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European Code against Cancer 4th Edition: Ionising and non-ionising radiation and cancer☆

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ABSTRACT

Ionising radiation can transfer sufficient energy to ionise molecules, and this can lead to chemical changes, including DNA damage in cells. Key evidence for the carcinogenicity of ionising radiation comes from: follow-up studies of the survivors of the atomic bombings in Japan; other epidemiological studies of groups that have been exposed to radiation from medical, occupational or environmental sources; experimental animal studies; and studies of cellular responses to radiation. Considering exposure to environmental ionising radiation, inhalation of naturally occurring radon is the major source of radiation in the population – in doses orders of magnitude higher than those from nuclear power production or nuclear fallout. Indoor exposure to radon and its decay products is an important cause of lung cancer; radon may cause approximately one in ten lung cancers in Europe. Exposures to radon in buildings can be reduced via a three-step process of identifying those with potentially elevated radon levels, measuring radon levels, and reducing exposure by installation of remediation systems. In the 4th Edition of the European Code against Cancer it is therefore recommended to: "Find out if you are exposed to radiation from naturally high radon levels in your home. Take action to reduce high radon levels". Non-ionising types of radiation (those with insufficient energy to ionise molecules) – including extremely low-frequency electric and magnetic fields as well as radiofrequency electromagnetic fields – are not an established cause of cancer and are therefore not addressed in the recommendations to reduce cancer risk.

1. Sources and physical and biological properties of radiation

1.1. Introduction

Natural and man-made sources generate radiant energy in the form of electromagnetic waves; these are characterised by their wavelength, frequency and photon energy. The electromagnetic spectrum includes static (non-alternating) electric and magnetic fields, low-frequency electric and magnetic fields (low energy, long wavelengths), intermediate and radiofrequency (RF) electromagnetic fields (EMF), microwaves, optical radiation (infrared, visible light, ultraviolet radiation) and gamma- and X-rays (ionising radiation with high energy and very short wavelengths) (Fig. 1). In addition to electromagnetic waves, ionising radiations include particulate sources: notably neutrons, electrons (beta particles)

Abbreviations: AGIR, Advisory Group on Ionising Radiation; CT, computerised tomography; EMF, electromagnetic fields; IARC, International Agency for Research on Cancer; ICRP, International Commission on Radiological Protection; ICNIRP, International Commission on Non-Ionising Radiation Protection; RF, radiofrequency; UVR, ultraviolet radiation; UNSCEAR, United Nations Scientific Committee on the Effects of Atomic Radiation.

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Box 1. European Code Against Cancer.

EUROPEAN CODE AGAINST CANCER
12 ways to reduce your cancer risk

1. Do not smoke. Do not use any form of tobacco.
2. Make your home smoke-free. Support smoke-free policies in your workplace.
3. Take action to be a healthy body weight.
4. Be physically active in everyday life. Limit the time you spend sitting.
5. Have a healthy diet:
   - eat plenty of whole grains, pulses, vegetables and fruits;
   - limit high-calorie foods (foods high in sugar or fat) and avoid sugary drinks;
   - avoid processed meat; limit red meat and foods high in salt.
6. If you drink alcohol of any type, limit your intake. Not drinking alcohol is better for cancer prevention.
7. Avoid too much sun, especially for children. Use sun protection. Do not use sunbeds.
8. In the workplace, protect yourself against cancer-causing substances by following health and safety instructions.
9. Find out if you are exposed to radiation from naturally high radon levels in your home. Take action to reduce high radon levels.
10. For women:
    - breastfeeding reduces the mother's cancer risk; if you can, breastfeed your baby;
    - hormone replacement therapy (HRT) increases the risk of certain cancers. Limit use of HRT.
11. Ensure your children take part in vaccination programmes for:
    - hepatitis B (for newborns);
    - human papillomavirus (HPV) (for girls).
12. Take part in organised cancer screening programmes for:
    - bowel cancer (men and women);
    - breast cancer (women);
    - cervical cancer (women).

The European Code Against Cancer focuses on actions that individual citizens can take to help prevent cancer. Successful cancer prevention requires these individual actions to be supported by governmental policies and actions.

and alpha particles. While non-ionising and ionising electromagnetic waves and neutrons can penetrate the body from external sources, charged particles – including alpha and beta particles – have limited ability to penetrate body tissues, and risks are generally associated with their entry into the body by inhalation or ingestion.

Ionising radiation and ultraviolet radiation (UVR) are known to cause cancer [1,2], but the evidence regarding non-ionising radiation is equivocal [3,4]; while there is a mechanistic understanding of the cellular effects of ionising radiation and UVR, plausible mechanisms have not been established for the effects of non-ionising radiation. The cancer risk from ionising radiation, in particular radon, justifies the recommendation of the 4th edition of the European Code against Cancer (Box 1). Ionising radiation from medical diagnostics and treatment is discussed elsewhere, together with other medical exposures [5]. UVR, also subject to a recommendation, is discussed elsewhere [6]. In this paper, we also cover non-ionising radiation (the EMF part), for which the scientific evidence has been evaluated and shows that it is not an established cause of cancer, and is therefore not addressed by a recommendation of the Code.

1.2. Exposure to sources of ionising radiation

Radioactive substances are a source of ionising radiation. An important characteristic of these radioactive materials is the rate at which they decay, either into another radioactive nuclide or into a stable (i.e. non-radioactive) nuclide. The decay rate is normally expressed in terms of the nuclide's half-life, namely, the time taken for the radioactivity of any given amount of the particular radionuclide to decay to half of its initial value. The amount of a radioactive substance is generally measured in terms of its activity or radioactive decay rate, with units of becquerel (Bq); 1 Bq equals one nuclear decay event per second. Each radionuclide, depending on its degree of nuclear instability, has a characteristic radioactive half-life, and nuclear decay is accompanied by a specific yield of energy depending on the radiations emitted (e.g. alpha, beta).

Many radioactive materials exist naturally. Primordial radioactive elements include uranium-238 that has a radioactive half-life of around 4.5×10^9 years leading to the radioactive decay chain that includes radon-222 (which together with its progeny/daughter isotopes/decay products is referred to as 'radon' below). Some human activities create radioactive materials either deliberately or as a by-product. Nuclear fission of uranium-235 in nuclear reactors is a source of man-made radionuclides. Some devices, such as x-ray sets used in medicine and in industrial inspection, generate and emit ionising radiation without the presence of radioactive material.

Radioactive materials external to the body can result in radiation exposure and cancer risk if the emitted radiations can penetrate to body organs and tissues, as is the case for gamma rays, X-rays and neutrons [7]. Entry of radioactive materials into the body, mainly by inhalation or ingestion, can lead to their deposition and retention in body organs and tissues, resulting in continued irradiation. For so-called non-penetrating radiations – including beta and alpha particles – risk to health is largely the result of such internal exposures. The extent to which specific organs and tissues are exposed from a radionuclide within the body depends on various factors: the mode of entry into the body; the physical and chemical properties of the incorporated radionuclides; the radiations emitted; the radioactive half-lives of the incorporated radionuclide and its decay products; and the distribution within and elimination from the body [7]. A short-lived, insoluble, alpha-emitting radionuclide that is ingested would irradiate the gut more than other tissues. In contrast, a long-lived, highly soluble, gamma-emitting radionuclide that is inhaled may be distributed around and irradiate most of the body's tissues before being excreted.

For all types of ionising radiation exposure, radiation dose is defined as the energy deposited as a result of ionisations and excitations per unit mass of material. This quantity is referred to as the absorbed dose and has the unit of gray (Gy), where 1 Gy equals 1 J/kg. At sufficiently high doses, the predominant effect is cell killing, leading to gross organ damage and potentially to death. If an individual escapes death (from exposure-related cell killing) and at all lower doses, the predominant effect of concern is an increased probability of cancer (see below). For radiological protection purposes, the International Commission on Radiological Protection (ICRP) has defined the quantity, the effective dose (unit of Sievert, Sv), as a risk-adjusted dosimetric quantity for use in the control of radiation exposures. The effective dose is calculated from absorbed dose, adjustments being made for differences between radiation types in their ability to cause cancer (per Gy) and differences between organs and tissues in their sensitivity to the induction of cancer. For example, alpha particles are more effective in causing cancer per Gy of radiation than gamma rays, and this is recognised for protection purposes using a radiation weighting factor of 20. The greater sensitivity of the colon than the liver to radiation-induced cancer (as suggested, for instance, by the higher risk of colon cancer than liver cancer in the atomic bomb survivors in Japan, shown in Fig. 2), for example, is recognised in tissue weighting factors of 0.12 and 0.04, respectively [7]. It should

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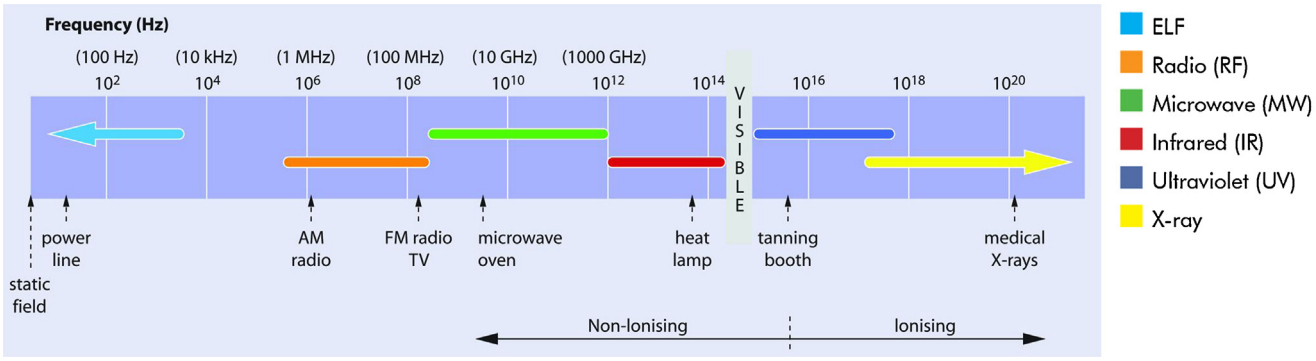

Fig. 1. Electromagnetic spectrum. The electromagnetic spectrum extends from below the low frequencies used for modern radio communication to gamma radiation at the shortest wavelength and highest frequency. Reproduced from the European Commission, Research Directorate-General, European Communities (2005). Health and Electromagnetic Fields: EU-funded research into the impact of electromagnetic fields and mobile telephones on health. © European Communities, 2005.

be appreciated, however, that these are simplified risk adjustments applied for protection purposes and they do not fully reflect our scientific understanding and would not be used in the calculation of risks to specific population groups or individuals. Thus, for example, radiation effectiveness is known to be dependent on cancer type and organ/tissue sensitivity and is age- and sex-dependent [8,9].

Estimates are made, nationally and internationally, of the sources and distribution of radiation exposures of populations. According to the latest periodic review of radiation exposures by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) [10], reference individuals receive an average of about 3 mSv effective dose annually but, within a population, there may be a wide range of individual exposures from less than 1 to more than several tens of mSv. For any individual, the absolute and relative contributions of different sources of radiation exposure will depend on many factors, including their home location (e.g. radon and cosmic ray exposure), exposure as patients during medical diagnostic procedures (e.g. X-rays, computerised tomography (CT) scans) or radiotherapy, their job (workplace exposure), and dietary choices (ingestion of radionuclides). However, everybody is exposed to ionising radiation to some extent owing to the abundance of natural sources. Fig. 3 shows the relative contributions from different sources to the estimated average annual exposure estimated for the global population. Much of the radiation exposure of a typical individual comes from natural radiation sources, including internal exposure from inhaling radon decay products when indoors, external exposure from gamma-emitting radionuclides in rocks, soil and building materials, and internal exposure from ingestion of natural radionuclides in food and drink [10].

The predominant source of man-made radiation exposure is the use of radiation for medical diagnostic and therapeutic purposes [10]; medical exposure to ionising radiation will be discussed in a separate article [5]. Other anthropogenic sources include: external and internal exposure of the public to radionuclides released into the environment from nuclear power plants, both low-level releases during normal operations and exposures resulting from past accidents (such as those at Chernobyl and Fukushima); exposures to fallout from nuclear weapons testing; and occupational radiation exposures of workers including those in the health care, nuclear industry, airline pilots and some miners [10]. Together, these non-medical man-made sources make only a minor contribution to the overall population exposure. For most people, radon is the largest individual component of exposure to ionising radiation.

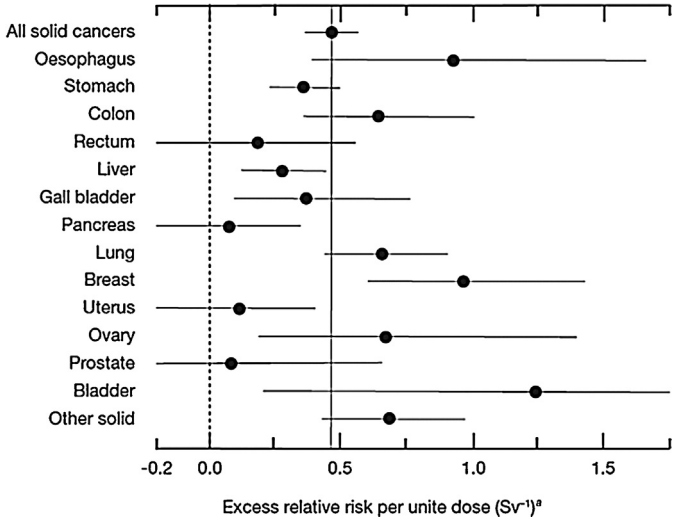

Fig. 2. Estimates of solid cancer mortality risk for different organs from studies of the survivors of the atomic bombings in Japan. The figure shows the excess relative risk per unit dose (Sv^{-1}) of various cancer types from radiation exposure among the survivors of the atomic bombings in Japan. Reproduced with permission from United Nations/UNSCEAR [18]. [a]While the absorbed dose is expressed in gray (Gy), because radiations differ in their ability per Gy to cause cancer, a radiation-weighted quantity, equivalent dose, is used, expressed in Sievert (Sv) (see Section 1.2). The horizontal bars represent 90% confidence intervals.

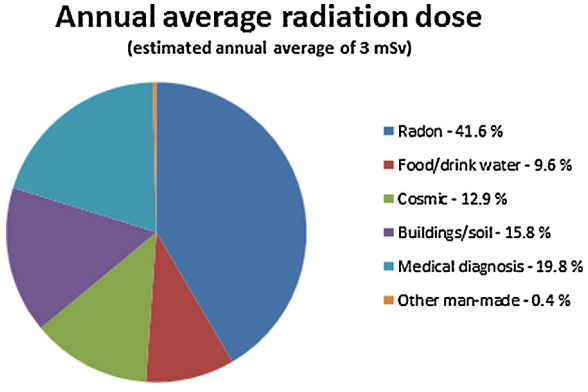

Fig. 3. Components of worldwide annual average individual radiation dose. The pie chart shows the annual average dose to the representative individual from the different radiation sources. Inhalation of radon (=Radon); ingestion of radionuclides in food and drink (=food/drink water); external irradiation from cosmic rays (=Cosmic); external irradiation from radionuclides in building materials and soil (=Buildings/soil); external and internal irradiation from medical diagnosis (=Medical diagnosis); external radiation and ingestion/inhalation from other man-made sources (=Other man-made). Reproduced from [10].

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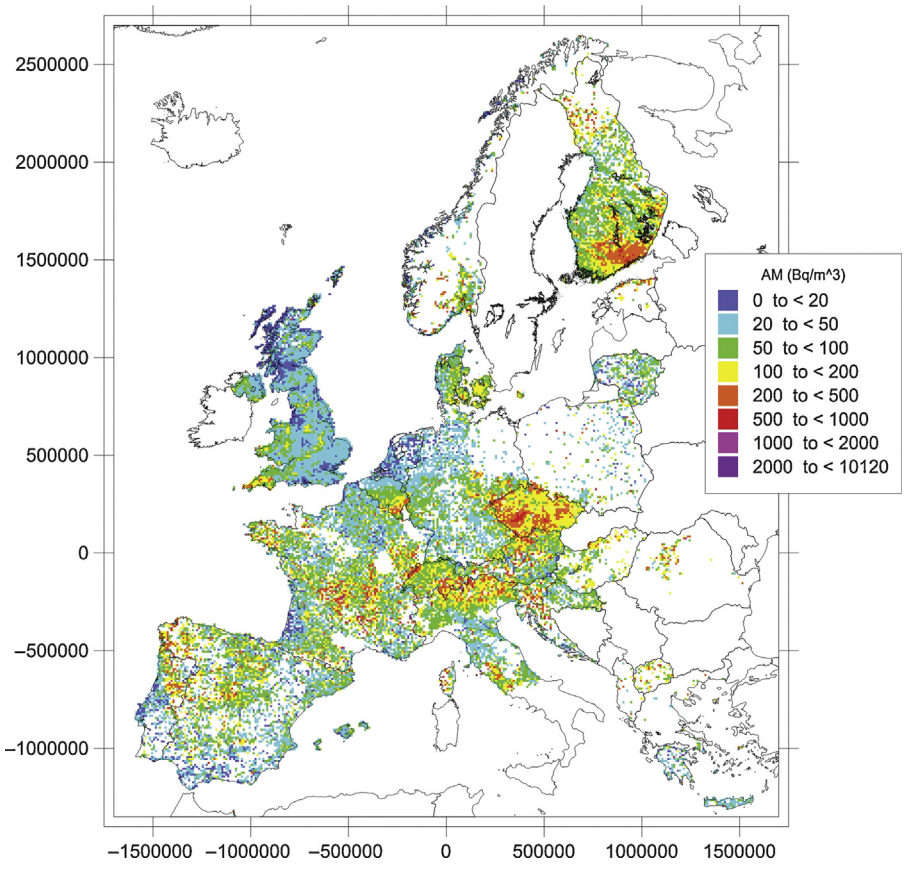

Fig. 4. Map of radon in Europe. Arithmetic means over 10 km × 10 km cells of long-term radon concentration in ground-floor rooms. Data available up until May 2014 included. Reproduced with permission of Oxford University Press [52].

1.3. Exposure to radon

Radon is an inert gas with several radioactive isotopes. Radon-222 is formed by the radioactive decay of uranium-238 that is present in small quantities in all soils and rocks. Other radon isotopes are generally less important for health than radon-222 because their short half-lives limit their presence in inhaled air. Radon-222 has a 3.8-day half-life, sufficient to allow time for accumulation above ground in homes and other buildings. In outdoor air, it is generally diluted to negligible concentrations [11].

Buildings, including homes, have slightly reduced air pressure relative to outdoor air, due to indoor heating and air movement. Soil air, containing radon, is drawn from the ground into a building through openings and minor defects in the foundations such as in seams and utility entry points. It may be retained within the building unless removed by ventilation, and this can lead to elevated concentrations in indoor air which can reach hundreds or thousands of becquerels per cubic metre (Bq m^{-3}) [12]. As an inert gas, inhaled radon is mostly exhaled. However, radon has a number of radioactive decay products with very short half-lives which include alpha-particle-emitting isotopes of polonium (218 and 214) which are deposited within the lungs and are a recognised cause of lung cancer.

Radon is present in most rocks and soil. The concentrations in homes and workplaces depend on a number of factors, including: the abundance of radium-226 (a long-lived intermediate decay product of uranium-238) in the ground; the permeability of the soil; the openings in the foundations of the building through which radon can enter a building from the ground; and the extent to which a particular building retains radon. These variations can result in a wide range of indoor radon concentrations even in a small geographical area. Two apparently identical adjacent homes can have very different indoor radon levels. UNSCEAR [13] estimated a worldwide population-weighted geometric mean indoor level of 30 Bq m^{-3}. Fig. 4 shows the geographical distribution means of long-term radon concentrations in ground floors across Europe. A small proportion of radon exposure arises from its presence in and emanation from building materials and water supplies.

1.4. Exposure to non-ionising radiation

Exposure to static and to extremely low-frequency electric and magnetic fields is ubiquitous due to natural phenomena and power transmission and the use of electrical appliances. Examples of natural sources of exposure include the geomagnetic field of the earth and, as extreme phenomena, thunder and lightning. Normal residential background exposure to extremely low-frequency magnetic fields is usually below 0.1 μT (flux density or magnetic field strength) [14]. A small fraction of households located very close to high-voltage power lines or other sources (including indoors) can have higher exposures, but usually well below protection limits – defined by the International Commission for Non-Ionising Radiation Protection (ICNIRP) – for the general population [15]. Higher but short-term exposures occur in particular jobs such as those of electricians.

For the majority of people, highest exposures to radiofrequency electromagnetic fields occur when using mobile phones because the source of emission is held close to the head. Much lower levels of exposure arise from high-power TV and radio transmitters, but the electric field strength may exceed 1 V/m even at points several kilometres from transmitters [16]. Exposures from smaller

transmitters – such mobile phone base station antennas – are normally even lower except in their immediate vicinity [17]. The number of sources continues to increase with further utilisation of the whole electromagnetic frequency spectrum and further development of new wireless technologies.

2. Cancer risk from ionising radiation

2.1. Ionising radiation and cancer

Large numbers of studies have investigated the effects of ionising radiation exposure as a cause of haematological malignancies and solid cancers. Ionising radiation has been classified by the International Agency for Research on Cancer (IARC) as an established or class I carcinogen [1]. Key evidence for the carcinogenicity of ionising radiation has been reviewed by IARC, the United Nations Scientific Committee on the Effects of Atomic Radiation [11], and the International Commission on Radiological Protection [7]; it includes: the Life Span Study of survivors of the atomic bombings in Japan exposed at the end of the second world war; other epidemiological studies of groups that have been exposed to radiation from medical, occupational or environmental sources; experimental animal studies; and studies of cellular responses to radiation including DNA damage.

Fig. 2 illustrates some of the evidence for radiation-associated cancer and the magnitude of risk to different tissues. It shows the excess relative risk per dose unit (Sv) of various cancer types among the survivors of the atomic bombings in Japan.

In its 2011 summary report of low-dose radiation effects on health [18], UNSCEAR stated that "... the energy deposited in the cell after irradiation can damage all subcellular components. The main subcellular targets for radiation-associated cellular change are the DNA molecules residing in the chromosomes... The cell may survive but with DNA mutations that affect cellular behaviour. A small fraction of such mutations can contribute to cancer development.... Complex DNA damage is difficult to repair correctly, and even at low doses of radiation it is likely that there is a very small but non-zero chance of the production of DNA mutations that increase the risk of cancer developing. Thus, the current balance of available evidence tends to favour a non-threshold response for the mutational component of radiation-associated cancer induction at low doses and dose-rates."

ICRP judges [7] that the weight of evidence supports the view that it is "scientifically plausible to assume that the incidence of cancer... will rise in direct proportion to an increase in the equivalent dose in the relevant organs and tissues."

These conclusions from UNSCEAR and ICRP embody what is generally referred to as the linear, no-threshold (LNT) dose–response model. It implies that there is no level at which the risk is zero, but any additional exposure to ionising radiation increases the lifetime cancer risk, adding to the underlying cancer risk from other causes. The ICRP risk factor [7] for cancer induction in a mixed age population is 5.5% per Sv of effective dose delivered at low dose and dose rate.

2.2. Radon and cancer

There is substantial epidemiological evidence that indoor exposure to radon and its decay products is an important cause of lung cancer, second only to tobacco smoking. Several large-scale epidemiological studies – including pooled analyses of uranium miners and populations exposed to elevated radon levels at home [19–22] – have demonstrated that long-term exposure to radon increases the risk of lung cancer. Pooled case–control studies have also shown that the excess relative risk of lung cancer is proportional to long-term radon exposure levels for smokers, non-smokers and ex-smokers, as illustrated in Fig. 5 [20,23]. The UK independent Advisory Group on Ionising Radiation (AGIR) reported a 16% excess relative risk from long-term (30 years) exposure to radon in air at a concentration of 100 Bq m^{-3}, with a 95% confidence interval of 5–31% [23]. The results provide direct evidence of increased lung cancer risk at radon levels below 200 Bq m^{-3}. The greatest absolute lung cancer risks from radon exposure were to continuing smokers, primarily because smoking induces a much higher baseline lung cancer risk, and radon acts multiplicatively with other lung cancer risks. In other words, the vast majority of radon-induced cancers develop among smokers as a joint effect of radon and smoking. Darby et al. [19,20] estimated the fraction of the lung cancer burden attributable to indoor radon in Europe to be about 9%. The World Health Organization (WHO) [12] reported estimates ranging from 3% to 14% across some selected populations around the world, including some from Europe, based on a large pooling study for the UK (3.3%), Germany (5%), France (5%), and Switzerland (8.3%).

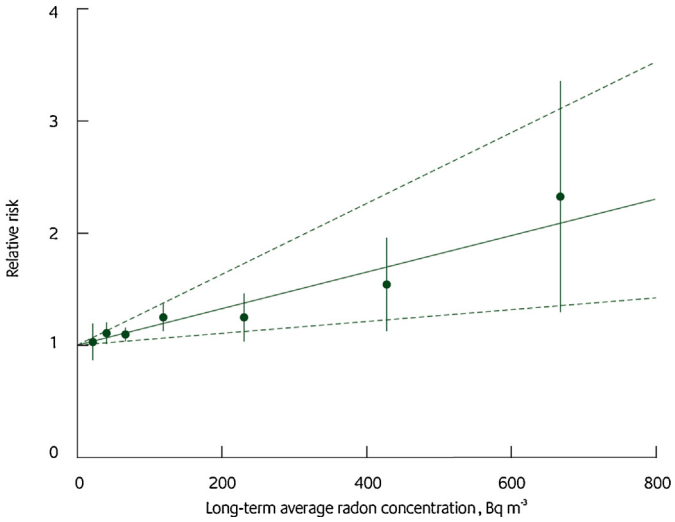

Fig. 5. Relative risk of lung cancer in relation to long-term residential radon concentrations in the European pooling study (with 95% confidence intervals). Relative risks and 95% confidence intervals are shown for categorical analyses and also the best-fitting straight line. Risks are relative to that at 0 Bq m^{-3}. From Radon and Public Health [23]. © Crown copyright. Reproduced with permission of Public Health England.

2.3. Other relevant sources of ionising radiation and cancer

Studies of nuclear workers exposed mainly to low doses of external radiation under relatively well controlled conditions demonstrated a small increase in cancer mortality associated with exposure at work [24,25]. In a study of nuclear workers from 15 countries, 1–2% of deaths from solid cancers were considered to be possibly related to their occupational exposure [24]. Analysis of cancer incidence in the very large cohort of workers included in the UK National Registry for Radiation Workers showed a significant dose–response relationship consistent with the extrapolation of the A-bomb risk factors to low doses [25]. Studies of cancer incidence in plutonium workers at the Russian Mayak plant have shown plutonium-239-related excesses of lung and liver cancers [26,27]. Comparisons of lung cancer incidences following exposures to radon progeny (uranium miners), plutonium and external gamma rays show that risk estimates are consistent when account is taken of the relative biological effectiveness (RBE) of alpha particles and gamma rays [28]. The data are consistent with alpha particle RBE values of around 10–20, although Marsh et al. [28] noted the considerable uncertainties associated with these estimates.

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Excesses of childhood leukaemia incidence in populations near nuclear installations in the UK, Germany and other countries have been recorded, but a number of similar studies have failed to show any increased risks [9,29]. The radiation doses in these populations are well below the levels that might cause any discernible excess risk of cancer in the light of current understanding, particularly as doses from natural sources have been shown to dominate and exceed any contributions from radioactive discharges from nuclear facilities. Overall there is no good evidence that any step in the production of nuclear power under controlled conditions is related to any cancer excess in the populations of the adjacent areas. However, nuclear accidents such as that at the Ukrainian Chernobyl plant can result in exposure to radiation doses resulting in elevated cancer risks, depending on the release of radionuclides and the location [10]. In addition, radioactive discharges from the Mayak plant into the Techa River were sufficiently high in the early years of operation to lead to increases in both haematological malignancies and solid cancers [30,31]. The recent accident at the Fukushima plant in Japan resulted in exposures that were an order of magnitude or more below those experienced following the Chernobyl reactor, and discernible increases in cancer incidence are not expected [32,33].

2.4. Non-ionising radiation and cancer

Epidemiological studies have consistently shown a positive association of extremely low-frequency magnetic fields with an approximately two-fold higher childhood leukaemia risk at average exposure levels exceeding 0.3–0.4 μT [15]. A causal relationship, however, has not been established due to the potential for bias and confounding in the studies and because supporting evidence from experimental studies and mechanistic data are lacking. The 2002 IARC Monograph [3] on extremely low-frequency magnetic fields classified them as possibly carcinogenic to humans (group 2B) based on the findings for childhood leukaemia; the evidence for other types of malignancy was evaluated to be inadequate. This view was recently confirmed by the European Commissions' Scientific Committee on Emerging and Newly Identified Health Risks [34]. Radiofrequency electromagnetic fields (group 2B) have also been classified by the IARC [4] as possibly carcinogenic to humans on the basis of findings for glioma and acoustic neuroma. Case–control studies on mobile phone use and cancer have reported increased risks of glioma and acoustic neuroma in heavy users of mobile phones, based on self-reported mobile phone use [35,36]. Cohort studies have shown no associations, but had fewer data on heavy users [37,38]. Time trends in glioma incidence based on Nordic countries excluded any significant increased incidence attributable to mobile phone usage of up to 10 years [39]. With regard to environmental exposures from transmitters – including television, radio, and military transmissions as well as mobile phone base stations – the evidence is inadequate due to paucity of high-quality studies with accurate individual exposure assessment [40]. Some large studies on childhood cancer and fields generated by high-output TV and/or radio transmitters reported no associations [15]. Overall, currently available information does not provide unequivocal evidence that non-ionising radiation at low and high frequencies is a cause of cancer.

3. Scientific justification of the recommendation on radon

The carcinogenicity of ionising radiation is well documented [1]. Ionising radiation can cause many types of cancer and haematological malignancies. Some exposure to ionising radiation is unavoidable – for instance that from cosmic radiation or terrestrial radiation. The major source of man-made radiation is medical exposure; the exposure is intentional and brings benefit through diagnoses or treatment. Therefore controlled and judicious use of radiation in medicine is associated with risks that are counterbalanced with benefits [5]. Man-made radiation also occurs in some occupational settings for which regulations are in place, such as the Euratom 2014 Basic Safety Standards [41]. These regulations provide a range of controls, including: risk assessment; control of radiation use and procedures for radiation safety and protection; and personal and environmental radiation monitoring where appropriate. The recommendation of the Code to follow health and safety advice to reduce occupational exposure defined elsewhere also applies to ionising radiation [42]. Other man-made exposures – such as for example those related to the use of nuclear energy under normal conditions – are sometimes of concern in the population. Nevertheless, they generally contribute little to overall radiation exposure (Fig. 3). This does not apply to major nuclear accidents with major radionuclide releases.

The major source of exposure to ionising radiation, modifiable by the individual, comes from naturally occurring radon. While this naturally occurring exposure cannot be eliminated, it can be substantially reduced at places where people spend much of their time, namely in their own homes or at their workplaces. Radon is estimated to account for about one in ten lung cancers in Europe [18], therefore causing a major cancer burden. The respective recommendation is: "Find out if you are exposed to radiation from naturally high radon levels in your home. Take action to reduce high radon levels".

3.1. Individual action for protection against radon

3.1.1. Variation in radon exposure

Radon concentrations in homes and other buildings vary substantially, as discussed in Section 1.3. The radon exposures of building occupants depend primarily on the proportion of time they spend in the building. Over the course of a year, most people spend a majority of their time in their home, mostly in living rooms and bedrooms. Homes are therefore the primary source of indoor radon exposure, with workplaces presenting the second most important source of exposure with radon concentrations typically similar to or slightly lower than those in homes (although high concentrations can occur in particular workplaces, especially underground).

It is not generally possible to accurately predict the indoor radon concentration in a specific building, and measurements are required. However, a number of countries (see for example [43–45]) have used radon or related measurements or geological information to identify radon-prone areas where high radon levels are more common. Maps indicating radon-prone areas are used in some countries to provide guidance on whether radon measurements should be made in existing properties to inform remediation decisions (Fig. 4).

3.1.2. Measuring radon in the home

Indoor radon levels vary considerably over short periods (hours and days) [46], and seasonally through the year [47]. Within any home, there is often a variation in concentration between rooms. Measurements of radon are generally intended to represent the long-term average concentration in the home. For this reason, radon measurements in homes are often made using two detectors placed in regularly occupied rooms, including a bedroom, for several weeks. Measurements made during different times of the year can be adjusted to reflect seasonal variations [47]. Shorter duration measurements may be made but the results are less accurate and have greater uncertainties.

3.1.3. Managing individual risks from radon exposure

The distribution of residential radon exposures in a population reflects the geometric mean of indoor radon concentrations with a

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log-normal distribution. A large proportion of the population exposure to radon will therefore arise from the many homes that have relatively modest indoor radon concentrations [12]. The modest cost of including radon preventative measures in new buildings is sufficiently low as to support preventive measures in new buildings [12]. Maps of radon-prone areas can be used to support policies on radon preventive measures in new buildings, such as requiring the installation of impermeable membranes at the building foundation level.

Most radon strategies focus on identifying and managing the homes with the highest radon concentrations. International guidance is available from the ICRP [48] and the WHO [12] on radon concentration levels (termed "reference levels" by the ICRP), above which action should be taken to reduce indoor radon concentrations, and below which concentrations should be reduced as far as is reasonably achievable. The WHO and ICRP have advised that relevant national authorities should establish radon reference levels for homes in the range 100–300 Bq m^{-3}. The ICRP system of radiological protection [7] advises that reference levels of radiation dose for "existing exposure situations" such as radon in buildings, should be implemented using dose criteria in the range 1–20 mSv y^{-1}. ICRP has advised [48] that a derived reference level of 300 Bq m^{-3} for homes is consistent with this aspect of its system of radiological protection.

A European Union directive, setting out requirements for protection against ionising radiation [41], has established criteria for managing indoor radon, setting an upper limit of 300 Bq m^{-3} on national reference levels unless there are extenuating circumstances. Means to manage high individual radon exposures in the home include provision of resources and funding for radon risk assessments, measurements or remediation [49] and provision of information to the householder [50]. The European Code Against Cancer recommendation concerning radon in the home expects the householder to take responsibility for managing the radon risk in their home. Such an approach complements programmes to encourage or support householders in radon management and complements responsibilities that landlords have to provide safe housing for their tenants.

3.1.4. Reducing high indoor radon levels

Practical methods are available for reducing high radon levels in existing properties [12], usually at modest cost. These generally work by either reducing the radon concentration at the point where it enters the building from the ground, or reducing the air pressure differential between the building and the ground that is the driving force for soil air and radon to enter the home. Experience to date [51] suggests that the most effective solutions are based on low-power electrical air pumps, typically consuming a few tens of watts that work continuously and can achieve reductions in radon concentration to a tenth of the original level. The most commonly used remediation systems include: (1) a "radon sump" – a small, engineered, partially depressurised void beneath the building from which soil air and radon are continually pumped through pipes and expelled to atmosphere; and (2) positive pressure ventilation, in which air is pumped into a central area of the home to reduce the pressure differential between indoor air and soil air. Some passive (non-powered) methods are available but these generally result in smaller concentration reductions and are therefore not suitable for reducing the highest radon levels [52,53].

4. Conclusions

Ionising radiation has been shown to be carcinogenic and everyone is exposed to a range of natural and man-made sources. Radon is the single biggest source of ionising radiation exposure for most people, with most exposure occurring in the home. Radon is the second leading cause of lung cancer after smoking, with long-term exposure shown to result in excess lung cancers. Radon levels vary between regions and even between neighbouring buildings. A suitable radon measurement is needed to determine the radon level in any specific property. National agencies can prepare maps indicating the geographical variation of indoor radon. In areas where high indoor radon levels are more common, radon measurements should be made comprehensively, particularly in homes. International organisations, including the WHO, have advised that countries should establish reference levels of indoor radon in the range 100–300 Bq m^{-3}, above which steps should be taken to reduce concentrations. Minor building modifications can be made to reduce high indoor radon levels. For new buildings, techniques should be employed to minimise radon levels, as this can be achieved easily and also reduces other hazards such as moisture damage.

Householders should:

- take ownership of the radon issue for their home;
- use the available national information to decide whether to test their home for radon;
- test their home for radon where this is advised, reduce high radon levels in the home.

Conflict of interest

The authors declare no conflicts of interest.

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