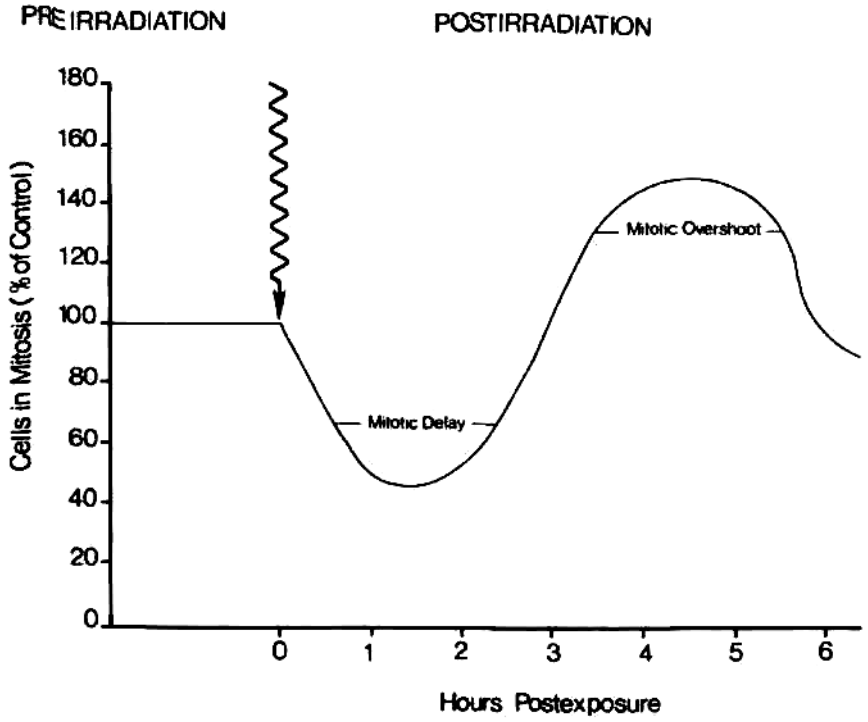


FIG 6-1.

Effects of radiation on an asynchronous, dividing population of cells. Prior to irradiation, the mitotic index remains at a constant value; radiation (wavy arrow) disturbs this constant ratio of cells, effecting a decrease in the number of cells in mitosis (mitotic delay), which may be overcome

(depending on dose) to produce an increase in the number of cells in mitosis at any time (mitotic overshoot).

Canti and Spear observed division delay in chick fibroblasts in tissue culture irradiated with varying doses of γ-rays from a radium source (Fig 6-2). Low doses (0.5 Gy) produced a negligible effect on mitotic index; as dose increased (0.83 and 3 Gy), the response became more pronounced, i.e., both the length and magnitude of the delay were increased. The mitotic overshoot increased in magnitude with these effects, the length and magnitude of the overshoot reflecting the delay.

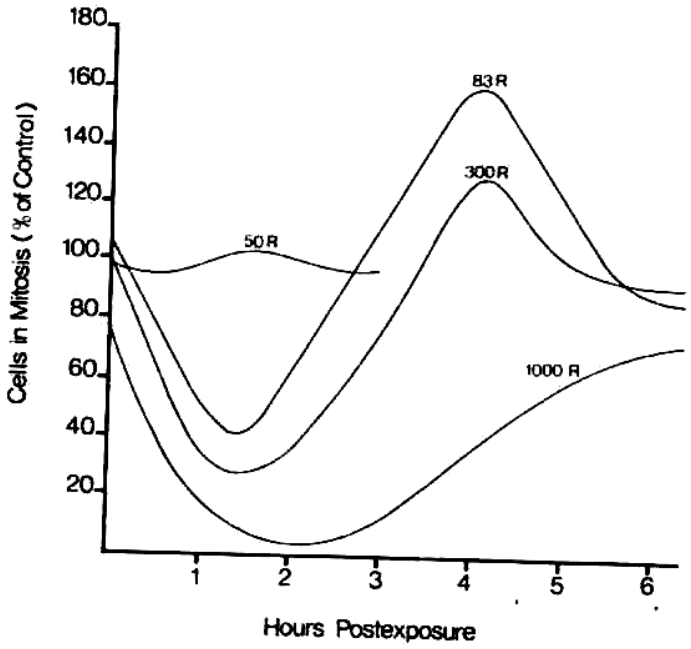


FIG 6-2.

Experimental findings by Canti and Spear illustrating the dose dependence of mitotic delay. Doses in R are equivalent to 0.5 Gy, 0.83 Gy, 3 Gy and 10 Gy.

The overshoot was followed by a return of the mitotic index to its pre-irradiated (100%) value after exposure to low doses (0.5 and 0.83 Gy). However, after higher doses, the mitotic index fell below the pre-irradiated value and remained there. At these doses a third mechanism of damage was operational: the cells divided but died after division. This response, termed *reproductive failure*, will be discussed in a later section.

A more dramatic response was observed following a dose of 10 Gy.

Not only were the length and magnitude of delay greatly increased, but no mitotic overshoot occurred, indicating the cells apparently were not able to overcome the block imposed by the radiation, and therefore died before division *(interphase death).*

Division delay can be induced in cells by doses as low as 0.1 Gy; 0.5 Gy to human kidney cells in tissue culture results in division delay. An opportunity to observe division delay in vivo occurred when five people were overexposed to radiation in a reactor accident (Y-12 accident). Dose estimates to these individuals ranged from 0.5 to 2 Gy. Observation of cells in the bone marrow of these individuals showed a progressive decrease in mitotic index, approaching zero on the 4th day after irradiation.

The underlying cause of mitotic delay is unknown. Some theories proposed to explain this phenomenon are (1) a chemical involved in division is altered by irradiation; (2) proteins necessary for mitosis are not synthesized; and (3) DNA synthesis does not progress at the same rate following irradiation.

In summary, division delay is a dose-dependent phenomenon; the decrease in mitotic index and the length of the delay are a function of dose. At low doses, the duration of delay and decrease in mitotic index are much less than at higher doses. The mitotic overshoot reflects the ability of the cells to overcome the radiation-induced block and proceed through mitosis along with unaffected cells, indicating that the process is reversible. Division delay occurs only at specific points in the cell cycle, in G_2 and at the beginning of DNA synthesis. Essentially, radiation acts as a synchronizing agent by selectively affecting cells in these two stages of the cell cycle, delaying their progression through mitosis.

Choose the proper meaning of the word in *bold.*

2. If this ratio is plotted on graph paper, with mitotic index plotted on the *y* axis and time plotted on the *x* axis, the mitotic index remains relatively constant — as some cells are completing mitosis, others are entering prophase, ***maintaining*** the mitotic index at a status quo.

1) cause or enable (a condition or situation) to continue; keep (something) at the same level or rate

2) provide with necessities for life or existence

3) keep (a military unit) supplied with equipment and other requirements

4) give one's support to

5) state something strongly to be the case; assert

1.2. Interphase Death

A second response of the cell to radiation is death before it enters mitosis. This response is called interphase *death;* synonymous terms are nonmitotic or nondivision *death.* Interphase death can occur in cells that

do not divide and are long-lived (e.g., adult nerve), and in rapidly dividing cells (e.g., blood cell precursors in the bone marrow), and has been observed after irradiation of oocytes, erythroblasts, and cancer cells. Recent studies have shown that interphase death occurs in nondividing cells in tissues that are of importance in radiotherapy. The prototypical cell that has long been known to die after low doses of irradiation via this mechanism is the small mature lymphocyte, a nondividing cell. More recently, interphase death has been identified as the mechanism whereby cells die in the serous acini of parotid glands (salivary glands) and lachrymal glands (the glands of the eye that produce tears).

The radiation dose for interphase death is dependent on the cell: lymphocytes exhibit interphase death at doses less than 0.50 Gy, mouse spermatogonia at 0.25 Gy, and parotid cells after a single dose of about 9.0 Gy. Although the relationship between interphase death, cell type, and dose is poorly understood, in general, rapidly dividing, undifferentiated (radiosensitive) cells exhibit interphase death at lower doses than nondividing, differentiated (radioresistant) cells. The one exception to this generalization is the lymphocyte, (usually a nondividing cell), which undergoes interphase death at very low doses.

Morphologically, interphase death is not a degenerative process like cellular necrosis in which the whole cell disintegrates, although these two modes of cell destruction share some common nuclear changes, such as fragmentation. In interphase death the cell condenses and breaks up into pieces, but the cytoplasmic organelles remain intact. These pieces are then phagocytosed by other cells.

Interphase death is not a unique effect of irradiation on cells, but is a general phenomenon that occurs spontaneously in healthy as well as diseased tissues. Termed apoptosis, which comes from Greek and means "falling off," as leaves from a tree, this process appears to be programmed for self-destruction. A familiar example of apoptosis is the loss of the tail by a tadpole during metamorphosis.

The mechanism of interphase death and apoptosis is obscure. It is unrelated to mitosis, as it is not an unsuccessful attempt by the cell to divide. Recently, it has been suggested that this mode of cell death may be due to changes in the plasma membrane, with accompanying imbalances in extracellular and intracellular salts, e.g., Na, K, and Ca.

Choose the proper meaning of the word in *bold*

3. A second response of the cell to radiation is death before it ***enters*** mitosis.

1) come or go into (a place)
2) come or be introduced into
3) penetrate (something) the bullet entered his stomach
4) begin to be involved in
5) become a member of or start working in (an institution or profession)
6) start or reach (a stage or period of time) in an activity or situation

4. The prototypical cell that has long been known to die after low doses of irradiation via this mechanism is the small ***mature*** lymphocyte, a nondividing cell.

1) fully developed physically; full-grown
2) (of thought or planning) careful and thorough
3) used euphemistically to describe someone middle-aged or old
4) having reached the most advanced stage in a process

5. These two modes of cell destruction ***share*** some common nuclear changes, such as fragmentation.

1) have a portion of (something) with another or others
2) give a portion of (something) to another or others
3) use, occupy, or enjoy (something) jointly with another or others
4) possess (a view or quality) in common with others
5) tell someone about (something, especially something personal)

1.3. Reproductive Failure

A third type of cellular response to radiation is a decrease in the percentage of cells surviving after irradiation that have retained their reproductive integrity, i.e., are capable of reproducing. This is termed reproductive *failure* and is defined as the inability of the cell to undergo repeated divisions after irradiation. By this definition, all cells that cannot *repeatedly* divide and produce a large number of progeny are considered nonsurvivors or "dead," even though they may still be technically alive (metabolizing or capable of a limited number of divisions). This concept can be understood in terms of the target theory (there are critical sites in the cell that, if damaged, have a higher probability of resulting in lethality than damage in other sites). The ability of a cell to reproduce is directly related to the integrity of the chromosomes. If it is assumed that chromosomes (or DNA) are the critical sites (targets) in the cell and that only an ionizing event occurring in the target is responsible for cell death, then damage to the chromosomes may result in death of the cell. However,

much of this damage can be, and usually is, repaired. If it is not repaired, the cell may still retain some ability to divide, doing so one or more times following irradiation. These cellular responses to radiation are summarized in Table 6-1.

TABLE 6-1.

Types of Cell Damage

Type	Changes	Dose	Mechanism
Interphase death	Normal nuclear architecture disappears	High in most cases, except for lymphocytes	May be biochemical
Division delay	Lowered mitotic index; delayed mitosis	Exhibited by diving cells; dose-dependent, degree of response varies with dose	Unknown: chance in a chemical involved in division; proteins are not synthesized; DNA synthesis is affected
Reproductive failure	Loss of reproductive integrity; cells cannot undergo repeated division	Exhibited by diving cells; dose-dependent, high doses affect greater number	Damage to genomic DNA

Puck and Marcus experimentally quantified reproductive failure by exposing human cells (HeLa) to various doses of radiation and counting the number of colonies formed by these irradiated cells. They graphically expressed the ability of cells to reproduce after different doses of radiation in the form of a semilogarithmic curve, where dose is plotted on a linear scale (*x* axis) and surviving fraction on a logarithmic scale (*y* axis). This curve, illustrated in Figure 6-3 is termed a *cell survival* curve.

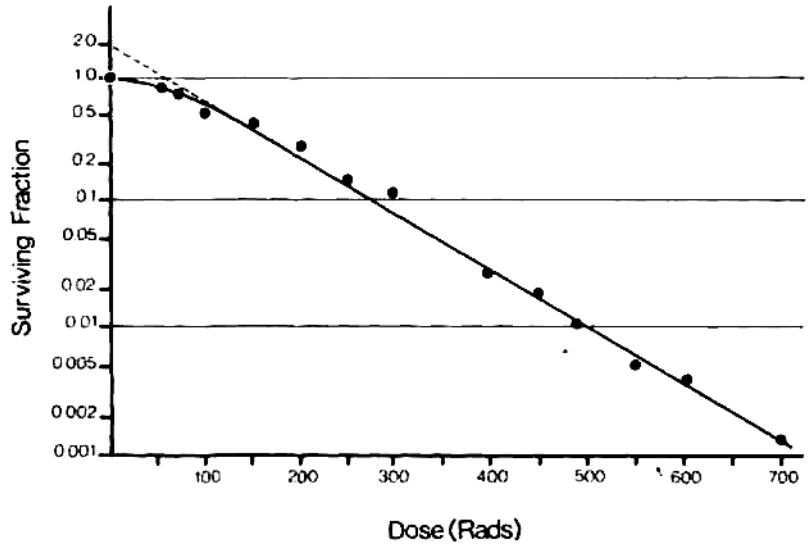


FIG 6-3.

Illustration of the survival curve determined by Puck and Marcus. Below 150 rad (1.5 Gy) the curve exhibits a shoulder region, becoming exponential at higher doses.

2. Survival curves for mammalian cells

A cell survival curve describes the relationship between radiation dose and proportion of cells that survive. Critical to an understanding of this relationship between dose and cell kill is the appreciation of the randomness of the deposition of energy by radiation. Some cells will sustain more than one "hit," some will be hit only once, and some will not be hit at all. Thus, if each cell in a population requires one hit to be killed, for a given increment in dose, the proportion of cells killed will remain the same but the absolute number of cells killed will vary, as shown in Table 6-2. This table illustrates the exponential function of the response of cells exposed to equal dose increments. Note the same dose (5.0 Gy) always kills the same proportion (50%) of cells, but the absolute number of cells killed varies. This type of data indicates a logarithmic relationship between dose and surviving fraction. These data would form a straight line on a semi-logarithmic plot (Fig 6-4) and indicate that cell kill is an exponential function of dose. Two doses of 5.0 Gy actually inactivate only 75%, not 100%, of the original population. If two doses of 5.0 Gy did inactivate 100% of the population, the response would be linear, not exponential.

TABLE 6-2.

Typical Data Relating Dose and Surviving Fraction

Original Cell	Dose Delivered (Gy)	Fraction (%) Cells	Number of Cells

Number		Killed	Killed
100,000	5	50	50,000
50,000	5	50	25,000
25,000	5	50	12,500
12,500	5	50	6,250
6,250	5	50	3,125
This is the same principle that describes the decay of a radioactive isotope.			

Few mammalian cells irradiated with sparsely ionizing x- or γ-rays exhibit this survival curve shape. Rather, the survival curve for mammalian cells exposed to different doses of x- or γ-rays exhibits a broad initial shoulder; followed by a steep, straight portion (the survival curve in Figure 6-3 is typical for mammalian cells). In the shoulder region, equal increases in dose do not cause a corresponding equal decrease in surviving fraction. In other words, in the example in Figure 6-3, doses less than 2 Gy are inefficient in producing cell death. This region of the cell survival curve implies that, in mammalian cells, damage must be accumulated before the cell dies. If damage did not have to be accumulated, each dose of radiation, starting with the lowest, would be as efficient as the next in causing cell death. This curve then would be a straight line from its origin on the *y* axis at 0 dose and 100% surviving fraction (see Fig 6-4). After higher doses (>2 Gy in Fig 6-3), the curve does form a straight line on a logarithmic plot; cell kill is now an exponential function of dose.

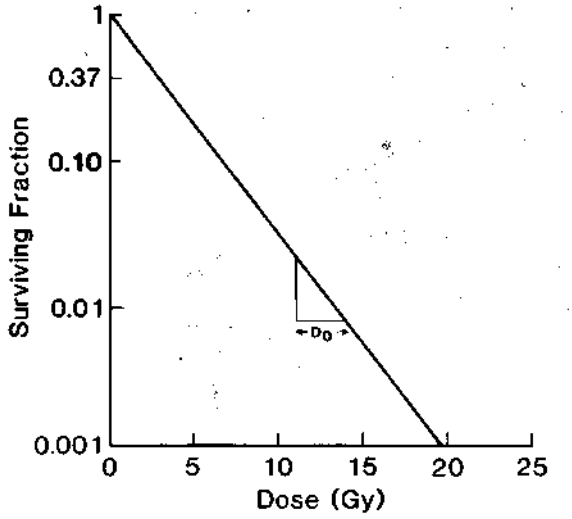


FIG 6-4.

Survival curve for bacteria (Escherichia coli), showing that in this system survival is a simple exponential function of dose.

In recent years the shoulder region of the survival curve has been examined more closely and it is now known that survival also is exponential over the initial "low-dose" region of the shoulder, after which it bends to form the shoulder. Both the initial and final ("high dose") regions of the survival curve are exponential; however, the two exponential regions of the survival curve have different slopes, i.e., the initial slope is generally more shallow than the final.

Two different mechanisms of cell killing have been suggested to describe the shape of this curve:

1. Lethal single-hit killing.
2. Interaction of a sufficient number of sublethal lesions to cause death.

The model most often used to describe the effects of these two types of lesions on cell killing is the target theory. The target theory states that there are *n* targets in a cell, all of which must be "hit" to kill the cell. If one target is not hit, the cell will survive and repair the damage. As the dose increases, however, more and more sublethal damage is accumulated and the cell dies. The final exponential shape of the survival curve is obtained when all cells have sustained *n* -1 hits and the population now has only one target in each cell that must be hit to be killed. The initial slope in the shoulder region is more difficult to explain. After such low doses, it is unlikely that sufficient sublethal damage will be accumulated to kill the cell. Thus, cell killing must be by a single-hit event.

1. Choose the correct word and fill in the blanks. Change the form if it is necessary.

observe/observation /observable

3. Physicians can _____ late effects of radiation exposure.
4. The examination showed no _____ changes in the structure of the material.
5. She was brought into hospital for further _____.

propose/proposition

3. The general purpose of the present _____ is to study the radiation hazards during the Moon exploration.
4. Scientists _____ a new method for this phenomenon investigation.

investigate/investigation/investigator

5. His _____ started a new period in the development of radiation protection.
6. The type of analysis will be performed according to the information needs of the _____.
7. Future studies will _____ whether long-term use of the drugs could prevent cancer.

use/useful/usefulness

3. The device is effective, _____ and perspective for prophylactic usage both under production conditions and in private life.
4. Only about one-third of patients actually _____ these scripts.
5. More well-done trials will increase the information about the _____ of supplements in cancer prevention.

divide/division/

4. Before a cell _____, all the essential components, for example the genome, are duplicated.
5. There are two types of cell _____: mitosis and meiosis.
6. When cells _____ abnormally they often develop into tissue masses called tumors.

2. Match the terms and the definitions.

1) reproductive failure	a) the process in which a cell divides into two cells, each containing identical genetic material, as that of the original cell;
2) mitotic index	b) the ratio of the number of cells in a population undergoing mitosis to the number of cells not undergoing mitosis;
3) cell division	c) the type of cell death induced by severe injury occuring prior to cell division;
4) response	d) the inability of the cell to undergo repeated divisions after irradiation; it can be defined as either sterility or infertility;
5) mitotic overshoot	e) the increase in the number of cells undergoing mitosis;
6) cell survival curve	f) describes the relationship between radiation dose and proportion of cells that survive;

7) interphase cell death	g) visible or detectable changes seen after a given dose of radiation within a given time period.

3. Descriptions of "shouldered" survival curves

The cell survival curve can be defined by three graphic parameters: *n* (extrapolation number) and D_q (quasi-threshold dose), both of which refer to the shoulder region, and D_0 dose, which refers to the terminal slope. A fourth term $1D_0$ is used to describe the initial exponential slope.

The extrapolation number *n* is determined by extrapolating the linear portion of the curve back to its intersection with the *y* axis (Fig 6-5). This term was originally referred to as the target number and was assumed to represent the number of targets that must be hit in each cell to cause cell death. However, objections arose over the use of the term "target," and it is now referred to as the extrapolation number. The *n* for mammalian cells ranges from two to ten.

The D_q defines the width of the shoulder region of the curve, and is the dose at which the extrapolation of the terminal portion of the curve intercepts the dose axis at 100% survival (i.e., surviving fraction of 1.0) (Fig 6-5). The point cannot be made too emphatically that D_q and *n* provide information only on the size of the shoulder and not its shape.

D_0 is determined from the final exponential portion of the curve and is the reciprocal of the slope (1/slope) (Fig 6-5). This expression was derived mathematically from the target theory, and is defined as the dose that inactivates all but 37% of the population. D_0 is an expression of radiosensitivity of a population. Cells with high D_0 doses exhibit a shallow survival curve and are less sensitive (more resistant) than populations with low D_0 doses, which give steep survival curves. D_0 doses for different populations of mammalian cells vary between 1 and 2Gy.

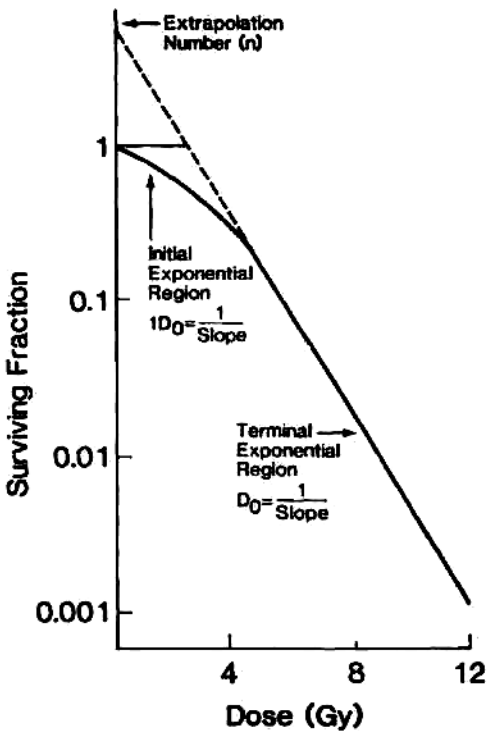


FIG 6-5.

A typical survival curve for mammalian cells exhibiting an initial shoulder followed by a terminal

exponential region. The curve is characterized by an initial shoulder with some slope to it ($1D_0$), the terminal exponential slope (D_0), n (extrapolation number) and D_q (quasi-threshold dose).

The three parameters are related by the expression

$$\text{Log}_e\, n = D_q / D_0$$

or Surviving Fraction (SF) = ne^{-D/D_0}

A second model, the linear quadratic model, has also been proposed to describe the survival curve for mammalian cells, but with only two parameters, α and β. This model assumes that there are two components to cell killing: (1) α, which is proportional to dose (D), and (2) β, which is proportional to dose squared (D^2). Survival is then expressed as

$$\boldsymbol{SF=\alpha D+\beta D^2}$$

One interpretation of the parameters of this model is that α refers to single-hit killing and β to the interaction of lesions. Regardless of its mechanistic interpretation, the linear quadratic model provides a good empirical description of mammalian cell survival curves, particularly in the low-dose region.

The ratio of these two parameters, α/β, which has a unit dose, has been shown to divide normal tissues into two categories based on their responses to dose fractionation. This has obvious importance to clinical radiotherapy.

Survival curves can be obtained from in vitro cultures of cell lines, as well as for certain tissues in vivo — those that contain proliferating cells that form a clone after irradiation. Survival curves can now be obtained for many normal tissues in vivo, e.g., crypt cells of the intestine, stem cells in the bone marrow, and epithelial cells in the skin.

1. In summary, three things happen in a population of cells after irradiation:
2. Some cells will receive no damage to a critical site and will be unaffected.
3. Some cells will accumulate enough damage to be lethal and will die in the next division.

Some cells will accumulate a degree of damage that is not lethal (sublethal) and which, given enough time, can be repaired, thus forming

the shoulder. If more damage is received before the first damage is repaired, the two may interact to become lethal.

1. Combine the words to make word-combinations from the text.

1. Division	a) failure
2. Reproductive	b) death
3. Intrephase	c) delay

2. Insert the appropriate word-combination from Ex. 1.

1. Cell killing, chromosomal aberrations, and … as thermal sensitivity is modified during the cell cycle.
2. … is defined as inability to carry a pregnancy.
3. The radiation-induced disorganization of the cells may be the cause of … .

4. Survival curves and repair

It is well known that after sparsely ionizing radiations (e.g., *x + y)* damage is repaired. This phenomenon has been demonstrated in many systems, including cells in culture, and in normal tissues and malignant tumors in experimental animals. Two types of repair have been defined, based on the type of experiment performed. The first, sublethal damage (SLD) repair, occurs when two doses are separated by time. Sublethal damage normally can be repaired unless another dose of radiation is added, in which case the effect becomes cumulative, resulting in cell death. The second, potentially lethal damage (PLD) repair, occurs when the postirradiation conditions are modified.

It is important to recognize that these are both operational definitions because little is known about either type of damage, where it actually occurs in the cell, and if the two are in any way related. However, they are important concepts to understanding cellular responses to radiation, and further explanation is warranted.

4.1. Sublethal Damage (SLD)

Sublethal damage and its repair were first described in cells grown in culture by Elkind and Sutton-Gilbert in 1960. Their investigations showed that when a given dose of radiation was divided into two equal doses (split dose) separated by various intervals of time, the surviving fraction of cells was larger than if the same total dose were given as a single dose (Fig 6-6).

In addition, survival increased with time between the two doses, up to 2 hours, when survival reached a plateau that was four times higher than survival after this same total dose had been given as a single dose. No further increase in survival was observed after 2 hours in this cell line. The investigators suggested that the increase in repair was due to repair of sublethal damage.

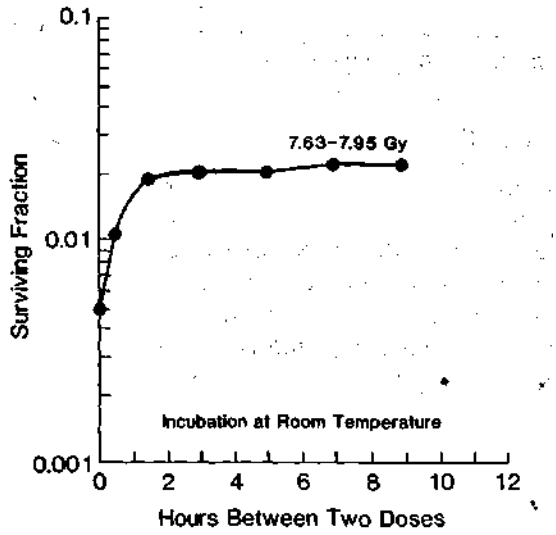


FIG 6-6.

The effect of two doses of radiation separated by various periods of time on surviving fraction in Chinese hamster cells in vitro. The data show that survival is increased if sufficient time is allowed to elapse between two doses of radiation. The increase in survival is due to the repair of sublethal damage.

Sublethal damage and its repair are measured experimentally in split-dose experiments and can be understood by a study of what happens to the survival curves in these experiments. An example of the survival curves from a split-dose experiment is shown in Figure 6-7. The first dose reduces survival to the terminal exponential portion of the curve. If sufficient time elapses between the two doses, the surviving cells respond as if they were never irradiated, i.e., the survival curve for the surviving cells is exactly the same shape and the shoulder has been repeated. This indicates that all damage after the first dose must have been repaired, for if it were not, the second dose survival curve would be different, most likely by having a smaller shoulder or perhaps no shoulder.

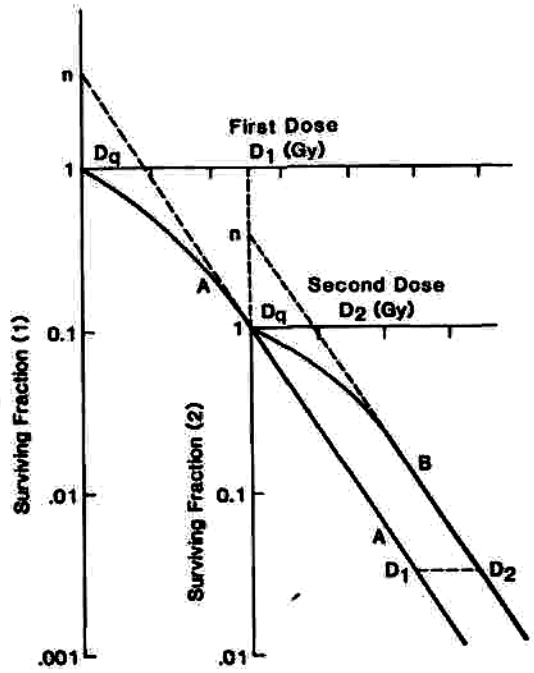


FIG 6-7.

Split-dose survival curves showing the effect of repair of sublethal damage on survival. If sublethal damage is fully repaired, then the slope of the second-dose survival curve (survival curve B, D_2) is the same as that for the single-dose survival curve (survival curve A, D_1). Note that both the D_q and extrapolation number are exactly the same in surviving cells. The first dose has killed a proportion of cells, but surviving cells respond as if they had never been previously irradiated—they have repaired all of their sublethal damage.

It is important to emphasize that all of the above discussion regarding repair of sublethal damage applies only to *x*- or γ-rays. Repair of sublethal damage is practically nonexistent for neutrons.

Sublethal damage and its repair have been measured for almost every cell that can be grown in vitro, and for every normal tissue in vivo for which a quantitative endpoint is available. In general, the amount of sublethal damage repair agrees well with the size of the shoulder on the survival curve. Cells and tissues with a broad shoulder on the plotted curve, such as jejunum, exhibit a large amount of sublethal damage repair. Other cells and tissues, such as bone marrow stem cells, have a narrow shoulder on the curve and exhibit little repair of sublethal damage. In terms of the linear quadratic model, cells with a narrow shoulder on the survival curve have a large α/β ratio, whereas cells and tissues with a large shoulder have a small α/β ratio.

The half-time for repair of sublethal damage has been shown consistently to be about 1 hour for cells in vitro, regardless of cell line.

However, repair half-times for in vivo systems, specifically normal tissues, have been shown to vary from 0.5 hour to 1.5 hours.

The basis and the lesions that cause sublethal damage and its repair are unknown. Since the critical target in the cell for radiation is most likely genomic DNA, it is probable that DNA strand breaks are responsible. However, the exact DNA lesion responsible for sublethal damage is unknown.

Sublethal damage and its repair are very important factors in the sparing effect in normal tissues during fractionated radiotherapy

4.2. Potentially Lethal Damage (PLD)

Even more of an operational term than sublethal damage is potentially lethal damage. This term is quite appropriate, however, since it reflects exactly what is observed. An example may best demonstrate this phenomenon: when cells are placed in suboptimal growth conditions (depleted nutrients) after irradiation, survival is *increased* relative to when these same irradiated cells are incubated in full-growth conditions (nutritionally complete). This damage then has the *potential* to develop, but only if the postirradiation conditions are conducive.

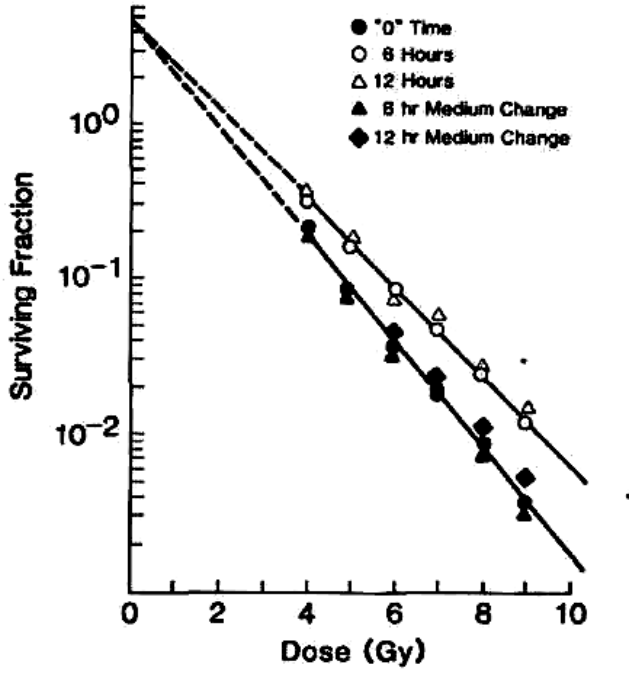


FIG 6-8.

The effect of changing postirradiation conditions on survival of cells in vitro. The upper curve represents cells that were not supplied with fresh medium after radiation. The lower curve

represents cells that were given fresh medium up to 12 hours after radiation. Allowing the cells to remain in the medium in which they were irradiated increases survival, showing that potentially lethal damage can be repaired if the cells are not forced to divide immediately after irradiation.

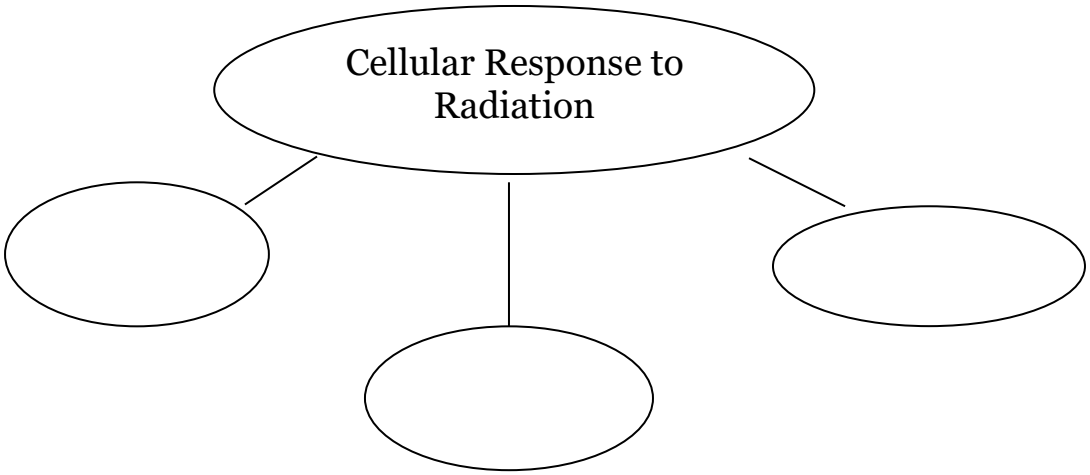
Although this may seem paradoxical (why should a depleted nutritional state increase survival, when intuitively one might expect it to *decrease* survival?), placing the cells in suboptimal growth conditions delays their entry into mitosis. Since, in most cases, cell damage is expressed at division, this time permits repair of DNA damage and survival is increased.

This concept was clearly demonstrated by Little, who irradiated cells in conditions suboptimal for cell division, and then either immediately placed the cells into an environment in which they could divide by subculturing them, or kept them under suboptimal conditions for 6 to 12 hours before subculturing them. Survival was increased in cells that remained in the suboptimal growth conditions, compared with cells that were placed in optimal growth conditions, thus being "forced" to divide (Fig 6-8).

Potentially lethal damage and its repair have been demonstrated for cells in culture and in animal tumors, but only after sparsely ionizing radiations. No repair of PLD has been demonstrated after high-LET radiation (e.g., neutrons).

Clearly, an interesting question is whether PLD and SLD are related. Potentially lethal damage differs from SLD as far as it is demonstrated after a single dose of radiation, whereas repair of sublethal damage can be demonstrated only after two doses. They appear to be quite different, but the possibility cannot be excluded that they share a common mechanism.

1. Complete the scheme:



2. Give the definitions of the following notions:

- Tissue culture is …
- Asynchronous population of cells is ...
- Synchronous population of cells is ...
- HeLa cells are …
- The mitotic index is …
- Mitotic overshoot is …
- Interphase death is …
- Reproductive failure is …
- A cell survival curve is …
- A split dose is …

3. Complete the theories proposed to explain mitotic delay:

(1) a chemical …;
(2) proteins …;
(3) DNA synthesis … .

4. Speak about the contribution to cellular response to radiation studies made by such researchers as Puck and Marcus, Withers; McCulloch and Till, Canti and Spear, Elkind and Sutton-Gilbert, Little.

5. There are a lot of terms in this chapter, containing the word "cell". Can you guess them?

1. It can result in death of individual cells, tissue or organ failure and/or death of the organism. Harmful molecules are continually bombarding the human body, such as free radicals, by-products of energy production. These damage the proteins, fats and DNA that make up cells.

2. It is a terminal failure of a cell to maintain essential life functions.

3. It depicts the relationship between the fraction of cells retaining their reproductive integrity and the absorbed dose.

4. As a function of radiation dose it is graphically represented by plotting the surviving fraction on a logarithmic scale on the ordinate against dose on a linear scale on the abscissa.

5. Putting to death, depriving of life, putting an end to, destroying a vitally essential quality.

6. Cells grown in tissue culture and representing generations of a primary culture.

(*cell death, cell survival, cell line, cell damage, cell kill, a cell survival curve*)

6. Give the opposites of the following words using prefixes *-non, -in, -un:*

Activate, existent, affected, efficient.

7. Explain two types of damage repair: SLD repair and PLD repair.

8. Render the following:

На клітинному рівні, в залежності від дози опромінення та радіочутливості клітини, може відбуватися часова затримка першого пострадіаційного ділення,(яке спостерігається в певному, хоча і досить великому, діапазоні доз (для більшості клітин – в межах 10 Гр), або повне пригнічення мітозу. Така реакція відбувається після дії великих доз, коли клітина продовжує жити достатньо довго, але назавжди втрачає здатність до ділення. Внаслідок цієї незворотної реакції на опромінення часто утворюються патологічно гігантські клітини, які іноді мають декілька наборів хромосом. Це відбувається тому, що редуплікація таких клітин продовжується, а фаза мітозу не наступає. Даний вид порушення мітотичного процесу називають ендомітозом. Процес ендомітозу призводить до того, що в одній і тій самій клітині, яка не пройшла поділ, міститься декілька наборів хромосом. В такому випадку говорять про репродуктивну загибель клітин, або просто про загибель клітин.

Control points to Charter 6

1) Possible changes after cell irradiation.
2) Terms “mitotic overshoot”, “mitotic delay”.
3) Nonmitotic death.
4) Reproductive failure.
5) Survival curve.
6) Shoulder of survival curve.
7) SLD repair.
8) PLD repair.

Science vocabulary

1**. nutrient** поживна речовина; поживний
2. **asynchronous** асинхронний, не синхронний
3. **carcinoma** рак, карцинома
4. **cervix** шийка матки
5. **reproductive failure** репродуктивна нездатність
6. **mitotic index** мітотичний індекс
7. **mitotic overshoot** мітотичний промах
8. **division delay** затримка поділу
9. **interphase death** загибель в інтерфазі, інтерфазна загибель
10**. prophase** профаза
11. **bone marrow** кістковий мозок
12. **salivary gland (parotid gland)** слинна залоза (привушна залоза)
13. **cellular necrosis** некроз клітин
14. **oocyte** ооцит
15. **serous acinus** серозний ацинус
16. **critical site (target)** критична ділянка (мішень)
17. **progeny** потомство
18. **shoulder region** ділянка плеча кривої виживання
19. **lesion** пошкодження
20. **“shouldered” survival curve** крива виживання з «плечем»
21. **threshold dose** порогова доза
22. **proliferating cell** клітина в стадії проліферації, проліферативні клітини
23. **crypt cell** клітина крипти
24. **intestine** кишечник
25**. split dose** фракціонування дози
26. **jejunum** порожня кишка

7. Tissue Radiation Biology

1. Tissues and organs. 2. Cellular "Radiosensitivity". *2.1. Differentiation.* **3. Cell Populations**. **4. Radiation Response of Cells.** *4.1. Vegetative Intermitotic Cells (VIM). 4.2. Differentiating Intermitotic Cells (DIM). 4.3. Multipotential Connective Tissue Cells. 4.4. Reverting Postmitotic Cells (RPM). 4.5. Fixed Postmitotic Cells (FPM).* **5. Tissue Response to Radiation**. *5.1. Tissue Organization. 5.2. Mechanisms of Damage in Normal Tissues.* **6. Measurement of Radiation Damage in Tissues**. *6.1. Assays of Tissue Response. 6.2. Clonogenic Assays. 6.3. In Situ Assays. 6.4. Transplantation Assays. 6.5. Functional Assays. 6.6. Lethality*. **7. Shapes of Survival Curves for Acutely Responding and Late Responding Normal Tissues.**

1. Tissues and organs

Tissues and organs are made up of cells — in some cases just a few cell types, in other cases many cell types. The underlying assumption throughout this chapter is that the visible and detectable changes induced by radiation, whether at the tissue level or the whole-body level, are due to the killing and subsequent depletion of critical "target" cells in that tissue. In some tissues and organs this target cell has been identified and can be quantified; in others it remains elusive and often controversial despite the efforts of many investigators to identify it. Nonetheless, it is assumed that it is the depletion of these target cells that results in the types of damage to be discussed in this chapter.

Keeping this basic premise in mind, the response of an organ or tissue to radiation depends on two factors:

1. The inherent sensitivity of the various cell populations in that tissue or organ.

2. The turnover kinetics of each population in the tissue (Do they divide, and if so, how often?).

Inherent sensitivity as defined by the loss of reproductive capacity for all cells is similar both in vivo and in vitro (see Chapter 6), yet normal tissues differ widely in their responses to radiation. Thus it must be the "when" and "if" individual cells divide that account for the apparent differences in tissue radiation response. Before tissue response to radiation can be discussed it is necessary to understand the term "sensitivity" and the factors that govern both the sensitivity of individual cells to radiation and the expression of damage following irradiation.

2. Cellular “Radiosensitivity”

The role of cell division in the radiation response of tissues and organs was appreciated as early as 1906 by two scientists, Bergonie and Tribondeau. Based on physicians' reports that (1) x-rays appeared to destroy the cells of a malignant neoplasm (tumor) without permanently harming the adjacent healthy tissue, and (2) some tissues were damaged by doses of radiation that did not appear to harm other tissues, Bergonie and Tribondeau deduced that cell division was critical to this "selective" cell killing. They performed experiments on rodent testicles to further define this observed selective effect of radiation. They chose the testes because they contain mature cells (spermatozoa), which perform the primary function of the organ, and also contain immature cells (spermatogonia and spermatocytes), which have no function other than to develop into mature, functional cells. Not only do these different populations of cells in the testes vary in function, but their mitotic activity also varies — the immature spermatogonia divide often, whereas the mature spermatogonia never divide.

After irradiation of the testes, Bergonie and Tribondeau observed that the immature dividing cells were damaged after lower doses than were the mature nondividing cells. Based on these observations of the response of the different cell populations in the testes, they formulated a hypothesis concerning radiation sensitivity for all cells in the body. In general terms, their hypothesis states that ionizing radiation is more effective against cells that are actively dividing, are undifferentiated, and have a long dividing future.

Bergonie and Tribondeau defined cell sensitivity in terms of specific cellular characteristics of the cells studied, mitotic activity and differentiation rather than on the radiation. Bergonie and Tribondeau's criteria for cellular radiation sensitivity can be interpreted as determinants of the inherent susceptibility of a cell to radiation damage.

In 1925 Ancel and Vitemberger modified the hypothesis of Bergonie and Tribondeau by proposing that the inherent susceptibility of any cell to damage by ionizing radiation is the same, but that the time *of appearance* of radiation-induced damage differs among different types of cells. In a series of extensive experiments in mammalian systems, they concluded that the appearance of radiation damage is influenced by two factors: (1) the biologic stress on the cell, and (2) the conditions to which the cell is exposed pre-irradiation and postirradation. On this latter point, Ancel and Vitemberger were well ahead of their time in their thinking, for now, it is

well known that postirradation conditions can and do affect cellular sensitivity by allowing the expression (or repair) of potentially lethal damage (see Chapter 6).

Ancel and Vitemberger postulated that the greatest influence on radiosensitivity is the biologic stress placed on the cell, and that the most important biologic stress on the cell is the necessity for division. In their terms, all cells will be damaged to the same degree by a given dose of radiation (i.e., all cells are similar in their inherent susceptibility), as has been shown, but the damage will be expressed only *if* and when the cell divides. Ancel and Vitemberger were truly clever in their thinking, for they recognized that if all cells had a common target for radiation, then a given dose would deposit the same amount of energy and produce the same amount of damage irrespective of the mitotic status of the cell. However, cells which divided quickly would simply express the damage sooner and appear "sensitive" compared with those that divided more slowly, and would express their damage later and thus appear "resistant."

Thus, in the early twentieth century it was suggested that it was not only cell division and cell turnover that were important in the expression of radiation injury, but also the kinetics of turnover, i.e., whether it occurred rapidly or slowly.

2.1. Differentiation

One term that may need clarification is differentiation. A differentiated cell is one that is specialized functionally and/or morphologically (structurally); it can be considered a mature cell, or end cell, in a population. An undifferentiated cell has few specialized morphologic or functional characteristics; it is an immature cell whose primary function is to divide, thus providing cells to maintain its own population and to replace mature cells lost from the end cell population. Undifferentiated cells can be considered precursor, or stem, cells in a population.

An example of a tissue that contains a series of cells in various stages of differentiation is the testis. The spermatozoon is the mature, nondividing cell that is morphologically and functionally specialized. However, since mature sperm are periodically lost, more cells must replace them. These cells, also present in the testis, are immature type A spermatogonia; their principal function is to divide and supply the cells that will maturate into spermatozoa. The spermatozoan is a differentiated cell; it is the end cell in the population. The spermatogonium is an undifferentiated cell — the stem cell for the mature spermatozoan. The

process by which immature spermatogonia become mature spermatozoa is termed differentiation (Fig 7-1).

Another example of a differentiated cell is the erythrocyte (red blood cell, or RBC). Just as the spermatozoan is the mature end cell in the testis, the RBC is the mature, differentiated cell in the red cell line of the hemopoietic system. The major function of the RBC is to transport oxygen to cells of the body. Not only is this cell specialized in function, but it also is specialized in structure; the RBC differs from other cells in the body in that it does not have a nucleus. Therefore, both morphologically and functionally, RBCs are differentiated cells. The average lifetime of RBCs in the circulating blood is 120 days, necessitating a continual replacement of these cells by newly produced cells. The stem *cell* (see below) for the RBC, the erythroblast, is present in the bone marrow and is an undifferentiated cell that divides and supplies cells which will differentiate to become erythrocytes.

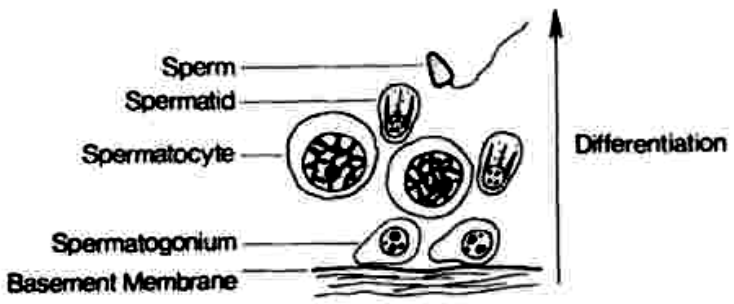


FIG 7-1.

Diagrammatic representation of the testes illustrating differentiation. The cell becomes more differentiated as it progresses from spermatogonium (stem cell) to sperm (end cell).

3. Cell Populations

For our purposes here, cell populations can be divided into three categories:

1. Stem cell population.
2. Transit cell population.
3. Static population.

A *stem cell population* is one whose sole purpose is to divide to (1) first maintain its own population (i.e., self-renewal), and (2) produce cells for another population. Stem cells are undifferentiated. Classic examples of stem cell populations are basal cells in the epidermis of the skin, cells in the bone marrow, the cells in the crypts of Lieberkuhn in the intestine, and

spermatogonia in the testis. Tissues and organs containing stem cell populations are referred to as self-renewing.

Transit cell populations are defined precisely by their name — they are cells on their way from one place (stem cell compartment) to another place (end cell compartment). While in transit these cells may or may not divide. An example of a cell that divides while in transit is the nucleated red cell. A cell that does not divide is the reticulocyte in the bone marrow; it simply receives precursor cells and sends them on their way into the peripheral blood.

The third population, *a static population*, loses cells throughout the life of the organism. These cells are fully differentiated and exhibit no, or at least little, detectable mitotic activity. Examples of such populations are found in adult nervous tissue and muscle.

4. Radiation Response of Cells

Based on the aforementioned cell population categories, Rubin and Casarett have defined five categories of cell populations (Table 7-1) in terms of their radiation sensitivities. The criteria used were histologic signs of cell death, not the loss of proliferative potential.

4.1. Vegetative Intermitotic Cells (VIM).

VIM cells are rapidly dividing, undifferentiated cells that have a short lifetime. According to Bergonie and Tribondeau, these cells comprise the most radiation-sensitive group of cells in the body. Examples of VIM cells are basal cells of the epidermis, crypt cells of the intestines, type A spermatogonia, and erythroblasts.

4.2. Differentiating Intermitotic Cells (DIM).

DIM cells are produced by division of VIM cells and, although actively mitotic, they are more differentiated than VIM cells. Therefore, these cells are less sensitive (or more resistant) to radiation than are the VIM cells. Examples of DIM cells are intermediate and type B spermatogonia.

4.3. Multipotential Connective Tissue Cells.

These cells divide irregularly, are more differentiated than either VIM or DIM cells, and are intermediate in sensitivity to radiation. Cells included in this category are endothelial cells (blood vessel liners) and fibroblasts (composing connective tissue).

TABLE 7-1

Characteristics and Radiosensitivites of Mammalian Cell Populations

Cell Type	Characteristics	Examples	Radiosensitivity
VIM	Divide regularly and rapidly; undifferentiated; do not differentiate between divisions	Type A spermatogonia, erythroblasts, crypt cells of intestines, basal cells of epidermis	High ↓ Low
DIM	Actively dividing; more differentiated than VIMs: differentiate between divisions	Intermediate spermatogonia myelocytes	
Multipotential connective tissue	Irregularly dividing; more differentiated than VIMs or DIMs	Endothelial cells, fibroblasts	
RPM	Do not normally divide but retain capability of division; variably differentiated	Parenchymal cells of liver, lymphocytes*	
FPM	Do not divide; highly differentiated	Nerve cells,muscle cells erythrocytes (RBCs), spermatozoa	

*Lymphocytes, although classified as relatively radioresistant by their characteristics, are very radiosensitive

Match the abbreviations with their decryptions.

1. FMP
2. VIM

a) red blood cells
b) fixed postmitotic cells

3. RBC	c) differentiating intermitotic cells
4. RPM	d) vegetative intermitotic cells
5. DIM	e) reverting postmititic cells

4.4. Reverting Postmitotic Cells (RPM).

Cells in this category normally do not undergo mitosis; however, they retain the capability of division under specific circumstances. RPM cells are long-lived as individuals and are more differentiated than cells of the previous categories; therefore, RPM cells are relatively radioresistant. Examples of RPM cells are liver cells and the mature lymphocyte. The mature lymphocyte is included in this category because of its mitotic characteristics – it does not usually divide, but has the capability of dividing when a stimulus is present. The lymphocyte also is a differentiated cell; however, in contrast to other RPM cells that are relatively radioresistant, the mature lymphocyte is very radiosensitive. It is one important exception to the general law of Bergonie and Tribondeau.

4.5. Fixed Postmitotic Cells (FPM).

FPM cells do not divide. These cells are highly differentiated both morphologically and functionally; therefore, they are resistant to radiation. In fact, this category comprises the group of cells most resistant to radiation. Some of the cells in this category have long lives, whereas others are relatively short-lived. When the short-lived cells die, they are replaced by differentiating (DIM) cells. Other cells in this category may not be replaced if cell death occurs. Examples of cells in this category include some nerve cells, muscle cells, erythrocytes (RBCs), and spermatozoa.

Table 7-2 gives a classification of cells according to decreasing radiosensitivity, again using histologic signs of cell death as the determining factor.

TABLE 7-2

Cell Classification by Decreasing Radiosensitivity

Group	Sensitivity	Examples
1	High	Mature lymphocytes, erythroblasts, certain spermatogonia
2		Granulosa cells, myelocytes, intestinal crypt cells, basal cells of

		epidermis
3		Endothelial cells, gastric gland cells, osteoblasts, chondroblasts, spermatocytes, spermatids
4		Granulocytes, osteocytes, spermatozoa, erythrocytes
5	Low	Fibrocytes, chondrocytes, muscle cells, nerve cells

1. Choose the correct word and fill in the blanks. Change the form if it is necessary.

deplete/depletion/depletable

1. The _____ of natural resources is a continuing concern for society.

2.People should be careful about the use of Earth's _____ recourses.
3.There is growing evidence that CFCs rise high into the atmosphere and_____ the ozone layer which protects us from the Sun's ultraviolet radiation.

sensitive/sensitivity

1.Radiation _____ is the relative susceptibility of cells, tissues, organs or organisms to the harmful effect of ionizing radiation.
2.Some tissues are very _____ to radiation, and the cells do not recover from treatment. Nerve and muscle cells are least _____ to ionizing.

destroy/destruction/destructive

1.Ray or radiotherapy is defined as the influence of X-rays (Roentgen rays) or gamma rays of radioactive isotopes on tumor tissues for the purpose of their _____.
2.Radiotherapy is the use of high energy X-rays to _____ tumor cells.
3.Fast neutrons can be very _____ to human tissue.

differ/difference/different/differentiate/differentiation

1._____ of radiation pathology from metastatic tumor or new malignancy can be difficult.
2.Human organism consists of _____ types of cells.

3.UV light _____ from other forms of electromagnetic radiation as it does not cause ionization in atoms or molecules, but rather excitation.
4.Radiation-induced damage _____ among _____ types of cells.
5.The inherent _____ in radiosensitivity between the tumor and adjacent normal tissues allow it to destroy the former with minimal disruption to the latter.
6.In order for cells to become whole organisms, they must divide and _____.
7.A cell that upon division replaces its own numbers and also gives rise to cells that _____ further into one or more specialized types.

contain/container/

1.As determinated in the Atomic Energy Act, _____ for radioactive materials have to undergo a safety-related survey.
2.The average adult _____ about 13 mg of radioactive potassium-40 in body tissue.

5. Tissue Response to Radiation

It was pointed out in Chapter 6 that the D_0 for mammalian cells obtained both in vivo and in vitro is between 1 and 2 Gy, indicating that there is not a substantial difference in the radiosensitivity of mammalian cells. However, it is well known that there is a vast difference in the doses at which different organs and tissues exhibit damage. Reasons for these dose differences must be sought elsewhere. Since cell division is necessary for radiation damage to be expressed, then the time of expression of injury in an organ must be dependent on the turnover time of the critical target cells – not only if they divide, but when and how often. The term *target cell* does not imply that radiation is selective for any given cell, but refers to those cells in the tissue that can divide and regenerate the tissue after radiation, i.e., the stem cells. When sufficient numbers of cells are killed and subsequently depleted due to a failure of the stem cells to regenerate after irradiation, overt functional and structural tissue damage occurs. Thus, to understand tissue response to radiation it is important to first have some knowledge of how tissues and organs are organized. This knowledge also is critical to an understanding of how the effects of radiation on different tissues are measured.

5.1. Tissue Organization

Tissues and organs are made up of two compartments: the parenchymal compartment, containing the cells characteristic of that individual tissue or organ, and the stromal compartment, composed of connective tissue and vasculature, which makes up the supporting structure of the organ (Fig 7-2).

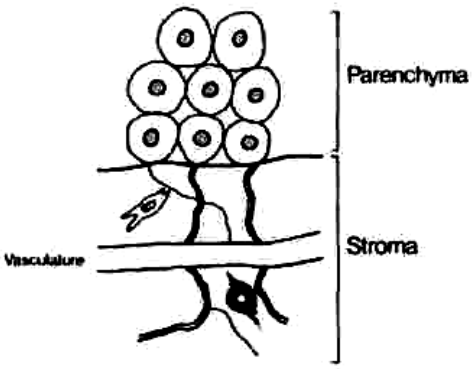


FIG 7-2.
Diagram of the parenchymal and stromal compartments of any organ. The parenchymal compartment contains cells typical of the organ, whereas the stromal compartment contains connective tissue, (light-colored background), vasculature and other cells such as mast cells (below vessel) and fibrocytes (above vessel).

The parenchymal compartment of tissues and organs may be composed of one or more than one category of cells, as defined by Rubin and Casarett. The testis is an example of an organ that contains more than one category of cells: stem cells — type A spermatogonia (VIM cells); intermediate cells — type B spermatogonia, spermatocytes, and spermatids (DIM cells); and mature, functional cells — spermatozoa (FPM cells). Another example is the hemopoietic system: the bone marrow contains the undifferentiated stem cells, and the circulating blood contains the mature end cell. Two other examples are the skin and the intestinal tract.

In these types of organs where the parenchymal compartment is composed of various cellular populations, cells flow from the stem cell compartment to the differentiated compartment to the end cell compartment as needed (Fig 7-3).

Examples of tissues and organs whose parenchymal compartments are composed of only RPM cells or FPM cells are the liver, muscle, brain, and spinal cord. The hepatic cells of the liver are RPM cells, dividing only when the need exists. If a partial hepatectomy is performed, the hepatic cells will begin to divide and replace the part of the liver that has been removed. However, most cells of the brain and most muscle cells do not retain the capability of division; these tissues and organs are composed of FPM cells.

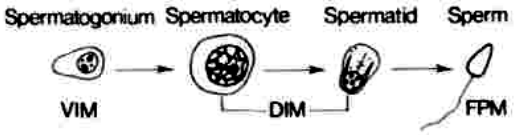


FIG 7-3.

Flow of the cell from the stem cell compartment (VIM) to differentiating compartment (DIM) to the end cell compartment (FPM), illustrated by cells of the testis.

Regardless of the population of cells in the parenchymal compartment, all tissues and organs will have a supporting stromal compartment composed of connective tissue and vasculature (multipotential connective tissue cells).

2. Match the terms and the definitions.

1) depletion	a) the act of using up or reducing;
2) sensitivity	b) the ability of an organism or part of an organism to react to stimuli;
3) fixed postmitotic cells	c) an undifferentiated cell of a multicellular organism which is capable of giving rise to indefinitely more cells of the same type, and from which certain other kinds of cell arise by differentiation;
4) stem cell	d) the group of cells that do not divide, highly differentiated both morphologically and functionally; these cells are the most resistant to radiation (examples include some nerve cells, muscle, erythrocytes, and spermatazoa);
5) RBC	e) the process by which cells or tissues undergo a change toward a more specialized form or function, especially during embryonic development;
6) differentiation	f) a cell in the blood of vertebrates that transports oxygen and carbon dioxide to and from the tissues.

5.2. Mechanisms of Damage in Normal Tissues

Tables 7-1 and 7-2 indicate that cells in the vasculature are intermediate in sensitivity to radiation, i.e., they are more sensitive than

either the RPM or FPM cells of organs such as the lung, kidney, and spinal cord. For this reason, it had long been suggested that damage in such tissues was a consequence of damage to the vasculature (tissue damage occurred indirectly via vascular narrowing and occlusion, resulting in tissue ischemia), rather than damage to cells specific to that organ (the parenchyma). Recently, however, this hypothesis has been questioned and, in fact, a new classification of normal tissue responses according to the time in which the tissues express injury has been suggested. This new hypothesis states that the response in all normal tissues is due to killing and subsequent depletion of the critical parenchymal cells of that organ, and that the differences in the time it takes for damage to be expressed are due simply to differences in turnover kinetics of the target cells. The current philosophy, then, is that tissue damage is due to depletion of critical target cells and is not an indirect result of vascular damage. For example, damage is seen in the intestine within a week to 10 days after irradiation, and is quite predictable based on the turnover kinetics of the stem cells in the crypts (i.e., 12-hour cell cycle). On the other hand, damage in the lung is not expressed for at least 3 months after irradiation, which, rather than being a consequence of vascular damage, most likely reflects the slow turnover of the critical parenchymal cells in the lung (perhaps type 2 cells), whose loss results in observable damage.

Based on the difference in turnover kinetics of the critical target cells in different tissues, normal tissues can be divided into two categories: acutely responding and late responding normal tissues. The acutely responding tissues manifest their injury within a few months after radiation is completed because they are self-renewal tissues containing rapidly dividing stem cell populations. Examples are the bone marrow, skin, intestine, and testis. On the other hand, late responding normal tissues do not express injury for at least 3 months or longer because they contain slowly dividing cell populations. Two examples of the latter are lung and kidney.

Thus, differences in the times within which different tissues express damage after radiation are most likely not an issue of vascular vs. parenchyma, but rather are due simply to the fact that some cells in some tissues, such as the lung, divide more slowly than cells in other tissues, such as the intestine. Table 7-3 lists acutely responding and late responding normal tissues and the known or hypothesized critical target cells.

TABLE 7-3

Acutely Responding and Late Responding Normal Tissues

Tissue	Target Cells
Acutely responding	
Skin	Basal cells of the epidermis
Hair	Follicle
Lip mucosa	Basal cells
Jejunum	Crypt cells
Colon	Crypt cells
Testis	Spermatogonia
Bone marrow	Stem cells
Late responding	
Kidney	? Epithelial cells of proximal tubules
Lung	? Type 2 pneumonocytes
Spinal cord	Glial cell
Brain	?
Bladder	?

6. Measurement of Radiation Damage in Tissues

6.1. Assays of Tissue Response

In order to compare and contrast the responses of different tissues to radiation, assays that allow the assessment of damage as a function of dose are essential. Two criteria are necessary for an assay of tissue effect to be of value:

1. It must be quantifiable (i.e., assign a number to it).
2. The effect must increase with increasing radiation dose.

Many techniques that meet these criteria for a wide variety of normal tissue are now available for measuring tissue response to radiation in experimental animals. These techniques either provide cell survival curves or dose response curves.

There are many ways to assess the effects of radiation on tissues in vivo, but for our purposes the most critical test will be the ability of the dividing clonogenic (stem) cells to undergo unlimited division, i.e., to retain their reproductive integrity. It is clear that such an assay is

reasonable for cells grown in vitro. In this situation cell survival can be assessed as a function of dose and cell survival curves obtained. The questions are whether it is possible to obtain survival curves for cells of tissues in vivo and, if it is not, how tissue responses to radiation are then measured.

Assays of damage in organized tissues and organs can be divided into three categories:

1. Clonogenic (related to the reproductive integrity of the clonogenic stem cells in the tissue).
2. Specific tissue function.
3. Lethality.

6.2. Clonogenic Assays

Based on the previous discussion of cell populations, it is clear that if a tissue contains stem cells that divide and form clones in vivo and if these stem cells can be easily identified and quantified, then the construction of survival curves for the target cells of this tissue in situ is possible. There are a number of such "clonogenic" assays for some normal tissues: bone marrow, testis, and mammary and thyroid glands, to name just a few. In some of these, clonogenic survival is assessed in situ in the same animal that was previously irradiated (skin, basal cells of the epidermis; intestine, number of surviving crypt cells; testis, number of tubules containing spermatogenic epithelium). In others, the cells are taken from the irradiated animal (donor) and transplanted into a genetically identical mouse for assay.

6.3. In Situ Assays

Withers and his colleagues have been instrumental in developing in situ clonogenic assays for a number of normal tissues, including skin, intestine, testis, and kidney. The intestine will be used to illustrate this technique.

The intestine is an example of a tissue in which dividing cells are confined to one location, the crypts of Lieberkühn. These cells divide about every 12 hours, replacing their own population, plus providing a constant supply of cells for the nondividing differentiated cells that are sloughed from the villi every 24 hours. The villi are dependent on the crypts for cell replacement; if the cells in the crypt are dead, the villi become shortened, flattened, and partially or completely denuded. In the intestine, then, damage is due to killing, with subsequent depletion of the

cells in the crypts of Lieberkühn followed by denudation of the epithelial lining of the mucosa. Figure 7-4 shows a control, nonirradiated intestine tissue (A), and two examples of irradiated intestine tissue (B and C). Because the crypts are easily identified using the light microscope, the number of surviving crypts can be counted and plotted as a function of dose. Since it is assumed that a crypt can be repopulated by one surviving cell, a cell survival curve can be constructed. An example of such a crypt cell survival curve is given in Figure 7-5. Similar techniques are used in the testis and skin to obtain cell survival curves. In all of these acutely responding normal tissues, survival is assayed within a month after irradiation, reflecting the rapid turnover of the clonogenic stem cells in each tissue.

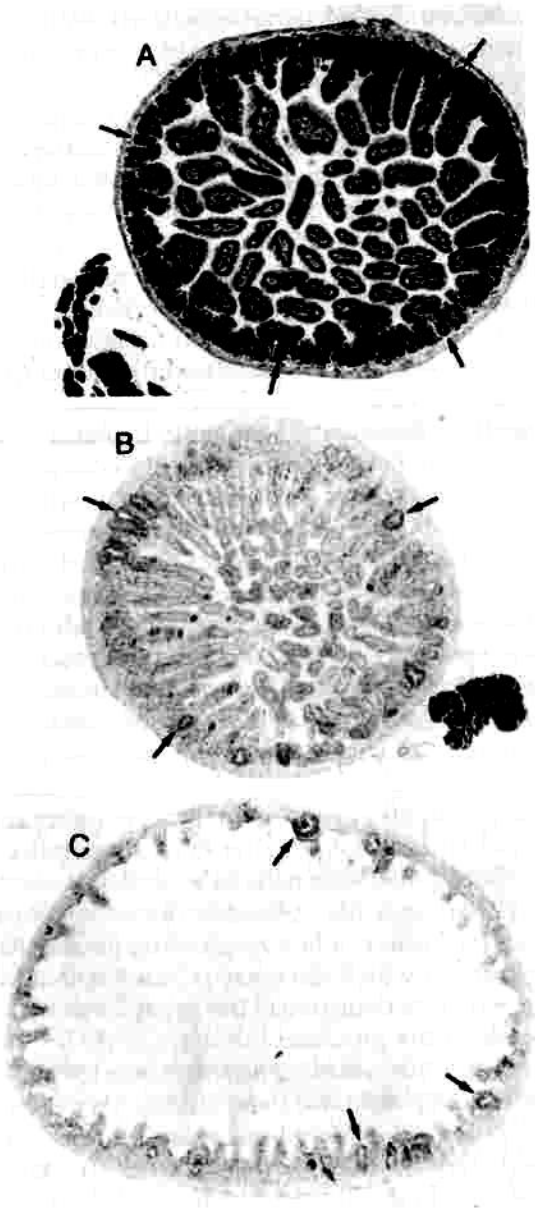


FIG 7-4.

*Examples of jejunal tissue from **(A)** a nonirradiated mouse, **(B)** a mouse given a moderate single dose of radiation, and **(C)** a mouse given a high single dose of radiation. Crypts are easily recognizable (arrows). They are quantifiable, and cell survival curves can be constructed from the data.*

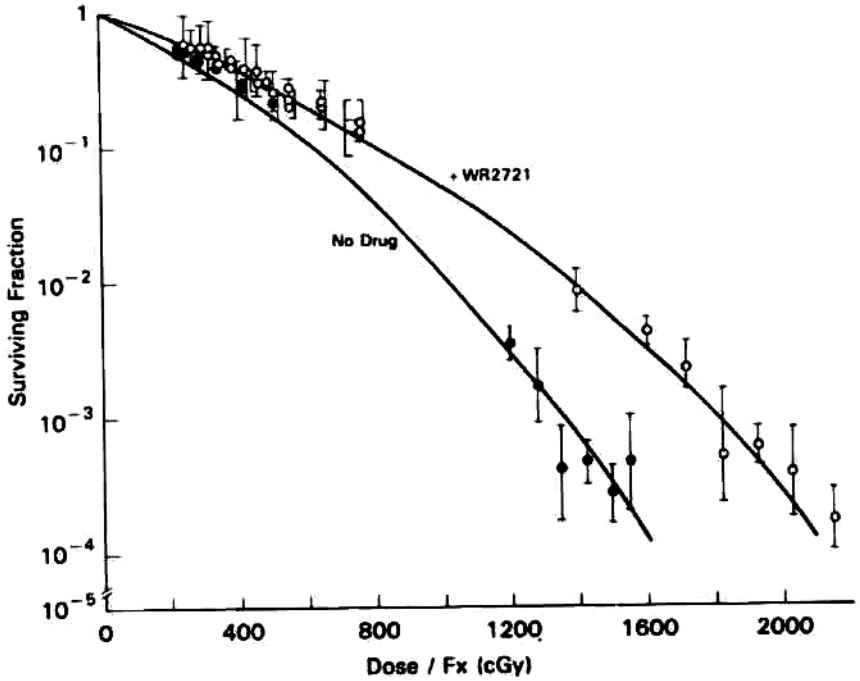


FIG 7-5. *Survival of crypt cells following radiation either alone or in the presence of a known radio-protector, WR-2721.*

Recently, Withers and his colleagues have developed an in situ clonogenic assay for kidney, a late responding normal tissue. The underlying hypothesis on which the assay is based is that radiation damage in the kidney is due to depletion of the parenchymal cells, specifically the epithelial cells of the proximal tubules.

At first glance this may seem surprising, since the cells of the tubule epithelium are well differentiated and divide very slowly. However, unlike the other tissues in which damage is expressed within a month after irradiation (3 days in intestine, 2 to 3 weeks in skin, and 4 weeks in the testis), damage in the kidney is expressed at 1 year after irradiation, reflecting the slow turnover of the tubule cells suggested to be the critical cells killed by radiation. The survival curve for epithelial cells in kidney tubule is shown in Figure 7-6. The D_0 for these cells is 1.5 Gy. Thus, the target cells for this late responding normal tissue have sensitivity similar to that of the acutely responding normal tissues.

5.4. Transplantation Assays.

The assays of clonogenic survival in bone marrow and thyroid and mammary glands require that the irradiated tissue be removed from the animal and a single cell suspension be made and then injected into another animal. In other words, the recipient animal acts like a culture dish. This technique is best illustrated by the bone marrow colony-forming units (CFUs) assay developed by Till and McCulloch: (1) animals are irradiated to the whole body with a range of doses, (2) bone marrow is removed from their legs, and (3) single cell suspensions are made, various amounts of which are injected into previously irradiated syngeneic recipient animals. (The recipient animals must be previously irradiated so that all their bone marrow cells are destroyed, allowing the cells of the donor mice to grow.) These donor cells colonize the bone marrow and spleen, forming visible colonies in the latter. The spleen is removed 9 days later and the number of colonies counted, each of which is assumed to have arisen from the injection of one surviving cell. The number of colonies after each dose is counted; the proportion of cells surviving calculated and plotted as a function of dose. An example of a survival curve for bone marrow cells is given in Figure 7-7. Similar assays are available for thyroid and mammary glands.

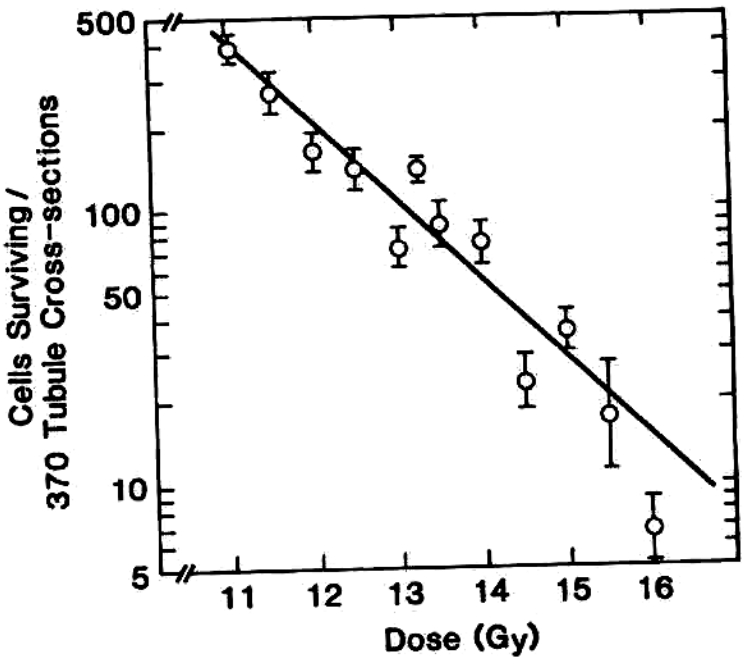


FIG 7-6.

Dose survival curves for kidney tubule cells showing a D_0 of about 1.5 Gy.

Survival curves for all clonogenic assays in vivo are plotted in Figure 7-8. Although there is a range of sensitivities, the biggest difference between these survival curves for tissues is the shoulder, not the slope (i.e., D_0 values are more similar than the shoulders). Although the data for the kidney are not plotted, it is clear that the kidney has a similar sensitivity to the more rapidly dividing normal tissues, i.e., the D_0 is within the range for the rapidly dividing normal tissues.

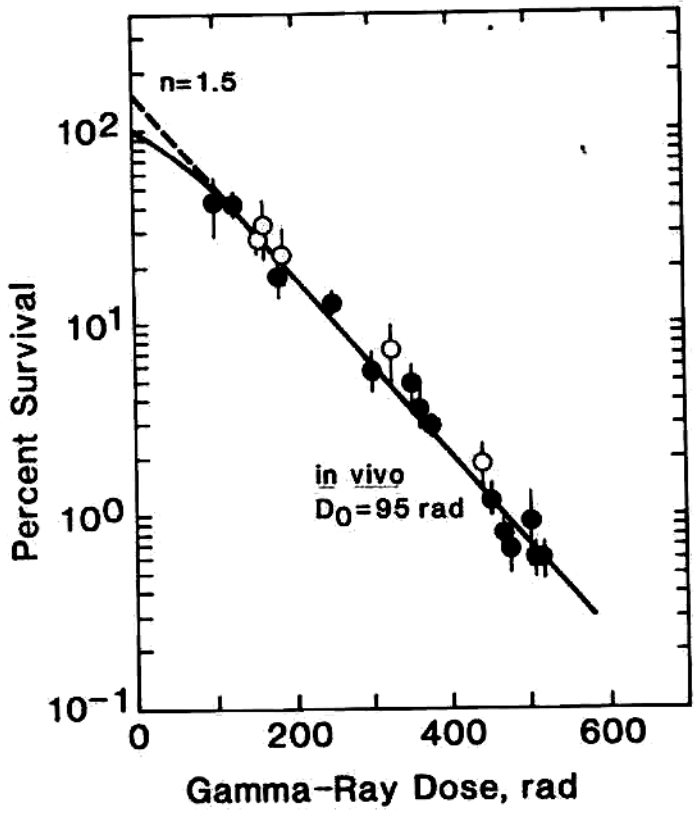


FIG 7-7.

Percent survival as a function of dose for colony-forming ability of mouse bone marrow cells. This is an example of a survival curve from a transplantation assay. The cells are irradiated in a donor and then transferred to a lethally irradiated recipient, and the resultant spleen colonies are counted.

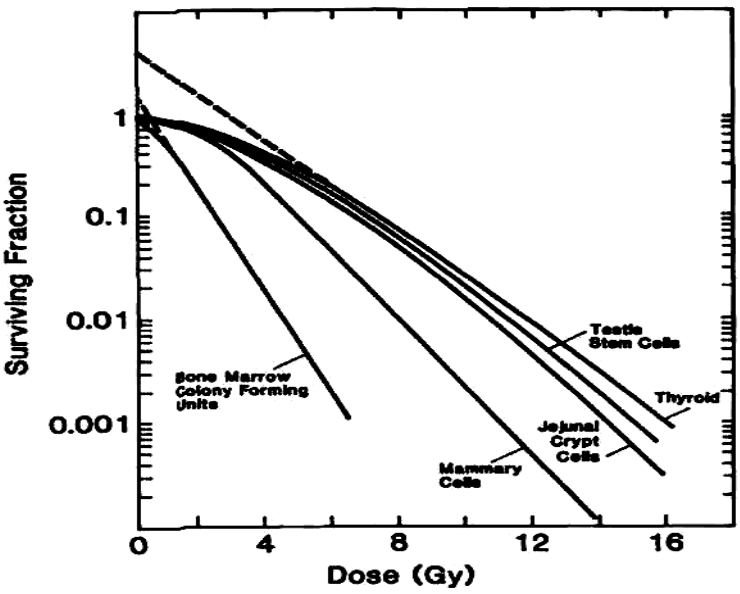


FIG 7-8.

Survival curves as a function of dose for a number of clonogenic assays in vivo, showing that the slopes of the survival curves are similar (D_0 values fall within a narrow range). However, the biggest variation in these survival curves is in the shoulder region.

6.5. Functional Assays

Many tissues do not have clonogenic stem cells that can be readily identified and quantified, particularly those tissues classified as late responding. Thus our knowledge of how these tissues respond to radiation has been minimal. However, it is obvious that these tissues are as important as the acutely responding normal tissues for obtaining a favorable outcome when treating a tumor with radiation. This has prompted the development of new assays of function for many tissues. These functional endpoints meet the criteria that damage must increase as a function of dose. Such data produce dose response curves rather than cell survival curves, and although they tell little about the survival of the underlying putative target cells, they do allow comparison of tissue responses to radiation. Most of these are based on either the physiology of the organ (e.g., breathing rate measurements after lung irradiation, frequency of urination after bladder irradiation), whereas others rely on scoring visible changes in the organ that occur after irradiation (e.g., acute skin reactions consisting of hair loss, erythema, and desquamation). Such techniques have been invaluable in increasing our understanding of the responses of late responding normal tissues to radiation.

6.6. Lethality

The single most often used nonclonogenic assay for quantifying damage in normal tissues is lethality. In these studies the number of animals dead after localized irradiation of a *specific* organ is quantified as a function of dose and dose response curves are then constructed.

The lethal dose that kills 50% of the animals, LD_{50} is obtained for different normal tissues, allowing comparisons of the dose for this same effect (called isoeffect) between tissues.

The LD_{50} for a given tissue is further defined by the time when deaths occur. Based on the assumption that cell division is necessary for radiation damage to be expressed, deaths would occur quickly after irradiation of the intestine (by irradiating the whole abdomen), but much more slowly after irradiation of the lungs, reflecting the differences in turnover times of the critical cells in these two tissues.

Figure 7-9 presents a series of dose response curves for lethality after localized irradiation of different normal tissues. For comparison, the dose response curve for spinal cord paralysis is also shown. The LD_{50} for each tissue is given in Table 7-4.

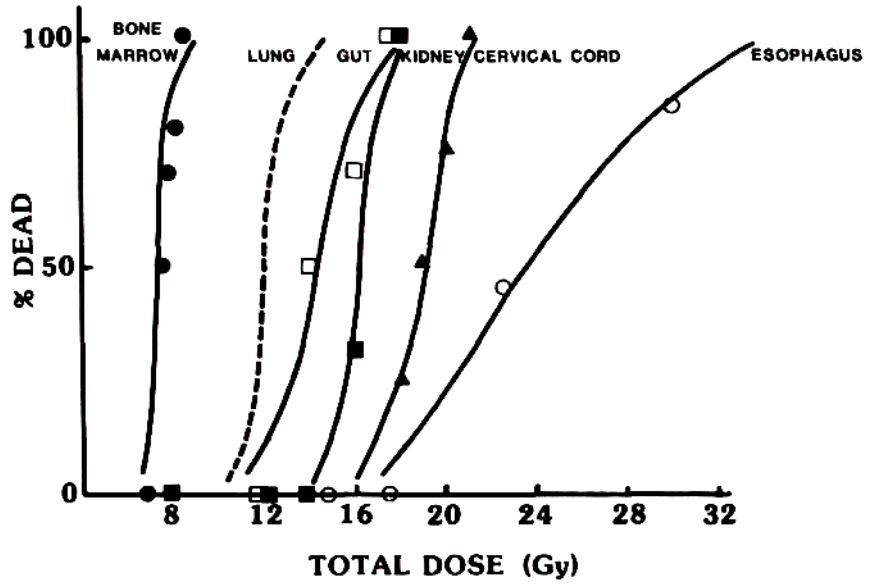


FIG 7-9.

Number of animals dead is a function of dose for six different normal tissues. In general, the curves are very steep, although they are displaced on the dose axis, bone marrow being most "sensitive," and esophagus, most "resistant."

TABLE 7-4

LD_{50} Values Estimated from Dose-Response Curves for Radiation Damage to Various Normal Tissues in Experimental Animals.

Tissue	Animal	Assay	LD_{50} (Gy)
Bone marrow	Mouse	Death, 30 days	7.20
Lung	Mouse	Death, 80-100 days	12.34
Gut*	Mouse	Death, 10-12 days	14.20
Kidney	Mouse	Death, 500 days	16.00
Spinal cord	Rat	Paralysis, 7 mos	19.00
Esophagus	Mouse	Death, 20 days	24.80
*Total abdominal irradiation. ED_{50} effect dose 50; used in tissues where an effect other than death is quantified; for example, paralysis after spinal cord irradiation.			

Table 7-5 lists all the quantitative endpoints which are available for assessing the response of normal tissues to radiation in experimental animals.

TABLE 7-5

Quantitative Normal Tissue Endpoints

Tissue	Clonogenic	Functional	Lethality
Bone marrow	Spleen colonies (transplantation)		$LD_{50/30\ days}$
Intestine	Crypt colonies (in situ)		$LD_{50/7-10\ days}$
Testis	Tubules with spermatogonic epithelium (in situ)	Weight	–
Skin	Skin colonies (in situ)	Early skin reaction, late deformites	–
Esophagus	–	–	$LD_{50/28-60\ days}$
Mammary gland	Tpansplantation	–	–
Liver	In situ	–	–
Thyroid	Tpansplantation	–	–
Kidney	Tubules with epithelial cells	^{51}Cr EDTA clearance, hematocrit, urination frequency, weight	$LD_{50/12-15\ mos}$
Lung	–	Breathing rate, CO_2 clearance	$LD_{50/80-180days}$ $LD_{50/360\ days}$
Bladder	–	Urination frequency, contracture	–
CNS	–		Incidence of paralysis, $ED_{50/7\ mos}$, $ED_{50/18\ mos}$

7. Shapes of Survival Curves for Acutely Responding and Late Responding Normal Tissues

It is now possible to construct dose survival curves for many normal tissues in vivo. However, for those tissues for which clonogenic assays do not exist because the target cells in the tissue are either unknown or cannot

be quantitatively assessed, survival curves can only be deduced from their dose response curves. Based on such deductions, it has been suggested that not only do acutely and late responding normal tissues express their damage at vastly different times, but that their survival curves for the "target" cells are also different. Shown in Figure 7-10 are dose survival curves for an acutely responding and a late responding normal tissue. It is clear that the shapes of the survival curves for the two classes of tissue differ, and that the curve for late responding normal tissues is "curvier" than that for acutely responding normal tissues. Some knowledge of the differences in survival curve shapes is important to an understanding of the factors that govern cellular and tissue responses, since modifiers of radiation damage may differentially affect these two classes of normal tissues. This hypothesis has important implications for dose fractionation as used in radiotherapy.

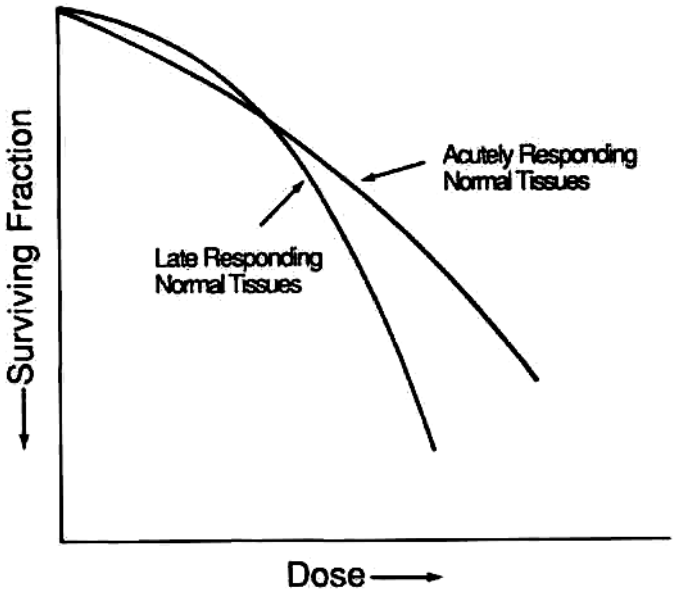


FIG 7-10.

Schematic of the hypothesized survival curves for acutely responding and late responding normal tissues. The curve for the late responding normal tissues is "curvier" than that for the acutely responding normal tissues.

1. Complete the following statements:

The response of an organ or tissue to radiation depends on two factors:

1) …
2) …

The appearance of radiation damage is influenced by two factors:

1) …
2) …

Cell populations can be divided into three categories:

1) …
2) …
3) …

Tissues and organs are made up of two compartments:

1) …
2) …

Based on the difference in turnover kinetics of the critical target cells in different tissues, normal tissues can be divided into two categories:

1) …
2) …

Two criteria are necessary for an assay of tissue effect to be of value:

1) …
2) …

Assays of damage in organized tissues and organs can be divided into three categories:

1) …
2) …
3) …

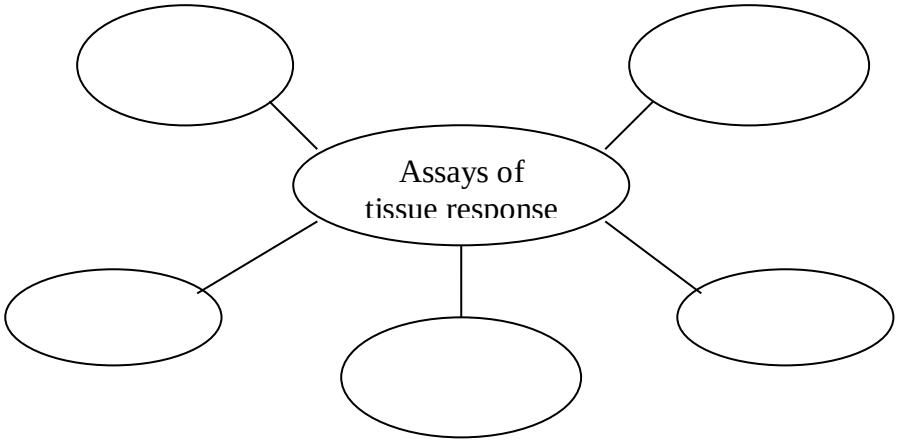
2. Speak about the contribution to cellular radiosensitivity studies made by such researchers as

Bergonie and Tribondeau, Ancel and Vitemberger, Rubin and Casarett, Withers, Till and McCulloch

3. Decode the following abbreviations and give their definitions:

RBC, *VIM, DIM, RPM, FPM, CFUs*, LD_{50}

4. Complete the scheme and comment on it:



5. Guess the terms, containing the word "cell":

1) The susceptibility of a material to physical or chemical changes induced by radiation.

2) The process by which a parent cell divides into two or more daughter cells.

3) The constant shedding of dead skin cells and subsequent replacement with younger cells; the replacement of old cells with newly generated ones from the existing ones.

4) It is specialized functionally and/or morphologically (structurally); it can be considered a mature cell, or end cell, in a population.

5) It has few specialized morphologic or functional characteristics; it is immature, its primary function is to divide, thus providing cells to maintain its own population and to replace mature cells lost from the end cell population. They are considered precursor, or stem, cells in a population.

6) The process by which immature spermatogonia become mature spermatozoa.

(An undifferentiated cell, cellular radiation sensitivity, differentiation, cell division, cell turnover, a differentiated cell)

6. Render the following:

Через різну радіочутливість органів і тканин важливо чи буде опромінено весь організм, чи тільки його частина, а також, чи організм буде опромінено повністю, але нерівномірно. Повне рівномірне опромінення організму викликає найбільший радіобіологічний ефект. Взагалі, радіочутливість органу залежить не тільки від радіочутливості тканини, але й від функції даного органу.

Ступінь радіочутливості тканин залежить від певних функціонально-біологічних характеристик, що визначають сорбційний показник окремої тканини. Стосовно радіочутливості різні органи можна розподілити в послідовності від більше радіо чутливих до менше: великі півкулі, мозочок,

гіпофіз, надниркові залози, тимус (вилочкова залоза), лімфатичні вузли, спинний мозок, ШКТ, печінка, селезінка, нирки, серце, шкірі і кісткова тканина.

Control points to Charter 7

1) Factors that influence on organ or tissue response to radiation.
2) Radiosensitivity of a cell.
3) Differentiation.
4) Categories of cell populations.
5) Terms “VIM”, “DIM”, Multipotential Connective Tissue Cells, “RPM”, “FPM”.
6) Tissue organization (compartments).
7) Normal tissue damage.
8) Categories of arrays of damaged tissue; criteria necessary to value tissue effect.
9) Clonogenic assays. In Situ Assays.
10) Transplantation Assays. Functional Assays.
11) Lethality.
12) Shapes of survival curves.

Science vocabulary

1. **assay** аналіз, аналізувати
2. **rodent** гризун
3. **testicle** яєчко
4. **testis (pl. testes)** яєчко
5. **mature cell** зріла клітина
6. **repair** відновлення
7. **blood vessel** кровоносна судина
8. **endothelial cell** ендотеліальна клітина
9. **mitotic** мітотичний
10. **spinal cord** спинний мозок
11. **hepatic cell** гепатоцит, клітина печінки
12. **occlusion** оклюзія; закупорка; непрохідність
13. **ischemia** ішемія
14. **clonogenic cell** клоногенна клітина
15. **in situ** в природному середовищі
16. **mammary gland** молочна залоза
17. **tubule** трубочка, каналець

18. **slough** лущитися, сходити
19. **villus (villi)** ворсинка
20. **culture dish** чашка для культивування
21. **syngeneic** ізогенний
22. **spleen** селезінка
23. **bladder** сечовий міхур, порожнина
24. **desquamation** десквамація
25. **lethality** смертність, летальність
26. **abdomen** живіт**,** черевна порожнина

8. Radiation Pathology

1. "Acute„ vs. Chronic Effects. 2. Healing. 3. Clinical Factors Influencing Response. 4. General Organ Changes. 5. Hemopoietic System. *5.1. Bone Marrow. 5.2. Circulating Blood. 5.2.1. Diagnostic Radiology. 5.2.2. Nuclear Medicine. 5.2.3. Radiation Therapy.* **6. Skin.** *6.1. Accessory Structures. 6.1.1. Diagnostic Radiology. 6.1.2. Nuclear Medicine. 6.1.3. Radiation Therapy.* **7. Digestive System.** *7.1. Diagnostic Radiology and Nuclear Medicine. 7.2. Radiation Therapy.* **8. Reproductive System.** *8.1. Male. 8.1.1. Diagnostic Radiology and Nuclear Medicine. 8.1.2. Radiation Therapy. 8.2. Female. 8.2.1. Diagnostic Radiology and Nuclear Medicine. 8.2.2. Radiation Therapy.* **9. Cardiovascular System.** *9.1. Vasculature. 9.2. Heart. 9.2.1. Diagnostic Radiology and Nuclear Medicine. 9.2.2. Radiation Therapy.* **10. Growing Bone and Cartilage.** *10.1. Diagnostic Radiology and Nuclear Medicine. 10.2. Radiation Therapy.* **11. Liver.** *11.1. Diagnostic Radiology and Nuclear Medicine. 11.2. Radiation Therapy.* **12. Respiratory System.** *12.1. Diagnostic Radiology and Nuclear Medicine. 12.2. Radiation Therapy.* ***13. Urinary System.*** *13.1. Diagnostic Radiology and Nuclear Medicine. 13.2. Radiation Therapy.* **14. Central Nervous System.** *14.1. Diagnostic Radiology and Nuclear Medicine. 14.2. Radiation Therapy.* **15. Eye.** *15.1. Diagnostic Radiology. 15.2. Radiation Therapy.*

Normal tissues can be divided into two categories, acutely responding and late responding, based solely on the time in which they express damage after irradiation. However, this classification does not describe what is observed, i.e., the morphologic and structural changes that occur after irradiation. The pathologic changes that occur after irradiation of specific organs are the topic of this chapter.

The underlying assumption throughout this chapter is that cell death, whether via reproductive failure or interphase death, and subsequent loss of cells from the organ is the initial event that leads to the visible changes. In most cases the visible effects of radiation on the morphology of an organ are not unique — without the knowledge that radiation exposure has occurred, the observed changes would not implicate radiation as the causative agent. Many other types of trauma will produce the same changes.

1. “Acute” vs. Chronic Effects

The morphologic response of an organ or tissue after irradiation occurs in two general phases, often referred to as "acute" and "late" effects. In this chapter the term chronic effect will be used rather than 'late" effect to avoid confusion with the true "late" effects of radiation. These terms, which refer to what is observed, are not to be confused with the terms "acutely" responding and 'late" responding normal tissues (see Chapter 7), which refer only to when the damage is expressed, not to what this damage looks like.

The first phase, i.e., the "acute" effect, may occur soon after irradiation as in "acutely" responding normal tissues, or at long times after irradiation as in "late" responding normal tissues, dependent on the turnover kinetics of the putative target cells in the parenchyma of the tissue. However, regardless of the time after irradiation that this initial response occurs, the cause is the same: depletion of *parenchymal* cells specific to the tissue. Examples of an acute response in two tissues which is expressed at vastly different times are the initial response in the esophagus, esophagitis, and in the lung, pneumonitis, acutely responding and late responding normal tissues, respectively. Esophagitis appears within the first month after irradiation, whereas pneumonitis is not manifested until 3 months or longer after irradiation. However, damage in both tissues is due to depletion of parenchymal cells, basal cells in the mucosa of the esophagus, and (most likely), type 2 pneumocytes of the alveolar epithelium of the lung. These changes may be reversible or irreversible, depending on dose and the proliferative potential of the target cells.

Chronic (late) effects may occur either (1) as a consequence of irreversible and subsequently progressive early changes, or (2) due to depletion of critical *nonparenchymal* cells, perhaps in the stroma or the vasculature. Chronic effects occurring as a consequence of severe acute effects (as in item 1 above) can be termed "secondary" chronic effects, and those that are a result of depletion of nonparenchymal cells (as in item 2 above) can be termed "primary" chronic effects. The former are dependent on the acute effects, whereas the latter would be independent of the acute effects. Both types are permanent, irreversible, and most likely progressive. Because secondary chronic effects are a consequence of severe acute effects, it is likely that they appear sooner and progress more quickly than primary chronic effects. The latter would appear at a time consistent with the very slow turnover of the critical target cell population.

These changes would appear at long times after the acute response had subsided and would progress over a longer period of time, perhaps, even, for years. Chronic effects can occur years after radiotherapy is completed. In general, whether a primary or secondary chronic effect occurs is a function of the type of healing that occurs in the organ.

2. Healing

Healing of a tissue or organ occurs by one of two means: *regeneration*, the replacement of damaged cells in the organ by the same cell type present before radiation; or *repair*, the replacement of the depleted original cells by a different cell type. Regeneration results in a total or partial reversal of early radiation changes, actually restoring the organ to its pre-irradiated state both morphologically and functionally. In this situation, any chronic changes would be of a primary nature, i.e., due to depletion of a different cell type in a different part of the tissue.

On the other hand, catastrophic and irreversible acute changes heal by *repair*. This process does not restore the organ to its pre-irradiated condition, thus producing a secondary chronic response. Repair of radiation damage usually does not contribute to the ability of the organ to perform its function.

Healing of either type is not an absolutely certain event, and under conditions that produce massive and extensive damage, may not occur, resulting in tissue necrosis.

The type of healing that occurs in an organ following radiation is a function of both dose and specific organ irradiated. Although repair can occur in any organ, whether acutely or late responding, regeneration occurs after low, moderate, and even high doses in organs whose cells are either actively dividing or retain the capability of division, such as skin, small intestine, and bone marrow (acutely responding normal tissues). In these organs, repair occurs only after high doses that destroy large numbers of parenchymal cells, rendering regeneration impossible or incomplete. On the other hand, late responding organs consisting of slowly dividing cells (e.g., lung and kidney) have minimal regenerative capabilities; therefore, moderate and high doses of radiation result mostly in repair.

An important factor in understanding the responses of different organs to radiation is time. Acutely responding normal tissues will show changes sooner than late responding organs exposed to the same dose; in fact, an acutely responding organ may manifest a severe response, while a

minimal response may be observed in a late responding organ exposed to the same dose and observed at the same time post-exposure. However, at a later time the reverse situation may be true. For example, irradiation of one lung (late responding) and the overlying skin (acutely responding) with a single dose of 20 Gy produces marked changes in the skin at 6 months postexposure, but lung changes are less severe. Observations at 1 year postexposure reveal minimal skin changes, but now the irradiated lung exhibits severe changes.

3. Clinical Factors Influencing Response

Because the response of each organ will be related to the three medical specialties using radiation, a word is necessary at this point concerning the doses received from each of these specialties. Low doses (less than 1 Gy) are generally delivered to only a portion of the patient's body by diagnostic radiography, fluoroscopy, and nuclear medicine. Patient doses in radiation therapy are much higher, usually on the order of 40 to 60 Gy. However, the total dose in radiotherapy is fractionated; it is split into many small daily doses administered over a period of time (generally 2 Gy/day over 4 to 6 weeks, a "standard" fractionation schedule). It is sufficient for our purposes here to realize that a dose administered in multiple fractions is biologically less effective than a single dose of the same magnitude (Chapters 6 and 7). In other words, most organs show less response if the total dose is fractionated than if given as a single dose.

Another vital factor in understanding clinical organ response is the relationship of volume. In general, although irradiation of part of an organ will elicit the same morphologic response in that specific area as in the whole organ exposed to the same dose, these two situations will have different consequences to the life of the individual. Irradiation of the whole organ may be life-threatening; however, a sufficient amount of undamaged organ may remain after only partial irradiation of a critical organ to ensure function and, therefore, life of the individual. Since this factor is of obvious clinical concern, particularly in radiotherapy, volume effects will be briefly discussed when appropriate.

4. General Organ Changes

In general, acute changes in most organs are characterized by inflammation, edema, and hemorrhage and a denudation of mucosal surfaces. Chronic changes consist of fibrosis, atrophy (decrease in size of

an organ), ulceration, stricture, stenosis, and obstruction. Pathologically, it is not possible to distinguish between secondary and primary chronic changes, and time is most likely the critical factor in distinguishing between these two chronic effects. Necrosis is the result of failure to repair damage by any means and represents the ultimate secondary chronic effect.

Specific organ response will be discussed by system. Because the general response of a system is determined by the most radiosensitive organ in that system, attention will be focused on the organ or organs that account for the changes.

5. Hemopoietic System

The hemopoietic system includes the bone marrow, circulating blood, lymph nodes, spleen, and thymus (these last three organs are termed lymphoid organs).

5.1. Bone Marrow

Bone marrow tissues include the parenchymal cells of the marrow, consisting of precursor (stem) cells and material end cells in the circulating blood, fat cells, and a connective tissue stroma. There are two types of marrow in the adult: red and yellow. Red marrow contains a large number of stem cells, in addition to fat cells, and is primarily responsible for supplying mature, functional cells to the circulating blood. In adults, red marrow is present in the following sites: ribs, ends of long bones, vertebrae, sternum, and skull bones. Yellow marrow, consisting primarily of fat cells with very few stem cells, is not active in supplying mature cells to the circulating blood and, due to the fat content, is commonly termed "fatty" marrow. Fetal bone marrow is predominantly red marrow, whereas in the adult, red marrow is located in specific sites.

The primary effect of radiation on the bone marrow is to decrease the number of stem cells. Low doses result in a slight decrease with recovery (stem cell repopulation of the marrow) occurring within a few weeks postexposure. Moderate and high doses produce a more severe depletion of cells in the bone marrow, resulting in either a longer period of recovery (time before repopulation of the marrow is complete) and/or less recovery – manifested as a permanent decrease in stem cell numbers and an increase in the amount of fat and connective tissue.

Although all stem cells in the bone marrow are very radiosensitive, variations in sensitivity exist among these different cells. Erythroblasts

(precursor cells for red blood cells) are the most radiosensitive; myelocytes (precursors for some white blood cells) are second in sensitivity; and megakaryocytes (precursors for platelets) are the least radiosensitive. This variation in sensitivity is manifested as a difference in the time of depression of counts in the different stem cells as follows: erythroblasts decrease first and return to normal approximately 1 week after a moderate dose, myelocytes are depressed in the same time period as erythroblasts but require a longer time to recover (2 to 6 weeks), and depression of megakaryocytes occurs at 1 to 2 weeks postexposure requiring a recovery time of 2 to 6 weeks. Low doses result in decreased stem cell numbers and fast recovery, whereas a more severe decrease in numbers in all cell lines occurs after moderate and high doses, with either slow recovery or incomplete recovery of cell numbers relative to pre-irradiated values.

5.2. Circulating Blood

With the exception of lymphocytes, the cells in the circulating blood are resistant to radiation (they are nondividing, differentiated cells). However, the circulating blood reflects radiation damage in the bone marrow; as the number of stem cells in the marrow decreases, a corresponding decrease will be exhibited in the number of the respective, mature circulating cells.

The reflection of bone marrow damage in circulating blood cells is dependent on two factors:

1. The sensitivity of the different stem cells.
2. The lifespan of each cell type in the circulating blood.

Although both these factors are important, the latter is more significant in terms of the time of appearance of changes in the circulating blood. All cells in the circulating blood have a finite lifespan (i.e., at certain times they die and must be replaced), varying on the average from 24 hours (granulocytes) to 120 days (erythrocytes). Damage to the respective stem cells in the bone marrow will be reflected in the circulating blood only when the mature cells die and must be replaced.

Lymphocytes decrease first (counts are affected by doses as low as 0.1 Gy), neutrophils are second (doses of 0.5 Gy are necessary to produce a decrease), and platelets and RBCs are third (at doses greater than 0.5 Gy; Fig 8-3). Lymphocyte counts will approach zero within a few days following a moderate dose, with full recovery occurring within a few months postexposure. Lower doses produce a slight depression of

lymphocytes, followed by recovery and a return of the lymphocyte count to pre-irradiated values.

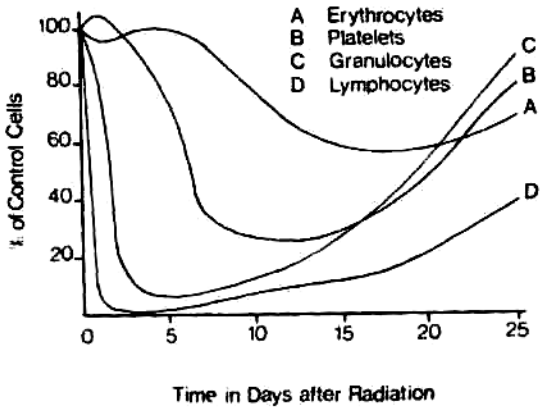


FIG 8-1.

Illustration of decrease in number of various blood cells in circulating blood of rat exposed to a moderate dose of total body irradiation. Note the order and time of depletion and recovery of the four cell lines.

Granulocytes counts fall to minimal values approximately 1 week following a moderate dose. However, recovery begins soon and neutrophil counts approach normal values within a month postexposure.

The lower doses in the moderate range will have a minimal effect on platelets and RBCs, but the higher doses of this range result in marked depression of these cells. Recovery begins later in these cell lines, approximately the 4th week postexposure, and is usually complete within a few months.

A decrease in the numbers of these various cells has implications for life. Granulocytes and lymphocytes are part of the body's defense mechanism and are important in fighting infection; a decreased number of these cells increases the individual's susceptibility to infection. A decrease in platelets (necessary for blood clotting) results in hemorrhage. Anemia follows depression of RBCs and is compounded by hemorrhage throughout the body.

5.2.1. Diagnostic Radiology – Radiation doses in the diagnostic range pose no major hazard to the blood and blood-forming organs of the patient or occupationally exposed personnel, in terms of decreased cell counts. However, chromosome changes have been observed in circulating lymphocytes following doses in this range.

5.2.2. Nuclear Medicine – Because radionuclides are primarily given intravenously for diagnostic purposes, the circulating blood is exposed to

radiation. Chromosomal changes may occur as a result of these doses, but the probabilities are small because of the small amount of radionuclide given and the consequent low dose to which the blood is exposed. In addition, any chromosome changes in the circulating cells will not be propagated due to the finite lifespan of the cells involved. Whether changes occur in stem cells is not known.

5.2.3. Radiation Therapy – When active bone marrow is in the treatment volume, doses in the therapeutic range will cause a depression of all blood cells, particularly white cells. For this reason blood counts should be routinely obtained on all patients receiving radiotherapy, particularly those receiving radiation to large volumes of tissue – e.g., in the treatment of Hodgkin's disease and ovarian cancer – or those in which the treatment field includes a large amount of red marrow.

6. Skin

The skin consists of an outer layer (epidermis), a layer of connective tissue (dermis), and a subcutaneous layer of fat and connective tissue. The skin is supplied with nutrients by blood vessels and contains specialized structures, e.g., hair follicles, sebaceous glands, and sweat glands, which arise in the dermis.

The epidermis is made up of layers of cells consisting of both mature, nondividing cells (at the surface) and immature, dividing cells (at the base of the epidermis – the "basal layer"). Cells are periodically lost from the surface of the skin and must be replaced by division of cells in the basal layer. The specific characteristics of the basal cells in the epidermis render the skin sensitive to radiation.

Acute changes in the skin following a moderate or high dose of radiation are inflammation, erythema (redness of the skin), and dry or moist desquamation (denudation of the skin surface). The skin erythema produced by radiation is not unlike that seen after prolonged exposure to the sun. Produced by an acute dose of 10 Gy, this particular reaction was at one time used as a yardstick to measure the amount of radiation to which an individual had been exposed. The term denoting that dose of radiation that causes this skin erythema is the *skin erythema dose (SED).*

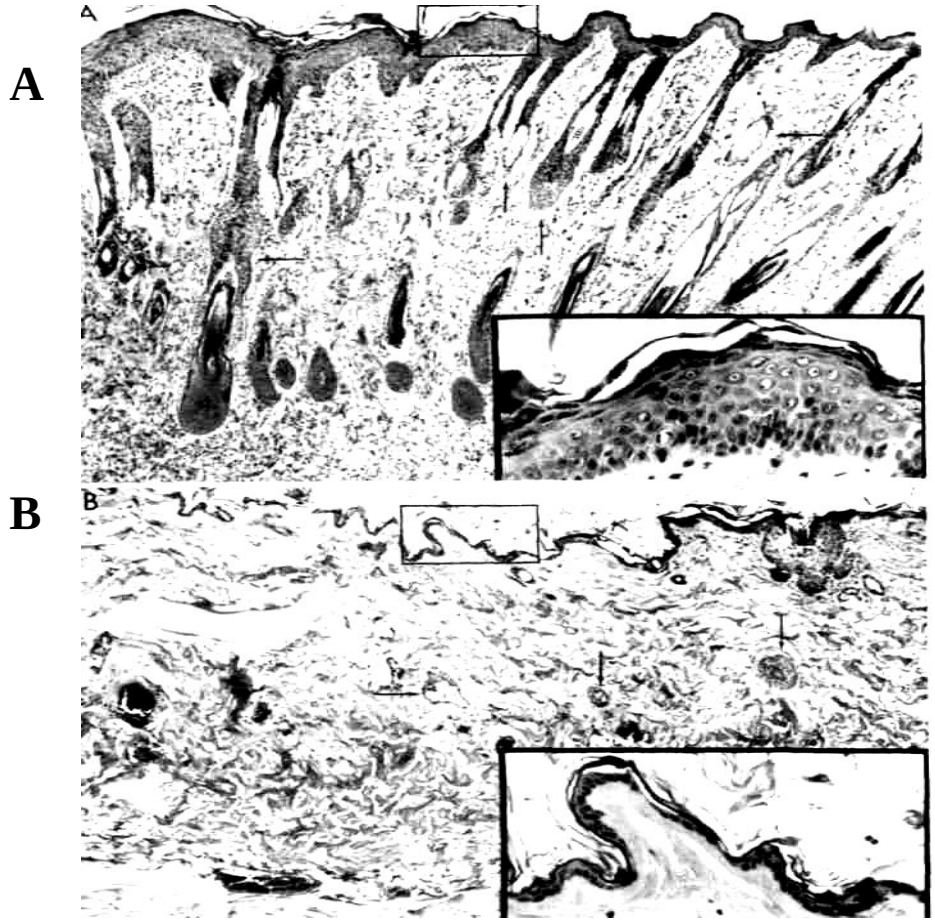


FIG 8-2.

*Photomicrograph of normal **(A)** and irradiated **(B)** rat skin exposed to 20 Gy to a localized area of the body; the animal was sacrificed 1 year postexposure. **Insets** show magnified views of the epidermis. Note the number of cell layers in the epidermis of the unirradiated animal, while that of the irradiated animal consists of only one cell layer. Normal skin contains numerous hair follicles and sebaceous glands (arrows), but the irradiated area contains only fibrotic accessory structures (arrows).*

Moderate doses permit healing to occur in the epidermis by regenerative means, resulting in minimal chronic changes. However, chronic changes such as atrophy (thinning of the epidermis, Fig 8-2), fibrosis, decreased or increased pigmentation, ulceration, necrosis, and cancer (the latter late effect appearing many years postexposure) may be seen after exposure to high doses.

1. Choose the correct word and fill in the blanks. Change the form if it is necessary.

occur/occurence

1. The _____ of cancer increases with age.
2. The accident _____ at about 3.30 p.m..

.

visible/visibility /visibly

1. _____ spectrum is the portion of the electromagnetic spectrum which is _____ to the human eye..
2. The patient was _____ affected by radiation.
3. In meteorology, _____ is a measure of the distance at which an object or light can be clearly discerned.

progress/progressive/ progression

1. People made no considerable _____ in solving the problems of air pollution.
2. As medical radiation technology continues to _____, many professionals find the need to take classes to stay current with the newest equipment.
3. A_____ is a gradual development from one state to another.
4. _____ stomach failure can be observed after high doses of irradiation.

heal/healing/healable

1. Creams and ointments with _____ and anti-inflammatory properties were applied freely on the raw surfaces of the injuries.
2. The are so
3. me problems concerning chronic radiation injury as well as how _____ such local and systemic injures acutely.
4. There is an opinion that any and all diseases under the sun are 100% curable or _____.
5. Doctors could potentially accelerate _____ by injecting extra signalling molecules into damaged tissue.

2. Match the terms and the definitions.

1) repair	a) a health problem that occurs months or years after a disease is diagnosed or after treatment has ended. It may be caused by

	cancer or cancer treatment an may include physical, mental, and social problems and second cancers;
2) late effect	b) adverse effect (due to exposure to a harmful substance) on animals or humans, whereby severe symptoms develop rapidly and lead quickly to a health crisis. These symptoms often subside when the exposure stops;
3) parenchymal cell	c) any cell that is a functional element of an organ, such as a hepatocyte;
4) acute effect	d) adverse effect on animal or human body with symptoms that develop slowly, due to long and continuous exposure to low concentrations of a hazardous substance. Such symptoms do not usually subside when the exposure stops;
5) chronic effect	e) the act or process of regenerating or the state of being regenerated; (p.108/p.2)
6) regeneration	f) to restore to a sound or healthy state.

6.1. Accessory Structures

Hair follicles, as an actively growing tissue, are radiosensitive, with moderate doses causing a temporary epilation or alopecia (synonyms for hair loss), while high doses may cause permanent epilation. Sebaceous and sweat glands are relatively radioresistant; damage after high doses produces glandular atrophy and fibrosis, resulting in minimal or no function (Fig 8 - 2).

6.1.1. Diagnostic Radiology – Doses from diagnostic radiographic and fluoroscopic procedures today pose no hazard in terms of the above-described changes (providing, of course, that proper precautions are taken). However, many of these changes, particularly erythema and cancer, occurred on the hands of pioneer workers in radiology. There are known cases of erythema produced in patients as a result of failure to place filtration in the beam.

6.1.2. Nuclear Medicine – No early or late skin changes have been observed on the hands of occupationally exposed persons in nuclear medicine, but hand doses are increasing due to both an increase in the number of procedures performed and the amounts of certain radionuclides used, e.g., ^{99m}Tc.

6.1.3. Radiation Therapy – Both the early and chronic changes described above have been observed in patients receiving radiation therapy, particularly when orthovoltage units were in widespread use. With today's high-energy units, chronic skin changes are minimal; fractionated doses in the range of 60 Gy in 6 weeks usually produce only atrophy of the irradiated area. Although atrophy does decrease the ability of the irradiated area to withstand trauma of any type, this is a relatively minor effect that can be circumvented if further treatment of the area is necessary. Severe necrosis is extremely rare today, and is never produced deliberately in practice. It may occur in an individual who is particularly sensitive to radiation due to unusual treatment protocols or to failure to follow the prescribed treatment plan (e.g., wedges not placed in the radiation beam when specified).

7. Digestive System

The alimentary canal consists, in part, of the mouth, esophagus, stomach, small intestine, large intestine, and rectum. The system is a closed tube throughout the body lined by a mucous membrane, which, like the skin, contains layers of cells, some of which are dividing and undifferentiated (radiosensitive), and some of which are nondividing and differentiated (radioresistant).

Moderate to high doses of radiation produce inflammation in the mucous membranes of the oral cavity (mucositis) and esophagus (esophagitis); however, healing occurs with minimal chronic changes after moderate doses, while high doses result in atrophy, ulceration, fibrosis, and esophageal stricture.

The stomach appears to be more sensitive than the esophagus, with moderately high doses producing ulceration, atrophy, and fibrosis. The small intestine is the most radiosensitive portion of the gastrointestinal (GI) tract. The lining of the small intestine forms fingerlike projections (villi) which aid in the absorption of digested materials into the bloodstream. The cells of this lining are nondividing and are sloughed (lost) from the tips of the villi daily and replaced by cells that arise from the crypts of Lieberkühn (nests of cells at the base of the villi – a rapidly dividing, undifferentiated stem cell population). Radiation damage in the small intestine is a result of damage to these cells.

Moderate doses of radiation result in shortening of the villi due to a killing of the crypt cells, followed by regeneration of these cells with a corresponding repopulation and healing of the villi. After high doses, more

cells are killed, minimal recovery occurs, the villi become shortened and flattened and the intestine may become denuded (complete loss of cells) leading to ulceration, hemorrhage, fibrosis, and necrosis (Fig 8-3).

Changes in and damage to the large intestine and rectum after high doses are similar to those already outlined; the rectum, along with the esophagus, appears to be much more resistant to radiation than the stomach or small intestine. Chronic effects in the intestine consist of intestinal strictures, obstruction, and adhesions.

7.1. Diagnostic Radiology and Nuclear Medicine – Neither diagnostic radiography and fluoroscopy nor radionuclide procedures deliver doses of a magnitude great enough to result in the type of changes detailed above.

7.2. Radiation Therapy – Changes in the digestive system have implications for radiotherapy. Esophagitis and mucositis commonly occur during and after treatment at doses of 10 to 20 Gy, but minimal chronic effects are observed even at total doses of 60 to 70 Gy. Irradiation of the small intestine is often unavoidable when treating certain diseases (e.g., ovarian cancer by moving-strip or whole-abdomen technique), but chronic effects are minimal. Early effects are often manifested by symptoms such as nausea, vomiting, and diarrhea. The incidence and severity of chronic effects in different parts of the GI tract increase with the total fractionated dose reflecting and the sensitivity of the individual organs. For example, 9% of the patients receiving 50 Gy to the colon develop partial obstruction, while at doses greater than 60 Gy, 25% develop this chronic change.

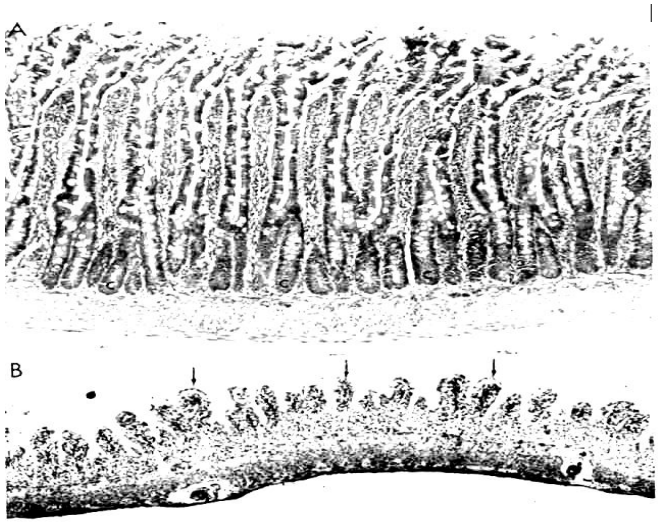


FIG 8-3. *Small intestine of a rat exposed to 20 Gy total body dose, sacrificed 5 days postirradiation.* ***A****, normal intestinal mucosa with typical long villi (V), and numerous crypts (C).* ***B****,*

edema and blunting of the villi, loss of crypts, and almost total denudation of the intestinal mucosa (arrows).

8. Reproductive System

8.1. Male

Most of the tissues of the male reproductive system, with the exception of the testes, are radioresistant. The testes contain both non-dividing, differentiated, radioresistant cells (mature spermatozoa) and rapidly dividing, undifferentiated, radiosensitive cells (immature spermatogonia). It is this latter cell population in the testes that accounts for the radiosensitivity of the system.

The primary effect of radiation on the male reproductive system is damage and depopulation of the spermatogonia, eventually resulting in depletion of mature sperm in the testes, a process termed *maturation depletion* (Fig 8-4). A variable period of fertility occurs after testicular irradiation, attributable to the radioresistance of the mature sperm, and is followed by temporary or permanent sterility, depending on the dose. Sterility is due to a loss of the immature spermatogonia, which divide and replace the mature sperm lost from the testes. Permanent sterility can be produced by an acute radiation dose in the moderate range (5 to 6 Gy), whereas a dose of 2.5 Gy results in temporary sterility (12 months' duration).

Another potential hazard of testicular irradiation is the production of chromosome aberrations that may be passed on to succeeding generations. The fertile period occurring postexposure does not exclude the possibility of chromosome damage in functional spermatozoa. Chromosome changes in the immature spermatogonia also cannot be discounted, and may either be propagated or eliminated through the many divisions needed to produce spermatozoa.

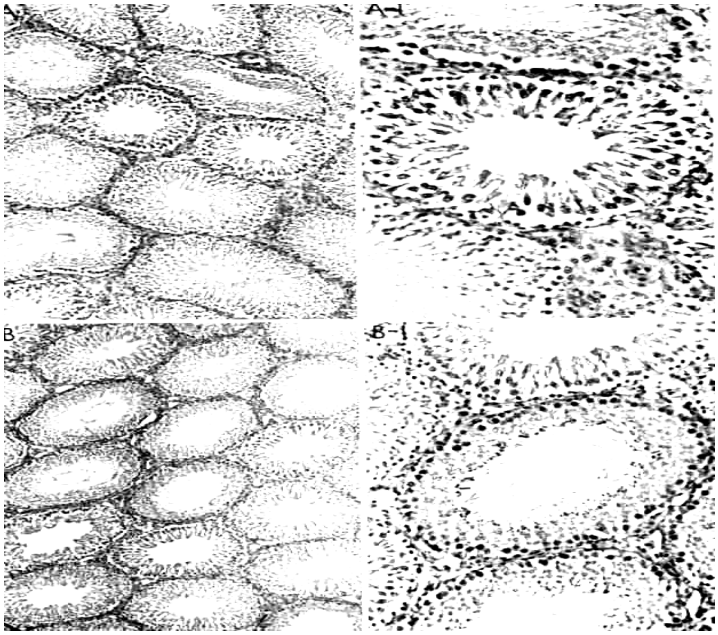
8.1.1. Diagnostic Radiology and Nuclear Medicine – These two clinical specialties involving acute low doses to patients and chronic low doses to personnel present no hazard in terms of sterility. These doses, however, may produce chromosomal changes, possibly resulting in mutations in future generations. For this reason, the utmost care should be taken to shield the testes from unnecessary radiation of all types.

8.1.2. Radiation Therapy – In contrast to diagnostic procedures, total doses administered in radiotherapy can produce sterility in addition to chromosomal changes. Every effort should be made to shield the testes

from scattered radiation when the treatment field is situated close to this tissue. In addition, the patient should be informed of the possibility of temporary or permanent sterility and be given procreation advice when the situation warrants it. Another point that must be clarified is that impotency is not caused by radiation-induced sterility.

FIG 8-4.

Testes from a rat exposed to 5 Gy total body radiation. ***A*** *and* ***A-1,*** *normal testes illustrating both immature and mature cell types.* ***B*** *and* ***B-1****, one week postexposure illustrating minimal changes; mature sperm are still present. (Continued.)*



8.2. Female

The ova are contained within saclike enclosures (follicles), designated by size as small, intermediate, and large, which vary in radiosensitivity as follows: intermediate follicles, most sensitive; small follicles, most resistant, and mature follicles, moderately sensitive. Unlike in the male, the reproductive cells in the female are not constantly dividing and replacing those lost through menstruation. An ovum is released from a mature follicle at ovulation, followed by either fertilization or menstruation. An initial period of fertility occurs after moderate doses of radiation to the ovaries, due to the presence of moderately resistant mature follicles that can release an ovum. This fertile period is followed by

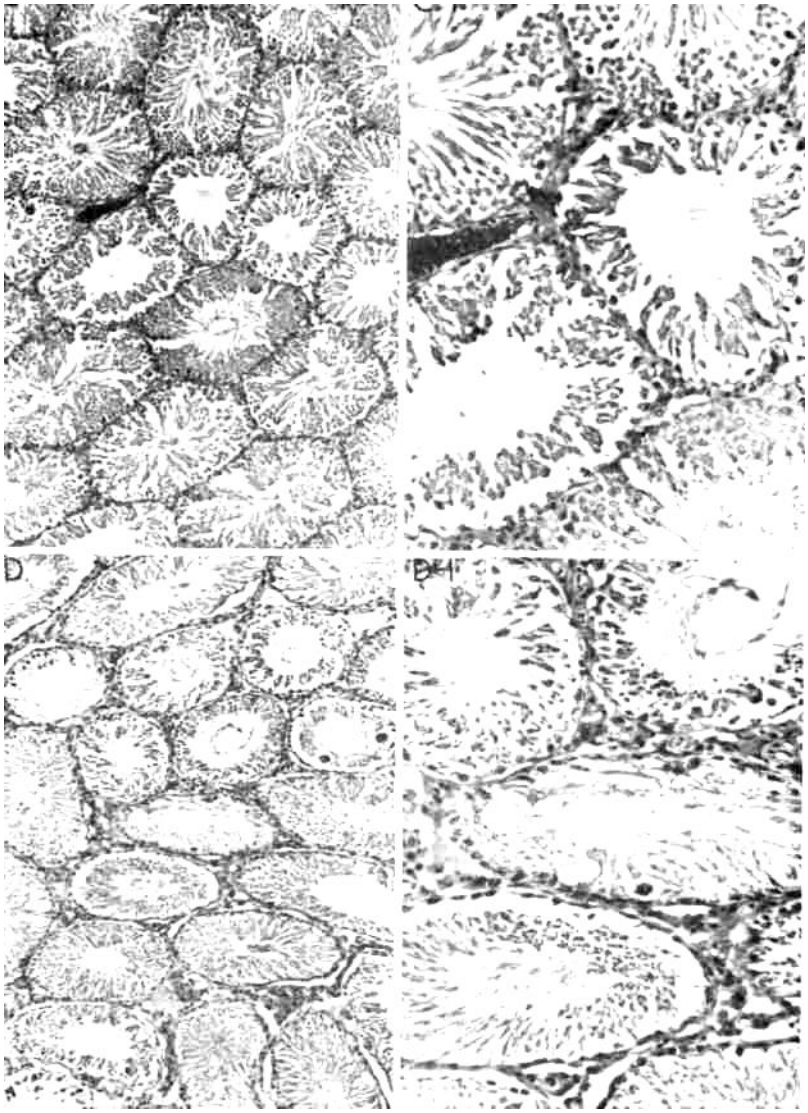


FIG 8-4 (cont.).

C *and* ***C-1,*** *three weeks;* ***D*** *and* ***D-1****, four weeks postexposure; both times exhibit disappearance of normal architecture, looseness in the appearance of the network, and a decrease in all cells, both precursor and mature, with a loss of polarity in the remaining cells.*

temporary or permament sterility resulting from damage to ova in the radiosensitive intermediate follicles, which inhibits their maturation and release. Fertility may recur due to the maturation of ova in the radioresistant small follicles.

Although the dose necessary to produce sterility in females is a function of age (a higher dose is necessary in young women than in older women), in general, a dose of greater than 6.25 Gy produces sterility in women.

Major concern arises over the possibility of genetic changes in functional ova after irradiation. Although fertility recurs after low and moderate doses, the possibility cannot be excluded that these functional

ova have incurred chromosome damage that may result in either grossly abnormal offspring or in offspring carrying nonvisible mutations that can be passed on to succeeding generations.

8.2.1. Diagnostic Radiology and Nuclear Medicine – As in the male, low doses received from diagnostic procedures do not produce sterility in the female, but may cause chromosome changes. Although the body forms a natural shield for the ovaries, precautions always should be taken to avoid unnecessary ovarian exposure whenever possible.

8.2.2. Radiation Therapy – Doses in the therapeutic range pose a double hazard: chromosomal damage and sterility. In addition, unlike in the male, where radiation-induced sterility does not produce effects in secondary sexual organs resulting in impotency, radiation sterilization of the female may produce an artificial menopause with marked effects on secondary genitalia and sexual characteristics. In the case of a malignant disease requiring irradiation of the ovaries, the patient should be informed of the possible consequences. Also, when sterility is not induced but the ovaries receive significant scattered radiation, procreation advice always should be given to the patient.

9. Cardiovascular System

9.1. Vasculature

Blood vessel damage may result in occlusion through two means: (1) damaged endothelial cells, or substances released from them, may stimulate division of undamaged cells in regenerative efforts (if too many cells are replaced, occlusion may occur); or (2) destruction of the endothelial cells may induce the formation of blood clots in the vessels (thrombosis). Small vessels, possibly due to their small lumens, are more radiosensitive than large vessels. These changes in blood vessels may be manifested in chronic changes such as petechial hemorrhages (pinpoint hemorrhages), telangiectasia (dilation of small terminal vessels), and vessel sclerosis (a type of fibrosis – actually, a hardening and concomitant loss of elasticity of the vessel wall).

Because blood vessels are responsible for the transport of oxygen and nutrients to all organs of the body, occlusion of the vessels can have serious consequences to any organ. A complete loss of oxygen and nutrients will result in necrosis of the cells and tissues of that organ. A partial loss of these substances may result in atrophy and fibrosis of the organ, with a corresponding decrease in functional ability and a generalized decreased ability to withstand trauma.

9.2. Heart

Although for many years the heart was believed to be radioresistant, closer appraisal of the response of the heart to radiation is throwing doubts on this thought. Although the heart is undamaged at low and moderate doses except for functional (EKG) changes, high doses can produce pericarditis (inflammation of the pericardium, the membrane covering the heart) and pancarditis (inflammation of the entire heart).

9.2.1. Diagnostic Radiology and Nuclear Medicine **–** Doses in these two clinical areas are not of sufficient magnitude to produce changes in the heart.

9.2.2. Radiation Therapy **–** The heart is often totally or partially included in the radiation field, e.g., in the treatment of malignant lymphomas and of the chest wall following mastectomy for breast cancer. Fractionated doses totaling 40 Gy produce the above changes in a small percentage of individuals, with the incidence increasing with increasing dose. When possible, the heart should be shielded during the entire treatment course, and particularly when total doses exceed 40 Gy.

10. Growing Bone and Cartilage

Although mature bone and cartilage are radioresistant, growing bone and cartilage are moderately radiosensitive. In general, mature bone is formed through the mineralization (calcium deposition) of cartilage. Growing bone and cartilage consist of both nondividing, differentiated cells (osteocytes, chondrocytes) and rapidly dividing, undifferentiated cells (osteoblasts, chondroblasts); the latter group accounts for the moderate sensitivity of these tissues.

Damage to both small blood vessels and bone marrow also plays an important contributing role in radiation injury to growing bone. Moderate doses of radiation produce temporary inhibition of mitosis and death of the proliferating immature cells. Recovery does occur at doses of this magnitude, resulting in minimal late damage.

High doses may produce a permanent inhibition of mitosis and destruction of proliferating cells, resulting in cessation of bone formation. Few early gross changes are evident in bone even at these high doses. However, alterations in shape and size of the bone and scoliosis are evident late changes.

10.1. Diagnostic Radiology and Nuclear Medicine – The low doses administered during these procedures do not result in the changes outlined above. However, the administration of bone-seeking radionuclides can cause these changes.

10.2. Radiation Therapy – Treatment of Wilms' tumor and neuroblastoma in children often unavoidably includes a growing bone in the radiation field, therefore producing bone abnormalities and scoliosis. Fractionated total doses greater than 20 Gy produce marked changes in the bones of children irradiated when less than 2 years of age. The incidence of bone abnormalities decreases with decreasing dose and increasing age at time of treatment.

11. Liver

The liver is usually considered part of the digestive system (an accessory gland essential to storage, metabolism and excretion of the products of the digestive process). For many years the liver was considered to be radioresistant, but current opinion is that the liver is a moderately sensitive, responsive organ.

The hepatic cells (parenchymal cells of the liver), while relatively resistant to radiation, do retain the capability of regeneration through mitosis. However, the liver has a large blood supply and a great number of both large and small blood vessels; for this reason, radiation injury to the hepatic cells is believed to be secondary to vascular changes.

Low and moderate doses produce little observable acute response; early changes after high doses are difficult to detect, except possibly through function studies. In some cases, the liver may be enlarged and fluid may accumulate in the abdominal cavity (ascites).

Delayed radiation effects in the liver, termed *radiation hepatitis,* are consequences of vascular sclerosis and consist primarily of fibrosis (sometimes called cirrhosis). The primary lesion observed in the human liver after irradiation is veno-occlusive disease, which impairs the function of the liver, resulting in liver failure and jaundice.

11.1. Diagnostic radiology and nuclear medicine – No observable response is detected in the liver subsequent to the doses delivered by these procedures.

11.2. Radiation Therapy – The liver, either totally or partially, is sometimes included in the treatment field, e.g., in the treatment of malignant diseases of the kidney, lymphomas, and ovarian cancer with

moving-strip or whole-abdomen technique. Doses in the clinical range produce radiation hepatitis, ranging from 35 to 45 Gy with a standard fractionation schedule. The clinical significance of this will depend on the volume of the organ irradiated.

12. Respiratory System

The respiratory system consists of the nose, pharynx, trachea, and lungs. Although considered relatively resistant to radiation, the lungs are actually responsive to radiation in the high dose range (greater than a single dose of 10 Gy).

The primary early change in the lungs after irradiation is inflammation, termed *radiation pneumonitis*. This is a transitory response after moderate doses, and recovery occurs with minimal damage. A high dose to both lungs produces a progressive reaction that may develop from an early pneumonitis to chronic fibrosis, an outcome that can certainly cause death (Fig 8-5).

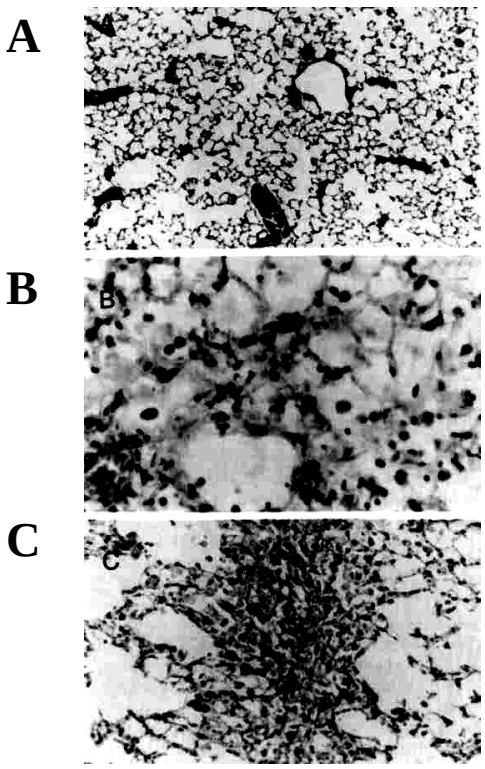


FIG 8-5.

*Lungs from an unirradiated mouse (**A**); 20 weeks after 13 Gy (~LD_{50}) (**B**); and at 52 weeks after a sublethal dose of 11 Gy (**C**). The acute response seen in **B** is termed radiation pneumonitis and occurs between 3 and 7 months after radiation, whereas the late fibrotic response in **C** occurs 9*

months after radiation. Pneumonitis is characterized by edema and cellular infiltrate, whereas the fibrotic response is a focal scarring process with the laying down of collagen.

12.1. Diagnostic Radiology and Nuclear Medicine **–** Radiation pneumonitis is not a response observed in the lungs after low doses.

12.2. Radiation Therapy – One lung is often the primary treatment area, or a portion of it may be included in the treatment field when other organs are irradiated, e.g., irradiation of the breast. Doses of 25 Gy to both lungs with a standard fractionation schedule may produce a progressive fibrosis in a small percentage (8%) of individuals treated. Increasing doses cause corresponding increases in the numbers of patients with this response, reaching 50% at a total dose of 30 Gy. The response is dependent on the volume irradiated; one lung can be given a higher dose than both lungs. Although fibrosis occurs in the irradiated lung, rendering it nonfunctional, the remaining, undamaged lung continues to function.

13. Urinary System

The kidneys, ureters, bladder, and urethra constitute the urinary system. Damage in the kidney, termed radiation *nephritis,* appears as a loss of tubules (Fig 8-6), with little change in the glomeruli. The kidney becomes atrophic and renal failure ensues.

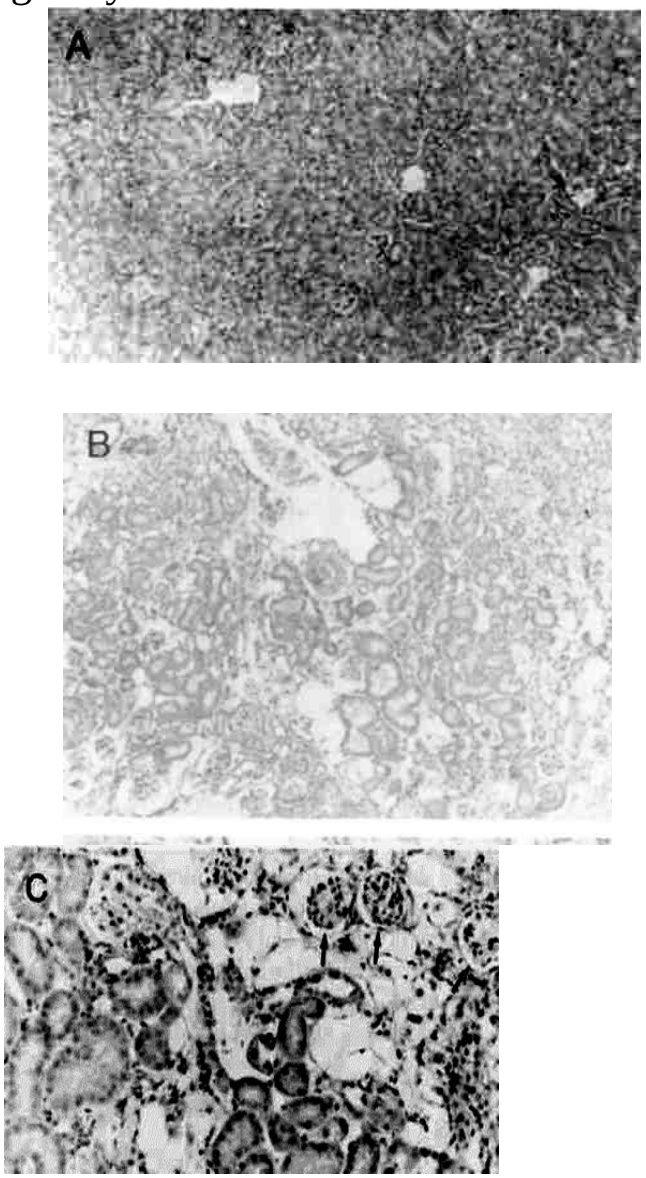
Work on the bladder by Stewart and her colleagues has shown that damage in the bladder of experimental mice does not occur before 6 months after large single doses, with the maximum damage expressed at 1 year after all doses. The major pathologic changes were epithelial denudation and loss of the specialized surface cells of the bladder. Fibrosis of the muscularis did not appear until after 12 months.

13.1. Diagnostic Radiology and Nuclear Medicine **–** Doses from diagnostic radiography, fluoroscopy, and nuclear medicine do not produce this response in the urinary system.

13.2. Radiation Therapy **–** When both kidneys are included in the treatment field, they must be shielded at a total dose of 26 Gy. The statistical incidence of these changes occurring increases sharply after this dose — 28 Gy to both kidneys in 5 weeks results in a high probability of fatal radiation nephritis.

As in the lungs, the volume irradiated plays an important role. Exclusion of one third of the kidney volume from the treatment field

greatly minimizes renal failure. When irradiation is given to only one kidney, the unirradiated kidney will continue to function if the irradiated one is surgically resected.



A

B

C

FIG 8-6.

*Histologic sections of kidney from a nonirradiated mouse (**A**) and a low-power view (**B**) and higher-power view (**C**) from an irradiated mouse. Note the empty holes in the kidney of the irradiated mouse, representing a loss of tubules. **C** shows glomeruli (arrows), which are surrounded by once existent but now destroyed tubules.*

14. Central Nervous System

The nervous system consists of the brain and spinal cord. In general, the cells of the various parts of the nervous system are nondividing differentiated cells, rendering them relatively radioresistant. In fact, the

nervous system is considered the most radioresistant system in the adult; therefore, low and moderate doses of radiation will result in minimal, if any, morphologic damage (however, some authors have reported functional changes at low doses).

Early changes in the CNS after high doses include inflammation (termed myelitis in the spinal cord), progressing to necrosis and fibrosis of the brain or spinal cord. These early changes are thought to be due to loss of glial cells, whereas the chronic changes are suggested to be of vascular origin. Of particular interest is the comparatively higher radiosensitivity of the white than the gray matter of the brain. The threshold level for radiation injury to the CNS is between 20 and 40 Gy.

14.1. Diagnostic Radiology and Nuclear Medicine – No observable changes result from doses of this low magnitude.

14.2. Radiation Therapy – Doses in the clinical range totaling 50 Gy can cause delayed radiation necrosis in the brain. Because brain irradiation occurs for treatment of brain tumors, it is often difficult to distinguish the effects caused by the tumor from those caused by irradiation. The response of the spinal cord varies with the volume and area irradiated; the cervical and thoracic cord are both more sensitive than the lumbar cord. The incidence of radiation myelitis increases at doses greater than 50 Gy given to small volumes and greater than 45 Gy to large volumes. This is of importance because the cord is often included in the treatment field of many diseases, e.g., lung cancer, cancer of the esophagus, Hodgkin's disease, and tumors of the head and neck region.

15. Eye

The lens of the eye contains a population of actively dividing cells that may be damaged and destroyed by radiation. Because there is no mechanism for removal of injured cells, those damaged cells form a cataract (lens opacity). Moderate doses of radiation (as low as 2 Gy) produce cataracts in a few individuals, with the incidence increasing to 100% in individuals exposed to an acute dose of 7 Gy. The degree of opacity is reflected as visual impairment, ranging from minimal impairment at 2 Gy, becoming progressive, and causing complete visual obstruction at higher doses. The frequency of cataracts varies with exposure to chronic and acute doses, with chronic doses producing a lower frequency of cataracts than acute doses.

15.1. Diagnostic Radiology **–** Because radiation is scattered to the eye during fluoroscopic procedures, occupationally exposed personnel may exhibit cataracts. More common in the early days of radiology when little knowledge existed of the biologic effects and hazards of radiation, cataracts are considered a late effect of radiation, appearing from 1 to 30 years postexposure. Although doses in diagnostic radiology today are much lower and equipment is vastly improved, precautions should be taken to shield the eyes during fluoroscopic procedures.

15.2. Radiation Therapy **–** Doses to the eye in the therapeutic range certainly can induce cataracts. The minimal cataract inducing dose appears to be a total of 4 Gy. Total doses of 12 Gy delivered by fractionated schedules induce cataracts in almost all patients, becoming progressive at 14 Gy. When treating lesions of the face located near the eyes, eye shields should always be used to reduce the formation and severity of cataracts.

Give Ukrainian equivalents of the terms:

Acute effects, chronic effects, hemopoietic system, bone marrow, circulating blood, diagnostic radiology, nuclear medicine, radiation therapy, skin, reproductive system, cardiovascular system, vasculature, heart, growing bone and cartilage, liver, respiratory system, urinary system, central nervous system, eye.

1. Complete the sentences:

- Normal tissues can be divided into two categories …
- The morphologic response of an organ or tissue after irradiation occurs in two general phases …
- The "acute" effect may occur …
- Chronic (late) effects may occur …
- "Primary" chronic effects …
- "secondary" chronic effects …
- Healing of a tissue or organ occurs by one of two means: …
- The type of healing that occurs in an organ following radiation is …
- Acute changes in most organs are characterized by …
- Chronic changes consist of …
- The primary effect of radiation on the bone marrow is …
- The reflection of bone marrow damage in circulating blood cells is dependent on two factors: …
- Acute changes in the skin following a moderate or high dose of radiation are …

- The primary effect of radiation on the male reproductive system is …
- Blood vessels are responsible for …

2. Guess the term:

1) the replacement of damaged cells in the organ by the same cell type present before radiation;
2) the replacement of the depleted original cells by a different cell type;
3) it is split into many small daily doses administered over a period of time;
4) it includes the bone marrow, circulating blood, lymph nodes, spleen, and thymus (these last three organs are termed lymphoid organs);
5) it contains a large number of stem cells, in addition to fat cells, and is primarily responsible for supplying mature, functional cells to the circulating blood;
6) it consists primarily of fat cells with very few stem cells, is not active in supplying mature cells to the circulating blood;
7) they are part of the body's defense mechanism and are important in fighting infection;
8) an outer layer of the skin;
9) it consists, in part, of the mouth, esophagus, stomach, small intestine, large intestine, and rectum;
10) it is the branch of medical science dealing with medical imaging. It may use x-ray machines or other such radiation devices. It also uses techniques that do not involve radiation, such as MRI and ultrasound;
11) it is concerned with the use of various imaging modalities to aid in the diagnosis of disease;
12) it is the medical use of ionizing radiation, generally as part of cancer treatment to control or kill malignant cells;
13) it is a medical specialty involving the application of radioactive substances in the diagnosis and treatment of disease.
(*radiology, radiation therapy, the fractionated dose, red marrow, epidermis, regeneration, yellow marrow, granulocytes and lymphocytes, repair, the hemopoietic system, nuclear medicine, the alimentary canal, diagnostic radiology*)

3. Give the opposite:

dividing, differentiated, radioresistant, mature, primary, male, population, temporary, fertility, acute, exclude, damaged.

4. Complete the sentences with *radioresistent* or *radiosensitive:*

1. All stem cells in the bone marrow are very … . 2. With the exception of lymphocytes, the cells in the circulating blood are … . 3. The specific characteristics of the basal cells in the epidermis render the skin … . 4. Although considered relatively … , the lungs are actually responsive to radiation in the high dose range. 5. Sebaceous and sweat glands are relatively … . 6. The stomach appears to be more … than the esophagus, with moderately high doses producing ulceration, atrophy, and fibrosis. 7. The small intestine is the most … portion of the gastrointestinal (GI) tract. 8. Most of the tissues of the male reproductive system, with the exception of the testes, are … . 9. The ova are contained within saclike enclosures (follicles), designated by size as small, intermediate, and large, which vary in radiosensitivity as follows: intermediate follicles, most …; small follicles, most …, and mature follicles, moderately … . 10. Small blood vessels, possibly due to their small lumens, are more … than large vessels. 11. The nervous system is considered the most … system in the adult. 12. The lens of the eye contains a population of actively dividing cells that are … . 13. For many years the heart was believed to be … . 14. For many years the liver was considered to be ... 15. Mature bone and cartilage are ..., growing bone and cartilage are ...

5. Render the following:

Легені. Легені є найбільш чутливим органом грудної клітини. Радіаційні пневмонити супроводжуються втратою епітеліальних клітин, які покривають дихальні шляхи альвеоли легенів, запаленням дихальних шляхів, альвеол легенів та кровоносних судин, що призводить до виникнення фіброзів. Такі ефекти можуть викликати легеневу недостатність і навіть загибель протягом декількох місяців після опромінення грудної клітини. Дані, отримані при проведенні променевої терапії показують, що порогові дози, які викликають гостру легеневу загибель, - близько 25 Гр рентгенівського чи гама-випромінювання, а після опромінення легень дозою 50 Гр загибель складає 100%.

Write as many terms as you can next to each letter of alphabet.

A	atom, attain
B	
C	chemical
D	
E	emit

F
G
H hydrogen
I
J
K
L
M measurement
N
O
P pollution
Q
R
S
T
U
V
W
X
Y
Z

Control points to Charter 8

1) Acute effects.
2) Chronic effects.
3) Regeneration.
4) Repair.
5) Clinical organ response.
6) Possible organ changes.
7) Types of marrow; the effect of radiation.
8) Blood cells; their reaction on irradiation.
9) SED. Medical Radiology.
10) Alimentary canal. Medical Radiology.
11) Male reproductive system. Maturation depletion. Medical radiology.
12) Female reproductive system. Sterility. Medical Radiology.
13) Damage of blood vessel. Heart. Medical Radiology.
14) Bone and cartilage. Medical Radiology.
15) Liver. Medical Radiology.
16) Respiratory system. Radiation pneumonitis. Medical Radiology.
17) Urinary systems. Radiation nephritis. Medical Radiology.
18) CNS. Medical Radiology.
19) Eye. Opacity (cataract). Medical Radiology.

Science vocabulary

1**. accessory structure** додаткова структура
2**. cartilage** хрящ
3. **causative agent** причинний фактор, збудник
4. **putative target cell** передбачувана клітина-мішень
5. **parenchymal cell** паренхімна (~ альна) клітина
6. **esophagus [i:sofəgəs]** стравохід
7. **esophagitis** езофагіт
8. **pneumonitis** пневмоніт
9**. alveolar** альвеолярний
10**. edema [iˈdimə]** набряк
11**. hemorrhage** [ˈheməriʤ] крововилив, кровотеча
12. **fibrosis [faiˈbrəvsis]** фіброз
13. **atrophy** атрофія
14. **ulceration** виразка, утворення виразки
15**. stricture** звуження судини (каналу)
16. **stenosis** стеноз
17. **obstruction** закупорка, запір
18**. lymph node** лімпфовузол
19**. thymus** тимус, вилочкова залоза
20**. lymphoid organ** лімфоїдний орган
21**. rib** ребро
22**. vertebra (e-pl.)** хребець, хребет
23. **sternum** грудина
24**. myelocyte** мієлоцити
25**. megacaryocyte** мегакаріоцит
26. **finite lifespan** обмежений життєвий цикл
27. **neutrophil** нейтрофіл
28. **ovarian cancer** рак яєчників
29. **subcutaneous layer [sʌbkju:ˈteiniəs]** підшкірний шар
30. **sebaceous gland** сальна залоза
31. **sweat gland** потова залоза
32. **desquamation** десквамація, лущення
33. **alopecia** алопеція, облисіння
34. **orthovoltage** ортовольтаж
35. **alimentary canal** травний тракт
36. **esophageal stricture** звуження стравоходу
37. **adhesion [ədˈhi:ʒn]** спайка
38. **saclike enclosure (follicle)** мішкоподібна оболонка (фолікул)
39. **ovum** яйцеклітина

PART II

ADDITIONAL READING

1.Interaction of ionising radiations with matter

1.1. Introduction

The whole of radiation protection is involved with the interaction of ionising radiations with matter. It is important for the radiation protection physicist to have a thorough knowledge of the physics of these processes in order to understand why particular techniques and materials are used for different applications and to enable him/her to develop solutions for new problems as they present themselves. This chapter gives an overview of the physics relating to ionising radiation. Radioactive decay is discussed briefly for completeness and the remainder of the chapter deals with interactions of radiation with matter. Areas of medical physics where properties resulting from different interactions are important are highlighted. More in-depth treatments can be found in texts on radiological physics and radiation dosimetry.

1.2. Radioactive decay

The mode of decay of a radioactive atom or radionuclide depends on whether the ratio of neutrons to protons in the parent nucleus is too high or too low and on the mass-energy relationship between parent and daughter nuclides. The various modes of decay and particles that can be emitted are described in Box 1.1. Individual atoms of a particular radionuclide may decay by emission of particles with different energies (Box 1.2) or even through more than one mode of decay. Data on emissions from different radionuclides are summarized in various handbooks. The changes in activity with time for all radioactive decay processes are governed by the same simple law. A physical half-life in which the activity will have dropped to one-half of the original value can be defined for every radionuclide. The half-life ($7_{1/2}$) is a statistical property and the law is only valid because of the large numbers of atoms involved.

From the definition of half-life:

$$A_n = A_0/2^n \qquad (1.1.)$$

where A_0 is the original activity and A_n the activity after *n* half-lives. The activity A_t at time *t* after the original activity A_0 was measured can be expressed as an exponential:

$$A_t = A_0 e^{-\mu} \qquad (1.2.)$$

The decay constant

$$\lambda = In\ 2/T_{1/2} = 0.693/T_{1/2} \qquad (1.3.)$$

or

$$\lambda = -(1/N)(dN/dt) \qquad (1.4.)$$

where dN is the change in the number of atoms (N) of a radionuclide during a short time interval d*t*. Useful rules of thumb are that the activity of any radionuclide is reduced to less than 1 % in 7 half-lives and less than 0.1% in 10 half-lives.

Activity is measured in terms of the becquerel (Bq), which is the amount of material in which one disintegration of a radioactive atom occurs every second. The old unit is the curie (Ci), equal to 3.7×10^{10} Bq. The specific activity is the number of becquerels per unit mass $[(0.693\times6.02\times10^{26})/(T_{1/2}\times\text{atomic mass})$ Bq $kg^{-1}]$ for a pure sample of the radionuclide.

1.3. Electron interactions

When a particle or a photon passes through a material it may interact with the electrons or the nucleus of an atom. The electrons surrounding the nucleus are arranged in orbitals or shells with discrete 'binding' energies. Successive shells are labelled alphabetically and can contain the following maximum numbers of electrons: K 2, L 8, M 18, N 32, and O 50. The binding energy of an electron in a particular shell depends on the charge on the nucleus and so is greater for elements with higher atomic numbers (Figure 1.1). These energies are characteristic of each element and are important in determining particle and photon interactions with different materials.

Energetic electrons may undergo a large number of interactions in matter. They collide with atomic electrons producing excitation and ionisation and they lose a small amount of energy each time. A small percentage of the interactions results in the production of X-ray photons.

Box 1.1. Radionuclide emission

Modes of decay

α-particle

α-particles consist of two protons (p) and two neutrons (n) and are emitted from heavy nuclei when the n/p ratios are too low. α-particles are monoenergetic because the energy released is shared entirely between the product nucleus and the α –particle.

β-particle

A β-particle is a high-energy electron emitted when a neutron is transformed into a proton within the nucleus. The energy released in the transition is shared between the β-particle and an anti-neutrino, so the β-particles from a particular decay may have an energy anywhere from zero up to the maximum (Figure B1.1). The average *β*-particle energy is about one-third of the maximum.

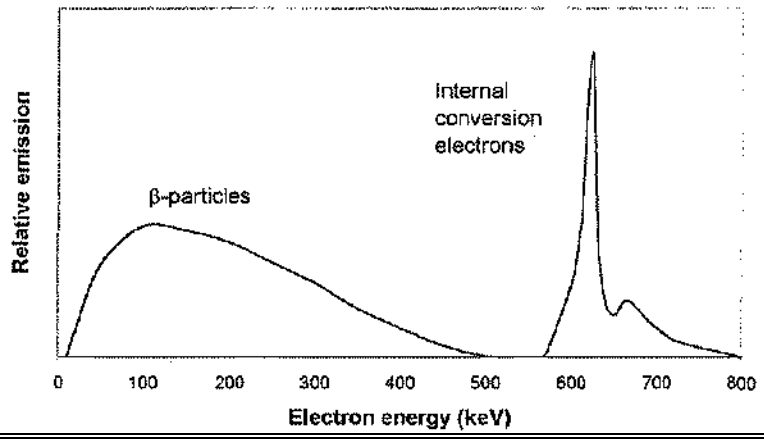


FIG B1.1. *Electron energy spectrum for ^{137}Cs showing the broad range of energies from β-particie emission with narrow peaks at 624 and 656 keV from internal conversion electrons.*

1.3.1. Bremsstrahlung X-rays

A bremsstrahlung X-ray may be produced as an energetic electron undergoes a violent change in direction, when it comes close to an atomic nucleus. This is the most important mechanism involved in the production of X-rays in an X-ray tube, although, the proportion of the energy from an electron beam that is converted into X-rays is less than 1%. The yield of bremsstrahlung X-rays is proportional to atomic number, so metals such as tungsten are used for X-ray tube anodes.

Bremsstrahlung X-ray photons have a range of energies from zero up to the energy of the interacting electron. When an electron strikes a thin sheet of metal, the probability of bremsstrahlung production at every energy up to the maximum is the same. However, when electrons hit the surface of a thick object, X-ray emissions may occur at some depth below the surface, and this alters the energy distribution. The electrons lose energy through minor interactions as they penetrate deeper, so the

Box1.1 (continued)

Positron

A positron *(β^+)* is a β-particle with a positive charge. It results from the transformation of a proton into a neutron and is accompanied by emission of a neutrino. The positron will dissipate its energy locally and then amalgamate with an electron to produce two *γ-rays* travelling in opposing directions (annihilation radiation) with energies equal to the mass equivalent of the positron and the electron (511 keV).

Orbital electron capture

A neutron-deficient atom may decay by capturing an orbital electron, which combines with an intranuclear proton to form a neutron. A characteristic X-ray will be emitted as an electron falls from an outer orbit into the energy level formerly occupied by the captured electron (§1.3.2).

Emission of excitation energy

Following a radioactive decay process, the nucleus may be left in an excited state. The nucleus can lose this excitation energy by emission of either γ-rays or internal conversion electrons.

γ-ray emission

γ-rays, emitted during radioactive decay are monoenergetic and are characteristic of the decay occurring. The lifetimes of nuclear excited states are typically of the order of 10^{-10} s, so γ-rays are usually emitted effectively at the same time as the nuclear transformations. However, in some cases quantum mechanical selection rules prevent photon emission for an extended period. The excited state of ^{99}Tc following the decay of ^{99}Mo has a half-life of 6.02 h before it makes the isomeric transition to the ground state. A nuclear excited state with a long half-life is termed metastable and is designated by the symbol m, e.g. ^{99m}Tc.

Internal conversion

Internal conversion is a process in which a tightly bound electron absorbs nuclear excitation energy and is ejected from the atom. Internal conversion electrons are monoenergetic (Figure B1.1). Characteristic X-rays are emitted during the process as outer orbital electrons fill the vacancies left by the internal conversion electrons (§1.3.2). Internal conversion occurs more frequently in heavy nuclei and γ-ray emission predominates in lighter ones.

maximum photon energy decreases with depth. In addition, the X-rays are attenuated before they emerge from the material, with the low-energy photons being attenuated more. Further attenuation occurs in the body of the X-ray tube itself. The net result is a continuous spectrum of X-ray energies between about 15 keV and the maximum electron energy,

with a peak near the middle (see Figure 1.8). Bremsstrahlung X-rays are also produced when high-energy β-particles interact with heavier materials.

Box 1.2. Energy level diagrams

Nuclear transitions can be portrayed as energy level diagrams. Comprehensive diagrams for all radionuclides are collected in ICRP. Figure B1.2. shows a much simplified example for ^{131}I. Ninety per cent of the atoms emit β-particles with energy of 0.61 MeV, and 10% with energy of 0.33 MeV. Both leave the daughter nuclide in an excited state and the additional energy is lost by emission of γ-rays (Box 1.1).

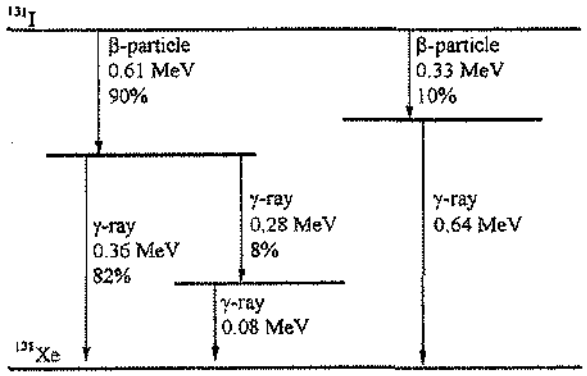


FIG B 1.2.

Energy level diagram showing decay scheme for ^{131}I. This is a simplification of the scheme in which each of the energy levels is split into subsidiary levels separated by a few tens of keV .

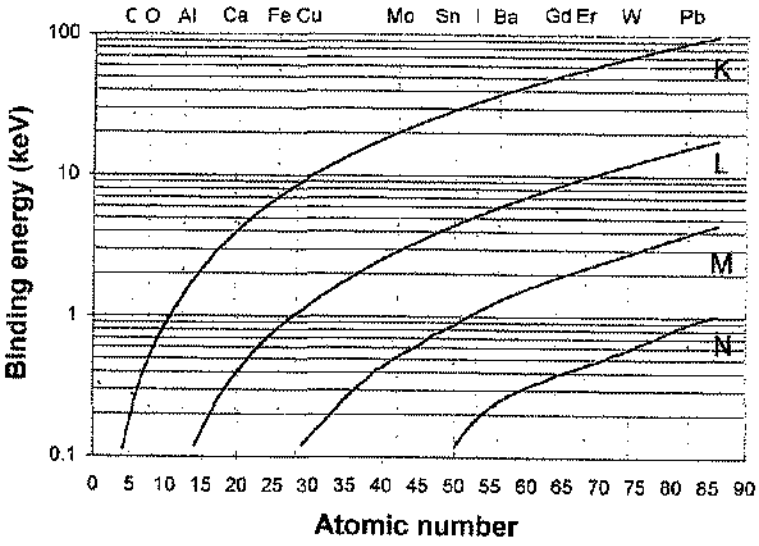


FIG 1.1.

Binding energies for electrons in the K, L, M, and N atomic shells as a function of atomic number. The energies equate to photoelectric absorption edges (§1.4.2) and the difference between energies of individual shells relate to energies of characteristic X-rays (§1.3.2). Positions of elements which are important for medical applications are marked.

The average energy (E_{av}) of bremsstrahlung produced by β-particles with a maximum energy E_β keV, when interacting with a material of atomic number Z, will be approximately

$$E_{av} = 1.4\times10^{-7} Z E_\beta^2 \text{ keV.} \qquad (1.5.)$$

1.3.2. Characteristic X-rays

When an electron from an inner K or L shell of an atom has been ejected or excited, this leaves a vacancy which may be filled by an electron falling from a shell with a lower binding energy (L, M, or outer shells). The excess energy is emitted in the form of an X-ray photon. The energies of each shell vary with the atomic number (Figure 1.1) and the energies of the X-rays emitted are characteristic of that element. For low atomic number elements in soft tissue, the energies are small and the X-rays are absorbed rapidly.

1.3.3. Auger electrons

An atom in which an L electron makes a transition to fill a vacancy in the K shell does not always emit a characteristic X-ray, particularly in low atomic number elements. The energy may be transferred to another L electron which is then ejected from the atom (KLL emission). The ejected electron is called an Auger electron and the process leaves an additional vacancy in the L shell. As the atomic number increases, LMM and MNN transitions can also occur.

1.4. Interactions of X-rays and γ-rays with matter

The interaction of photons with atoms in matter is random, but it is possible to specify the probability of an interaction occurring. Each atom can be regarded as having a cross-section or an apparent area which if traversed will lead to an interaction. One consequence of this is that a thickness of a material can be specified in which there will be a certain fractional change in radiation intensity. This can be expressed in terms of a linear attenuation coefficient (μ) or a mass attenuation coefficient (μ/p) as

$$I_x = I_0\, e^{-\mu x} = I_0\, e^{-(\mu/p)px} \qquad (1.6.)$$

where I_0 is the incident intensity and I_x is the intensity after traversing thickness x of the material (density p).

X-rays and γ-rays covering a range of energies may interact with matter through several mechanisms. Five processes will be considered; Rayleigh or coherent scattering, the photoelectric effect, Compton

scattering, pair production, and photonuclear interactions, which have linear attenuation coefficients represented by σ_{coh}, τ, σ_c, k, and τ_{nucl} respectively.

1.4.1. Rayleigh scattering

An incident photon collides with an electron which is bound tightly enough to the nucleus for the whole atom to absorb the recoil. The photon is scattered in a different direction but the transfer of energy to the atom is negligible. The interaction occurs more frequently when the atomic number (Z) of the scattering material is high ($\sigma_{coh}/p \propto Z^2$) and is only important in tissue for photons with energies $(E) < 10$ keV ($\sigma_{coh}/p \propto 1/E^2$) (Figure 1.2.).

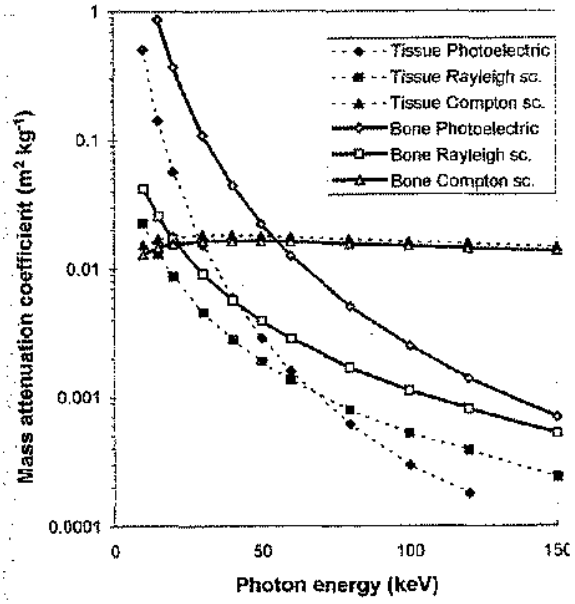


FIG 1.2.

Attenuation coefficients for photoelectric absorption, and Compton and Rayleigh scattering for interactions with soft tissue and cortical bone as a function of photon energy.

1.4.2. Photoelectric effect

This effect dominates at low photon energies. All the energy from an incident photon is absorbed and transferred to an electron which is ejected from an inner shell of the atom. A characteristic X-ray is emitted as an electron from a higher orbital fills the vacancy (§1.3.2). There are discontinuities in the variation of the photoelectric absorption coefficient with photon energy at the binding energies of the ejected electrons. When the photon energy is slightly greater than that required to remove an electron from a particular shell, there is a sharp increase in the photoelectric absorption coefficient (Figure 1.3), which is referred to as an absorption edge. The probability of interaction decreases rapidly as photon energy increases above an absorption edge $(\tau/p \propto E^{-3})$. Energies of absorption edges associated with K shells of elements with atomic numbers greater than 30 lie in the diagnostic X-ray range (10-100 keV)

(Figure 1.1). They are important in the selection of materials for intensifying screens, contrast agents, and filters.

Mass attenuation coefficients for some materials used for shielding diagnostic X-ray rooms are shown in Figure 1.4. Since the K-edge of lead lies in the upper part of the diagnostic energy range and the attenuation falls to one quarter at energies below the K-edge, care is required in considering relative attenuation properties of different shielding materials.

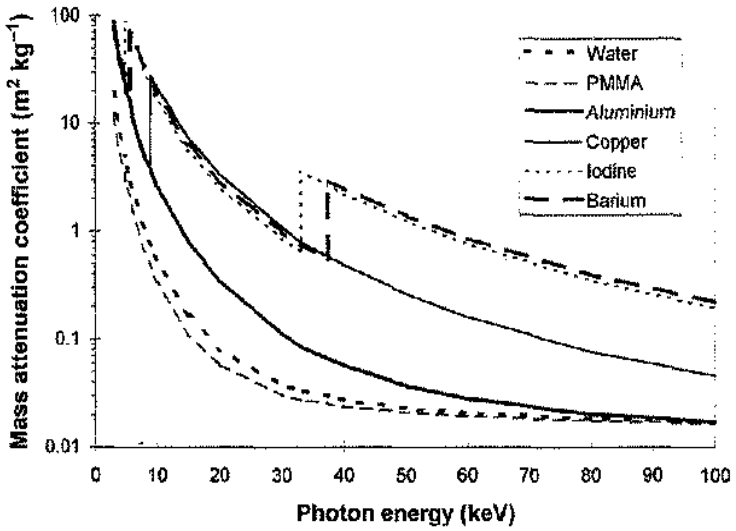


FIG 1.3.

Plots of mass attenuation coefficients (μ/p) (m^2 kg^{-1}) against photon energy for materials used in X-ray test phantoms (water, PMMA, or perspex), beam filters (aluminium, copper), and contrast agents (iodine, barium).

Contrast in diagnostic radiology

K-edges of elements present in tissue are below the diagnostic X-ray energy range (Figure 1.1.) and so the probability of photoelectric interaction decreases rapidly with photon energy (Figure 1.2).

Photoelectric absorption is the most important mode of interaction for elements in soft tissue up to 30 keV. The probability of photoelectric interaction in this energy range increases with atomic number *($\tau/p \; \alpha \; Z^3$).* It is the mechanism responsible for the large difference in attenuation between calcium (which makes up 14% of bone) and the lighter elements in soft tissue (Figure 1.2) and thus primarily responsible for the contrast in an X-ray image. Preparations containing elements with their K-edges in the diagnostic energy range (iodine 33 keV, barium 37 keV) are used to enhance X-ray contrast for the study of vessels in the body (Figure 1.3). The best contrast in an X-ray image is obtained where the photoelectric effect predominates, but because the energy absorption is high, the radiation dose to the tissue is also greater.

1.4.3. The Compton effect

The Compton effect involves an interaction in which a portion of the energy from a photon is transferred to a loosely bound or free electron (i.e.

the electron binding energy (Figure 1.1) is much less than the energy of the photon). Energy and momentum are conserved and the angles at which the electron and scattered photon travel are determined by the amount of energy transferred. Compton scattering is the predominant mode of interaction in soft tissue between 30 keV and 10 MeV. The Compton mass attenuation coefficient (σ_c/p) is approximately constant in the energy range of diagnostic X-rays (Figure 1.2). Thus attenuation by Compton scattering is closely related to the tissue density, but is independent of atomic number Z. This relationship is utilized in computed tomography in which images relating to tissue density are reconstructed from X-ray transmission measurements. A higher energy X-ray beam (120-140 keV) is used, which is heavily filtered to remove the majority of the lower energy photons that would interact via the photoelectric effect.

The Compton mass attenuation coefficient starts to decline at photon energies above 100 keV $(\sigma_c/p \propto E^{-1})$. This decline can be seen in Figure 1.4 for the mass attenuation coefficients for concrete and iron between 200 and 2000 keV, for which attenuation is predominantly due to Compton scattering.

It is instructive to consider the variation in Compton interactions with scattering angle, as this is relevant to radiation protection. The collision differential cross-section of the Klein-Nishina equation for the Compton effect can be used to predict the angular distribution of scattered photons for different incident photon energies resulting from interaction with a free electron (Figure 1.5a). This shows that:

• the probabilities of forward or backward scatter are greater than that through 90°

• the number of photons scattered in the forward and backward directions is almost symmetrical for low energy X-rays (30-40 keV), but as photon energy increases, more are scattered in the forward direction.

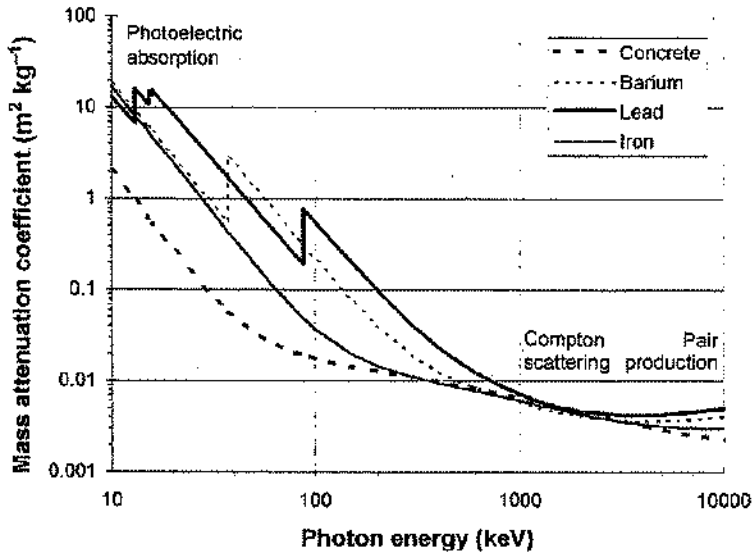


FIG 1.4.

Plots of mass attenuation coefficients (μ/p) (m^2 kg^{-1}) against photon energy for various shielding materials used in diagnostic radiology and radiotherapy. Positions where photoelectric absorption, Compton scattering, and pair production predominate are marked.

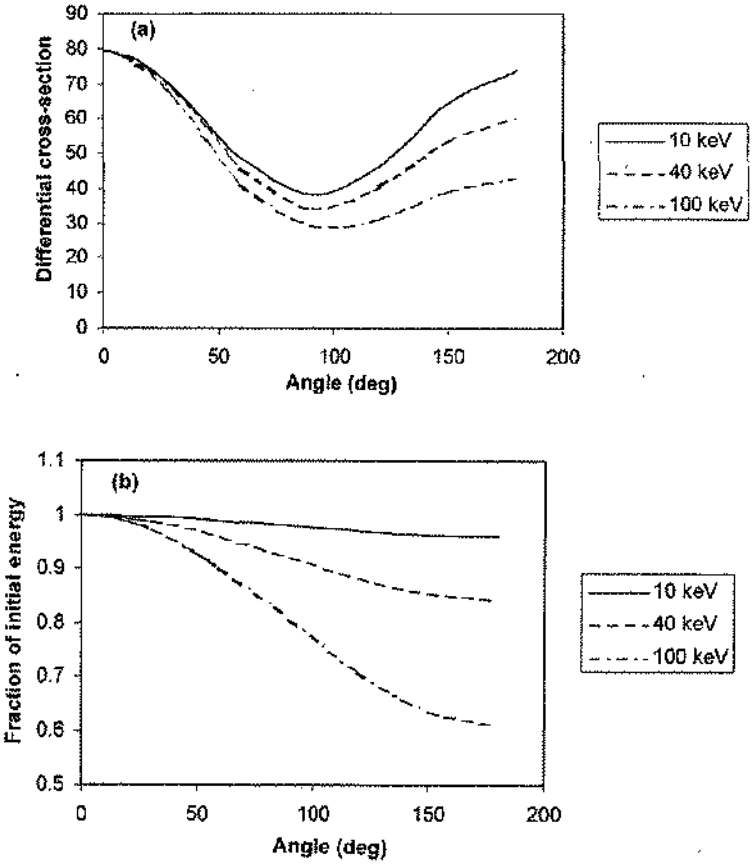


FIG 1.5.

Variation of Compton scatter from a single unbound electron with angle of scatter (0° = no deflectio) for monoenergetic photons: (a) differential collision cross section in units of 10^{31} m^2 steradian^{-1} per electron; (b) proportion of the interaction energy retained by the photon following scattering.

The change in wavelength ($\Delta\lambda$) for a photon scattered through angle θ is given by:

$$\Delta\lambda = (h/m_e c)\,(1 - \cos\theta). \qquad (1.7.)$$

The energy loss increases with scattering angle and with photon energy as shown in Figure 1.5b. Some consequences of this relationship are:

• photons scattered in the forward direction only lose a small proportion of their energy;

• photons that are scattered back towards the surface have a lower energy than those scattered in the forward direction;

• the proportion of the energy lost by the incident photon increases with photon energy, e.g. for a photon scattered at 60°, the proportion of the energy taken up by the electron varies from *5%* at 60 keV, to 9% at 100 keV, and 50% at 1 MeV.

The relationships considered are for interactions with a free electron. However, where the body is irradiated, the distribution of photons is determined by attenuation of the scattered photons in the body tissues and the implications of this for radiation protection are considered in §1.5.2.

1.4.4. Pair production

Pair production is the conversion of a photon to an electron-positron pair. This effect dominates at high photon energies (> 5-50 MeV). Energy greater than 1.02 MeV is required, which is the energy equivalence of the masses of a positron and an electron. Additional energy is distributed evenly between the two particles. The positron amalgamates with an electron to produce annihilation radiation (Box 1.1). Thus 1.02 MeV of energy is radiated again and only the kinetic energy of the electron and positron is absorbed. The probability of pair production *(k/p)* increases with photon energy *[k/p α (E - 1.02 MeV)],* unlike the other three types of process.

The interaction is more likely to occur in the vicinity of a heavy nucleus and the mass attenuation coefficient is proportional to Z. As a result, differences in mass attenuation coefficients between heavier and lighter shielding materials are more pronounced above 3000 keV, where pair production predominates for heavier materials (Figure 1.4.).

1.4.5. Photonuclear interactions

Photons interacting with a nucleus may induce the emission of a neutron or proton, if the photon energy is sufficient. For most stable nuclei heavier than carbon the threshold energy lies between 6 and 16 MeV. The threshold is 6.3 MeV for ^{235}U, 7.4 MeV for ^{108}Pb, and 10.8 MeV for ^{63}Cu, but tends to be higher for lower atomic number materials. The cross-section for neutron production rises to a maximum at 12-24 MeV, falling off at higher energies, but the interaction never makes up more than a few per cent of the total attenuation. Significant numbers of neutrons are produced through this mechanism by linear accelerators operating above 10 MV.

1.4.6. Attenuation and absorption coefficients

The interaction processes occur independently and the resultant transmitted intensity can be expressed in terms of the linear attenuation coefficient μ as:

$$I_x = I_0 e^{-\mu x} = I_0 e^{-\sigma coh\, x}\, e^{-\tau x}\, e^{-\sigma c x}\, e^{-k x} \qquad (1.8.)$$

or in terms of the mass attenuation coefficient (μ/p) where p is the density:

$$I_x = I_0 e^{-(\mu/\rho)\rho x} = I_0 e^{-(\sigma coh/\rho + \tau/\rho + \sigma c/\rho + k/\rho)\rho x} \qquad (1.9.)$$

The mass attenuation coefficient includes energy carried away by the scattered Compton photon and lost as annihilation radiation from pair production. It is useful to define a mass transfer coefficient μ_{tr}/ρ ,excluding these components, that relates to the photon energy transferred to charged particles as kinetic energy which is linked to kerma (§1.7.3.). Not all the energy transferred to charged particles is absorbed, as a small fraction g is converted again to photon energy (bremsstrahlung, §1.3.1), so the coefficient for mass energy absorption μ_{en}/ρ is given by

$$\mu_{en}/\rho = (\mu_{tr}/\rho)(1-g) \qquad (1.10.)$$

1.5. Practical implications of photon interactions

The interactions of photons of different energy with matter affect diagnostic radiology imaging techniques, influence the choice of materials for use with X-rays, and have implications for radiation protection. This section deals with some of these issues.

1.5.1. Influence of photoelectric interaction on materials for filters and phantoms

Interaction mechanisms and the resulting attenuation and absorption coefficients influence the choice of materials for applications such as filters and phantoms. Materials which have K-edges at the bottom of the diagnostic X-ray energy range will absorb low-energy photons more strongly through the photoelectric effect. Aluminium (K-edge 1.6 keV) has traditionally been used to filter X-ray beams, but copper (K-edge 9.0 keV) attenuates photons in the energy range above 9 keV more strongly (Figure 1.3.) and is used to reduce skin dose. Some rare earth materials with L absorption edges in this range and K-edges at the upper end of the diagnostic X-ray energy range (e.g. Er: L-edge, 8.7 keV; K-edge, 57.5 keV) have been used for filters to produce a beam with a narrower photon energy spread. Copper is used to harden X-ray beams for equipment tests, such as measurement of image intensifier dose rates. The high attenuation due to the photoelectric effect enables a smaller amount of material to be

used and gives a much smaller scattered component than tissue. However, there will be differences in the spectrum of X-rays transmitted by copper and tissue (Figure 1.3.), and where this is important, because of differences in detector energy sensitivities (e.g. testing of AEC system), more tissue equivalent materials should be used.

The energies of absorption edges, which equate to removal of an electron from an atom, are slightly greater than the energies of the characteristic X-rays, which are equal to the difference in energy between the energy level and higher energy states (§1.3.2.). As a result, materials are relatively transparent to their own characteristic X-rays. This property is used in mammographic equipment, where a molybdenum anode is used with a filter of the same material to enable the characteristic X-ray peaks to be utilized.

1.5.2. Scattered radiation in diagnostic radiology

Compton scattering is the source of the majority of the radiation dose to staff in diagnostic radiology as well as the reason of the diagnostic quality of the radiograph degrading. Knowledge of the distribution of scattered radiation around a patient is important for the protection of staff and for determining shielding requirements. Variations in the scattering cross-section and energy for monoenergetic photons scattered from single unbound electrons are shown in Figure 1.5. However, the X-ray spectrum is not monoenergetic and, in addition, all photons scattered following an interaction in a patient will undergo further interactions, both photoelectric and Compton, within the patient. As a result, it is not possible to use simple analytical techniques to describe the distribution of scattered radiation around a patient. The problem must be approached either by using direct measurements or by seeking numerical solutions using Monte Carlo methods.

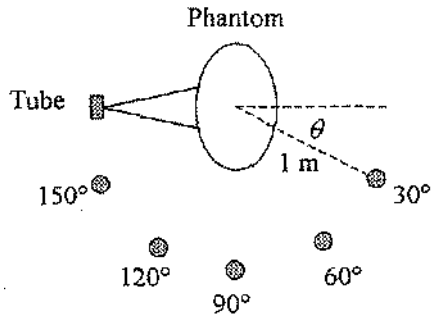


FIG 1.6.

Arrangement used to simulate and measure scatter of an X-ray beam from a body.

Numerical and experimental determinations of the distribution of scattered radiation have been determined using the geometry shown in Figure 1.6 and both yield similar results. Figure 1.7 shows a generalized form of the distribution of scatter around the phantom. Since the amount of scatter produced depends on the volume irradiated, it is proportional to the area of the X-ray beam at the surface of the phantom. Therefore, scatter dose is shown normalized with respect to the easily measured quantity dose-area product. For all values of kVp, the lowest scatter dose (i.e. fluence) occurs at small angles and the greatest as the scattering angle approaches 180°. It is possible to fit a polynomial to describe analytically the scatter distribution function and thus define the scatter fluence at any angle. This approach has been used to determine the scatter levels against which shielding is required for X-ray rooms.

The spectrum of the scattered radiation will vary with direction because of the characteristics of the Compton interaction process (§1.4.3.) and also because of the differing levels of attenuation within the phantom in different directions. Plots of the distribution of photon energies in the incident beam and scattered radiation in two directions are shown in Figure 1.8. The radiation that is scattered at 30° has a greater proportion of higher energy photons than that scattered at 120° and consequently a higher average energy, although the scatter fluence at 120° will be much greater.

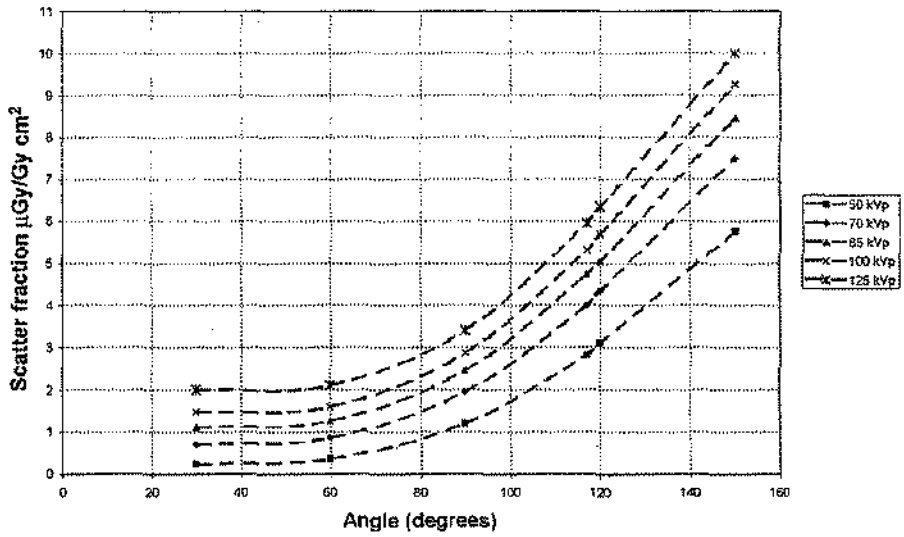


FIG 1.7.

Variation in scattered air kerma per unit dose-area product with angle of scatter for X-ray beams of different energies.

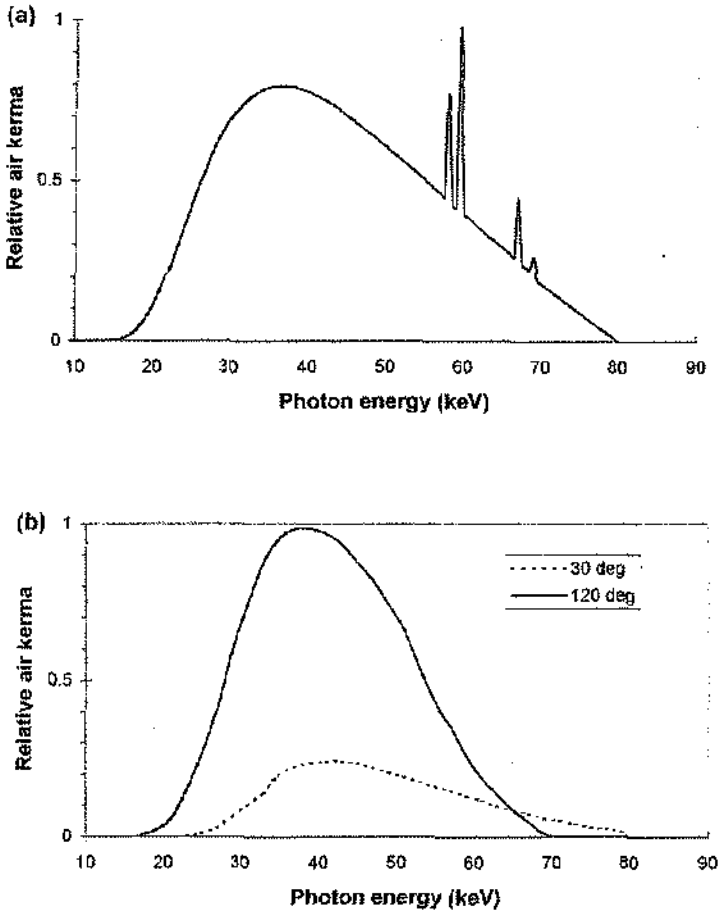


FIG 1.8.

Spectra of (a) an 80 kVp X-ray beam produced from a tungsten target filtered by 3 mm of aluminium and (b) the radiation scattered at angles of 30 and 120 from a phantom simulating a human trunk. Units are arbitrary.

The same pattern is observed for all accelerating potentials. The variation of the photon energy distribution (or quality) of the scattered radiation is shown in Figure 1.9. The quality is commonly expressed in terms of the thickness of aluminium to reduce the air kerma by half, or the half-value layer (HVL). The HVL of the scattered radiation is described by a curve which is opposite in sense to that observed for scatter fluence. These results show that for scattering of X-rays from a body:

- the greater the scattering angle, the greater the scattered air kerma
- the greater the scattering angle, the lower the HVL of the scattered radiation
- the spectrum of X-rays scattered back from the patient is softer than the incident X-ray beam (lower HVL) as the proportion of high-energy photons is lower
- the spectrum of X-rays passing through a patient after scattering through angles less than 60° is harder then the incident X-ray beam.

1.6. Neutrons

1.6.1. Neutron production

There are no radionuclides that emit neutrons, other than a few nuclear fission fragments with very short half-lives and certain heavy radionuclides, which decay by spontaneous fission, such as ^{252}C. Neutrons are produced by nuclear reactions and the largest sources of neutrons are nuclear reactors and particle accelerators. The interaction of α-particles with certain nuclides such as ^{9}Be can be used to make small neutron sources. The α-particle enters the Be nucleus to form a compound nucleus which disintegrates, emitting a neutron. Thus a neutron source can be made by mixing ^{9}Be with an α-particle source such as ^{24l}Am. The neutrons produced by this type of source have a range of high energies.

$$^{9}_{4}\mathbf{Be} + ^{4}_{2}\mathbf{He} \rightarrow ^{13}_{6}\mathbf{C} \rightarrow \text{compound nucleus} \quad ^{12}_{6}\mathbf{C} + \mathbf{n} \qquad [^{9}\mathbf{Be}\ (\alpha, \mathbf{n})\ ^{12}\mathbf{C}]$$

1.6.2. Neutron interactions

Neutrons are divided into two classes, fast neutrons which have energies over 0.1 MeV and thermal neutrons which have the same average kinetic energy as gas molecules in the environment. All neutrons produced by nuclear reactions are fast. They lose energy by collision with atomic nuclei and when they have been slowed down to thermal energies, they are captured by nuclei. The most important collision interaction is elastic scattering in which the kinetic energy of the neutron is shared with the collision nucleus.

When a neutron undergoes an elastic interaction, the energy change is given by

$$\Delta E = E_0 - E_f = E_0\,[1-(M-m)^2/(M+m)^2]\,\cos^2\theta = E_0\,4Mm/(M+m)^2\cos^2\theta \quad (1.11)$$

where *Eo* is the initial energy of the incident neutron, E_f is the final energy of the neutron, θ is the angle of recoil, and *M* and *m* are the masses of the scattering nucleus and the incident neutron, respectively.

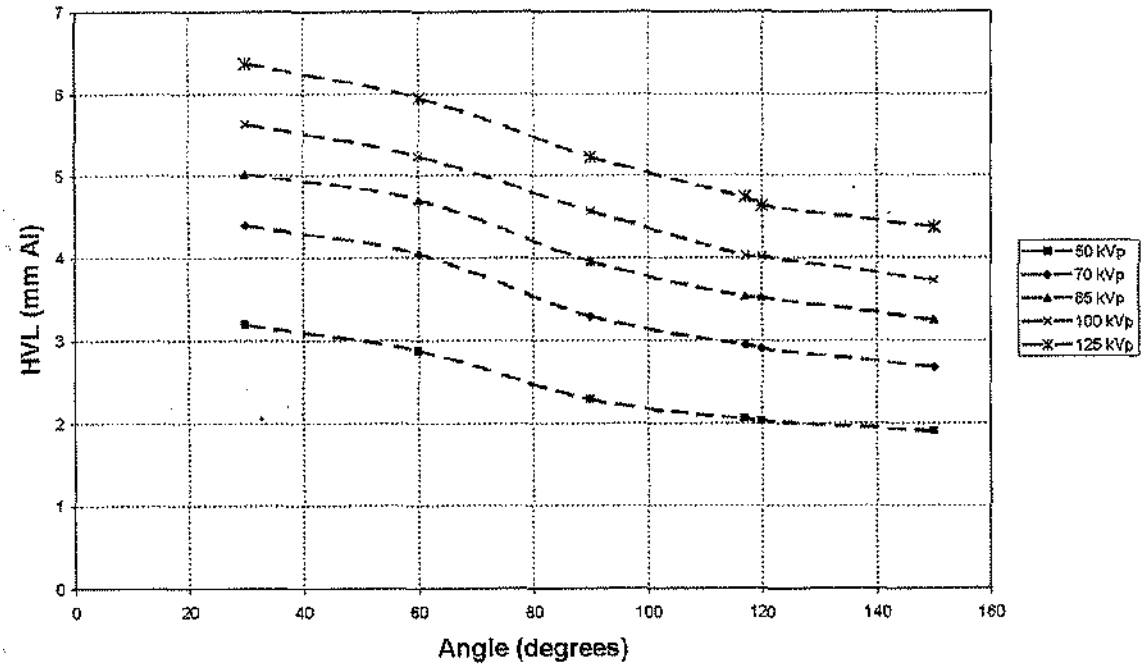


FIG 1.9

Variation in the half-value layer (HVL) for scattered radiation with the angle of scatter for X-ray beams with different energies.

As can be seen, a larger fraction of the neutron's energy is transferred in interactions with smaller nuclei, and the hydrogen nucleus, which has a similar mass to a neutron, is the most efficient nuclei for slowing down neutrons. Neutrons are damaging to biological tissue, which has a large component of hydrogen atoms, and hydrogen-rich materials such as water and paraffin are used as neutron moderators. Fast neutrons may also interact via inelastic scattering in which the atomic nucleus is left in an excited state. The excitation energy will be radiated rapidly in the form of a γ-ray or if the neutron energy is greater than 10 MeV, a second high-energy neutron may be produced.

Neutrons that have been slowed down to thermal energies of the order of 0.025 eV are captured by a nucleus. The neutron absorption cross-section is inversely proportional to the square root of the neutron energy above 0.025 eV. Neutron-shielding materials contain atoms such as ^{10}B which have a large neutron absorption cross-section. Neutron capture may be followed by γ-ray emission or may transform the nucleus to a radionuclide (activation), usually of short half-life, which decays by emission of particle radiation. It is important to ensure that materials used

in areas exposed to neutron fluxes do not contain atoms which may be transformed to radionuclides with significant half-lives (e.g. $^{59}Co(n)^{60}Co$, 5.3 years half-life).

1.7. The radiation field and radiation dose

The damage to biological tissue produced by the interaction of ionising radiations described in §1.4 is quantified in terms of the deposition of energy. Dosimetric quantities are determined by the interaction of a radiation field with a material and can be expressed in terms of the product of a radiation field quantity and an interaction coefficient.

1.7.1. The radiation field

The passage of particles through a radiation field is described in terms of the fluency φ, which is defined as $\varphi = dN/da$, where dN particles are incident on a sphere of cross-sectional area da. A sphere is used to avoid the need to take account of the beam direction or to specify the orientation of the area. Other important quantities for specifying a radiation field are the fluence rate (m^{-2} s^{-1}), which is the number of particles that cross unit area in unit time, the energy fluence ψ (J m^{-2}), which is the energy that passes through unit area, and the energy fluence rate, which is the rate of energy flow per unit area, the energy flux density or the intensity (J m^{-2} s^{-1} or W m^{-2}).

1.7.2. Absorbed dose

Absorbed dose quantifies the transfer of energy from ionising radiation to matter and is equal to the mean energy per unit mass imparted to a small volume of a material. It is measured in units of gray (Gy), equal to the absorption of 1 joule (J) in 1 kilogram of matter (1 Gy = 1 J kg^{-1}). The absorbed dose (D_m) in a material (m) is equal to the product of the energy fluence and the mass energy absorption coefficient:

$$D_m = \psi(\mu_w/p) \qquad (1.12.)$$

Absorbed dose in a small volume has been adopted by the ICRU and used in defining operational quantities for dose measurement. However, for assessment of harm from radiation exposure, the dose averaged over a tissue or an organ is more appropriate and this definition is used by ICRP for dose evaluation.

1.7.3. Kerma

Kerma (acronym for kinetic energy released in matter) is a measure of all the kinetic energy of charged ionising particles liberated by uncharged ionising particles per unit mass of material. It is also measured in units of gray and is equal to the product of the energy fluence ψ (§1.7.1.) and the coefficient of mass energy transfer (μ_{tr}/ρ) (§1.4.6.):

$$K = \psi(\mu_{tr}/\rho) \qquad (1.13.)$$

Kerma quantifies the first stage of energy absorption, i.e. the transfer of energy from photons or neutrons to charged particles. The second stage in which energy is imparted to matter by the charged particles is described by absorbed dose. This does not include energy lost as bremsstrahlung from electron interactions and so not deposited in the material.

The relationship between absorbed dose in air and air kerma is given by

$$D_{air} = K_{air}(\mu_{en}/\rho)_{air}/(\mu_{tr}/\rho) = K_{air}\,(1-g) \qquad (1.14.)$$

The difference between $(\mu_{en}/\rho)_{air}$ and $(\mu_{tr}/\rho)_{air}$ results from energy lost in bremsstrahlung production (§1.3.1. and §1.4.6.). For air and water, the difference between absorbed dose and kerma *(g)* is less than 0.4% for photon energies under 1 MeV but increases with energy, rising to 4% at 10 MeV.

1.7.4. Radiation measurement

Since the amounts of energy deposited in matter by ionising radiations are small, measurements related to absorbed dose for X- and γ-radiations are based on the number of ion-pairs created. The charge generated by photon interactions in a defined mass of air includes both ions produced directly by the incident photons and those produced by the secondary electrons. Some electrons produced by photon interactions within the measurement volume will escape and not be detected, while some electrons from photon interactions outside the measurement volume will be collected. Practical measurement systems are designed so that these two components are approximately equal, so that there is no net loss of charge. Under these conditions electronic equilibrium is said to exist. The mean energy to produce an ion-pair in air is constant except at very low energies and so energy deposition can be determined from the number of

ion-pairs formed. Kerma is the quantity determined by radiation measuring instruments.

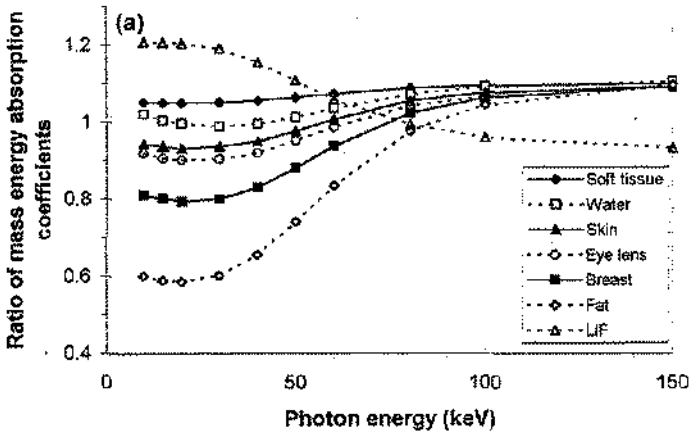
The energy absorbed per unit mass of materials subjected to the same energy fluence will be proportional to the mass energy absorption coefficients (μ_{en}/ρ) of those materials. Thus the absorbed dose (D_m) in a material other than air can be calculated from the equation

$$D_m = D_{air}(\mu_{en}/\rho)_m/(\mu_{en}/\rho)_{air} = K_{air}(\mu_{en}/\rho)_m/(\mu_{tr}/\rho)_{air} \qquad (1.15.)$$

The ratio $(\mu_{en}/\rho)_m/ (\mu_{en}/\rho)_{air}$ only varies slowly with photon energy for materials with atomic numbers close to that of air (Figure 1.10a), so the photon energy does not have to be known accurately to determine dose in tissue. However, this is no longer true for materials with higher atomic number such as bone (Figure 1.10b) or with large numbers of hydrogen atoms such as fat (Figure 1.10a). The ratio for water is 1.08±0.03 between 100 keV and 10 MeV, and that for lithium fluoride, which is used for dose measurement in the diagnostic X-ray energy range, is about 1.1. Average mass energy absorption coefficient ratios for a range of X-ray spectra, which may be used for making adjustments to LiF dose measurements made at different X-ray tube potentials, are given in Table 1.1.

1.7.5. Exposure

Exposure in air is the term given to the amount of charge of one sign produced when all the electrons liberated by photons in unit mass of air have been stopped completely (C kg^{-1}). This includes the ions produced directly by the incident photons and those produced by all the secondary electrons, but not ionisation resulting from bremsstrahlung. It is the quantity formerly used for measurement of ionising radiation.



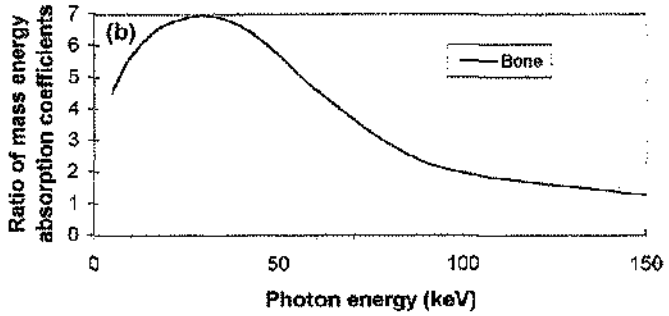


FIG 1.10

Ratios of the mass energy absorption coefficients for tissues relative to that of air [$(\mu_{en}/\rho)_m$/: $(\mu_{en}/\rho)_{air}$] as a function of photon energy: (a) various tissues, water, fat, and lithium fluoride; (b) bone.

1.7.6. Absorbed doses from charged particles

Charged particles are strongly attenuated in matter, so will primarily affect the surface layer of tissues, α -particles with energies less than 7.5 MeV cannot penetrate the outer layer of the skin and do not give rise to an external hazard, although they present a severe hazard if taken into the body. However, β-particle radiation may give significant doses to the skin. A radionuclide deposited on a surface with a concentration of 100 Bq cm^{-2} (1 MBq m^{-2}) emitting β-particles with energies over 0.6 MeV will give a dose rate of 250 μGy h^{-1} through the protective layer of the skin.

TABLE 1.1.

Average ratios of mass energy absorption coefficients for LiF and various tissues (m) with respect to air [$(\mu_{en}/\rho)_m$/ $(\mu_{en}/\rho)_{air}$] for X-ray spectra of different energies. Each result was derived by summing relative contributions (Figure 1.10) across the air kerma spectra for a constant potential X-ray unit filtered by 3 mm of aluminium. Factors can be used to adjust X-ray patient dosimetry TLD calibration factors to allow for different tube potentials.

Tube potential (kVp)	Lithium fluoride	ICRU soft tissue	Fat
60	1.178	1.054	0.638
70	1.168	1.055	0.655
80	1.157	1.057	0.673
90	1.147	1.058	0.691

100	1.137	1.060	0.709
110	1.127	1.062	0.727

Control points to Charter 1

1) The process of radioactive decay.
2) The modes of electron interactions.
3) Interactions of X-rays and γ-rays with matter.
4) Practical implications of photon interactions.
5) Neutron production. Neutron interactions.
6) The radiation field and radiation dose. Dose measurements.

2. Biological effects of ionising radiation

2.1. Introduction

Ionising radiations have the potential to disrupt the structure of organic molecules in cells. This chapter looks at this damage at the cellular level, reviews evidence on the effects that may result in humans, and outlines how the risks are quantified. *In vitro* studies fusing proliferating cells have provided information on the primary physicochemical effects and on the relative biological effectiveness of different types of radiation. *In vivo* studies and follow-up of individuals after radiation exposure have shown the effects of radiation on the organism.

Acute exposure of the whole or parts of the body to doses of radiation equivalent to a few thousands of times that from naturally-occurring background radiation may result in the functional impairment of tissues and organs. This response is referred to by the International Commission on Radiological Protection (ICRP) as a "*deterministic effect*". The probability of the effect occurring and the severity of damage is related to dose, duration of exposure, and the amount of tissue irradiated. It is known from extensive experience in radiotherapy that there are tissue-specific threshold doses below which damage does not occur. Radiation effects seen above these thresholds include bone marrow aplasia, degeneration of the lining of the gastrointestinal tract, inflammation of the lining of the lungs, atrophy of the gonads, and skin burns. The replacement of functional tissue with non-functional connective tissue occurs as a late effect. If tissue damage is extensive, death of the organism may occur.

With an increasing understanding of dose-response relationships for radiation exposure, interest in radiation protection has focused increasingly on the effects of low doses, that is, up to a few tens of times the natural background radiation. The manifestation of this type of damage is not the loss of functional tissue but damage to the genetic make-up of cells leading to the induction of cancer in the organism or hereditary disease in subsequent generations. In radiological protection terminology, these diseases are referred to collectively as 'stochastic effects'. It is assumed that the probability of these effects, but not their severity, depends on the radiation dose, without a dose threshold.

The chapter reviews the biological effects of radiation on the adult organism and the developing conceptus. The risks associated with radiation exposure are also reviewed in relation to radiological protection

criteria for acceptable exposure of workers and members of the general public. More detailed information on biological effects and risks may be obtained from the 1990 Recommendations of the ICRP and publications of the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).

2.2. Cellular effects

2.2.1. Primary physical and chemical events following exposure

When radiation passes through matter, it deposits energy in the material concerned. Radiations can be classified as *directly* or *indirectly ionising.* Charged particles (α-particles and β-particles emitted from radionuclides) are directly ionising and deposit energy through electrical interactions with electrons in the material. Other types of radiation (X-rays generated artificially or γ-rays from nuclear transitions) are indirectly ionising. When passing through matter, they lose energy in various ways but each results in giving up some of their energy to atoms with which they collide and electrons are ejected from these target atoms leaving behind positive ions. These high-velocity electrons move randomly through matter and may ionise atoms in their path. More electrons are then ejected, the incident electrons continuing on their trajectories with decreased energy and velocity until they eventually come to rest. Neutrons also lose energy in various ways, an important means being through collisions with hydrogen nuclei, which are single protons: the protons are set in motion and, being charged, they again deposit energy through electrical interactions. So in all cases, the radiation ultimately produces electrical interactions in the material. Another process, *excitation,* may occur if the energy transferred transiently moves orbiting electrons to a higher energy level in the atom. In biological terms, excitation is considered of less significance than ionisation. These physical processes are completed within 10^{-12} s.

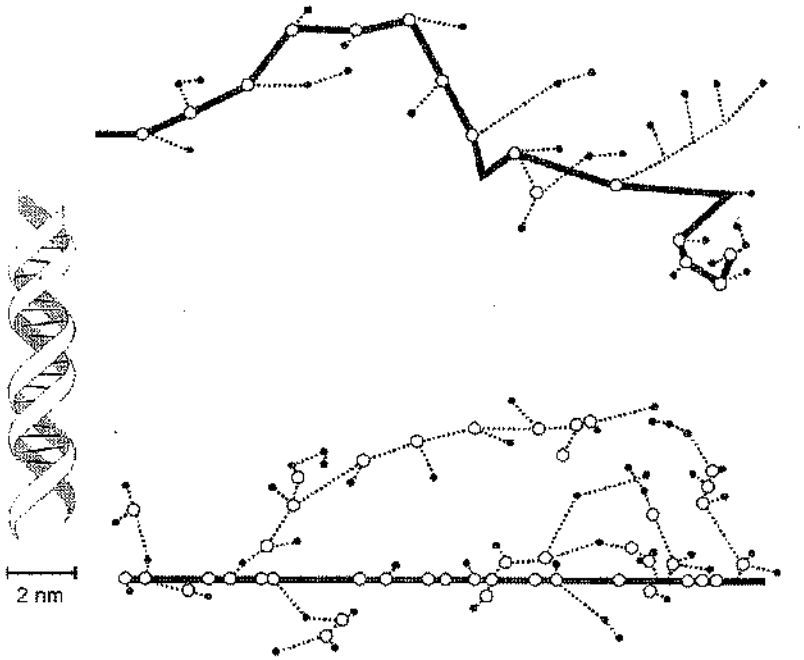


FIG 2-1. Simulated low-energy electron track *(upper trace,* initial energy 500 eV) and simulated short portion of α-particle track *(lower trace,* 4 MeV). Open circles are ionisations, filled circles are excitations. A section of DNA is shown to give a perspective on dimensions.

The unique feature of ionising radiation is the highly localized release of energy along a *particle track* in sufficient amounts to alter atomic and molecular structure. The particle track is the ensemble of ionisations and excitations along the trajectory of electrons and protons. The random nature of the particle track can be simulated by computer analysis using Monte Carlo techniques. A two-dimensional clustering of ionisations is shown diagrammatically in Figure 2.1. It is stressed that this is a gross approximation of the more complex three-dimensional events that involve random clustering of ionisations on a sub-atomic scale. Nevertheless, the figure suffices to illustrate the concept that low-energy electrons are *sparsely ionising* because the individual ionisations are well separated. Alpha-particles, in contrast, are *densely ionising* because the ionisations are closely packed together along the track and have the potential to cause more damage to tissues.

The energy lost by a charged particle per unit path length is referred to as the unrestricted *linear energy transfer* (LET or *L),* expressed as kiloelectron volts per micrometre (keV μm^{-1}). In general terms, photons (X-and γ-rays) and electrons have LET values in the range of about 0.2 to 10 keV μm^{-1}. Protons, α-particies, and neutrons have higher LET values, between about 10 and 100 keV μm^{-1}; and heavy charged particles (e.g.

nuclei of elements such as carbon, neon, and silicon) have values of up to a few thousands of kilo electron volts per micrometre.

LET does not define the amount of energy lost to matter in the *volume* of interest. This can be expressed as *mean lineal energy* which, in concept, is more meaningful in physical terms than LET. Nor does it address the size of the individual energy-loss events that occur along the particle track, which is the microdistribution of dose at the sub-atomic level. This approach, using other radiation quantities based upon the statistical distribution of events at a molecular level may well be adopted in the future for assessing the biological consequences of radiation exposure.

2.2.2. Dose quantities

The fundamental dosimetric quantity presently used in radiological protection is the *absorbed dose, D* (Box 2.1). The ICRP define this as the mean energy absorbed per unit mass of tissue or organ, in contrast to the International Commission on Radiological Units and Measurements (ICRU) who define it as the mean energy absorbed at the point of interest in matter. The SI unit for average absorbed dose in a tissue, D_T is the gray (Gy), which is equal to 1 joule per kilogram.

It has been calculated that a particle track of low-LET radiation (e.g. 1 MeV γ-rays) passing through an 8 μm diameter spherical nucleus in a cell delivers an absorbed dose of about 1 mGy. In contrast, a high-LET radiation (e.g. 1 MeV neutrons) would deliver an estimated absorbed dose of a few hundred mGy in the same volume. The probability of stochastic effects occurring depends, then, not only on the absorbed dose but also on the type and energy of the radiation. This is taken into account by weighting the absorbed dose by a factor related to the quality of the radiation. Called the *quality factor (Q)* by ICRU, it is related to *L* by the so-called *Q - L* relationship to reflect higher values for intermediate energy neutrons. The dose equivalent *(H)* at a point in tissue is given by

$$H = QD \qquad (2.1)$$

In comparing the biological damage caused by radiations of different "quality", the term relative biological effectiveness (RBE) is frequently used. This is defined as the ratio of an absorbed dose of reference low-LET radiation to a dose of the test radiation that gives an identical biological endpoint. RBE values are influenced by various in LET, dose

and dose rate. RBE values increase from unity in relation to LET values up to about 100 keV μm^{-1} , decreasing thereafter because of the "overkill effect" when more energy is deposited than is necessary to cause damage. Thus some radiation is effectively "wasted". The absolute value of the RBE is not unique but depends on the level of biological damage and, therefore, on the absorbed dose. For tumour induction, for example, the RBEs for fission neutrons at the most biologically effective energy, versus 1 MeV γ-rays, are generally taken to be between about 15 and 60 and for particles in the range from about 5 to 40. For cytogenetic effects, the RBE value for neutrons falls between about 35 and 55. For deterministic effects, however, lower RBE values between about 5 and 10 are generally found.

The ICRP have selected weighting factors to be representative of values of relative biological effectiveness of that radiation for the induction of stochastic effects at low doses. Called *radiation-weighting factors*, w_R, they are numerically similar to values of *Q* but are conceptually different. Radiation weighting factors recommended by ICRP are given in Table 2.1. The weighted absorbed dose is called the *equivalent dose*, $H_{T.R}$, and the name of the special unit is the sievert, Sv.

$$H_{T.R} = w_R D_{T.R} \qquad (2.2)$$

where $D_{T.R}$is the average absorbed dose from radiation R in tissue T. Defined in this way, the equivalent dose provides an index of the risk of harm to a particular tissue.

TABLE 2.1

Radiation weighting factors

Type and energy range		Radiation weight factor, w_R [a]
Photons, all energies		1
Electrons and muons, all energies[b]		1
Neutrons, energy	< 10 keV	5
	10 keV to 100 keV	10
	> 100 keV to 2 MeV	20
	> 2 MeV to 20 MeV	10
	> 20 MeV	5

Photons, other than recoil protons, energy > 2 MeV	5
α particles, fission fragments, heavy nuclei	20

[a]AII values relate to the radiation incident on the body or, for internal sources, emitted from the source.
[b]Excluding Auger electrons emitted from nuclei bound to DNA.

Box 2.1. Hierarchy of dose quantities based on mean dose values

Absorbed dose

Energy imparted by radiation to unit mass of tissue

Equivalent dose

Absorbed dose weighted for harmfulness of different radiations

Effective dose

Equivalent dose weighted for susceptibility to harm of different tissues

or organ from exposure to various radiations, regardless of their type or energy. So 1 Sv of α-radiation to the lung would give the same risk of induced fatal cancer as 1 Sv of β- or γ-radiation. The total equivalent dose, H_T, is the sum of $H_{T.R}$ over all radiation types:

$$H_T = \sum_R H_{T.R} \qquad (2.3)$$

The risk to the various parts of the human body varies from organ to organ: for example, the risk of fatal malignancy per unit equivalent dose is lower for the the thyroid than for the lung. Moreover, there are other important types of harm such as non-fatal cancers or the risk of various hereditary disease caused by irradiation of the testes or ovaries. These effects are different in kind and in magnitude and we must take them into account when assessing the overall detriment to health of an exposed individual. This is taken into account by taking the equivalent dose in each of the major organs and tissues and multiplying it by a *tissue weighting factor*, w_T, related to the risk associated with that tissue or organ. The sum of these weighted doses is a quantity called the *effective dose*, *E;* it allows

the risk to the whole body from either whole of partial body exposure to be expressed as a single number:

$$E = \sum_{T} wt H_{T} \qquad (2.4)$$

Generally, the effective dose gives a broad indication of the detriment to health from any exposure to ionising radiation regardless of the energy of the radiation or the number of organs exposed. It applies equally to external and internal exposure and to uniform and non-uniform irradiation.

Another quantity that is frequently calculated in relation to exposure to internally incorporated radionuclides is the *committed dose.* This is the dose calculated over the remaining lifespan of the individual and is taken to represent the total risk resulting from an intake of a radionuclide. In the case of a worker this is normally considered to be until 50 years after the intake and for a member of the public it is taken to be up to age 70 years. The *committed equivalent dose* is the dose received by an organ or tissue over the lifespan. When summed over all tissues the quantity is the *committed effective dose.*

2.2.3. Cellular damage and repair following the primary radiation events

The mean energy dissipated per ionising event is approximately 33 eV. This is more than sufficient to break a strong chemical bond; for example, the energy associated with a C=C bond is 4.9 eV. This is referred to as a *direct effect*.

Alternatively, an ionising event may break the molecular bonds in a molecule, but the effect may be manifest elsewhere. This is referred to as an *indirect effect.* The latter is the predominant reaction after exposure of cells to low-LET radiation. Free hydroxyl and other highly reactive radicals are produced by ionising the abundant water molecules in cells and during their short existence of about a microsecond, these highly reactive radicals are capable of diffusing a few micrometres to reach and damage molecular bonds in nuclear deoxyribonucleic acid (DNA).

It is widely accepted that the most important cellular constituent to be damaged by radiation is DNA. The DNA molecule consists of a double helix formed from two complementary strands of nucleotides. Nucleotides are made up of deoxyribose molecules (sugars), phosphates, and nitrogenous bases. The sugar and phosphate molecules form the helical

strands, while the bases form the cross-links between them. There are four bases, adenine and guanine (termed purines) and thymine and cytosine (pyrimidines). Adenine always bonds with thymine through two hydrogen bonds and guanine always bonds with cytosine through three hydrogen bonds. The unique pairing of the nucleotide bases provides DNA with its ability to replicate. The cell's genetic information is carried in a linear sequence of nucleotides that make up the organisms set of genes (its genome). Each gene controls a discrete hereditary characteristic corresponding to a segment of DNA coding for a single protein. Together with some binding protein, these genes make up the 23 pairs of chromosomes in the nuclei of all cells.

Just as cells inherit genes, they also inherit a set of instructions that tell the genes when to become active. These gene-regulatory proteins recognize short stretches of nucleotide sequences on the double helix and determine which of the genes in the cell will be transcribed. Genes provide instructions for cell division and for the synthesis of tens of the many proteins that provide the structural components of cells, as well as numerous enzymes promoting and controlling cellular activity. Ribonucleic acid (RNA) is the molecule that helps to transport, translate, and implement the coded instructions from the genes. All cell types contain the same genes, but encoding sets of genes is cell-specific. This uniqueness ensures that cells in each tissue produce their own proteins.

Maintaining stability in the genes is essential for cell survival. This stability requires not only extremely accurate mechanisms for DNA synthesis and replication but also precise mechanisms for repairing DNA damage before replication.

The most frequent changes during metabolic activity are DNA single-strand breaks, without base involvement.

This type of damage is effectively repaired by simple enzymatic ligation. *Base excision repair pathways* require other groups of enzymes whose roles are to identify and excise the damaged base site, make a complementary copy of the sequence of bases on the opposite undamaged strand, and seal the correct sequence of copied bases in the gap on the damaged strand. If nucleotide damage occurs, which involves strand breaks and bases, *nucleotide excision repair pathways* exist to repair the more extensive damage. The damaged nucleotides are removed and repair proceeds thereafter as for base damage.

DNA 'double-strand' damage, with or without base damage, occurs rarely during metabolism. *Recombination repair pathways* do exist, but

they are not totally effective, mainly because there is no undamaged strand to act as a template for base or nucleotide replacement. When the repair processes fail, the resulting *misrepair* is referred to as a *mutation.* These chemical processes are mainly completed within a few tens of minutes.

Observations with proliferating cells *in vitro* indicate that DNA is subjected to only an occasional permanent base-pair or nucleotide change during metabolism, even though metabolic processes alter thousands of bases and nucleotides every day.

DNA damage due to radiation results in similar lesions to those occurring during metabolism, but double-strand breaks and more extensive expressions of damage (multiple gene losses and the translocation of gene sequences) occur more frequently and are considered the hallmark of radiation. The probability of misrepair is greater under these circumstances. Estimated yields of damage caused by low-LET radiation are shown in Table 2.2.

Recent *in vitro* investigations have revealed that DNA repair pathways may work in conjunction with other cellular activities in order to minimize cell damage. These include delay in cell-cycling as a means of maximizing the chances of repair, and programmed cell ' death (apoptosis), whereby severely damaged cells are eliminated to stimulate cell proliferation.

2.2.4. Classification of radiation-induced damage in terms of cell survival

Radiation-induced cell damage can be classified in terms of survival or inherent damage in viable cells (deletions, translocations in gene structure-mutations) and oncogenic transformation (neoplasia). Dose-response relationships in terms of survival are considered in this section, and those in terms of damage to viable cells in §2.2.5.

Expressed graphically as the logarithm of the surviving fraction plotted against absorbed dose on a linear scale, the dose response for cell survival following acute exposure to low-LET radiation is initially linear followed by a quadratic response as the dose increases. A plausible explanation of the linear component is that the majority of DNA interactions are single-particle track events. Under these circumstances, DNA damage can be effectively repaired before interaction with another single track, a process that is influenced by dose rate. As the dose (or dose rate) increases, multi-track events reflecting the quadratic component and associated with clustered DNA damage increasingly predominate with a consequent increase in the probability of misrepair and *lethal events.* After

acute exposure to 1Gy, for example, lethal events have a frequency of about 0.2 to 0.8 per cell (Table 2.2).

TABLE 2.2

Examples of damage in a mammalian cell nucleus from 1 Gy of low-LET radiation

Initial physical damage	
ionisations in cell nucleus	~ 100 000
lonisations directly in DNA	~ 2000
Excitations directly in DNA	~ 2000
Selected biochemical damage	
DNA single-strand breaks	1000
Base (8-hydroxyadenine) damage	700
Base (thymine) damage	250
DNA double-strand breaks	40
DNA-protein cross-links	150
Selected cellular effects	
Lethal events	~ 0.2-0.8
Chromosome aberrations	~ 0.4
Hprt gene mutations	0.6×10^{-5}
Translocation frequency (two loci)	1.2×10^{-4}

Protracted exposure to low-LET radiation results in less damage compared with acute exposure. This is referred to as the *dose rate effect* and is due to the ability of cells to repair more *sublethal* damage as the dose rate is reduced. Below about 1 Gy min^{-1}, the slope on the exponential portion of the survival curve typically becomes progressively shallower as more and more sublethal damage is repaired, whereas below about 0.01 Gy min^{-1}, undamaged or repaired cells are able to proliferate at a sufficient rate to offset the reduction in cell numbers while further repair is progressing. These responses are illustrated diagrammatically in Figure 2.2. The dose-response relationship for high-LET radiation approximates to linearity and there is no dose-rate effect, suggesting little repair of sublethal damage.

2.2.5 Dose-response relationships expressed as damage to viable cells

Chromosome aberrations and gene mutations

A technique of culturing human lymphocytes *in vitro* and measuring the frequency of radiation damage to chromosomes has been available for many years. This frequency, expressed as dicentric aberrations (Box 2.2), increases from a base level of about 1 in 1000 cells to about 4 in 100 cells *per* gray after exposure to low-LET radiations. Dose-response relationships for X-rays and fission neutrons are shown in Figure 2.3. In general, high-LET radiations are more damaging than low-LET radiations. Measurement of dicentric chromosome aberrations has provided an important method for assessing doses in known or suspected cases of acute radiation exposure.

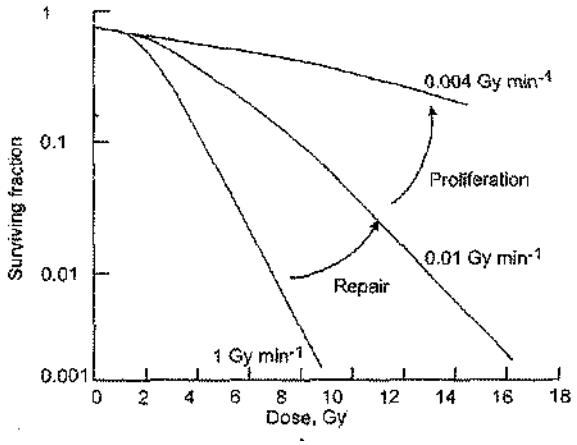


FIG 2.2

Dose-rate effect showing the influence of repair and repopulation on the dose-survival relationship for dose rates of 1, 0.01, and 0.004 Gy min^{-1}.

A number of mutation test systems using mouse, hamster, and human fibroblast cells have been developed. For acute exposure of human lymphoblastoid cells to 100 kVp X-rays, a linear dose-response relationship for specific locus mutation induction has been observed. For protracted exposure, a slight increase in mutation rate was observed, in contrast to a sparing effect seen using hamster cells. For continuous exposure to neutrons, there is a substantial increase in mutation rate compared to acute exposure. Unfortunately, different types of cultured cells and radiation modalities have produced different results, making it difficult to generalize on the value of mutation assays.

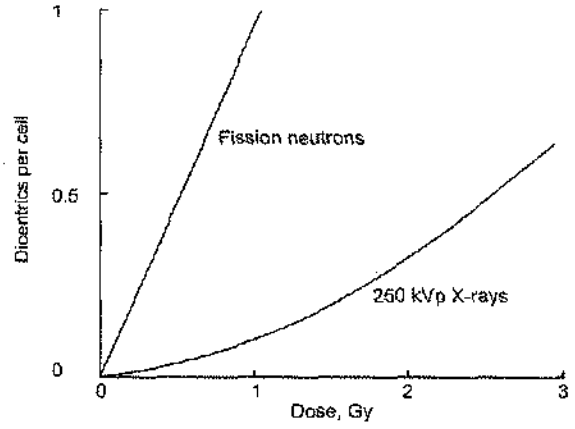


FIG 2.3

Dicentric yield in chromosomes per cultured human lymphocyte as a function of dose for selected radiations (see §2.2.5).

Cell transformation

An established technique for studying carcinogenic potential is that of culturing cells that can grow indefinitely. This is made possible by frequently transferring the growing cells to fresh media. Cells that have acquired this ability are said to be *immortalized*. *A* characteristic of these immortalized cells is that they stop dividing when they come into contact with similar cells in the culture medium *(contact inhibition).* They are not classified as malignant cells because they do not cause tumours when injected into immunologically suppressed animals. Occasionally, an immortalized cell undergoes a spontaneous change, whereby it loses its contact inhibition and continues to proliferate by spreading over adjacent immortalized cells to form recognized foci of cells. Such cells are said to have undergone *transformation* and when they are injected into animals, they develop into tumours. Spontaneous transformation is a rare event, occurring at a rate of about 1 in 10 000 to 1 in 100 000 per surviving cell. The mechanism is not fully understood but it is thought to involve the mutation of two (or more) classes of genes. These are 'gain-of function' mutations of proto-oncogenes, whereby the mutated genes (oncogenes) stimulate cell proliferation in an uncontrolled manner; and 'loss-of function' tumour suppressor genes, whereby cells are no longer prevented from proliferating in defiance of normal controls. Exposure to radiation increases the rate of cell transformation as a dose-related response.

Estimated yields of chromosome aberrations, mutation frequency, and cell transformation are shown in Table 2.2 as typical responses to acute low-LET radiation.

Generalized dose-response relationships

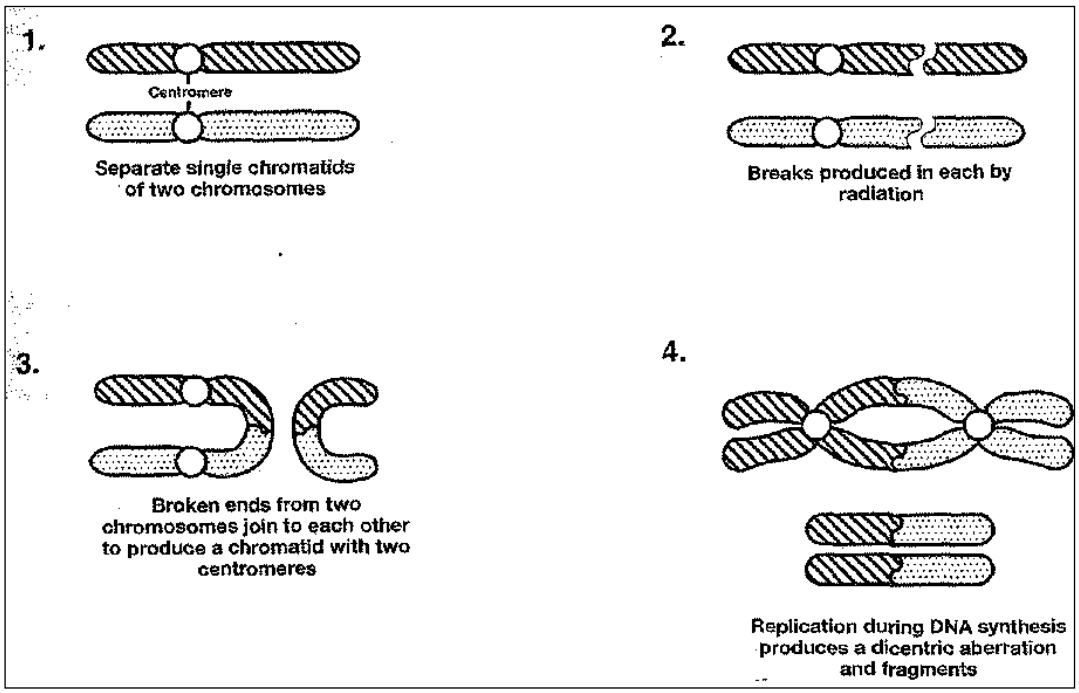
Dose-response relationships for proliferating cells exposed to low-LET radiation can be expressed mathematically over a wide range of doses. The probability of an effect (*E*) occulting after dose *(D)* in each irradiated cell is

$$E = (\alpha_1 D + \beta_1 D^2) \exp - (\alpha_2 D + \beta_2 D^2) \quad (2.5)$$

where α_1 and β_1, are coefficients for the linear and quadratic terms expressing the induction of aberrations, mutations, or transformations, and α_2 and β_2 are coefficients for the linear and quadratic' terms expressing cell killing.

Based on target theory, the linear component of the relationship for stochastic effects is interpreted as a region where only small numbers of cells are intersected by more than one particle track, the effect being independent of dose rate. The quadratic component is interpreted as reflecting multi-track events spread over time that are dose-rate dependent.

For high-LET radiations, it is generally accepted that the relationship approximates to linearity because of the intense clustering of ionisations along the particle track.



Box 2.2. The formation of a dicentric

2.3. Deterministic effects

2.3.1. The role of stem cells in healthy tissues

In the space of a few weeks, a single fertilized human egg gives rise to a complex multicellular organism consisting of embryonic, cells arranged in a precise pattern. In the subsequent period of fetal growth after the formation of organs and tissues, the cells continue to proliferate. Growth of many tissues and organs continues throughout childhood, but ceases in the adult when cell masses reach a predetermined size. The majority of cells in tissues and organs of the adult are *differentiated,* that is, they have developed specific morphology and function which is normally irreversible. These cells were programmed to die by the process of *apoptosis* during differentiation. In many, but not all, tissues, the rate of death of differentiated cells must be balanced by renewal from a reservoir of *stem cells* in order to maintain a healthy state. These cells have retained embryonic characteristics and are able to divide upon stimulation during the lifetime of the organism, yielding progeny that are destined to differentiate by a process of *clonal expansion.* Stem cells also retain the ability of *self-renewal.* These two characteristics are illustrated diagrammatically in Figure 2.4. The number of stem cells compared to differentiated cells varies according to the tissue, but they usually represent, at most, a few per cent of the total cell numbers. It is not known precisely how the balance between cell proliferation and cell death is achieved, but when differentiated cells die, a feedback mechanism has been shown to be activated to stimulate stem cells to divide. If sufficient numbers of cells are prevented from dividing at the appropriate rate, the tissue loses its ability to function effectively and may result in death of the individual.

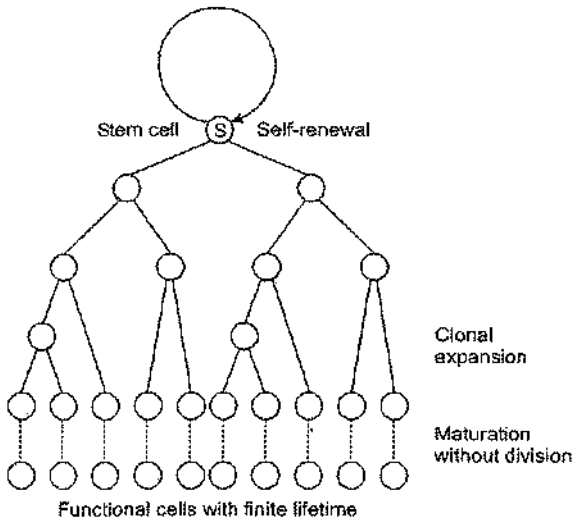


FIG 2.4.

Derivation of differentiated cells from a selfrenewing stem cell (see § 2.3.1).

2.3.2. Dose-response relationships

The probability of loss of tissue or organ function following exposure to radiation increases steeply above a threshold dose up to a maximum. Expressed as a generalized dose-response relationship, the plot of the frequency of the effect versus absorbed dose expressed on linear axes is sigmoid (Figure 2.5, upper panel). Above the threshold dose, the severity of the effect also increases with dose (Figure 2.5, lower panel). Protracting the dose results in a lower frequency and less severe symptoms at a given dose compared with acute exposure, reflecting the importance of repair and stem cell repopulation.

There is individual variation in radiosensitivity in any exposed population which is influenced by the age and state of health of the individuals. This variation reflects differences in the ability of individuals to cope with radiation-induced cellular damage.

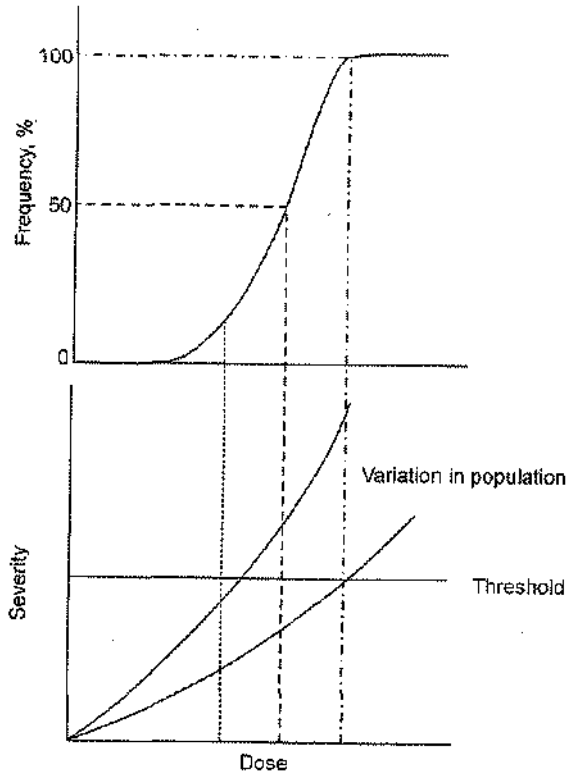


FIG 2.5.

Dose-response relationship for deterministic effects. Variation in frequency and severity (see 2.3.2).

2.3.3. Effects following whole-body irradiation

Evidence of deterministic effects comes from several sources. These include retrospective studies on radiotherapy patients, radiologists in the early part of this century who were inadequately protected, Japanese populations exposed to radiation from atom bombs, and individuals accidentally exposed to high doses following nuclear reactor accidents and unshielded radiographic sources. Deterministic effects following acute whole-body irradiation are summarized in Table 2.3. Understanding the syndromes associated with acute high doses is important as an aid to diagnosis and prognosis of accidental overexposure, and to ensure that deterministic effects are avoided in normal practices and minimized in accidents. The stages in the development of the various syndromes are summarized in Table 2.4.

2.3.4 Effects following partial-body irradiation

Tolerance doses in adults after radiotherapy

Extensive experience in the treatment of patients undergoing radiotherapy has provided data upon which to determine the tolerability of healthy tissues and organs to radiation. Called the *tolerance dose* by clinicians, it is defined as the amount of low-LET radiation received during conventional radiotherapy (typically, 20 to 30 fractions each of 2 to 6 Gy over several weeks) which is considered acceptable. The gonads, the lens of the eye, and the bone marrow contain the most radiosensitive tissues with tolerance doses after fractionated radiation below a few gray. For other tissues and organs, the tolerance doses are in the region of a few tens of a gray. In general, children are less tolerant to exposure.

TABLE 2.3.

Range of doses associated with acute radiation syndromes in adults exposed to low-LET radiation

Whole-body absorbed dose (Gy)	Principal effect contributing to death	Time of death after exposure (days)
1-6	Damage to bone marrow[a]	30-60
5-15	Damage to the gastrointestinal tract and lungs[b]	10-20
>15	Damage to nervous system and shock to the cardiovascular system	1-5

[a]Dose range considered to result in 50% of an exposed population dying (LD_{50}=3-5 Gy).

[b]Damage to vasculature and cell membranes especially at high doses is an important factor in causing death.

Source: ICRP.

TABLE 2.4.

Summary of acute radiation syndrome

Syndrome			
	Cerebral	Intestinal	Bone marrow
Critical organ	Brain	Small intestine	Bone marrow
Latent period	20 min	3-5 days	2-3 weeks
Syndrome threshold Gy)	20	3	1
Death threshold (Gy)	50	10	2
Death occurring within	2 days	2 weeks	3-8 weeks
Cause of death	Cerebral oedema, heart failure	Sloughing of gut, shock	Haemorrhage, Infection
Prodromal vomiting	Minutes	1 hour	A few hours
Symptoms	Tremors, cramps, loss of coordination, lethargy, impaired vision, coma	Loss of appetite vomiting, diarrhoea with bleeding, fever, electrolyte and fluid balance	Fever, breathlessness, internal bleeding, depletion of bone marrow leading to low blood counts
Treatment	Palliative	Barrier nursing, fluid and electrolyte replacement, transfusions of blood cells, bone marrow transplants	
Prognosis	Hopeless	Very poor	Dose-dependent and influenced by treatment

Threshold doses in radiological protection

The limitations of using data on tolerance doses to derive *threshold doses* for radiation protection purposes need to be recognized. In contrast to the precise fractionated exposure conditions of radiotherapy, accidental over-exposure of workers is most likely to be from non-uniform fields and from mixed high- and low-LET radiations. The tolerance dose can therefore at best be used as a cautious approximation to a threshold dose.

The threshold doses recommended by the ICRP for the most radiosensitive tissues and organs are summarized in Table 2.5.

Skin irradiation

Based upon extensive experience in the use of fractionated X- and γ-radiation, various degrees of skin damage can be observed according to the area and depth of skin involved, the absorbed dose, and the duration and frequency of the exposure. The types of damage after acute exposure are summarized in Box 2.3.

Quantifying the threshold doses for these effects is complicated, in practice, by the multiplicity of sensitive targets at different critical cell depths. This makes it difficult to select a single depth at which to specify the dose to the skin. The depths at which the most serious effects arise are estimated to be in the range of 300-500 μm. However, a conservative approach for protection purposes is to use shallower depths (in the range 20-100 μm, nominally 70 μm) for monitoring specifications.

The tolerance dose for skin damage increases as the radiation field is reduced. Thus, tolerance doses following a single treatment with orthovoltage X-rays was found to be 20 Gy for an area of 6×4 cm and 11 Gy for an area of 15 × 20 cm. Following fractionated treatment, exposure, the tolerance doses were estimated to be about 50 and 30 Gy, respectively, for the two field sizes.

In normal practices, the annual equivalent dose limit for occupational exposure recommended by the ICRP is 500 mSv averaged over any 1 cm^2, regardless of the area exposed. This becomes an important issue when considering the localized deposition of high-specific activity radioactive particulates which can give much higher doses in the immediate vicinity of the particles.

TABLE 2.5.

Thresholds for deterministic effects recommended in radiological protection

Tissue and effect	Equivalent dose brief exposure (Sv)	Equivalent dose rate protracted exposure (Sv year^{-1})
Testes		
Temporary sterility	0.15	0.4[a]
Permanent sterility	> 3.5	2.0
Ovaries		
Sterility	> 2.5	> 0.2
Lens		
Detectable opacities	> 0.5	> 1.0
Visual impairment (cataract)	> 0.1	> 0.15
Bone marrow		
Blood cell depletion	> 0.5	> 0.4[b]

[a]*This dose is higher because differentiating cells are more radiosensitive than the stem cells so the latter can replenish the differentiating cells at an adequate rate.*

[b]*Supported by evidence of effects after chronic irradiation of beagle dogs.*

Source: ICRP.

2.4. Radiation-induced cancer

2.4.1. The basic cellular process

The development of cancer is a major late effect resulting from exposure to radiation. The malignant changes occurring in cells (neoplasia) is a complex, multi-stage process that can be conveniently divided into four phases: initiation, promotion, conversion, and progression. The subdivisions are necessarily simplifications of the overall process but they do provide a basis from which to interpret the cellular and molecular changes.

Initiation encompasses the essentially irreversible DNA damage (§2.2.3), which provides the potential in cells for neoplastic development. *Promotion* is the stage where initiated cells receive an abnormal growth stimulus and begin to proliferate in a semi-independent manner. *Conversion* of these promoted cells to a form in which they are committed to become fully malignant is believed to be dependent upon further gene mutations. The subsequent *progression* stage depends upon changes that

involve invasion of adjacent tissues to other sites in the body. These secondary growths are referred to as *metastases*.

There is always a minimum period of time between irradiation and the appearance of a radiation-induced tumour. This period is termed the latent period and its length varies with age and from one tumour type to another. Some types of leukaemia and bone cancer have latent periods of only a few years but many solid tumours have latent periods of 10 years or more. For leukaemia and bone cancer there is fairly good evidence that the risk is complete expressed within about 30 years following exposure. For solid tumours of longer latency, such as those of the gastrointestinal tract and liver, it is not yet clear whether the incidence of tumours passes through a maximum and then declines with time or whether the risk levels out or alternatively increases indefinitely through the rest of life.

Box2.3 Radiation-induced acute effects on skin

Dose (Gy)	Lesion	Time of appearance	Signs and symptoms
5	Initial erythema	1-3 days	Reddening
5	Dry desquamation	2-3 weeks	Scaling Pigmentation Itching Depilation
5	Erythema proper	3-4 weeks	Reddening
20	Moist desquamation	4-5 weeks	Blistering Oozing
50	Cell death	2-3 weeks	Necrosis

To project the overall cancer risk for an exposed population, it is therefore necessary to use models that extrapolate over time data based on only a limited period of the lives of the individuals. Two such projection models have generally been used:

- the additive (absolute) risk model which postulates that radiation will induce cancer independently of the spontaneous rate after a period of latency, and variations in risk may occur due to sex and age at exposure;
- the multiplicative (relative) risk model in which the excess (after latency) is given by a constant or a time-varying factor applied to the age-dependent incidence of natural cancers in the population.

In most cases the spontaneous risk increases with age and therefore the multiplicative model will predict an increasing incidence of radiation-induced cancer with increasing age. The relative risk model also gives different risks of radiation-induced cancer in different populations, depending upon the natural cancer incidence. Data how available from the Life Span Study (LSS) of the A-bomb survivors in Japan and from studies

on uranium miners suggest that the multiplicative model gives a better fit to the data, at least for some of the most common cancer types. In some cases, however, there is evidence that the relative risk starts to decline a long time after exposure. This is the case, for example, for bone tumours and lung cancers.

2.4.2. Dose-response relationships for fatal cancers

The commonly-occurring cancers induced by radiation are indistinguishable from those occurring spontaneously and since cancer is the cause of death in about a quarter of the population in the developed countries, the problem of detecting a small radiation-induced excess is difficult. In general, large exposed compared with matched unexposed control populations are necessary to obtain statistically meaningful results. The chief sources of information on the occurrence of radiation-induced cancers are summarized in Box 2.4.

The continuing epidemiological study of the A-bomb survivors in Japan has provided the main source of risk estimates. A recent reassessment resulted in an increase in estimates of the risk of radiation-induced cancer from previous studies. This arose partly as a result of revised dosimetry and a longer follow-up of the population, but mainly it was attributed to the use of a multiplicative (relative) risk model (excess related by a constant factor applied to the age-dependent incidence of naturally-occurring cancers). Previously, an additive (absolute) risk model was used, where the excess was taken to be independent of the naturally-occurring rate.

UNSCEAR, in a report to the General Assembly, provided a total cancer risk at high doses and high-dose rates, estimated to be $(7\text{-}11)\times10^{-2}$ Sv^{-1} using age-averaged and age-specific constant relative risk models. (A risk of 1×10^{-2} Sv^{-1} corresponds to a risk of cancer of 1 in 100 per Sv or 1 in 100 000 per mSv). This compared with their 1977 assessment of 2.5×10^{-2} Sv^{-1} at high-dose rate using the additive model. Because children and young persons are more sensitive to radiation than adults, the application of age-specific risk coefficients increases the predicted numbers of radiation-induced cancers in a population of all ages compared with that for a working population.

Box 2.4 Human populations available for risk estimation

Atomic bombs	Japanese survivors
	Marshall Islanders[a]
Medical diagnosis	Multiple fluoroscopies (breast)
	Prenatal irradiation
	Thorotrast injections[b]
Medical therapy	Pelvic radiotherapy (cervix)
	Spinal radiotherapy (ankylosing spondylitis)
	Neck and chest radiotherapy thyroid)
	Scalp radiotherapy
	Radium treatment[b]
Occupational exposure	Uranium miners[b]
	Radium ingestion (dial painters)[b]

[a]Exposure to external radiation and β/γ ernitting radionuclides.

[b]Exposure to α-emitting radionuclides.

These risk estimates for whole-body radiation exposure were based on an extrapolation into the future which is somewhat uncertain for solid cancers because two-thirds of the Japanese survivors are still alive and the cancer risk has still to be expressed in these survivors. Up to 1985, about 80 excess leukaemias and 260 excess solid cancers had occurred in the LSS population out of a total of about 6000 cancer deaths.

In a more recent report on the LSS, scientists reported on five more years of follow-up (1986-1990). Their analysis includes an additional 10500 survivors (86 572 in total). During 1950-1990 there have been 7827 cancer deaths, of which it is estimated that there are 85 excess leukaemias and 335 excess solid cancers. The mortality curve for all solid cancers combined shows essentially a linear dose-response in the range 0 – 3 Sv, whereas for leukaemia the trend in dose is non-linear with an upward curvature. A significant increase in the risk of solid cancers is now seen at doses down to 50 mSv.

2.4.3. Dose and dose-rate effectiveness factors (DDREFs)

Risk coefficients for radiological protection purposes are based mainly on population groups exposed at high doses and high-dose rates. Studies at the molecular, cellular, tissue, and whole-animal level have demonstrated that radiation damage increases with dose and that, at least for low-LET radiation, at high-dose rates it is often greater per unit of exposure than at low-dose rates. Thus, although the assumption normally made is that the dose-response relationship for cancer induction is linear, with the risk proportional to absorbed dose, in practice a dose and dose-rate effectiveness factor (DDREF) has been used to allow for a reduced effectiveness of radiation at low doses and low-dose rates. The choice of a suitable DDREF has caused considerable debate, with relevant data being available from cellular, animal, and human studies giving values within the range of 1 to 10. A value of 2 is recommended by the ICRP for low-LET radiation. No DDREF is recommended for high-LET radiation.

2.4.4. Risk coefficients for protection

From these various sources, the ICRP have adopted a rounded value of 10×10^{-2} Sv^{-1} for the risk coefficient for fatal cancer at high doses and high-dose rate following exposure of a mixed population of all ages. Applying a DDREF of 2 gives a risk of 5×10^{-2} Sv^{-1} for radiation protection purposes. Risk coefficients for fatal cancer in named individual tissues and organs are given in Table 2.6. For workers the risk coefficient adopted for radiation protection purposes is 4×10^{-2} Sv^{-1}. These risk coefficients have been used by ICRP in developing the revised dose limits given in its 1990 Recommendations.

TABLE 2.6

Risk coefficients for fatal cancer adopted by ICRP and tissue weighting factors, w_T

Organ or tissue	w_T	Fatal cancer (10^{-2} Sv^{-1})	
		Population	Workers
Bladder	0.05	0.30	0.24
Red bone marrow	0.12	0.50	0.40
Bone surface	0.01	0.05	0.04
Breast	0.05	0.20	0.16
Colon	0.12	0.85	0.68
Liver	0.05	0.15	0.12
Lung	0.12	0.85	0.68
Oesophagus	0.05	0.30	0.24
Ovary	-	0.10	0.08
Skin	0.01	0.02	0.02
Stomach	0.12	1.10	0.88
Thyroid	0.05	0.08	0.06
Remainder	0.05	0.50	0.40
Gonads	0.20		
(hereditary disease)	–	–	
Total	1.0	5.0	4.0

Source: ICRP

Table 2.7 illustrates how the risk of cancer varies with age at exposure for the UK population. The results in the table have been calculated generally using a relative risk model and the spontaneous cancer rates for the UK. The table shows that whereas the total cancer risk predicted over a lifetime increases monotonically with decreasing age at exposure, the risk to 40 years following exposure is greatest for those irradiated at ages 50-59 years. Furthermore, the variation with age at exposure is not as great for the risk to 40 years as for the lifetime projected risk. These results demonstrate the importance of continued follow-up of groups such as the A-bomb survivors to improve estimates of lifetime risk for those in the younger age groups where only a small fraction of the risk has

so far been expressed. The total cancer risk calculated for the UK population, $5.9\times10^{-2}Sv^{-1}$ is greater than risk calculated for the world population, $5\times10^{-2}Sv^{-1}$ because of the higher spontaneous risk of cancer.

TABLE 2.7

Estimates of radiation-induced fatal cancer in a UK population of both sexes according to age at exposure

Age at exposure (years)	Deaths (10^{-2} Sv^{-1})	
	Risk up to 40 years following exposure	Lifetime projection
0-9	1.2	11.1
10-19	1.8	9.9
20-29	1.9	6.6
30-39	2.8	4.5
40-49	3.8	4.2
50-59	4.0	4.0
60-69	3.1	3.1
70-79	1.6	1.6
80+	0.75	0.75
Total	2.4	5.9

Exposure to low doses or at low-dose rates.

2.4.5. Low-dose studies

The majority of studies on which risk estimates for radiation-induced cancer are based are for populations exposed at high doses and high-dose rates. However, low dose and low-dose rate studies, although statistically weak, can provide a check on the upper bound of the risks derived by extrapolation from high-dose rate studies.

Several studies have been conducted of nuclear industry workers. In the USA, Gilbert *et al.* performed a joint analysis of data for about 36 000 workers al the Hanford site, Oak Ridge National Laboratory and Rocky Flats weapons plant. Neither for the grouping of all cancers nor for leukaemia was there an indication of an increasing trend in risk with dose.

A study of just over 95 000 individuals on the UK's National Registry for Radiation Workers (NRRW) examined cancer mortality in relation to dose. This study provided evidence of raised risks of leukaemia and multiple

myeloma associated with occupational exposure to radiation, but, unlike the combined study of US workers, is consistent with the risk estimates derived by ICRP from the Japanese survivor data. Combining the NRRW and US results to strengthen the database produces central estimates for lifetime risk of 4.9×10^{-2} Sv^{-1} (90% CI < 0, 18) for all cancers and 0.30×10^{-2} Sv^{-1} (90% CI < 0, 1.04) for leukaemia, excluding chronic lymphatic leukaemia (CLL).

A combined analysis of mortality among 95 673 workers (85.4% men) in the US, the UK, and Canada has also been published. As with the NRRW, mortality from leukaemias, excluding CLL, was significantly associated with cumulative external radiation exposure. There was no evidence of an association between radiation dose and mortality from all cancers. It was concluded that the results of the study did not suggest that current radiation risk estimates for cancer at low levels of exposure, as recommended by ICRP, can be appreciably in error.

A second analysis of the NRRW published in 1999 provides more precise information on mortality in relation to occupational exposure. By including additional groups of workers the database now contains records for nearly 125 000 workers, of whom just under 13 000 had died. The analysis shows borderline evidence of an increasing trend with dose in the risk of leukaemia, the central estimate of risk is similar to that estimated for the Japanese A-bomb survivors, at low doses. For all cancers, other than leukaemia, the central estimate of the trend in risk with dose is closer to zero than in the first analysis but is compatible with the risks obtained from the A-bomb survivors.

Studies of exposure to natural radiation (other than radon) have generally involved looking for any geographical correlation with cancer rates. Such studies are difficult to interpret, however, because of the effect of confounding factors such as socio-demographic variables and other factors that vary geographically.

2.5. Radiation-induced hereditary disease

2.5.1 Naturally-occurring hereditary diseases

Hereditary diseases occur spontaneously. Examples of commonly-occurring diseases are given in Box 2.5. Radiation damage to the germinal cells in the gonads is assumed to result in an increase in hereditary disease in the offspring of irradiated parents. This assumption is based mainly on animal studies.

There are three main types of gene mutation: dominant, recessive, and X-linked. A dominant gene mutation in one set of genes in one parent (there is a set of genes from both parents in the fertilized egg cell) can express itself despite its counterpart from the other parent being normal. On the contrary, a recessive gene mutation cannot be expressed unless the genes from both parents carry the identical mutation. Females have two X chromosomes while males carry one X and one Y chromosome, the Y chromosome being almost inert apart from genes for maleness. An X-linked gene mutation can readily express itself in the male, whereas in the female the X-linked mutation is not expressed unless both X chromosomes carry the same mutation. There is at present no good evidence for the induction of diseases of chromosomal origin by radiation.

The genetics of some inherited diseases are more complicated because additional factors such as environment play a part in their expression. These are called the 'multifactorial' diseases.

Box2.5 Examples of hereditary diseases	
Dominant disorders	congenital cataract
	cystic kidney disease
	Huntington's chorea (progressive mental retardation)
X-linked diseases	haemophilia, albinism
	colour blindness
	heart valve defects
Autosomal regressive	
diseases	Cretinism
	disorders of amino acid metabolism
	aplastic anaemia
	muscular dystrophy
Multifactorial diseases	ankylosing spondylitis
	varicose veins
	cleft palate
	diabetes mellitus
	schizophrenia
	asthma
Chromosome anomalies	Down's syndrome

Most live-born children with inherited chromosomal mutations exhibit mental and/or physical abnormalities. There is little or no chance of sufferers who reach adulthood reproducing and so passing these defects on to their children. These conditions are therefore maintained in the population by new mutations either arising spontaneously or being induced by an environmental insult such as radiation. Dominant mutations show up in the first generation after exposure, as do X-linked mutations in males, and may occur in

subsequent generations if they do not prevent childbearing. Recessive mutations, however, tend to occur in later generations. When assessing the risks of radiation it is therefore necessary to allow for hereditary effects which may not appear for several generations.

2.5.2. Risk coefficients for hereditary disease

No hereditary effects at levels that are statistically significant have been observed in human populations exposed to radiation. Scientists have reviewed all the genetic studies in Hiroshima and Nagasaki on the children born to irradiated survivors. No statistically significant effects were observed. Taken together, the data suggest a lower limit for the doubling dose (the radiation dose capable of doubling the spontaneous rate) for genetic damage following acute irradiation of approximately 1.4-1.8 Sv. This compares with a value of 0.3 Sv in the mouse for acute exposure and 1 Sv for chronic exposure.

For protection purposes, ICRP recommended a risk factor of 1.0×10^{-2} Sv^{-1} for members of the public and 0.6×10^{-2} Sv^{-1} for workers.

2.6. Irradiation *in utero*

2.6.1 Fetal brain development

On the basis of results of animal studies, it is assumed that radiation-induced malformations in humans, following acute exposure *in utero*, may occur above a dose threshold of about 0.2 Gy in the later stages of pregnancy.

There is one type of low-dose effect in fetal brain tissue that is considered to be deterministic on biological grounds, although it may not be associated with a threshold. It was described in a study of about 1600 Japanese children who survived into adolescence after acute exposure to atomic bomb irradiation. About 25 of these children who were exposed between 8 and 15 weeks after conception developed severe mental retardation (IQ < 70 points), on the assumption that their normal IQ would have been 100 points on the test system used.

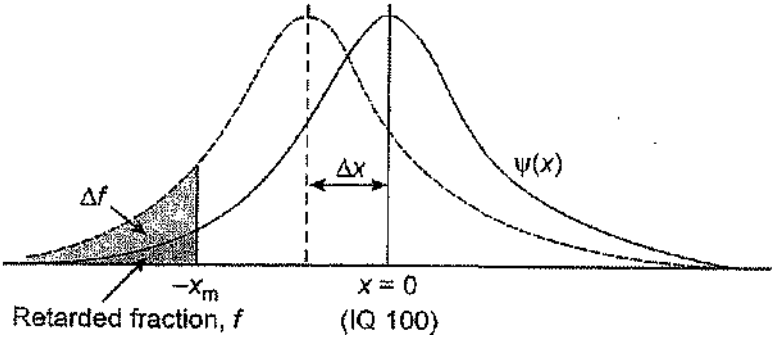


FIG 2.6

*The shift to the left from $\psi(x)$ by Δx (30 IQ points) increases the background retarded fraction, **f**, by Δf. Δx_m denotes the number of standard deviations below IQ 100 to classify an individual as mentally retarded.*

Other features observed were small head size and unprovoked seizures. The dose-response relationship was consistent with a frequency of 40% at 1 Gy and an IQ drop of about 30 points (Figure 2.6). At 0.05 Gy, the frequency was about 5% and the background frequency for comparison was 0.8%. Statistical analysis of the data could not prove or disprove the existence of a dose threshold. A period of less vulnerability was observed between 16 and 25 weeks after conception and there were no abnormalities before or alter this 'window' of 8 to 25 weeks when critical neuron development is taking place. On this basis the ICRP recommended that once pregnancy was declared, the fetus should be adequately protected by ensuring that the methods of protection at work provided a standard of protection comparable with that recommended for members of the public. This advice is embodied in the European Directive which states that "the equivalent dose to the child to be born will be as low as reasonably achievable and that it is unlikely that the dose will exceed 1 mSv during at least the remainder of pregnancy after declaration of pregnancy".

2.6.2. Risk of cancer

Estimates of cancer risk to age 15 years have been obtained by combining the excess risk observed in the Oxford Survey of Childhood Cancer with estimates of dose to the fetus from obstetric X-rays. This yields an estimated risk of leukaemia of 2.5×10^{-2} Gy^{-1} and of other cancers of 3.5×10^{-2} Gy^{-1} (low-LET); about half of these cases are assumed to be fatal. These risk coefficients for cancer are directly applicable to low doses and low-dose rates. The lifetime risk of fatal cancer following exposure *in utero* may exceed that in the first 15 years of life by a factor of up to four. There are, however, considerable uncertainties in projecting lifetime risks from the current data and this factor may perhaps be about two. For hereditary risks it is assumed that the risks from *in utero* exposure are the same as after birth; 2.4×10^{-2} Sv^{-1} following irradiation of male or female germ cells.

2.7. Summary

This chapter provides a basic understanding of the biological basis upon which dose limits are derived in the System of Protection

recommended by the ICRP in its 1990 Recommendations. The nominal probability coefficients for stochastic effects are summarized in Table 2.8.

Since completion of this review UNSCEAR have issued two further reviews covering the health effects of exposure to ionising radiation.

TABLE 2.8.
Risk factors (10^{-2} Sv^{-1}) for protection

	ICRP 1977	ICRP 1991	
		Public	Workers
Fatal cancer	1.25	5.0	4.0
Hereditary defects	0.4[a]	1.0[b]	0.6[b]
Total	1.65	6.0	4.6
Total (weighted)[c]	-	7.3	5.6

[a]Two generations.

[b]All generations.

[c]To allow for non-fatal cancers and years of life lost for cancers and hereditary disease.

Control points to Chapter 2

1) Cellular effects after exposure.
2) Types of dose. Dose quantities.
3) Cellular damage and repair.
4) Classification of radiation-induced damage.
5) Deterministic effects (whole-body irradiation, partial-body irradiation).
6) Radiation-induced cancer (high-dose and low-dose studies).
7) Hereditary diseases.
8) Irradiation *in utero*.

TESTS

Part I

1. Find the correspondence between the concept of a dose physical value and its definition.

1) exposure dose is defined by;	a)energy imparted by radiation to unit mass of tissue .
2) absorbed dose is defined by;	b) measurement of radiation in relation to its ability to produce ionization.
3) equivalent dose is defined by;	c)equivalent dose weighted for susceptibility to harm of different tissues.
4) effective dose is defined by.	d) absorbed dose weighted for harmfulness of different radiations.

2. Find correspondence between the concept of a radiation value and its definition:

1) exposure dose is defined by;	a)H;
2) absorbed dose is defined by;	b)X;
3) equivalent dose is defined by;	c)E;
4) effective dose is defined by.	d)D;
	e)F.

3. Find correspondence between a radiation value and its unit of measurement:

1) exposure dose is defined by;	a) Gy;
2) absorbed dose is defined by;	b) Sv;
3) equivalent dose is defined by;	c) C/kg .
4) effective dose is defined by.	

4. Find correspondence between the attachment to form CI multiple units and its numerical coefficient:

1) Tera, T;	a) 10^3;
2) Giga, G;	b) 10^6;
3) Mega, M;	c) 10^9;
4) Kilo, k;	d) 10^{12};
5) Milli, m.	e) 10^{-3};
	f) 10^8.

5. Find correspondence:

1) external irradiation;	a) penetration of a radioactive isotope into an organism through digestive apparatus;
2) whole body irradiation;	b) a source of exposure is inside an organism;
3) local irradiation;	c) exposure of a part of an organism;
4) percutaneous entry;	d) exposure of a whole organism;
5) oral administration.	e) penetration of radioactive isotopes through

skin;
f) a source of exposure is outside of an organism.

6. Find correspondence:

1) sensibilizator;
2) protector;
3) chemical radioprotector;
4) biological radioprotector;
5) concentration of a radionuclide.

a) reduce radiosensitivity;
b) improve general resistance of an organism to irradiation;
c) increase radioresistance;
d) increase radiosensitivity;
e) the amount of a radionuclide in a body;
f) the amount of a radionuclide in a unit of weight.

7. Find correspondence:

1) target theory;
2) structural-metabolic theory;
3) the model of a probable radiation injury of a cell;
4) stochastic theory;
5) the theory of lipid radiotoxins.

a) some substances are formed in a tissue in the first hours after irradiation; following entry of these substances in a tissue causes haemolysis;
b) the discrecity of energy absorption, high morphological and functional cell heterogeneity;
c) the theory that studies different disturbances of a biological system in vital functions or disturbances that can be caused by irradiation (according to the theory of probability);
d) different cells that were irradiated by the same dose have different levels of lesion according to the principle of a hit; and realized damages are exhibited with the probability of less than 1;
e) high reacting products are synthesized under the action of ionizing radiation which induces additional damage of biologically important macromolecules and causes formation of low-molecular toxic metabolites;
f) the theory that differentiates whether the biological action of ionizing radiations (α,β) on the same biological object is higher or lower in comparison with the action of standard irradiation (γ-rays, X(Roentgen) -rays) .

Part II

Choose suitable answer. (2 points for each correct answer)

1. Weighting factor for some types of ionizing radiation is used to calculate:

a) exposure dose;
b) absorbed dose ;
c) equivalent dose;
d) effective dose .

2. Weighting factor for tissues and organs is used to calculate:

a) exposure dose;
b) absorbed dose ;
c) equivalent dose;
d) effective dose.

3. Maximum value of weighting factor is used for:

a) mammary gland;
b) thyroid gland;
c) lungs;
d) gonad;
e) red bone marrow.

4. To find average value of a dose rate you need:

a) to add the dose of exposure to the time of exposure;
b) to divide the dose of exposure by the time of exposure;
c) to multiply the dose of exposure by the time of exposure.

5. Biological effect of exposure depends on:

a) absorbed dose;
b) an organism reactivity;
c) the time of exposure, exposure intervals;
d) amount and localization of exposed surface;
e) all mentioned above.

6. Radiation medical effect is a:

a) death of exposed experimental animals;
b) inactivation of organ cells and tissues;
c) changes in the health of a human induced by radiation;
d) laboratory animals radiogenic cancers.

7. Radiation medical effects are divided into:

a) stochastic and deterministic;
b) threshold and nonthreshold;

c) not immediate, early and late;

d) stochastic and deterministic, threshold and nonthreshold, not immediate, early and late.

8. Low doses of exposure are characterized by:

a) the level of radiation-induced effect;

b) individual risk of stochastic effects;

c) public risk of stochastic effects;

d) all mentioned above.

9. Stochastic radiation medical effects are:

a) birth defects in newborns;

b) genetic birth defects;

c) all radiation-induced oncological diseases and genetic effects;

d) different health disturbances caused by irradiation.

10. Radiation genetic risk is:

a) the probability to have genetic defects in a progeny of exposed person;

b) the frequency of genetic defects symptoms in a progeny group of exposed people;

c) the probability of genetic defect appearance in a progeny of exposed person or expected frequency of genetic defects symptoms in a progeny group of exposed people;

d) the risk of radiation mutagenesis.

11. Exposure in the range set by Radiation standards (RS-99):

a) eliminates appearance of radial leukemia;

b) can cause radial cataract;

c) can not cause radial cataract;

d) can not cause radiation disease;

e) can not cause radial cataract and radiation disease.

a) виключає виникнення променевих лейкозів;

12. According to RS-99 effective dose for the A group personnel should not exceed:

a) about 50 mSv annually during 5 different (following) years in consecutive order but 50 mSv annually for extremities;

b) 20 mSv annually;

c) about 20 mSv during 5 (following)different years (in consecutive order);

d) about 50 mSv annually during 5 different (following) years in consecutive order but 20 mSv annually for extremities;

e) about 2 mSv annually during 5 different (following) years in consecutive order but 50 mSv annually for extremities.

13. Irradiation from X-ray apparatus at some distance from an object depends on:

a) voltage rate;
b) current intensity;
c) filtration of a beam;
d) voltage rate and current intensity.

14. X-ray room has following dangerous, harmful factors:

a) X-ray radiation;
b) accelerated electrons;
c) neutron radiation;
d) ultraviolet radiation;
e) gamma (γ)-radiation.

15. Using X-rays examining the effective dose of a patient can not be determined by:

a) measurements during examining;
b) measurements of absorbed dose with following calculation;
c) measurements of equivalent dose with following calculation;
d) measurements of exposure dose with following calculation;
e) recording of exposure dose with following calculation.

16. The main principles of radiation safety.

a) the risk to refuse examining should be more serious than the risk to do it;
b) the dose after examining should be as low as reasonably practicable to get necessary diagnosing;
c) the annual effective dose after preventive diagnosing should not exceed 1 mSv;
d) all mentioned above.

Part III

Put appropriate words. (1 point for each correct answer)

1. The decrease of exposure effectiveness by dose penetrating in some portions and in definite time intervals is called _____.

2. To reduce lethal effect after an organism exposure some chemicals are injected into an organism before irradiation. These chemicals are called _____. The process of injury reduction is called chemical protection.

3. The main factor that can cause reproductive failure is _____.

4. The mechanism of energy absorption by molecules depends on _____.

5. The main difference between cumulative reactions of cells on exposure and lethal reactions of cells on exposure is the following: in cumulative reactions _____increases the degree of cell response, not the number of cells that react; in lethal reactions _____increases the number of cells that die.

6. Cell irradiation on the stage G_1 disturbs _____wich is necessary for replication.

7. Cell _____ can cause the appearance of giant cells.

8. Doses of X-rays irradiation that are less than 10 kR induce _____ of a cell; doses higher than 35kR induce ___ death.

9. The number of chromosome aberrations is a quantitative index that can show_____.

10. The technique to calculate surviving cells in vitro was developed by _____in 1956; in 1961 the scientists_____developed the technique to calculate in vivo.

ВИСНОВКИ

Знання англійської мови – це ключ до успіху в сучасному світі, де спілкування та обробка величезних обсягів інформації набуває все більшого значення. Інтерес до вивчення мов традиційно великий, бо перефразовуючи відомий вислів, можна сміливо сказати, що той, хто володіє мовами, володіє світом.

Метою навчання іноземної мови у закладах вищої освіти є оволодіння іноземною мовою як засобом комунікації, так і отримання професійно спрямованої іншомовної компетентності для успішної подальшої професіоналізації.

Завдання дисципліни «Іноземна мова за професійним спрямуванням (англійська)» полягають у формуванні, поглибленні та удосконаленні різних видів мовленнєвої діяльності (аудіювання, читання, реферування, письмо, переклад, спілкування у професійній сфері) для формування основних складових іншомовної професійної комунікативної компетентності в контексті розвитку екологічних галузей в Україні та міжнародного обміну науковою інформацією, зокрема, стажування за кордоном.

Головна мета навчального посібника – забезпечити студентів необхідним матеріалом у процесі вивчення курсу «Іноземна мова за професійним спрямуванням», підготувати студентів до читання і розуміння оригінальної літератури в галузі радіоекології, навчити анотувати і реферувати тексти, а також сформувати навички професійно-спрямованого мовлення у межах засвоєної фахової тематики.

Кожна тема містять лексичний мінімум відповідної теми, оглядові лексичні завдання, комунікативні вправи та ситуації для усного та писемного мовлення, а також тестові завдання для самостійного контролю.

Вивчення іноземної мови відіграє велике значення для професійного спілкування у закладі вищої освіти і впливає на підготовку студентів до ефективної комунікації в їх професійному середовищі. Тому одним з головних завдань закладу вищої освіти має стати надання допомоги студентам 3-4 го років навчання як у професійній адаптації, так і у вивченні іноземної мови за фахом.

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Навчальне видання

“Radiobiology and Radioecology (англійська мова за професійним спрямуванням)”

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