X-RADIATION AND γ-RADIATION

1. Exposure data

1.1 Occurrence

1.1.1 *X-radiation*

X-rays are electromagnetic waves in the spectral range between the shortest ultraviolet (down to a few tens of electron volts) and γ-radiation (up to a few tens of mega electron volts) (see Figure 2, Overall introduction). The term γ-radiation is usually restricted to radiation originating from the atomic nucleus and from particle annihilation, while the term X-radiation covers photon emissions from electron shells. X-rays are emitted when charged particles are accelerated or decelerated, during transitions of electrons from the outer regions of the atomic shell to regions closer to the nucleus, and as *bremsstrahlung*, i.e. radiation produced when an electron collides with, or is deflected by, a positively charged nucleus. The resulting line spectra are characteristic for the corresponding element, whereas *bremsstrahlung* shows a continuous spectrum with a steep border at the shortest wavelengths.

Interaction of X-rays with matter is described by the Compton scattering and photoelectric effect and their resulting ionizing potentials, which lead to significant chemical and biological effects. Ions and radicals are produced in tissues from single photons and cause degradation and changes in covalent binding in macromolecules such as DNA. In other parts of the electromagnetic spectrum, below the spectra of ultraviolet and visible light, the single photon energies are too low to cause genotoxic effects. The intensity (I) of X-rays inside matter decreases according to $I = I_0 \times 10^{-\mu \cdot d}$, where d is the depth and μ a coefficient specific to the interacting material and the corresponding wavelength. The ability to penetrate matter increases with increasing energy and decreases with increasing atomic number of the absorbing material. When X-rays penetrate the human body, they are absorbed more effectively in the bones than in the adjacent tissue because of the greater density of bone and the larger proportion in bone of elements with higher atomic numbers, such as calcium.

X-rays are usually generated with X-ray tubes in which electrons emitted from a cathode are accelerated by a high electric potential and hit a target which emits *bremsstrahlung* and a line spectrum characteristic for the material of the target. The expression 'kVp' refers to the applied voltage (kV) of an X-ray machine and is given as the maximum (p for peak) voltage that the machine can produce. According to the

applied voltage, ultrasoft (5–20 kVp), soft (20–60 kVp), medium hard (60–120 kVp), hard (120–250 kVp) and very hard (> 250 kVp) X-rays can be distinguished. Extremely hard X-rays are generated with betatrons, synchrotrons and linear accelerators and are in the mega electron volt range.

X-rays are used in many medical and technical applications. The most common are X-ray examinations of the human body and analysis of technical materials. In X-ray therapy, the biological effect of X-rays is used to destroy malignant tissue. It is applied mainly to treat cancer patients, when high doses are delivered to a limited area of the body, with restricted irradiation of adjacent tissue.

1.1.2 γ-*radiation*

Ernest Rutherford in 1899 found that the radiation from radioactive sources consisted of several components, which he called α-, β- and γ-rays. In 1914, he proved by interference experiments that γ-rays were electromagnetic waves. They are emitted by γ-transitions in atomic nuclei. The corresponding photons, called γ-quants, have widely different energies, ranging from 0.01 to 17.6 MeV, which reflect the fact that the energy of the transitions in the atomic nucleus is higher than that of the transitions of the orbiting electrons. The emission of γ-rays usually follows nuclear trans-formations, which place an atomic nucleus in a state of enhanced energy during processes of radioactivity and during capture of particles. Unlike α- and β-radiation, γ-rays cannot be deflected by electric and magnetic fields. The γ-transition, also called γ-decay, is not radioactive decay in the usual sense, because neither the charge nor the mass number of the nucleus changes.

Electromagnetic radiation in the same energy range can also be produced by the decay of elementary particles, annihilation of electron–positron pairs and acceleration and deceleration of high-energy electrons in cosmic magnetic fields or in elementary particle accelerators. γ-rays, especially those with high energy, can penetrate matter easily, and their absorption and deflection follow an exponential law, as in the case of X-rays. Their physiological effect is also similar to that of X-rays.

Interaction of γ-rays with matter is described by the Compton scattering and photoelectric effect. At energies above 1.02 MeV, pair production occurs, resulting in emission of electron and positron radiation. At even higher energies, in the range of several mega electron volts, absorption of γ-quants results in neutron emission.

1.2 Exposure

Electromagnetic waves in the ionizing range are ubiquitous in the human environ-ment and are responsible with α- and β-rays and to a lesser extent with particle radiation, such as neutrons or muons, for the total radiation dose to which the average person is exposed.

Exposure to X-rays and γ-rays can be external or internal, depending on the location of the source with respect to the human body. External exposure occurs, for example, during X-ray examinations or during natural irradiation from building materials containing γ-ray emitters. Most of the dose from external irradiation is due to X- or γ-rays, because α- and β-particles are readily absorbed by the clothes covering the body or by the superficial layer of skin, whereas X- and γ-rays can penetrate the body and even traverse it if their energy is sufficiently high (see Figure 1, Overall introduction). Internal irradiation occurs during the decay of radionuclides absorbed in the body, usually after ingestion or inhalation. In this case, α- and β-particles are more important than X- or γ-rays, because α- and β-emitters lose most or all of their energy in the tissues or organs in which they decay, while the energy of X- and γ-rays, which is usually lower than those of α- and β-rays, is diffused throughout the body or even leaves the body without creating any damage.
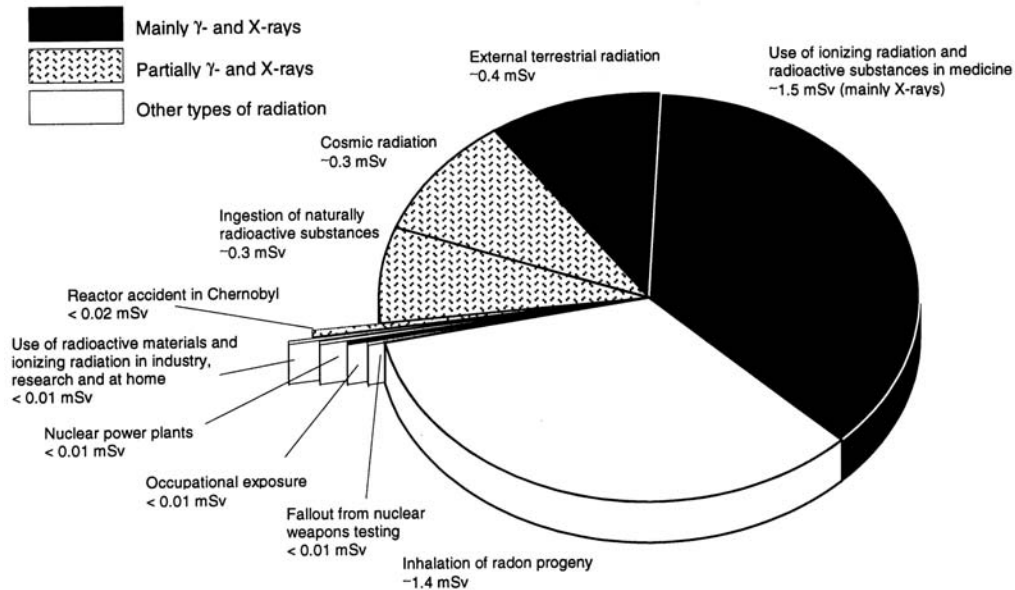
Doses of all types of radiation from external and internal exposure are summarized in the Overall introduction. In this chapter, only external exposure to X and γ-rays is discussed.

Although it is difficult to evaluate the relative contribution of electromagnetic radiation in mixed radiation fields, it can be estimated to be about 50% (Figure 1). There are major natural and man-made sources of exposure, some of which are increasing. Estimates of the average doses received by the general population are reviewed regularly by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and by many national bodies, such as the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit in Germany, the National Council on Radiation Protection and Measurements in the USA and the National Radiological Protection Board in the United Kingdom. Medical exposure and natural terrestrial exposure are due mainly to X- and γ-rays. Other important components of these estimates are mixed radiation fields, such as internal β-emitters with a considerable γ-ray component, whereas the important man-enhanced exposure from indoor radon and its short-lived daughter products is mainly internal exposure to α-radiation. Cosmic radiation at ground level consists of particle radiation (mainly muons), with increasing contributions from neutrons at higher altitudes (see section 4.4.1, Overall introduction).

1.2.1   *Natural sources*

Most natural exposure to X- and γ-rays is from terrestrial sources, with a small part from extraterrestrial sources. Exposure from terrestrial sources depends on the geological properties of the soil, which vary significantly. The average annual external exposure to γ-rays worldwide from terrestrial sources is 0.46 mSv (UNSCEAR, 1993). This value is derived from the average indoor (80 nGy h^{-1}) and outdoor (57 nGy h^{-1}) absorbed dose rates in air, assuming an indoor occupancy factor of 0.8 and a conversion factor from the absorbed dose in air to the effective dose of 0.7 Sv Gy^{-1}.

Figure 1. Estimated average exposure to ionizing radiation from various sources in Germany

■ Mainly γ- and X-rays

▒ Partially γ- and X-rays

□ Other types of radiation

External terrestrial radiation
~0.4 mSv

Use of ionizing radiation and
radioactive substances in medicine
~1.5 mSv (mainly X-rays)

Cosmic radiation
~0.3 mSv

Ingestion of naturally
radioactive substances
~0.3 mSv

Reactor accident in Chernobyl
< 0.02 mSv

Use of radioactive materials and
ionizing radiation in industry,
research and at home
< 0.01 mSv

Nuclear power plants
< 0.01 mSv

Occupational exposure
< 0.01 mSv

Fallout from nuclear
weapons testing
< 0.01 mSv

Inhalation of radon progeny
~1.4 mSv

From Bundesamt für Strahlenschutz (1998)

UNSCEAR (1993) also gives detailed data for exposure in various regions of the world. The lowest outdoor dose rates in air are reported for Canada (24 nGy h^{-1}) and the lowest indoor rates for Iceland and New Zealand (20 nGy h^{-1}). The maximum average values are found in Namibia (outdoors, 120 nGy h^{-1}; indoors, 140 nGy h^{-1}). In a survey of terrestrial γ-radiation in the USA, 1074 measurements were made in and around 247 dwellings (Miller, 1992). The absorbed dose rate in outdoor air was 14–118 nGy h^{-1} with an average of 46.6 nGy h^{-1}, whereas the average indoor rate was 12–160 nGy h^{-1} with an average of 37.6 nGy h^{-1}. The last value is considerably lower than the worldwide average reported by UNSCEAR (1993) and apparently results from the predominant use of wood-frame construction and other building materials with a low content of radionuclides in the USA. The average exposures in eight countries of Europe ranged from 50 to 110 nGy h^{-1} in buildings and from 30 to 100 nGy h^{-1} in the open air (Green *et al.*, 1992; Commission of the European Communities, 1993).

Little exposure is derived from X- and γ-rays in extraterrestrial natural sources (i.e. cosmic rays), as muons and electrons are the most important contributors to the average annual effective dose at ground level of about 0.4 mSv (UNSCEAR, 1993).

1.2.2 *Medical uses*

The medical uses of radiation include diagnostic examinations and treatment. The dose to individual patients undergoing radiotherapy is much higher than that experienced during diagnosis, although the number of patients is much smaller. As treatment with radiotherapy is intended to deliver high doses to target organs, mostly in elderly patients, attempts to transform collateral doses to non-target organs into effective doses are open to criticism. For this reason, data on exposure during radiotherapy are not described, although UNSCEAR (1993) made the crude estimate that the effective collective dose of the world population due to radiotherapy is comparable to that due to diagnostic applications (see section 4.2, Overall introduction).

Medical diagnosis involving ionizing radiation is based mainly on X-rays. Although the dose per examination is generally low, the extent of the practice makes diagnostic radiography the main source of radiation from medical use. The use of X-rays and γ-rays for medical purposes is distributed very unevenly throughout the world, being closely associated with general health care level (see section 4.2, Overall introduction). A survey undertaken by UNSCEAR in 1990–91, in which responses to a questionnaire were received from 50 countries, indicated that at that time there were 210 000 radiologists worldwide, 720 000 diagnostic X-ray units, 1.6 thousand million X-ray examinations performed in 1990 and 6 million patients undergoing some form of radiotherapy. Seventy per cent of these services were available in countries with a well-developed health-care system. In highly developed countries, most plain-film examinations of the chest and extremities involve relatively low doses (effective doses of about 0.05–0.2 mSv), whereas the doses used to examine the abdomen and lower back are higher (about 1–3 mSv). The approximate doses to the skin and the effective doses from a number of diagnostic procedures in developed countries are shown in Table 1. Computed tomography scanning has become widely available in many developed countries. In the USA, even though it accounts for less than 10% of procedures, it provides more than 30% of the absorbed dose since the effective dose is about 2.5–15 mSv, which is higher than that from most procedures in which plain- film X-rays are used for diagnosis (UNSCEAR, 1993). The estimated annual effective dose from all diagnostic uses of radiation in those countries was estimated to be 1.0 mSv per person, while that averaged over the whole world was about 0.3 mSv per person (UNSCEAR, 1993).

A source of uncertainty in these estimates is the use of fluoroscopy, which results in much higher doses than radiography; furthermore, its prevalence is not fully known and is changing with time. The doses may vary widely: modern equipment with image amplifiers results in lower doses than older equipment with fluorescent screens, but high doses may still be received when fluoroscopy is used in interventional radiology as a means of guidance during surgical procedures, although this practice is infrequent. The effective dose from most procedures is about 1–10 mSv. The collective dose is due mainly to the more frequent fluoroscopic examinations of the gastrointestinal tract. In the USA, the average effective doses are 2.4 mSv during examination of the upper

Table 1. Approximate mean effective doses from diagnostic radiology procedures in highly developed countries

Procedure	Average effective dose (mSv) per examination	Average number of examinations per 1000 population per year
Chest radiograph	0.14	197
Lumbar spine radiograph	1.7	61
Abdominal radiograph	1.1	36
Urography	3.1	26
Gastrointestinal tract radiograph	5.6	72
Mammography	1.0	14
Radiograph of extremity	0.06	137
Computed tomography, head	0.8	44
Computed tomography, body	5.7	44
Angiography	6.8	7.1
Dental X-ray	0.07	350
Average	1.05	887

From UNSCEAR (1993). Doses may vary from these values by as much as an order of magnitude depending on the technique, equipment, film type and processing.

gastrointestinal tract and 4.1 mSv during a barium enema. These two types of examination are the source of about 40% of the annual collective dose due to diagnostic X-ray application, whereas chest examinations account for over 5% of the *per caput* effective dose equivalent from medical X-rays in the USA (National Council on Radiation Protection and Measurements, 1989). The dose from chest examinations in a Canadian study was 0.07 mSv (Huda & Sourkes, 1989).

1.2.3   *Nuclear explosions and production of nuclear weapons*

The atomic bombings of Hiroshima and Nagasaki, Japan, in 1945 exposed hundreds of thousands of people to substantial doses of external radiation from γ-rays. Estimates of the doses are available for 86 572 persons in the Life Span Study out of about 120 000 persons who were in one of the cities at the time of the explosions. The collective dose to the colon for the 86 472 persons for whom dosimetry is available was 24 000 person–Sv (Burkart, 1996; see section 4.1, Overall introduction), to give an average of about 300 mSv. The doses decreased with distance from the epicentres, but the highest doses to the colon were > 2000 mSv.

Atmospheric nuclear explosions were carried out at several locations, mostly in the Northern Hemisphere, between 1945 and 1980. The most intense period of testing was between 1952 and 1962. In all, approximately 520 tests were carried out, with a

total yield of 545 Mt. Since 1963, nuclear tests have been conducted mainly underground, and the principal source of worldwide exposure due to weapons testing is the earlier atmospheric tests. The total collective effective dose of X- and γ-rays committed by weapons testing to date is about 2.2×10^6 person–Sv. The radionuclides that contribute the most to this dose are listed in Table 2. With the exception of ^{137}Cs and ^{125}Sb, all of these radionuclides have radioactive half-lives of less than one year, and therefore delivered their doses soon after the explosions. ^{137}Ce, with a radioactive half-life of about 30 years, is still present in the environment and continues to deliver its dose at a low rate. For the world population of 3.2×10^9 in the 1960s, the average effective dose from global fall-out resulting from external irradiation was about 0.7 mSv (UNSCEAR, 1993).

Table 2. Collective effective doses of the world population from external radiation committed by atmospheric nuclear testing

Radionuclide	Radioactive half-life	Collective effective dose (1000 person–Sv)
^{137}Cs	30 years	1210
^{95}Zr	64 days	270
^{54}Mn	310 days	180
^{106}Ru	370 days	140
^{95}Nb	35 days	130
^{125}Sb	2.7 years	88
^{140}Ba	13 days	49
^{144}Ce	280 days	44
^{103}Ru	39 days	39
^{131}I	8.0 days	4.4
^{141}Ce	33 days	3.3
Total (rounded)		2200

From UNSCEAR (1993)

People living near the sites where nuclear weapons were tested received higher doses than the average, but the magnitude of the local dose varies according to the conditions under which the tests were conducted. In the USA, about 100 surface or near-surface tests were conducted at a test site in Nevada between 1951 and 1962. The collective dose to the local population of about 180 000 persons has been estimated to be approximately 500 person–Sv (Anspaugh *et al*., 1990), corresponding to an average dose of about 3 mSv.

After a US test in 1954 at Bikini atoll in the Marshall Islands, the residents of Rongelap and Utirik atolls, located 210 and 570 km, respectively, east of Bikini,

received high external exposures, mainly from short-lived radionuclides, with doses of 1900 mSv on Rongelap (67 persons, including three *in utero*), 1100 mSv on nearby Ailinginae atoll (19 persons, including one *in utero*) and 100 mSv on Utirik (167 persons, including eight *in utero*) (Conard *et al*., 1980).

At the Semipalatinsk test site in the Kazakh region of the former USSR, atmospheric tests were conducted from 1949 through 1962, exposing 10 000 people in settlements bordering the test site. The collective dose from external irradiation was estimated to be 2600 person–Sv, corresponding to an average dose of 260 mSv (Tsyb *et al*., 1990).

γ-ray fields resulting from production of weapons material and chemical separation can be considerable, and, as in the case of testing, some local exposures have been substantial. For example, the release of nuclear wastes into the Techa River from a military plant of the former USSR near Kyshtym, in the Ural Mountains, resulted in a cumulative effective dose in the early 1950s of up to 1 Sv (Trapeznikov *et al*., 1993; Bougrov *et al*., 1998).

1.2.4   *Generation of nuclear power*

The generation of electrical energy in nuclear power stations has also contributed to exposure to radiation. The collective effective dose committed by the generation of 1 GW–year of electrical energy has been estimated by UNSCEAR (1993) for the entire fuel cycle, from mining and milling, through enrichment and fuel fabrication, reactor operation, to fuel processing and waste disposal, including transport of radioactive materials from one site to another. The doses of X- and γ-rays have not been estimated explicitly as most of the exposure is due to internal irradiation. The local collective effective dose from X- and γ-rays from external irradiation can be crudely estimated to be about 0.2 person–Sv per GW–year. If it is assumed that about 2000 GW–year of electricity have been generated by nuclear reactors throughout the world, the local collective effective dose from external irradiation is about 400 person–Sv, corresponding to an average dose for the world's population of about 0.1 μSv. An additional component of the exposure is the long-lived radionuclides that are distributed worldwide; the only one that contributes significantly to external irradiation, however, is ^{85}Kr, which has a radioactive half-life of about 10 years. UNSCEAR (1993) indicated that the global component of the collective effective dose due to environmental releases of ^{85}Kr is 0.1 person–Sv per GW–year, corresponding to an average dose for the world's population of about 0.05 μSv.

1.2.5   *Accidents*

The production and transport of nuclear weapons have resulted in several accidents. The two most serious accidents in nuclear weapons production were at Kyshtym and at the Windscale plant at Sellafield in the United Kingdom, both occurring in 1957 (see

section 4.1.3, Overall introduction). A major accident in a nuclear power plant occurred in Chernobyl, Ukraine, in 1986 (see section 4.4.2, Overall introduction).

The Kyshtym accident was a chemical explosion that followed failure of the cooling system in a storage tank of highly radioactive fission wastes. The highest doses were received by 1150 people who received an estimated effective dose from external irradiation of about 170 mSv (UNSCEAR, 1993; Burkart & Kellerer, 1994; Burkart, 1996).

The Windscale accident was caused by a fire in the uranium and graphite core of an air-cooled reactor primarily intended for the production of plutonium for military use. An important route of intake was through milk consumption, which was controlled near the accident, although it was a significant source of exposure further away. The total collective effective dose from external irradiation received in northern Europe was 300 person–Sv (Crick & Linsley, 1984). The total collective effective dose from the release is estimated to have been 2000 person–Sv (UNSCEAR, 1993).

The Chernobyl accident consisted of a steam explosion in one of the four reactors and a subsequent fire, which resulted in the release of a substantial fraction of the core inventory of the reactor. The collective effective dose from the accident is estimated to have been about 600 000 person–Sv, approximately half of which was due to external irradiation (UNSCEAR, 1988). The main contributor to the dose from external irradiation was [137]Cs. The doses to individuals throughout the Northern Hemisphere varied widely, some staff and rescue workers on duty during the accident receiving fatal doses > 4 Sv and the most affected people in the evacuated zone receiving effective doses approaching 0.5 Sv (Savkin *et al*., 1996).

Sealed sources used for industrial and medical purposes have occasionally been lost or damaged, resulting in exposure of members of the public. Examples include the sale of a ^{60}Co source as scrap metal in the city of Juarez, Mexico, in 1983 (Marshall, 1984); the theft and breaking up of a ^{137}Cs source in Goiânia, Brazil, in 1987 (IAEA, 1988); and the retrieval of a lost ^{60}Co source in Shanxi Province, China, in 1992 (UNSCEAR, 1993). While these incidents resulted in significant individual doses to a small number of people, the collective effective doses were not large. Tables 3 and 4 are based on recently published data and summarize radiation accidents and resulting early fatalities. Table 4 shows that the steady increase in the use of sources of ionizing radiation has led to an increase in the number of fatalities, despite progress in radiation protection.

1.2.6   *Occupational groups*

Occupational exposure to radiation occurs during nuclear fuel recycling, military activities and medical applications. The doses, including those from internal exposure, are given in Table 5.

Table 3. Major radiation accidents (1945–97) and early fatalities in nuclear and non-nuclear industries

Year	Place	Source	Dose (or activity intake)	No. of persons with significant exposure[a]	No. of deaths
1945–46	Los Alamos, USA	Criticality	≤ 13 Gy	10	2
1958	Vinèa, Yugoslavia	Experimental reactor	2.1–4.4 Gy	8	1
1958	Los Alamos, USA	Criticality	0.35–45 Gy	3	1
1960	USSR	^{137}Cs (suicide)	~15 Gy	1	1
1960	USSR	Radium bromide (ingestion)	74 mBq	1	1 (after 4 years)
1961	USSR	Submarine accident	10–50 Gy	> 30	8
1961	Switzerland	^{3}H	3 Gy	3	1
1961	Idaho Falls, USA	Explosion in reactor	≤ 3.5 Gy	7	3
1962	Mexico City, Mexico	^{60}Co capsule	9.9–52 Sv	5	4
1963	China	^{60}Co	0.2–80 Gy	6	2
1964	Federal Republic of Germany	^{3}H	10 Gy	4	1
1964	Rhode Island, USA	Criticality	0.3–46 Gy	4	1
1966	Pennsylvania, USA	^{198}Au	Unknown	1	1
1967	USSR	X-radiation medical diagnostic facility	50 Gy	1	1 (after 7 years)
1968	Wisconsin, USA	^{198}Au	Unknown	1	1
1968	Chicago, USA	^{198}Au	4–5 Gy (bone marrow)	1	1
1972	Bulgaria	^{137}Cs (suicide)	> 200 Gy (local, chest)	1	1
1975	Brescia, Italy	^{60}Co	10 Gy	1	1
1978	Algeria	^{192}Ir	≤ 13 Gy	7	1
1982	Norway	^{60}Co	22 Gy	1	1
1983	Constitu, Argentina	Criticality	43 Gy	1	1
1984	Morocco	^{192}Ir	Unknown	11	8
1985	China	^{198}Au (mistake in treatment)	Unknown, internal	2	1

Table 3 (contd)

Year	Place	Source	Dose (or activity intake)	No. of persons with significant exposure[a]	No. of deaths
1985–86	USA	Accelerator	Unknown	3	2
1986	Chernobyl, USSR	Nuclear power plant	1–16 Gy	134	28
1987	Goiânia, Brazil	^{137}Cs	≤ 7 Gy	50[b]	4
1989	El Salvador	^{60}Co irradiation facility	3–8 Gy	3	1
1990	Israel	^{60}Co irradiation facility	> 12 Gy	1	1
1990	Spain	Radiotherapy accelerator	Unknown	27	≤ 11
1991	Nesvizh, Belarus	^{60}Co irradiation facility	10 Gy	1	1
1992	China	^{60}Co	> 0.25–10 Gy	8	3
1992	USA	^{192}Ir brachytherapy	> 1000 Gy (local)	1	1
1994	Tammiku, Estonia	^{137}Cs	1830 Gy (thigh) + 4 Gy (whole body)	3	1
1996	Costa Rica	Radiotherapy	Unknown	110	≤ 40
1997	Kremlev, Sarov, Russian Federation	Criticality experiment	5–10 Gy	1	1

From IAEA (1998)

[a] 0.25 Sv to the whole body, haematopoietic or other critical organs: < 6 Gy to the skin locally; < 0.75 Gy to other tissues or organs from an external source, or exceeding half the annual limit on intake

[b] The number of persons who received significant overexposure is probably lower, as some of the 50 contaminated persons received doses < 0.25 Sv.

**Table 4. Time trends in numbers of major radiation accidents
and early fatalities, 1945–97**

Years	Nuclear or military installations		Other installations	
	Accidents	Fatalities	Accidents	Fatalities
1945–54	3	2	0	0
1955–64	12	14	15	10
1965–74	9	0	38	6
1975–84	1	0	35	12
1985–97	3	29[a]	20	66[b]

From IAEA (1998)
[a] Including 28 fatalities after the reactor accident in Chernobyl, 1986
[b] Including 40 fatalities after a radiotherapy accident in Costa Rica, 1996

**Table 5. Annual occupational exposures of monitored
workers to radiation, 1985–89**

Occupational category	Annual collective effective dose (person–Sv)	Annual average effective dose per monitored worker (mSv)
Mining	1100	4.4
Milling	120	6.3
Enrichment	0.4	0.08
Fuel fabrication	22	0.8
Reactor operation	1100	2.5
Reprocessing	36	3.0
Research	100	0.8
Total	2500	2.9
Other occupations		
Industrial applications	510	0.9
Military activities	250	0.7
Medical applications	1030	0.5
Total	1800	0.6
All applications	4300	1.1

From UNSCEAR (1993). Radiological, terrestrial and most occupa-
tional exposures are dominated by X- and γ-radiation.

1.2.7   *Summary of collective effective doses*

Typical collective effective doses from all significant sources of exposure over the period 1945–92 are presented in Table 6, which indicates that the two largest sources of X- and γ-rays are natural radiation and the use of X-rays in medicine. Exposures from atmospheric testing have diminished, and only small contributions to the collective dose are made by the generation of electrical energy from nuclear reactors, from accidents and from occupational exposure. These contributions can, however, result in significant exposure of small groups of individuals.

Table 6. Collective doses from X- and γ-radiation committed to the world population by continuing practices or by single events, 1945–92

Source	Basis of commitment	Collective effect dose from X- and γ-rays (million person–Sv)
Natural	Current rate for 50 years	120
Medical use	Current rate for 50 years	
Diagnosis		80
Treatment		75
Atmospheric nuclear weapons tests	Completed practice	2.5
Nuclear power generation	Total practice to date	0.2
	Current rate for 50 years	2
Severe accidents	Events to date	0.3
Occupational exposure	Current rate for 50 years	
Medical		0.05
Nuclear power		0.12
Industrial uses		0.03
Military activities		0.01
Non-uranium mining		0.4
Total		0.6

From UNSCEAR (1993)

Variations in individual doses over time and place make it difficult to summarize individual doses accurately, although some indications can be given. The average annual effective dose from γ-rays from natural sources is about 0.5 mSv, with excursions up to about 5 mSv. Medical procedures in developed countries result in an annual effective dose of about 1–2 mSv, of which about two-thirds results from diagnostic radiology. The annual effective doses of monitored workers are commonly 1–10 mSv (UNSCEAR, 1993).

1.2.8   *Variations in exposure to X- and γ-radiation*

Figure 1 shows the estimated average exposures to ionizing radiation in a developed country. As described in the Overall introduction, some of the components may vary by a factor of up to 10, and the distribution is almost log-normal. The distribution of doses from X- and γ-irradiation in medical diagnosis is extremely skewed, as the majority of the population receives no exposure in a given year, while the effective dose may be up to 100 mSv for a small number of people receiving computed tomography scans of the abdomen. Table 7 lists the exposure of the general population that includes considerable X- or γ-ray components.

1.3   Human populations studied in the epidemiology of cancer due to X- and γ-radiation

In view of the large, often poorly understood fluctuations in natural and non-occupational artificial radiation, studies of the carcinogenic potential of ionizing radiation should concentrate on populations with known exposures well above the background load of 2–4 mSv per year from all qualities of radiation from internal and external sources. Many such populations were exposed in the past either routinely or during accidents. A number of persons are still irradiated at high doses in the course of radiation therapy to eradicate tumour tissue. Figure 2 shows those organs and systems in which significant health effects have occurred in such population groups. Although these cohorts are often well characterized with respect to the dose and dose rate they received, possible confounders such as increased susceptibility to toxicants and accompanying chemical treatment must be considered. In addition, patients undergoing cancer therapy are usually in an age distribution that excludes the early years of life, which are of special importance in view of the assumed greater sensitivity of children to radiation. Unselected populations of all ages are therefore of particular interest. In view of the many instances of high exposure to radiation at the workplace in the past, occupational exposure is another important facet of risk (Schneider & Burkart, 1998).

1.3.1   *Unselected populations*

Entire communities received heavy exposure through military action, accidents and poorly controlled releases from weapon material production facilities. Table 8 lists the doses received by the cohorts that have been studied in order to quantify the carcinogenic potential of X- and γ-rays, the study of radiation effects in the survivors of the atomic bombs contributing a major element. Several populations exposed during the nuclear programme of the former USSR are now potentially accessible for epidemiological study, although it is unclear whether reliable retrospective dosimetry will be feasible. Nevertheless, except for partially unconfirmed high collective doses, the dose rates to which these populations were exposed are closer to those that

Table 7. Lifetime exposure of the general public to X- and γ-radiation, with doses and variations

Population	Route of exposure	Individual lifetime (75 years) dose (mSv)		Collective dose (person–Sv per year)	Variation
		Average	Maximum		
World (5800 million)	All	180	750	13 920 000	
Medical diagnosis, health-care level I (1500 million)	Diagnostic radiology	75	500	1 500 000	Highly skewed distribution
Medical diagnosis, health-care levels III and IV (1200 million)	Diagnostic radiology	3	380	48 000	Highly skewed distribution

From UNSCEAR (1993). For a description of health-care levels, see the Overall introduction, section 4.2.

Figure 2. Populations who received heavy exposure to ionizing radiation and were followed for cancer and other long-term effects on health

Site of cancer	Atomic bombs, Chernobyl				Radiotherapy and diagnosis										Occupation				
	Atomic bomb survivors	Inhabitants of Marshall islands	Participants in weapons tests	Chernobyl	Ankylosing spondylitis (X-rays)	Ankylosing spondylitis (radium)	Benign gynaecological disorders	Benign breast disease	Fluoroscopy of the chest	Tinea capitis	Thymus	Thorotrast	Thyroid (^{131}I)	X-rays in utero	Radium-dial painters	Radiologists	Underground miners	Nuclear workers	Aircraft personnel
Leukaemia	■		○	□	■		□	○		□	○	■	○	■		■	○		
Thyroid	■	□		■						■	■			○					
Breast	■						□	■	■		□				○				○
Lung	■				■							○					■		○
Bone						■						○			■				
Stomach	■				□													○	
Oesophagus	□				□				□										
Bladder	■							□											
Lymphoma	□				□		○					○		□		□			
Central nervous system	○				■					□			○	□		□			○
Uterus	○						□												
Liver	■											■						○	
Skin										■	□					■	○		
Salivary gland	□									□	□								
Kidney					○	○													
Colon	■				■		○												
Small intestine															○				

■ Statistically significant correlation   □ Strongly suspected but in some studies no significant correlation   ○ Some correlation found but not significant

From Schneider and Burkart (1998)

Table 8. Major human populations exposed to considerable doses of X- and γ-rays

Population	Main exposure	Individual lifetime dose (mSv)		Collective dose (person–Sv)
		Average	Maximum	
Survivors of atomic bombs, Japan (86 000)	Acute γ-rays, neutron component for subcohort with low exposure	280	4000	24 000
Chernobyl: population in 'contaminated areas' (7 million in Belarus, Ukraine and Russian Federation)	External from ^{137}Cs (deposition density of ^{137}Cs, 37 Bq/m^2)	6–17	> 100	45 000–120 000
Population along the Techa River, Russian Federation (80 000)	External and internal ^{90}Sr	200	3000	15 000
Population in area near Semipalatinsk, Kazakhstan	External and internal ^{131}I, ^{137}Cs, ^{103}Ru			
Near Polygon test field (10 000)		(1000)	3000	(20 000)
Altair area (northeast of test field) (90 000)		(300)	1500	(30 000)

From UNSCEAR (1993); Burkart (1996); Cardis *et al.* (1996). Values in parentheses are highly uncertain estimates.

contribute to current exposure to radiation than to those experienced during the atomic bombings in Hiroshima and Nagasaki (UNSCEAR, 1993).

1.3.2   *Workers*

Large work forces experienced considerable individual exposures during the first few decades of the nuclear age. Whereas uranium mining results in internal exposure to α-particles from radon daughter products, reactor operation and reprocessing result mostly in external exposure to X- and γ-rays. In the past, radiologists and other medical personnel were exposed to considerable doses of radiation. In the clean-up operations near Chernobyl, a workforce of several hundred thousand persons was exposed to a cumulative effective dose of up to 250 mSv, and even higher doses were received immediately after the accident. Several tens of thousands of military personnel were exposed primarily to external γ-radiation when they participated in the atomic bomb tests conducted by the United Kingdom and the USA in the 1950s and 1960s, but the individual doses were typically a few millisieverts. Table 9 lists the doses received by cohorts used to assess the effects of radiation among workers.

1.3.3   *Patients*

Even optimized tumour therapy results in high doses of X- and γ-rays to healthy tissue adjacent to or overlying the target volume. Whole-body irradiation before bone-marrow transplantation in leukaemia patients is an example of treatment used in younger patients with potentially long survival and a concomitant risk for a second cancer. Ionizing radiation was also used in the past against fungal infections by inducing epilation of the scalp, to reduce inflammatory processes and against enlarged thymuses. Patients with tuberculosis who underwent multiple fluoroscopies also received high doses (UNSCEAR, 1993). Table 10 gives an overview of the doses received by some of the cohorts used in studies to assess cancer risks in patients exposed to X- and γ-rays.