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REVIEW

Risks from ionising radiation: an HPA viewpoint paper for Safegrounds

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Abstract

Safegrounds is a forum for developing and disseminating good practice guidance on the management of radioactively contaminated land on nuclear and defence sites in the UK. This review has been provided to Safegrounds as a summary of the basis for current radiation risk estimates and the International Commission on Radiological Protection (ICRP) protection system, in a form that will be accessible to a wide range of stakeholders. Safegrounds has also received viewpoint papers from other members who contend that the ICRP methodology results in substantial underestimates of risk, particularly for internal emitters. There is an extensive literature on the risks of radiation exposure, regularly reviewed by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and other expert groups. These data provide a sound basis for the system of protection recommended by ICRP. The available epidemiological and experimental evidence supports the application of cancer risk estimates derived for acute, high dose, external exposures to low dose exposures to external and internal sources. In the context of radioactively contaminated land on nuclear and defence sites, the national standards for the cleaning up of land and for waste disposal correspond to very low doses, two orders of magnitude less than average annual doses in the UK from natural background radiation (10–20 μSv compared with 2–3 mSv). Risks at such very low doses can only be estimated on the basis of observations after exposure of population groups at much higher doses. The estimated risks at these very low doses, while uncertain, are as likely to be overestimates as underestimates.

1. Introduction

Safegrounds provides a network for the development and dissemination of good practice guidance for the management of radioactively and chemically contaminated land on nuclear

and defence sites in the UK (www.safegrounds.com). The risks from very low levels of ionising radiation have been a topic of discussion at Safegrounds for many years and the Safegrounds Project Steering Group, of which HPA (Mobbs) is a member, invited HPA and two other members to produce viewpoint papers summarising their views in a language that is accessible to a range of stakeholders.

The following summary (sections 2–6) is the viewpoint paper as submitted to Safegrounds, and also published as an HPA report (Mobbs *et al* 2010), with the addition of a few more recent references. The paper addresses the basis of the recommendations of the ICRP and considers issues that have been raised by those who consider that current risk estimates are gross underestimates, particularly for inhaled and ingested radionuclides. The data do not support such claims, most of which have been expressed previously and discussed in detail, for example, as part of the work of the Committee Examining Radiation Risks of Internal Emitters (CERRIE 2004, COMARE 2004) and in the HPA response (www.hpa.org.uk) to a report of the European Committee on Radiation Risks (ECRR[1]) (Green Audit 2003).

2. Overview of HPA position

One of the functions of HPA is the provision of information and advice on radiation protection of the community (or any part of the community) from risks connected with radiation. This function is inherited from one of the HPA's predecessor organisations, the National Radiological Protection Board (NRPB). HPA advises UK bodies with responsibility for protection against radiation on the applicability to the UK of recommendations issued by ICRP. HPA also provides advice to industry and the public and supports international standard setting organisations, including ICRP, the European Commission (EC) and the International Atomic Energy Agency (IAEA). ICRP recommendations form the basis for radiation protection legislation in Europe and throughout the world.

The HPA has, following a public consultation in 2008, developed its advice on the applicability to the UK of the 2007 Recommendations of ICRP (2007). HPA (2009a) endorsed the adoption of the ICRP recommendations in UK legislation, with a few small modifications, and endorsed the risk factors recommended by ICRP for use in radiological protection. In formulating this advice, HPA took account of all available epidemiological data on radiation risks, including a recent analysis of UK radiation workers (Muirhead *et al* 2009) and risk estimates for internal emitters (Darby *et al* 2005, 2006, 2007, HPA 2009b, Sokolnikov *et al* 2008). The available evidence provides good information on the risks of cancer induction at moderate doses, with consistent data for chronic and acute exposures to external and internal sources of radiation exposure. However, epidemiology has little prospect of providing direct risk estimates for exposures at low doses of a few milligray (mGy) or less because (a) radiation is a weak carcinogen and the effect is too small to quantify, and (b) we are all exposed to natural background radiation at around this level which will mask any effect.

HPA is actively involved in research to improve our understanding of radiation risks, publishing reports and papers on this subject. For example, HPA is responsible for a large study of health effects in UK radiation workers and the third analysis has recently been published (Muirhead *et al* 2009). Collaborative studies are in progress of health effects in the workforce employed at the Russian Mayak plutonium plant and in the nearby population exposed due to radioactive discharges to the Techa River (Shagina *et al* 2007, Azizova and Muirhead 2009, Azizova *et al* 2010a, 2010b). These studies are providing data on risks of cancer and non-cancer effects (e.g. circulatory disease; see HPA 2010a).

[1] ECRR is not a formal scientific advisory committee to the European Commission or to the European Parliament.

HPA also publishes periodic reviews of the exposure of the UK population to radiation from a variety of sources (Watson *et al* 2005). These show that radiation doses to the public from discharges from nuclear installations are extremely small compared with doses from natural background and from medical procedures.

Advice issued by the HPA has the aim of promoting reductions in radiation exposures. Particular examples are practical advice documents for medical practitioners on particular techniques and advice to government on the control of radon exposures in homes (HPA 2010b). HPA (2009a) has also recommended a reduced constraint on public doses resulting from discharges from new nuclear installations. HPA endorses the international view that properly controlled and considered use of radiation is perfectly reasonable and appropriate. In fact, radiation is used extensively in clinical medicine to save lives through both diagnostic and therapeutic applications. HPA views the risks from radiation in an objective manner and HPA advice is not influenced by either pro- or anti-nuclear arguments.

3. Doses in context

It is important to understand what is meant by 'low levels of radiation'. Epidemiologists, radiobiologists and medical practitioners will consider a few tens of millisievert (mSv) to be a low radiation dose (Smith 2010, Wakeford and Tawn 2010, Dauer *et al* 2010). National radiological protection standards are specified in the Ionising Radiations Regulations (UK Parliament 2000), with annual dose[2] limits of 20 mSv for workers and 1 mSv for members of the public. Public radiological protection standards for radioactive discharges include a dose constraint of 0.3 mSv (i.e. 300 microsievert (μSv)) per year, with a requirement to reduce doses as low as reasonably practicable below this level (DETR 2000). In the context of radioactively contaminated land on nuclear and defence sites and radioactive waste disposal, the radiological protection standards correspond to even lower doses. The Nuclear Installations Inspectorate (HSE 2005) requirement for clean up of radioactively contaminated land to 'no danger' is a risk criterion of one in a million per year (risk of death), which they equate to an annual dose of around 10 μSv. The environment agencies also specify a risk guidance level of one in a million per year for solid radioactive waste disposal and they equate this to about 20 μSv per year (Environment Agency 2009a, 2009b). HPA issued advice on radiological protection criteria for contaminated land (HPA 2006) and radioactive waste disposal (HPA 2009c) which informed these regulatory requirements. Levels of dose of around 10 μSv will be referred to as very low levels of dose in this document.

These very low levels of dose can be put into context by considering radiation doses received by people in the UK. The average annual dose of 2.7 mSv is made up of doses from naturally occurring and artificial (man-made) radiation sources (Watson *et al* 2005). The greatest contribution comes from naturally occurring sources, giving an average annual dose of 2.2 mSv. The annual dose from natural background in the UK ranges from less than 2 mSv to greater than 200 mSv. Medical exposures represent the largest exposures from artificial sources; in particular, doses from CT scans are generally of the order of 10 mSv (Watson *et al* 2005).

Thus, the 10 or 20 μSv per year dose criterion for cleanup of contaminated land equates to less than 1% of the UK average annual dose from natural sources and is small compared with the variation in natural background and doses from medical exposures.

Another way to put these doses into context is to consider the attendant risks to health. ICRP recommends that the risk of fatal cancer in a population receiving a dose of 1 mSv is

[2] The term 'dose' in this article refers to the ICRP concept of 'effective dose' unless otherwise stated.

taken to be 5 in 100 000 or 0.005%[3]. The current average risk of dying from cancer in the UK is about one in four (25%) (Cancer Research UK 2008). Hence the total risk of dying of cancer for a person exposed to 1 mSv increases on average from 25% to 25.005%, and for a person exposed to 10 μSv the average risk increases from 25% to 25.000 05% (and for a lifetime exposure at 10 μSv per year the average risk increases from 25% to 25.004%).

4. ICRP and radiation protection principles

Shortly after the discovery of x-rays, their diagnostic potential was recognised, and the appearance of acute undesirable effects (such as hair loss and erythema) soon made hospital staff aware of the need to avoid over-exposure. A similar set of events took place after the discovery of radium but it was some time before protection of exposed staff was fully coordinated. General radiation protection recommendations were proposed in the UK in the early 1920s and the First International Congress of Radiology was held in 1925. The International Commission on Radiological Protection (ICRP) was established in 1928 at the Second International Congress of Radiology (at the time it was called the International X-ray and Radium Protection Committee) and then restructured and given its current name in 1950; it has published a series of recommendations since then, reflecting the increased understanding of the biological basis of radiation-induced tissue damage. ICRP is an international professional body with formal relationships with the EU and UN organizations such as the International Atomic Energy Agency (IAEA), World Health Organization (WHO) and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). It draws its membership from individuals working in organisations such as HPA, from around the world. ICRP is a well-regarded expert body. Further information about ICRP can be found at: www.icrp.org.

ICRP Recommendations provide a 'system of radiological protection' which is intended to cover all situations involving exposure to ionising radiation; that is, normal operations where the source is under control, situations where there is a probability that exposure will occur (accidents and disposal of solid radioactive wastes), and situations where the source is not under control but exposure can be controlled by other means (e.g. radon in homes).

The system of protection must consider the range of dose that may be received. High doses of radiation (1–10 Sv) will kill a large number of body cells and may lead to serious injury and, at higher doses, to death within a relatively short time of exposure. However, serious 'deterministic' effects (also known as 'tissue reactions') that cause gross damage in short periods of time do not occur below a dose threshold of around a few sieverts. Below the threshold dose, a radiation dose leads to an increased risk of 'stochastic' effects, predominantly cancer, and the size of the increased risk depends on the dose received. Although there is no direct information on hereditary effects in humans, ICRP's estimate of radiation detriment includes a component (about 10%) for hereditary effects, estimated on the basis of animal data.

Radiological protection aims to (a) prevent serious injury by keeping doses below thresholds for deterministic effects, and to (b) limit the increased risk of stochastic effects, balancing the risk against the benefit. The three basic radiological protection principles can be summed up as 'justification, optimisation and dose limitation'. It is therefore important that there is a judgement as to whether a source of radiation will do more good than harm. No practice involving exposures to radiation should be adopted unless it produces more overall good than harm. However, this is not sufficient on its own: a process of optimisation has to be undertaken to minimise exposures, with costs and social factors being taken into account. Dose constraints are set (at a fraction of the dose limit) to ensure that the optimisation process has

[3] ICRP (2007) recommends that the overall fatal risk coefficient of 5% per Sv used in international radiation safety standards continues to be appropriate for the purposes of radiological protection.

been approached correctly. Finally, dose limits act as a backstop to take account of multiple sources.

ICRP recommendations emphasise that ionising radiation needs to be treated with care rather than fear and that its risks should be kept in perspective with other risks. All those concerned with radiological protection have to make value judgements about the relative importance of different kinds of risk and about the balancing of risks and benefits.

The ICRP system is intended for protection of populations, so the risk estimates used are based on averages of the risks of various cancers between males and females, and adults and children, and takes account of the underlying risk of cancer in different countries. This is done using the quantity 'effective dose'. Effective dose also allows the risks from external irradiation and from radionuclides incorporated in the body (internal emitters) to be added to give a total dose that relates to the risk to an average person in a population. Retrospective risk assessments for individuals can be more detailed and specific to the characteristics of the individual, e.g. their age and sex, but effective dose is not appropriate for this purpose.

After a consultation process lasting several years, ICRP issued new recommendations in 2007 (ICRP 2007), replacing the recommendations published in 1990 (ICRP 1991). As discussed below, the ICRP recommendations are based on the scientific information from the reviews and analyses published by UNSCEAR (2000, 2011) and others including the US BEIR committee (NAS/NRC 2006), as well as upon assessments of the scientific literature made by the various committees of ICRP. While the overall risk factors for stochastic effects used in the new recommendations have not changed appreciably from the previous recommendations, there are changes to the risk estimates for specific cancer types and a reduction in the risk estimates for hereditary effects. Importantly, the scientific basis for cancer risk estimates is substantially improved by longer follow-up in epidemiological studies, allowing greater precision in specifying risks for individual cancer types for different ages at irradiation of males and females.

ICRP's use of the scientific information presented by UNSCEAR is supported by independent scientists worldwide, not just by government organisations. The fact that the 1990 ICRP recommendations were adopted by both EC and IAEA in their Basic Safety Standards (European Commission 1996, IAEA 1996) emphasises their international standing. Both the EC and IAEA are updating their safety standards to take account of the 2007 ICRP recommendations, and the 2007 ICRP recommendations are also being implemented in the USA.

5. Scientific basis for ICRP recommendations

The health effects of ionising radiation on the human body are described in detail by ICRP (1991, 2007) and UNSCEAR (2000, 2011) and summarised by Mobbs *et al* (2009). It is important to appreciate that radiation is a weak carcinogen: there are many steps in the process from DNA damage to cancer and the chances of any particular damaged cell becoming malignant are extremely small. There are millions of ion pairs created every year in the DNA of a person from natural exposure to radiation but radiation is estimated to be responsible for only a small fraction of cancer deaths. Radiation is one of many causes of DNA damage and the vast majority of strand breaks are efficiently repaired. In addition, any radiation-induced cancer is indistinguishable from cancers produced by other causes.

The relationship between dose and the risk of health effects such as cancer is regularly reviewed by (e.g. UNSCEAR 2000, 2011). The resulting estimation of the risks from radiation is largely based on epidemiological studies on humans. As described by Mobbs *et al* (2009), epidemiological studies provide statistical associations, strengthened when a dose–response

relationship can be demonstrated and experimental data provide supporting information (Hill 1965).

There is a lot of information available on the effects of radiation on human tissues and this means that the basis for radiological protection is better founded than, for example, the basis for protection against some chemicals for which there are no human data. Risk estimates for radiation-induced cancers are largely derived from studies of the effects of external radiation, the principal source of information being long-term studies of those who survived the immediate effects of the atomic weapons' explosions at Hiroshima and Nagasaki, in 1945 (the so-called A-bomb survivors). The cancer incidence and mortality data for A-bomb survivors show a statistically significant increase in solid cancers at doses from around 100 mSv up to around 3 Sv (UNSCEAR 2000, Preston 2003, Preston *et al* 2007). The data on solid cancer incidence indicate that any dose threshold (i.e. below which risks are not increased) would not exceed 85 mSv (Preston *et al* 2007). Separate studies of cancers in children exposed *in utero* to x-rays during diagnostic radiography, principally the Oxford Survey of Childhood Cancers (OSCC), have shown statistically significant increases in childhood leukaemia and solid cancers at doses of the order of 10 mSv (Bithell and Stewart 1975, Wakeford and Little 2003). The risk per unit dose estimated for childhood leukaemia from the OSCC was compatible with that obtained from the A-bomb survivor studies (Wakeford and Little 2003). In applying the risk estimates derived from the A-bomb survivor data to cancer risks at low doses and dose rates, ICRP use an empirical correction factor, the Dose and Dose Rate Effectiveness Factor (DDREF), assuming a value of two for solid cancers (ICRP 1991, 2007). This assumption that risks per unit dose are lower at lower doses and dose rates is based largely on animal and *in vitro* data showing curvilinear dose–response relationships for acute exposures to gamma rays and x-rays. No DDREF is applied when considering risks from alpha particle or neutron irradiation. For leukaemia, the A-bomb survivor data are consistent with the use of a linear–quadratic dose–response relationship—in line with a reduction in the risk per unit dose by a factor of 2 at low doses and no additional correction is applied for low dose rates. The US BEIR Committee (NAS/NRC 2006) recently undertook probabilistic analyses of dose–response data from epidemiological and experimental studies and obtained a modal value for DDREF of 1.5. However, judgements on an appropriate value for DDREF depend on the weight given to different sources of data. On the basis of the A-bomb survivor data, it is not possible to distinguish between a DDREF of 1 (no DDREF) or 2 for solid cancers (UNSCEAR 2000, Preston 2003). Experimental data generally show greater values and the ICRP (2007) judgement is that a value of 2 should continue to be applied. HPA has also reviewed the information (HPA 2009a), and agrees with the ICRP recommendation.

ICRP (2007) recommend that the overall risk of fatal cancer in a population exposed to low doses and dose rates is taken to be 5% per Sv. As discussed above, there is little prospect of obtaining direct epidemiological data on cancer risks at levels of dose typically experienced by members of the public, a few mSv and less. However, on the basis of experimental data and our understanding of the biological mechanisms involved in the initiation and development of cancer, a linear non-threshold (LNT) dose–response relationship is assumed. It is the consensus view that LNT is the best approach on current evidence for radiation protection purposes (Preston 2003, NCRP 2001, ICRP 2007, HPA 2009b). The LNT assumption is essential for the operation of the current protection system, allowing the addition of external and internal doses of different magnitudes, with different temporal and spatial patterns of delivery. Nevertheless, the LNT dose–response remains controversial, with arguments being put forward for supra-linear low dose responses and for thresholds and/or hormetic effects (CERRIE 2004, French Academies Report 2005, Tubiana *et al* 2008, Feinendegen *et al* 2008, Allison 2009). ICRP (2007) conclude that the true validity of the LNT model may prove to be beyond definitive

resolution for the foreseeable future. For reasons of practicality, it is highly desirable to retain the LNT assumption unless or until this position becomes scientifically untenable. This is an active area of research involving European and international collaboration. The LNT assumption allows us to estimate the risks from the very low levels of dose that are relevant to public exposures arising from waste disposal and the cleanup of contaminated land on nuclear licenced sites. Similarly, the LNT assumption allows us to estimate the risks that are relevant to public exposures arising from planned discharges from nuclear power plants.

To calculate doses from radionuclides incorporated into the body, ICRP uses biokinetic and dosimetric models (ICRP 2006, 2007). Biokinetic models describe the movement of inhaled and ingested radionuclides between body tissues and their excretion, allowing the calculation of the number of transformations (radioactive decays) occurring in different tissues. Dosimetric models of the human body are then used to calculate doses to each tissue for which cancer risk estimates are made and for the ovaries and testes to take account of hereditary effects. For a number of organs, account is taken in these calculations of the distribution of radionuclides and target cells within tissues. For example, the model of the lung allows specific calculation of doses to the cells in airways thought to be the origin of lung tumours. Such detailed calculations are important when considering doses from short-range radiations, including alpha particles.

The ICRP quantity, effective dose, takes account of the effectiveness of different radiations in causing cancer using radiation weighting factors. For example, a weighting factor of twenty is used for alpha particles, compared with a value of one for beta particles and gamma rays; that is, alpha particles are taken to be twenty times more effective per Gy than gamma or x-rays. Effective dose also takes account of differences between organs/tissues in their contribution to total risk or detriment using tissue weighting factors. For example, a weighting factor of 0.12 is used for the colon, on the basis that colon cancer contributes 12% of the total detriment from cancer and hereditary effects. Details are given by ICRP (2007) and reviewed by Harrison and Day (2008) and Mobbs *et al* (2009). While absorbed dose (in gray; Gy) is a scientific quantity, effective dose (in sievert; Sv) is a risk-related quantity for use in radiation protection.

6. Challenges to UNSCEAR and ICRP

As explained by ICRP (2007) and Harrison and Day (2008) and summarised by Mobbs *et al* (2009), there are a number of uncertainties in the estimation of risks from radiation exposure. However, these are not as large as have been claimed by those wishing to challenge UNSCEAR risk estimates and the ICRP protection system. A particular focus has been on the applicability of risk estimates derived from studies of the effects of high doses of external radiation to situations of exposure to low doses of internal emitters, particularly radionuclides with short-range emissions. This has led, for example, to the ECRR (Green Audit 2003) disagreeing with the ICRP risk factors and suggesting that they contain large underestimates for some radionuclides. Most of these questions date from more than 5 years ago and were explicitly addressed by CERRIE (2004), COMARE (2004) and, more recently, by ICRP (2007). In both cases, it was concluded that there was not enough evidence to support these differing views. HPA (then NRPB) has also reviewed the ECRR report (Green Audit 2003) and disagrees with the ECRR views. The HPA response is available on our website (http://www.hpa.org.uk/, (HPA 2003)) and the summary statement is reproduced here: 'A critical examination of the ECRR report has been undertaken by NRPB staff. The cited epidemiological studies have been investigated in detail by NRPB staff and previously by other experts; their conclusions are generally different from those reached by ECRR. The methodology proposed by ECRR for estimating radiation risks from internal emitters is arbitrary and does not have a sound scientific basis. Furthermore, there are many misrepresentations of ICRP, misunderstandings,

inconsistencies and unsubstantiated claims in the ECRR report. The ECRR report therefore provides no scientific basis for changing protection standards.

Overall, NRPB believes that the recommendations of ICRP provide a sound basis for radiological protection standards. In particular, risks from internal emitters are acceptably well understood and may, in some cases, be overestimated by ICRP'. More recent claims do not cause HPA to change its view. A brief summary and response to some of the more recent questions follows.

The French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) also reviewed the ECRR report. The resulting IRSN (2005) report covers much of the same ground as CERRIE (2004) although in less detail, addressing issues recognised by ICRP (2007) and reviewed by Harrison and Day (2008). IRSN (2005) concluded that the ICRP methodology is the best approach currently available for the control of radiation exposures. Like HPA, IRSN (2005) considered that ECRR (Green Audit 2003) proposals for modification of the ICRP methodology for calculation of effective dose are poorly founded and unhelpful. Also, in agreement with IRSN, the HPA is fully supportive of the need for more research to understand radiation risks at low doses, including risks from internal emitters. Interesting findings are emerging on non-targeted effects of radiation, including genomic instability and bystander effects (ICRP 2007, Harrison and Day 2008). Epidemiological studies identifying non-cancer effects of radiation exposure, particularly circulatory disease (UNSCEAR 2011, ICRP 2007, HPA 2010a), will need to be followed by mechanistic studies in order to understand the possible implications for risks at low doses. The HPA and IRSN will continue to be actively involved in research on radiation risks as well as the development of international standards.

6.1. Risk factors

Follow-up studies of the A-bomb survivors provide the best single source of information on radiation-induced cancer and other health effects. The risk factors derived from this information apply to short, homogeneous, large external doses of gamma radiation at a high dose rate. ICRP recommends that they are applied in all situations, including those at the opposite extreme in almost all respects: namely heterogeneous, low dose exposures to charged particles at low dose rates over protracted time periods. Although CERRIE (2004) concluded that these risk factors are the best available, the Committee expressed reservations and considered that the application of these factors constituted an important source of uncertainty in dose and risk estimates. However, UNSCEAR (2000, 2011) has highlighted information available from very many other epidemiological studies of exposed populations. An important and more recent publication is the third analysis of the UK National Registry for Radiation Workers, which examined cancer risks in a very large cohort of workers exposed to low doses of radiation over many years (Muirhead *et al* 2009). The results show a dose–response relationship, consistent with the extrapolation of A-bomb risk factors to low doses. There are only a few epidemiological studies on internal emitters in which there are individual estimates of exposure that can be used to provide reliable estimates of risks. The best direct evidence of risks from internal emitters comes from studies of lung cancer following exposures to radon in mines and homes, bone cancer in radium exposed patients and workers, and liver cancer and leukaemia in patients given injections of Thorotrast (Harrison and Muirhead 2003, see below). The risk estimates from these studies are consistent with those from the A-bomb survivor study when account is taken of the greater effectiveness of alpha particles in causing cancer. Risks from internal emitters are considered in more detail in section 6.6 below.

Risk factors for very low levels of dose are assumed to be the same as for low levels of dose. Given the uncertainties associated with these estimates, they are as likely to be overestimates as underestimates (Harrison and Day 2008, Mobbs *et al* 2009).

6.2. Fallout studies

CERRIE (2004) examined the temporal pattern of childhood leukaemia incidence in the Nordic countries and in Great Britain in relation to patterns of fallout from atmospheric nuclear weapons testing in the 1950s and 1960s. CERRIE concluded that these studies suggest an increased risk due to this exposure, but provide no consistent or sufficiently persuasive evidence that this risk has been seriously under-estimated by standard radiation risk models (CERRIE 2004). Wakeford *et al* (2010a, 2010b) examined childhood leukaemia in eleven large-scale cancer registries and found no evidence of a wave of excess cases corresponding to the period of intense atmospheric weapons testing, providing further support to the conclusion reached by CERRIE.

Concerns have been raised over increased breast cancer incidence worldwide in recent decades and suggestions have been made of a link with fallout from nuclear weapons testing (Busby 1995). However, these suggestions are contrary to the consistent results on risks of radiation-induced breast cancer provided by the A-bomb survivor studies and studies on patients who received multiple chest fluoroscopies as part of their treatment for tuberculosis or were treated for benign disease (UNSCEAR 2011). Strong determinants of breast cancer incidence are lifestyle factors such as reproductive history and increased screening will also have affected time patterns in recorded breast cancer incidence. Consequently, studies that simply look at time trends in breast cancer incidence are not sufficient to determine causes. In the light of the available evidence, it is not possible to establish a link between breast cancer rates and the very small doses from fallout.

6.3. Post-Chernobyl studies

It is important that all sources of epidemiological data are explored fully so that their potential to inform judgements on radiation risks is maximised. Considerable efforts are being devoted to studies of health effects from external and internal exposures at the Russian Mayak plant and the associated discharges to the Techa River (Akleyev *et al* 2002). Unfortunately, much of the post-Chernobyl data cannot provide quantitative risk estimates because of the limited nature of data on levels of exposure. UNSCEAR (2000, 2011) has provided reviews of the available information. Apart from the emergency workers, several hundred thousand people were involved in recovery operations and there are indications of an increase in leukaemia and cataracts among those most highly exposed but no other evidence to date of health effects attributable to radiation (Kesminiene *et al* 2008, Romanenko *et al* 2008, UNSCEAR 2011). There has been a clear and substantial increase in thyroid cancer incidence in persons exposed as children or adolescents. For the period, 1991–2005, more than 6000 cases were reported of which a substantial proportion can be attributed to iodine-131 in milk (UNSCEAR 2011). In general, the future challenge in post-Chernobyl studies is to improve dose estimates for those individuals included in epidemiological studies, so as to provide a stronger basis for estimates of radiation risks.

Studies of leukaemia covering ages 0–14 years and 1–4 years in various western European countries have not indicated raised risks associated with the Chernobyl accident (CERRIE 2004, UNSCEAR 2011). These findings are noteworthy, because studies of exposure to x-rays *in utero* suggest that foetal irradiation increases the risk of leukaemia during early life to an extent which is proportionally similar to the risk that arises in childhood. Findings from post-Chernobyl studies of infant (<1 year of age) leukaemia have been variable, with the strongest evidence coming from a study in Greece that initially raised the hypothesis of an association with exposure from the accident (Petridou *et al* 1996). Subsequent studies in western Germany and Belarus did not show a clear association between infant leukaemia and

geographical measures of exposure. In addition, data for Great Britain that were analysed under the auspices of CERRIE (2004) were too sparse to allow firm conclusions to be drawn.

While the available data are consistent with increased risks of infant leukaemia following the Chernobyl accident, the study in Greece is the only one that—once statistical uncertainties are taken into account—provides notable evidence of a large discrepancy relative to estimates of radiation risk following external exposure. However, the Greek findings—which gave rise to the initial hypothesis—are inconsistent with those from a study in Belarus (Ivanov *et al* 1998), where the highest doses from the accident were received and for which the findings are consistent with current risk estimates. The British data are consistent both with the possibility of various levels of raised risk and with the absence of any increased risk (CERRIE 2004). Furthermore, uncertainties in risk estimates would be even greater if uncertainties in doses were taken into account. The quantification of risks based on this type of study is very difficult. The HPA view is that no firm conclusions can be drawn from the studies of infant leukaemia following the Chernobyl accident.

6.4. Childhood cancer clusters

As discussed by Mobbs *et al* (2009), clusters of childhood cancers, mainly leukaemias, have been reported around some nuclear sites in the UK and elsewhere, prompting suggestions that the radiation could be responsible for them. However, measured levels of radiation are too low by more than a factor of a hundred to account for them using current radiation risk factors. This has led to claims that risk factors are at least a factor of 100 too small, a suggestion that does not pass the test of scientific scrutiny. The Committee on Medical Aspects of Radiation in the Environment (COMARE), a scientific advisory committee providing independent authoritative expert advice on all aspects of health risk to humans exposed to natural and man-made radiation, has, for over twenty years, investigated the incidence of childhood cancer and other cancers around nuclear sites in the UK and cancer in the children of radiation workers (see, for example, COMARE (1986, 1988, 1989, 1996, 2002, 2005, 2006)). The 10th report (COMARE 2005) provides updated analyses of data for all of these sites. The results for power generating stations are unambiguous and, as would be expected from their extremely low discharges, do not suggest any effect on the incidence of childhood cancer. The study confirmed previous COMARE findings of excess childhood cancers in Seascale near Sellafield, Thurso near Dounreay and around Burghfield. Historically, Sellafield is the UK nuclear site with the largest of all radioactive discharges. In particular, the 4th COMARE report (COMARE 1996), which concentrated on Sellafield, reported a total of 8 cases of lymphoid leukaemia and non-Hodgkin lymphoma in Seascale during 1963–92 at ages less than 25 years, compared with 0.65 expected from national rates. COMARE concluded that 'on current knowledge, environmental radiation exposure from authorised or unplanned releases could not account for the excess' (of leukaemia and other cancers) (COMARE 1996). Analyses of doses received in the vicinity of Sellafield have shown that contributions from natural background radiation are dominant (Simmonds *et al* 1995). Similar conclusions were reached regarding doses in the vicinity of the La Hague reprocessing plant in France (Rommens *et al* 2000).

In its eleventh report, COMARE (2006) examined the general pattern of childhood leukaemia in Great Britain, considering over 32 000 cases of childhood cancer occurring between 1969 and 1993, and concluded that many types of childhood cancers 'have been shown not to occur in a random fashion'. In other words, they cluster 'normally'. The report also stated that 'The results of analyses ... suggest that there is no general clustering around nuclear installations'. An unusual pattern of exposure to infection has been proposed as a factor that could increase the risk of childhood leukaemia (Alexander *et al* 1998, McNally and Eden

2004), and studies have shown a link between population mixing and childhood leukaemia (Bellec *et al* 2008, Chang *et al* 2007, Kinlen and Doll 2004, Kinlen 2006, 2011, O'Connor and Boneva 2007, Stiller *et al* 2008). The most striking examples are from the United States at Niles, Illinois and Fallon, Nevada. In Niles, eight cases were observed in 1957–60, centred on a crowded parish school, following a massive population increase from 3587 to 20 393 from 1950 to 1960, much of the influx being into the parish concerned, from 1955 to 1960. In Fallon, ten cases of childhood leukaemia were diagnosed in only two years (1 expected) following a massive influx of military personnel to a naval station for training (Kinlen and Doll 2004).

A recent study (Spix *et al* 2008, Kaatsch *et al* 2008)—referred to as the KiKK study—reported a statistically significantly increased risk of leukaemia amongst children less than 5 years of age living within 5 km proximity of nuclear power plants in Germany from 1980 to 2003. This followed studies of leukaemia among children aged up to 15 years that did not show raised risks within 15 km of a German nuclear power plant during either 1980–90 (Michaelis *et al* 1992) or 1991–5 (Kaatsch *et al* 1998). An analysis by the German Commission on Radiological Protection (SSK 2008) concluded that the design of the KiKK study was suitable for analysing risks according to distance but not for establishing a correlation with exposure to radiation from nuclear power plants. It was pointed out that the natural radiation exposure within the study area, and its fluctuations, are both greater, by several orders of magnitude, than the additional radiation exposure from the nuclear power plants. Reanalysis of the data used for the COMARE 11th report for the same age range did not show a statistically significant association between leukaemia at ages less than 5 years and proximity to nuclear power stations in Great Britain (Bithell *et al* 2008, 2010) and a similar study in France was also negative (Laurier *et al* 2008). As part of its current work programme (see http://www.comare.org.uk/comare_work.htm), COMARE has set up a subgroup of committee members and external experts to provide comment on these findings. The report of this review is due to be published in 2011.

6.5. Natural radiation

It is difficult to establish an association between childhood leukaemia and exposure to natural radiation Richardson *et al* (1995),UK Childhood Cancer Study Investigators (2002a, 2002b), largely because the relatively low variation in doses to the red bone marrow limits the statistical power of epidemiological studies. Nevertheless, based on a detailed analysis of the possible association between exposures to natural background radiation and childhood leukaemia, Little *et al* (2009) estimated that natural radiation could account for around 15–20% of cases in Great Britain. This seems plausible and provides limits on possible underestimates of radiation risks. In particular, this would suggest that, depending on the risk model assumed, the risk of radiation-induced childhood leukaemia cannot be more than a factor of around 5–10 times greater than existing risk factors and is certainly not under-estimated by a factor of a hundred or more.

6.6. Risks from internal emitters

A legitimate concern is whether the risk factors derived from studies of the A-bomb survivors can be applied generally. As explained in section 6.1, these risk factors, which apply to short, homogeneous, high external doses of gamma radiation at a high dose rate, are applied by ICRP in all situations, including heterogeneous, low dose exposures to charged particles at low dose rates over protracted time periods. This question is particularly relevant to internal exposures to alpha particle emitting radionuclides since alpha particles only travel very short distances (a few tens of microns) in tissue.

In relation to the application of external risk factors to internal exposure to alpha particle irradiation, a number of human studies (UNSCEAR 2000, 2011, WHO 2001) provide information that has been used by ICRP (1991) and others to estimate risks of liver, bone and lung cancer.

- Liver cancer—patients given intravascular injections of 'Thorotrast', a colloidal thorium oxide preparation (^{232}Th is an alpha emitter), as a contrast medium for diagnostic radiology.
- Bone cancer—occupational exposure of radium dial painters to ^{226}Ra and ^{228}Ra; patients given ^{224}Ra for medical conditions.
- Lung cancer—occupational exposure of uranium miners to radon-222 and daughters, with consistent data from studies of residential exposure.

In addition, an excess of leukaemia has been reported in Thorotrast-treated patients, and quantitative estimates of plutonium-239 induced lung cancer have been derived for Russian workers at the Mayak nuclear site (WHO 2001, Harrison and Muirhead 2003, Gilbert *et al* 2004). In work for CERRIE (2004), Harrison and Muirhead (2003) compared risk estimates for radiation-induced cancer derived for these exposures to alpha emitting radionuclides and those derived for the atomic bomb survivors. They showed that, taking account of the greater effectiveness of alpha particles compared to gamma rays by up to a factor of around 20, the human data show enough consistency between estimates of radiation risk from internal emitters and external radiation for the two to be combined. Support is also provided by animal and *in vitro* data comparing the effects of different radionuclides and external radiation (UNSCEAR 2000, 2011, WHO 2001). None of these data suggest that risks from internal emitters have been substantially under-estimated. However, uncertainties in the dose estimates for internal emitters and in the risk factors should be recognised (Harrison and Muirhead 2003, ICRP 2007, Harrison and Day 2008).

6.7. Mechanisms of radiation action

While much remains to be learned about mechanisms of disease induction by radiation, much is known of the way in which ionisation causes damage to DNA, stable mutations can lead to uncontrolled cell division, cells can accumulate mutations, and clonal expansion can lead to malignancy (UNSCEAR 2000, 2011, Dauer *et al* 2010). There is no fundamental distinction between internal and external emitters from a physics standpoint. The energy deposition mechanisms for internally incorporated radionuclides are identical to those for exposure to external sources of radiation: a photon of a given energy within the body, interacts in precisely the same manner irrespective of whether it originated inside or outside the body. There is also no basis for the distinction by ECRR (Green Audit 2003) between the effects of internally incorporated natural and man-made alpha particle emitting radionuclides; there is no scientific reason why the effects of the alpha particles should be different other than differences in their energies.

With regard to cells at risk, there is growing understanding of the role of stem cells in the process of carcinogenesis and in the cellular interactions that maintain these cells in tissues. ICRP is currently reviewing data in this area, considering tissue radiosensitivity in terms of cancer induction, and the location of stem cells as targets for short-range emissions. The location of stem cells is currently taken into account in calculating doses from internal emitters in the respiratory and alimentary tracts and in the skeleton (ICRP 2007). The extent to which radiation damage to other cells may be important remains to be determined. There are suggestions that such non-targeted effects may add to the radiation response, or conversely,

may be protective. UNSCEAR has reviewed data on non-targeted effects of radiation and concluded that knowledge and understanding of these processes are insufficiently developed to inform judgements on dose–response at low and very low doses (UNSCEAR 2011). This conclusion was also reached by ICRP (2007) and endorsed by the HPA (2009a). As noted by ICRP, human epidemiological studies remain the primary source of quantitative risk data and all contributing processes should be accounted for adequately. However, uncertainties remain on the mechanisms operating at low and very low doses and the associated risks. HPA staff will continue to participate in collaborative European projects on low dose radiation effects.

ICRP (2007) discussed the issue of dose averaging within tissues at low doses, particularly in the case of radionuclides with short-range emissions for which energy deposition may be highly heterogeneous so that only a proportion of cells within a tissue are hit. However, considering the stochastic nature of radiation-induced cancer and hereditary effects, it is not clear that this heterogeneity is of significance in circumstances in which both energy deposition and target cells are randomly distributed within a tissue. CERRIE (2004) commissioned a review of data on the carcinogenicity of radioactive particles relative to more uniform irradiation. The available evidence from animal and *in vitro* studies indicates that the use of average dose to tissues will provide a reasonable estimate of risk from radioactive particles, within a factor of three (Charles *et al* 2003). This conclusion is supported by human data for plutonium-239 induced lung cancer and Thorotrast (thorium oxide particles) induced liver cancer and leukaemia (Charles *et al* 2003).

Busby and colleagues (Busby 1995, 1996, Busby and Scott Cato 2000) have suggested a mechanism whereby radionuclides with sequential decays may be more hazardous than has been realised. Referred to as the second event theory, this would apply to strontium-90 decaying with its daughter, yttrium-90, and to sequential emissions from radioactive particles. Edwards and Cox (2000) re-examined the proposals and concluded that a small effect was plausible (less than a factor of 2) but not the large effect that has been suggested. Animal and human data support this conclusion (WHO 2001, Krestinina *et al* 2005, Sokolnikov *et al* 2008).

Busby and colleagues (Busby 2005, Busby and Schnug 2007, Tickell 2008) have suggested that the toxicity of uranium may have been substantially under-estimated because, as a high Z element, it may convert natural background gamma rays into short-range photoelectrons. This secondary photoelectric effect is a well known phenomenon where photons passing through material lose energy by exciting atomic electrons, leading to the emission of a photoelectron followed by a cascade of Auger and Coster–Kronig electrons, and fluorescence[4]. Pattison *et al* (2010) have examined claims that enhancement by uranium particles could be as large as a factor of 500–1000, and concluded that the enhancement in the few microns around microparticles could be up to a factor of three. Eakins *et al* (2011) obtained similar results and concluded that the additional energy deposition will be several orders of magnitude lower than the energy deposited locally by alpha particles from the radioactive decay of the uranium. Hence the enhancement is of negligible biological significance compared to the intrinsic alpha activity of the uranium. Similar considerations apply to the suggestion that soluble forms of uranium might concentrate within cells, bind to DNA, and enhance the effect of natural background photon radiation. The extent of direct association with DNA will be important only for consideration of energy deposition from very short-range emissions, such as Auger electrons. Increased biological effectiveness could result from photoelectric events that take place in close proximity to DNA. However, calculations by Humm and Charlton (1988) showed that the effect will be small or negligible for bromine ($Z = 35$) and even smaller for iodine

[4] This is the main mechanism of interaction of lower energy gamma rays; however scattering of gamma rays (the Compton effect) is another important mechanism at the energies found in natural background radiation (see the NIST website http://www.nist.gov/physlab/data/xraycoef/index.cfm for more information.)

($Z = 53$). The effect will be of less biological significance for uranium ($Z = 92$) because the higher Z element produces relatively longer-range secondary radiation.

There is no evidence from animal experiments or human studies of unusually high toxicity of uranium (WHO 2001). For example, Ellender *et al* (2001) compared the effect of plutonium-239, americium-241 and uranium-233 in mice at cumulative average skeletal doses of 0.25–0.3 Gy, 0.5–1 Gy and 1–2 Gy. For both bone cancer and myeloid leukaemia induction, ^{233}U was considerably less effective than ^{239}Pu and ^{241}Am. Concerns over the toxicity of depleted uranium have led to a number of reviews; the Royal Society (2001, 2002) for example, discounted any association between DU and reported medical problems. Results from a recent study suggesting a link between lung cancer risk and exposure to reprocessed uranium oxide did not show uranium to be more toxic than expected (Canu *et al* 2010).

7. Summary and conclusions

This paper provides a brief commentary on the basis for current radiation risk estimates, referring to the comprehensive reviews undertaken by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and to the assessments that form the basis for recommendations issued by the International Commission on Radiological Protection (ICRP). The HPA is required to advise government and other stakeholders on the application of ICRP recommendations in the UK. Such advice is based on an objective review of the scientific evidence and its application in the development of standards, informed by direct involvement in epidemiological and biological research as well as substantial experience in setting protection criteria.

There is an extensive literature on the risks of radiation exposure, regularly reviewed by UNSCEAR, which provides a sound basis for the system of protection recommended by ICRP. The available epidemiological and experimental evidence supports the application of cancer risk estimates derived for acute, high dose external exposures to low dose exposures to external and internal sources. Follow-up studies of the A-bomb survivors provide the best source of information on radiation-induced cancer and other health effects after exposures to acute doses of around 100 mSv and greater. HPA has led on studies of cancer in UK radiation workers exposed to low doses over many years, and recently published data show consistency with risks derived from the A-bomb data. The best direct evidence of risk from internal emitters comes from studies of lung cancer following exposure to radon in mines and homes, bone cancer in radium exposed patients and workers, and liver cancer and leukaemia in patients given injections of Thorotrast (thorium oxide particles). The risk estimates from these studies are consistent with those from the A-bomb survivor studies when account is taken of the greater effectiveness of alpha particles in causing cancer (by factors of up to 20).

Considerable efforts are made to maximise information obtained from epidemiological studies of exposed populations, including those exposed as a result of the Chernobyl accident and operations at the Mayak nuclear complex in Russia. Much of the post-Chernobyl data cannot be used to provide risk estimates because of the limited nature of data on levels of exposure. There has been a substantial increase in thyroid cancer incidence in persons exposed as children or adolescents to the releases from the Chernobyl accident. Several hundred thousand people were involved in recovery operations and there are indications of an increase in leukaemia and cataracts among those most highly exposed but no other evidence to date of health effects attributable to radiation. Findings from post-Chernobyl studies of infant leukaemia are variable and the HPA view is that no firm conclusions can be drawn.

Clusters of childhood cancers, mainly leukaemias, have been reported around some nuclear sites in the UK and elsewhere and have been extensively studied for many years by the

Committee on Medical Aspects of Radiation in the Environment (COMARE). Recent studies have considered the general pattern of childhood cancer in Great Britain, concluding that many types of cancer are not distributed randomly. No clustering has been identified around power generating stations but studies have shown excess childhood cancers near Sellafield, Dounreay, Aldermaston, Burghfield and Harwell. Sellafield is the UK nuclear site with the largest radioactive discharges. Detailed analyses have shown, however, that radiation doses from discharges are too small to result in any increase in cancer incidence, and are much smaller than doses from natural background radiation. Evidence of risks of childhood cancer is derived from the A-bomb survivor studies, with consistent results on risks from *in utero* exposure from the Oxford Survey of Childhood Cancers (OSCC). While observations of clustering of childhood cancers near some nuclear sites are acknowledged, they remain unexplained, and it is noteworthy that clusters have also been observed in locations without such facilities, possibly due to infectious agents introduced by large population movements.

While much remains to be learned from ongoing studies of the mechanisms of disease induction by radiation, much is known of the way in which ionisation causes damage to DNA, stable mutations can lead to uncontrolled cell division, cells can accumulate mutations, and clonal expansion can lead to malignancy. There is no fundamental difference between external and internal sources of radiation in their capacity to cause such damage, or between man-made and natural radionuclides. However, it is important to consider the location of target stem cells within tissues when considering doses from short-range internal emitters (e.g., alpha particles, low energy electrons). Target cell location is taken into account in ICRP models for the respiratory and alimentary tracts, and the skeleton. The available evidence from animal and cellular studies indicates that the use of average dose within organs, tissues, or tissue regions, will provide a reasonable estimate of risk, even for radioactive particles. This conclusion is supported by human data for plutonium-239 induced lung cancer and Thorotrast (thorium oxide particles) induced liver cancer and leukaemia.

In the context of radioactive waste management and the cleanup of contaminated land, the dose criteria set by the regulatory bodies correspond to very low levels of dose: 10 or 20 microsieverts (μSv). Risks associated with these very low levels of dose, a small fraction of doses from natural background radiation, cannot be demonstrated directly by epidemiological studies but are estimated assuming a linear dose–response relationship. This is also the case for the levels of dose relevant to public exposure arising from planned discharges from nuclear power stations.

Uncertainties are larger—in relative terms—at low and very low doses than at doses for which direct evidence of risk is available, and are generally larger for internal exposures than for external exposures. However, claims that these uncertainties correspond to underestimates by factors of two or three orders of magnitude or more are unsubstantiated. Current estimates are as likely to overestimate as to underestimate the very low risks at very low doses.

References

Akleyev A V, Grosche B, Gusev B I, Kiselev V I, Kisselev M F, Kolyado I B, Romanov S, Shoikhet Y N and Neta R 2002 Developing additional resources *Radiat. Environ. Biophys.* **41** 13–8

Alexander F E *et al* 1998 Spatial temporal patterns in childhood leukaemia: further evidence for an infectious origin. EUROCLUS project *Br. J. Cancer* **77** 812–7

Allison W 2009 *Radiation and Reason. The Impact of Science on a Culture of Fear* (York: York Publishing Services) ISBN 0-9562756-1-3

Azizova T V and Muirhead C R 2009 Epidemiological evidence for circulatory diseases—occupational exposure *Radiation Protection No.* 158*: EU Scientific Seminar 2008 Emerging Evidence for Radiation Induced Circulatory Diseases* (Luxembourg: European Commission) pp 33–46

Azizova T V, Muirhead C R, Druzhinina M B, Grigoryeva E S, Vlasenko E V, Sumina M V, O'Hagan J A, Zhang W, Haylock R G and Hunter N 2010a Cardiovascular diseases in the cohort of workers first employed at Mayak PA in 1948–1958 *Radiat. Res.* **174** 155–68

Azizova T V, Muirhead C R, Druzhinina M B, Grigoryeva E S, Vlasenko E V, Sumina M V, O'Hagan J A, Zhang W, Haylock R G and Hunter N 2010b Cerebrovascular diseases in the cohort of workers first employed at Mayak PA in 1948–1958 *Radiat. Res.* **174** 851–64

Bellec S, Baccaini B, Goubin A, Rudant J, Ripert M, Hémon D and Clavel J 2008 Childhood leukaemia and population movements in France, 1990–2003 *Br. J. Cancer* **98** 225–31

Bithell J F, Keegan T J, Kroll M E, Murphy M F G and Vincent T J 2008 Childhood leukaemia near British nuclear installations: methodological issues and recent results *Radiat. Prot. Dosim.* **132** 191–7

Bithell J F, Keegan T J, Kroll M E, Murphy M F G and Vincent T J 2010 Response to the letter by Körblein and Fairlie *Radiat. Prot. Dosim.* **138** 89–91

Bithell J F and Stewart A M 1975 Pre-natal irradiation and childhood malignancy: a review of British data from the Oxford survey *Br. J. Cancer* **31** 271–87

Busby C 1995 *Wings of Death: Nuclear Pollution and Human Health* (Aberystwyth: Green Audit Books)

Busby C 1996 Recalculating the second event error http://llrc.org/secevnew.htm

Busby C 2005 Depleted uranium weapons, metal particles, and radiation dose *Eur. J. Biol. Bioelectromagn.* **1** 82–93

Busby C and Schnug E 2007 Advanced biochemical and biophysical aspects of uranium contamination *Loads and Fate of Fertilizer Derived Uranium* ed I J De Kok and E Schnug (Leiden: Backuys)

Busby C and Scott Cato M 2000 Increases in leukaemia in infants in Wales and Scotland following Chernobyl: evidence for errors in statutory risk estimates *Energy Environ.* **11** 127–39

Cancer Research UK 2008 *Cancer Stats, Key Facts, All Cancers* http://info.cancerresearchuk.org/cancerstats/incidence/ (last updated 06 November 2008)

Canu I G, Jacob S, Cardis E, Wild P, Caer-Lorho S, Auriol B, Laurier D and Tirmarche M 2010 Reprocessed uranium exposure and lung cancer risk *Health Phys.* **99** 308–13

CERRIE 2004 *Report of the Committee Examining Radiation Risks of Internal Emitters, October 2004* www.cerrie.org

Chang J S, Metayer C, Fear N T, Reinier K, Yin X, Urayama K, Russo C, Jolly K W and Buffler P A 2007 Parental social contact in the work place and the risk of childhood acute lymphoblastic leukaemia *Br. J. Cancer* **97** 1315–21

Charles M W, Mill A J and Darley P J 2003 Carcinogenic risk of hot particle exposures *J. Radiat. Prot.* **23** 5–28

COMARE (Committee on Medical Aspects of Radiation in the Environment) 1986 *First Report, The Implications of the New Data on the Releases from Sellafield in the 1950s for the Conclusions of the Report on the Investigation of the Possible Increased Incidence of Cancer in West Cumbria* (London: HMSO)

COMARE (Committee on Medical Aspects of Radiation in the Environment) 1988 *Second Report, Investigation of the Possible Increased Incidence of Leukaemia in Young People near the Dounreay Nuclear Establishment, Caithness, Scotland* (London: HMSO)

COMARE (Committee on Medical Aspects of Radiation in the Environment) 1989 *Third Report, Report on the Incidence of Childhood Cancer in the West Berkshire and North Hampshire area, in which are situated the Atomic Weapons Research Establishment, Aldermaston and the Royal Ordnance Factory, Burghfield* (London: HMSO)

COMARE (Committee on Medical Aspects of Radiation in the Environment) 1996 *Fourth Report, The Incidence of Cancer and Leukaemia in Young People in the Vicinity of the Sellafield site, West Cumbria: Further Studies and an Update of the Situation since the Publication of the Report of the Black Advisory Group in 1984* (London: Department of Health)

COMARE (Committee on Medical Aspects of Radiation in the Environment) 2002 *Seventh Report, Parents Occupationally Exposed to Radiation Prior to the Conception of their Children. A Review of the Evidence Concerning the Incidence of Cancer in their Children* www.comare.org.uk

COMARE (Committee on Medical Aspects of Radiation in the Environment) 2004 *Ninth Report, Advice to Government on the Review of Radiation Risks from Radioactive Internal Emitters Carried out and Published by the Committee Examining Radiation Risks of Internal Emitters (CERRIE)* www.comare.org.uk

COMARE (Committee on Medical Aspects of Radiation in the Environment) 2005 *Tenth Report, The Incidence of Childhood Cancer around Nuclear Installations in Great Britain* www.comare.org.uk

COMARE (Committee on Medical Aspects of Radiation in the Environment) 2006 *Eleventh Report, The Distribution of Childhood Leukaemia and other Childhood Cancers in Great Britain 1969–1993* www.comare.org.uk

Darby S *et al* 2005 Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies *Br. Med. J.* **330** 223–6

Darby S *et al* 2006 Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiological studies in Europe *Scand. J. Work Environ. Health* **32** 1–83

Darby S *et al* 2007 Residential radon and lung cancer—detailed results of a collaborative analysis of individual data on 7148 persons with lung cancer and 14,208 persons without lung cancer from 13 epidemiological studies in Europe (erratum) *Scand. J. Work Environ. Health* **33** 80

Dauer L T, Brooks A L, Hoel D G, Morgan W F, Stram D and Tran P 2010 Review and evaluation of updated research on the health effects associated with low-dose ionising radiation *Radiat. Prot. Dosim.* **140** 103–36

DETR 2000 *Radioactive Substances (Basic Safety Standards) (England and Wales) Direction 2000* (London: DETR)

Eakins J S, Jansen J T M and Tanner R J 2011 A Monte Carlo analysis of possible cell dose enhancement effects by uranium microparticles in photon fields *Radiat. Prot. Dosim.* **143** 177–80

Edwards A A and Cox R 2000 Commentary on the second event theory of Busby *Int. J. Radiat. Biol.* **76** 119–25

Ellender M, Harrison J D, Pottinger H and Thomas J M 2001 Induction of osteosarcoma and acute myeloid leukaemia by the alpha-emitting nuclides, uranium-233, plutonium-239 and americium-241 *Int. J. Radiat. Biol.* **77** 41–52

Environment Agency, Northern Ireland Environment Agency, Scottish Environment Protection Agency 2009a *Near-Surface Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*

Environment Agency, Northern Ireland Environment Agency 2009b *Geological Disposal Facilities on Land for Solid Radioactive Wastes: Guidance on Requirements for Authorisation*

European Commission 1996 Council Directive 96/29/Euratom of 13 May 1996 laying down the basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation Off J Eur Commun. L159 p.1European Commission (1996)

Feinendegen L E, Paretzke H and Neumann R D 2008 Two principal considerations are needed after low doses of ionizing radiation *Radiat. Res.* **169** 247–8

French Academies Report 2005 *La Relation Dose-Effect at l'Estimation des Effets Cancérogènes des Faibles Doses de Rayonnement Ionisants* http://www.academie-sciences.fr

Gilbert E S *et al* 2004 Lung cancer in Mayak workers *Radiat. Res.* **162** 505–16

Green Audit 2003 *2003 Recommendations of the European Committee on Radiation Risk: Health Effects of Ionising Radiation Exposure at Low Doses for Radiation Protection Purposes* Regulators' edn (Brussels: ECRR)

Harrison J and Day P 2008 Radiation doses and risks from internal emitters *J. Radiol. Prot.* **28** 137–59

Harrison J D and Muirhead C R 2003 Quantitative comparisons of cancer induction in humans by internally deposited radionuclides and external radiation *Int. J. Radiat. Biol.* **79** 1–13

Hill A B 1965 The environment and disease: association or causation? *Proc. R. Soc. Med.* **58** 295–300

HPA 2003 *Response to ECRR 2003* http://www.hpa.org.uk/web/HPAwebFile/HPAweb_C/1240212769871 p 41

HPA 2006 Radiological protection objectives for radioactively contaminated land *RCE-2* (Chilton: HPA)

HPA 2009a HPA advice on the application of ICRP's 2007 recommendations to the UK *RCE-12* (Chilton: HPA)

HPA 2009b Radon and Public Health *Report of the Independent Advisory Group on Ionising Radiation, RCE-11* (Chilton: HPA)

HPA 2009c Radiological protection objectives for the land-based disposal of solid radioactive waste *RCE-08* (Chilton: HPA)

HPA 2010a Circulatory disease risk *Report of the Health Protection Agency Independent Advisory Group on Ionising Radiation Docs HPA RCE-16* (Chilton: HPA)

HPA 2010b Limitation of human exposure to radon *RCE-15* (Chilton: HPA)

HSE 2005 Criterion for delicensing licensed sites, available from www.hse.gov.uk/nuclear

Humm J L and Charlton D E 1988 Double strand breakage in DNA produced by the photoelectric interaction with incorporated cold bromine *DNA Damage by Auger Emitters* (London: Taylor and Francis) pp 111–22

IAEA 1996 International Basic Safety Standards for the protection against ionizing radiation and the safety of radiation sources *Safety Series* 115 (Vienna: IAEA)

ICRP (International Commission on Radiological Protection) 1991 Recommendations of the International Commission on Radiological protection *ICRP Publication 60*

ICRP 2006 Human alimentary tract model for radiological protection *ICRP Publication 100*; *Ann. ICRP* **36** (Oxford: Elsevier Science)

ICRP 2007 The 2007 Recommendations of the International Commission on Radiological Protection *ICRP Publication 103* **37** 2–4

IRSN 2005 Health consequences of chronic internal contaminations by radionuclides *Comments on the ECRR Report 'The Health Effects of Ionizing Radiation Exposure at Low Doses for Radiation Protection Purposes' and IRSN Recommendations. IRSN Report DRPH/2005-20*

Ivanov E *et al* 1998 Infant leukaemia in Belarus after the Chernobyl accident *Radiat. Envrion. Biophys.* **37** 53–5
Kaatsch P, Kaletsch U, Meinert R and Michaelis J 1998 An extended study on childhood malignancies in the vicinity of German nuclear power plants *Cancer Causes Control* **9** 529–33
Kaatsch P, Spix C, Schulze-Rath R, Schmiedel S and Blettner M 2008 Leukaemia in young children living in the vicinity of German nuclear power plants *Int. J. Cancer* **122** 721–6
Kesminiene A *et al* 2008 Risk of haematological malignancies among Chernobyl liquidators *Radiat. Res.* **170** 721–35
Kinlen L 2006 Childhood leukaemia and ordnance factories in west Cumbria during the Second World War *Br. J. Cancer* **95** 102–6
Kinlen L 2011 Childhood leukaemia, nuclear sites, and population mixing *Br. J. Cancer* **104** 12–8
Kinlen L and Doll R 2004 Population mixing and childhood leukaemia: Fallon and other US clusters *Br. J. Cancer* **91** 1–3
Krestinina L Y, Preston D L, Ostroumova E V, Degteva M O, Ron E, Vyushkova O V, Stratsev N V, Kossenko M M and Akleyev A V 2005 Protracted radiation exposure and cancer mortality in the Techa River Cohort *Radiat. Res.* **164** 602–11
Laurier D, Hémon D and Clavel J 2008 Childhood leukaemia incidence below the age of 5 years near French nuclear power plants *J. Radiol. Prot.* **28** 401–3
Little M P, Wakeford R and Kendall G M 2009 Updated estimates on the proportion of childhood leukaemia incidence in Great Britain that may be caused by natural background ionising radiation *J. Radiol. Prot.* **29** 467–82
McNally R J and Eden T O 2004 An infectious aetiology for childhood acute leukaemia: a review of the evidence *Br. J. Haematol.* **127** 243–63
Michaelis J, Keller B, Haaf G and Kaatsch P 1992 Incidence of childhood malignancies in the vicinity of west German nuclear power plants *Cancer Causes Control* **3** 255–63
Mobbs S, Muirhead C and Harrison J 2010 Risks from ionising radiation *HPA-RPD-066* (Chilton: HPA)
Mobbs S, Watson S, Harrison J, Muirhead C and Bouffler S 2009 An introduction to the estimation of risks arising from exposure to low doses of ionising radiation *HPA-RPD-055* (Chilton: HPA)
Muirhead C R, O'Hagan J A, Haylock R G E, Phillipson M A, Willcock T, Berridge G L C and Zhang W 2009 Mortality and cancer incidence following occupational radiation exposure: 3rd analysis of the National Registry for Radiation Workers *Br. J. Cancer* **100** 206–12
NAS/NRC 2006 *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2* (Washington, DC: National Academies Press)
NCRP 2001 Evaluation of the linear-non threshold dose-response model for ionizing radiation *NCRP Report No. 136* (Bethesda, MD: National Council on Radiation Protection and Measurements)
O'Connor S M and Boneva R S 2007 Infectious etiologies of childhood leukemia: plausibility and challenges to proof *Environ. Health Perspect* **115** 146–50
Pattison J E, Hugtenburg R P and Green S 2010 Enhancement of natural background gamma-radiation dose around uranium microparticles in the human body *J. R. Soc. Interface* **7** 603–11
Petridou E *et al* 1996 Infant leukaemia after in utero exposure to radiation from Chernobyl *Nature* **382** 352–3
Preston D L, Ron E, Tokuoka S, Funamoto S, Nishi N, Soda M, Mabuchi K and Kodama K 2007 Solid cancer incidence in atomic bomb survivors: 1958–1998 *Radiat Res.* **168** 1–64
Preston R J 2003 The LNT is the best we can do—today *J. Radiol. Prot.* **23** 263–8
Richardson S, Monfort C, Green M, Draper G and Muirhead C 1995 Spatial variation of natural radiation and childhood leukaemia incidence in Great Britain *Stat. Med.* **14** 2487–501
Romanenko A Y *et al* 2008 The Ukranian–American study of leukaemia and related disorders among Chernobyl cleanup workers from Ukraine: III radiation risks *Radiat. Res.* **170** 711–20
Rommens C, Laurier D and Sugier A 2000 Methodology and results of the Nord-Cotentin radioecological study *J. Radiol. Prot.* **20** 361–80
Royal Society 2001 *The Health Hazards of Depleted Uranium Munitions—Part 1* (London: The Royal Society)
Royal Society 2002 *The Health Hazards of Depleted Uranium Munitions—Part 2* (London: The Royal Society)
Shagina N B, Tolstykh E I, Fell T P, Harrison J D, Phipps A W and Degteva M O 2007 *In utero* and postnatal haemopoietic tissue doses resulting from maternal ingestion of strontium isotopes from the Techa River *Radiat. Prot. Dosim.* **127** 497–501
Simmonds J R, Robinson C A, Phipps A W, Muirhead C R and Fry F A 1995 Risks of leukaemia and other cancers in seascale from all sources of ionising radiation exposures *R276* (Chilton: HPA)
Smith G M 2010 What is a low dose? *J. Radiol. Prot.* **30** 93–101
Sokolnikov M E, Gilbert E S, Preston D L, Ron E, Shilnikova N S, Khokhryakov V V, Vasilenko E K and Koshurnikova N A 2008 Lung, liver and bone cancer mortality in Mayak workers *Int. J. Cancer* **123** 905–11
Spix C, Schmiedel S, Kaatsch P, Schulze-Rath R and Blettner M 2008 Case-control study on childhood cancer in the vicinity of nuclear power plants in Germany 1980–2003 *Eur. J. Cancer* **44** 275–84

SSK 2008 *Bewertung der Epidemiologischen Studie zu Kinderkrebs in der Umgebung von Kernkraftwerken (KiKK-Studie) Heft 57* (Bonn: Stellungnahme der Strahlenschutzkommission)

Stiller C A, Kroll M E, Boyle P J and Feng Z 2008 Population mixing, socioeconomic status and incidence of childhood acute lymphoblastic leukaemia in England and Wales: analysis by census ward *Br. J. Cancer* **98** 1006–11

Tickell O 2008 How war debris could cause cancer *New Sci.* **195** 8–9

Tubiana M, Aurengo A, Averbeck D and Masse R 2008 Low-dose risk assessment: the debate continues *Radiat. Res.* **169** 246–7

UK Childhood Cancer Study Investigators 2002a The United Kingdom Childhood Cancer Study of exposure to domestic sources of ionising radiation: 1: radon gas *Br. J. Cancer* **86** 1721–6

UK Childhood Cancer Study Investigators 2002b The United Kingdom Childhood Cancer Study of exposure to domestic sources of ionising radiation: 2: gamma radiation *Br. J. Cancer* **86** 1727–31

UK Parliament 2000 *The Ionising Radiations Regulations 1999* SI(1999) 3232

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2000 *Sources and Effects of Ionizing Radiation. Volume II. 2000 Report to the General Assembly* (New York: United Nations)

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) 2011 *Sources and Effects of Ionizing Radiation. Volume II. 2008 Report to the General Assembly with Annexes* (New York: United Nations)

Wakeford R, Darby S C and Murphy M F G 2010a Temporal trends in childhood leukaemia incidence following exposure to radioactive fallout from atmospheric nuclear weapons testing *Radiat. Environ. Biophys.* **49** 213–27

Wakeford R, Darby S C and Murphy M F G 2010b *Radiat. Environ. Biophys.* **49** 503 (erratum)

Wakeford R and Little M P 2003 Risk coefficients for childhood cancer after intrauterine irradiation: a review *Int. J. Radiat. Biol.* **79** 293–309

Wakeford R and Tawn E J 2010 The meaning of low dose and low dose-rate *J. Radiol. Prot.* **30** 1–3

Watson S *et al* 2005 Ionising radiation exposure of the UK population: 2005 review *HPA-RPD-001* (Chilton: HPA)

WHO (World Health Organisation) International Agency for Research on Cancer 2001 *IARC Monographs on the Evaluation of Carcinogenic Risks to Humans* vol 78 *Ionizing Radiation, Part 2: Some Internally Deposited Radionuclides* (Lyon: IARC Press)