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Highlights of the UNSCEAR 2008 Report

Bruxelles, 15 avril 2011

Dit nummer bevat onder anderen, de teksten van uiteenzettingen ter gelegenheid van de vergadering van de Belgische Vereniging voor Stralingsbescherming (BVSABR)

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Brussel, 15 april 2011

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Highlights of the UNSCEAR 2008 report

INTRODUCTION AND OVERVIEW OF THE ACTIVITIES OF UNSCEAR

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1. Introduction

The UNSCEAR 2008 report [1], which has been published with a delay of more than 2 years, contains a wealth of information. The objective of this meeting is to give you a clear idea of the contents of the scientific annexes, to present some highlights and to go even beyond what can be found in the UNSCEAR report. Before diving into the scientific annexes, let me first give you a brief review of the origin and current activities of UNSCEAR.

2. Origin of UNSCEAR

UNSCEAR is the acronym of "United Nations Scientific Committee on the Effects of Atomic Radiation". It is just as the IAEA or the WHO an organization of the United Nations. UNSCEAR was established by the General Assembly of the United Nations in 1955. At that time the main concern was the radioactive fallout from the many atmospheric nuclear weapon tests and their possible health effects on the world population. The estimated annual per caput effective dose of ionizing radiation due to global fallout from atmospheric nuclear weapons testing is shown in figure 1.

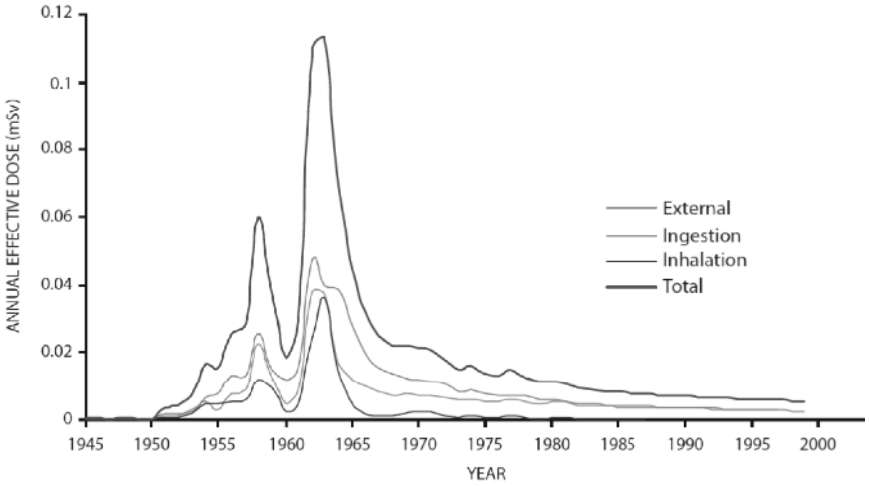

Fig 1. Worldwide average per caput effective doses from nuclear weapons tests, 1945-2005 [1].

The global average annual dose was highest in 1963, at 0.11 mSv, and subsequently fell to less than 0.005 mSv in the 2000s. External exposure generally made the largest contribution to annual doses; initially it was due to short-lived radionuclides and subsequently to cesium-137. The annual doses at present are due almost equally to external exposure (53%) and internal exposure due to ingestion (47%). The dose from carbon-14 (30% of the total) now exceeds that from ingestion of other radionuclides. This source of exposure will decline only very slowly in the future because of the long half-life of carbon-14.

UNSCEAR has evaluated in its reports the radiological exposures in all major accidents. An overview, in order of magnitude, of the collective doses received in these tragic events:

– 1986 Chernobyl 295 000 manSv
– 2011 Fukushima ?? 000 manSv
– 1957 Kyshtym 2 500 manSv
– 1964 SNAP 9A 2 100 manSv
– 1957 Windscale fire 2 000 manSv
– 1983 Ciudad Juarez 150 manSv
– 1987 Goiânia 60 manSv
– 1979 TMI 40 manSv
– 1978 Cosmos 954 20 manSv

– 1966 Palomares 3 manSv
– 1999 Tokai-mura < 0.6 manSv
– 1993 Tomsk 0.02 manSv

UNSCEAR is already involved in a detailed assessment of the levels and effects from the Fukushima nuclear accident. A preliminary assessment will be submitted for discussion at its next session in May 2012. A year later, a full assessment report will be submitted in view of publication as a scientific annex to the UNSCEAR 2013 report to the General Assembly.

For comparison, the collective dose caused by the testing of nuclear weapons in the atmosphere, from 1945 until 1980, was estimated by UNSCEAR at 22 000 000 manSv, while the collective dose of one year of medical imaging in Belgium in 2006 was estimated at 22 000 manSv [2].

3. Mandate of UNSCEAR

UNSCEAR is at present the main organization of the United Nations with respect to

- Worldwide levels and trends of radiation exposure to all sources of ionizing radiation in normal and accidental situations (nuclear fuel cycle, medical uses of radiation, natural radiation…)
- Review of the health effects of ionizing radiation:
  - at high exposures: radiation burns, acute radiation sickness or even death;
  - at lower levels the principal risk is an increase in radiation induced cancer;
  - but also hereditary disease, non-cancer effects and effects of radiation on non-human species.

4. Mode of operation of UNSCEAR

Representatives from 21 states participate to the annual UNSCEAR meetings in Vienna:

Argentina, Australia, Belgium, Brazil, Canada, China, Egypt, France, Germany, India, Indonesia, Japan, Mexico, Peru, Poland, Russian Federation, Slovak Republic, Sudan, Sweden, United Kingdom, United States of America.

All the countries with an extensive nuclear arsenal or with an important nuclear industry are represented, including a selection of smaller countries from the 5 continents. The scientific secretariat is located in Vienna in the same buildings as the IAEA. The Englishman Malcolm Crick is head of the secretariat since 2005. The scientific reports, prepared by the secretariat, are discussed during annual meetings. They are called annexes because they are appended to a summary report submitted for approval to the General Assembly of the United Nations. UNSCEAR reviews the scientific literature in cycles of 5 to 10 years.

The Belgian delegation includes also scientists from the Netherlands:

- Representative: Hans Vanmarcke (SCK•CEN)
- Alternate representative: Patrick Smeesters (AFCN-FANC)
- Advisors: André Wambersie (UCL, representing also ICRU), François Jamar (UCL), Hilde Engels (SCK•CEN and RIZIV), Gilbert Eggermont (VUB), Hilde Bosmans (KUL), Harmen Bijwaard (RIVM, the Netherlands) and Leon Mullenders (Univ. Leiden, the Netherlands)

5. UNSCEAR reports

All the reports of UNSCEAR are available for free download from the website: http://www.unscear.org/unscear/en/publications.html

In 2008 and 2009, with some delay the ***UNSCEAR 2006 report*** [3] on effects of ionizing radiation was published. It is the first part of the recently completed full cycle and consists of two volumes with the following scientific annexes:

VOLUME I

- Annex A. Epidemiological studies of radiation and cancer
- Annex B. Epidemiological evaluation of cardiovascular disease and other non-cancer diseases following radiation exposure

VOLUME II

- Annex C. Non-targeted and delayed effects of exposure to ionizing radiation
- Annex D. Effects of ionizing radiation on the immune system
- Annex E. Sources-to-effects assessment for radon in workplaces and homes

The ***UNSCEAR 2008 report*** [1] on sources and effects of ionizing radiation is the second part of the recently completed cycle and the subject of this meeting:

VOLUME I: SOURCES

Annex A. Medical radiation exposures

Annex B. Exposures of the public and workers from various sources of radiation

VOLUME II: EFFECTS

Annex C. Radiation exposures in accidents

Annex D. Health effects due to radiation from the Chernobyl accident

Annex E. Effects of ionizing radiation on non-human biota

The ***UNSCEAR report to the General Assembly of 2010*** [4] included a scientific chapter "Summary of low-dose radiation effects on health" that was published in 2011 in six languages.

6. Interaction with other international organizations

UNSCEAR maintains close contacts with other international organizations working in the field of radiation protection. Observers of IAEA, WHO, ICRP, ICRU, EU… are present at the annual meetings and take part in the technical discussions for the preparation of the UNSCEAR reports.

7. Current activities of UNSCEAR

UNSCEAR is currently reviewing the following documents

- Ability to attribute health effects to exposure to ionizing radiation
- Uncertainties in risk estimates for cancer due to exposure to ionizing radiation
- Biological effects of selected internal emitters
- Assessment of levels of radiation from electricity generation
- Methodology for estimating human exposures due to discharges

In addition to the Fukushima assessment UNSCEAR decided in 2011:

- to develop a report specifically on radiation risks and effects on children
- to evaluate epidemiological studies related to environmental sources of radiation at low dose rates
- to review developments on mechanisms of actions at low doses

References

[1] UNSCEAR (2008) Sources and effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes, United Nations sales publication, Volume I on sources: E.10.IX.3, Volume II on effects: E.11.IX.3, New York.

[2] H. Vanmarcke, H. Bosmans, G. Eggermont (2010) Ionizing radiation exposure of the Belgian population in 2006, Proceedings of the Third European IRPA congress, http://www.irpa2010europe.com/proceedings/P15.htm P15−02, Helsinki, Finland, 14−18 June, 2010.

[3] UNSCEAR (2006) Effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes, United Nations sales publication, Volume I: E.08.IX.6, Volume II: E.09.IX.5, New York.

[4] UNSCEAR (2010) comprises the main text of the 2010 report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly (A/65/46) and a scientific report: "Summary of low-dose radiation effects on health", United Nations sales publication M.II.IX.4, New York.

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LESSONS LEARNED FROM UNSCEAR'S 2008 REPORT ON MEDICAL EXPOSURE

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1. Introduction

Part of the mission of UNSCEAR consists in studying the amount and distribution of exposure to the worldwide population. Medical exposure is a substantial and growing part of this.

Numerous interesting figures from the specific data collection by UNSCEAR and from literature studies over the period 1997-2007 are given in Annex A of the 2008 report [1]. Several aspects of medical radiation are discussed in the main body of the text including the magnitude of medical exposure, the number of X-ray examinations, the doses differentiated towards different examinations and trends in time and among countries. The text has been reviewed thoroughly and a few facts have been extracted, in particular facts that contribute in situating the Belgian medical exposures and its expected future trends.

Medical exposures include both the exposure of patients as part of their medical diagnosis, the exposure of individuals as part of screening programmes and the exposure of healthy volunteers participating in research projects. All these exposures are planned and voluntary. Especially in developing countries, increasing availability of appropriate medical

procedures results in a net health benefit. Here, the availability of X-ray examinations is taken for granted. Nevertheless, the ALARA principle requires that every medical exposure has to be justified on an individual basis.

Medical exposure to radiation cannot be treated like exposure in nuclear industry or background radiation. The exposed part of the population is different with including very specific groups, such as prematurely born children, for medical reasons more frequently exposed than the average citizen. Screening is a particular case in which a well-defined fraction of a specific group without any clinical complaints is invited for an X-ray examination. Another major difference with most non-medical exposures is the fact that during an X-ray examination only part (or parts) of the body is (are) irradiated. A complicating factor for worldwide data collection and analysis is that dosimetric approaches to quantify the exposure depend on the type of X-ray examination under investigation and the type of dosimeters available. Several of these parameters have to be combined with other data to allow effective dose estimates. UNSCEAR survey questionnaires have been adjusted to this reality, and the secretary continuously improves them to obtain more representative and correct data.

2. Material, methods and results

UNSCEAR defines different categories of health care levels, based upon the number of physicians in the studied population. The four levels (I -> IV) correspond with > 1 physician/1000 inhabitants, 1 physician for 1000 to 2999 inhabitants, 1 physician for 3000 to 10000 inhabitants and less than 1 physician for 10000 people.

Figure 1 shows the distribution of the number of inhabitants per health care level as a function of time. Belgium belongs, obviously, in health care level 1, as do most of the European countries.

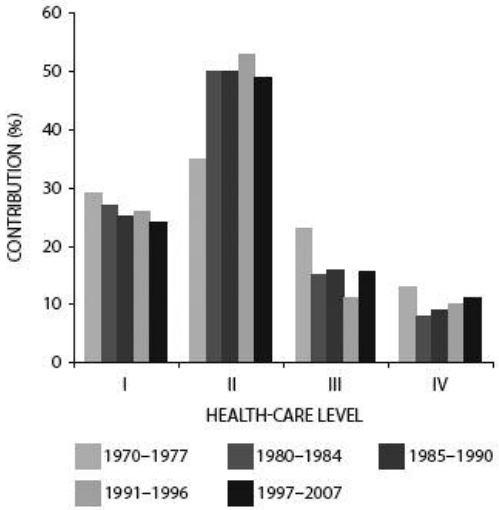

Fig 1. Population distribution across the four health care levels, from 1970-2007. Copied from the UNSCEAR 2008 report, Annex A [1].

Estimation of the population dose relies upon the number of exams and the effective dose per exam. It is further divided into diagnostic radiology, nuclear medicine and radiotherapy. Often, however, radiotherapy is not included in the analyses as doses delivered for cancer treatment scale vary differently with detriment or risk than do other exposures.

Radiological examinations are further subdivided in plain radiography, breast imaging, imaging with fluoroscopy, interventional procedures, CT and dental radiography. All these categories are then split into specific exams. Effective doses associated to these exams show a large variability.

The estimated annual collective dose to the world population (for radiology and dental exams) is 4 200 000 manSv. This is a 70% increase when compared to the values of UNSCEAR's 2000 report. The contribution of dental exposures and nuclear medicine is 11 000 manSv and 202 000 manSv respectively. Figure 2 illustrates the distribution over diagnostic radiology, dental and nuclear medicine for the different health care levels. The total sum of all effective doses divided by the number of inhabitants represents the national average of medical exposures. Belgium is among the highest, with an average of 1.8 mSv due to medical exposures. France is situated between 0.66 and 0.83 mSv, the UK around 0.33 mSv and the

USA at 3 mSv. The contribution of the different types of exams on the total medical exposure was also studied. Figure 3 shows these data for the USA; natural background accounts for 3.1 mSv. The contribution of CT is 1.5 mSv, interventional radiology 0.4 mSv and plain radiology 0.3 mSv. Analysis over time shows that the number of X-ray exams is increasing and more specifically for the higher dose exams such as CT and interventional radiology. The number of CT scanners per million population is the highest in Japan, with 92.6 scanners in 2002. In 2004, there were 31.6 CT-scanners per million inhabitants in Belgium, immediately followed by Austria, Luxembourg and Italy, with respectively 29.4, 28.6 and 27.7 scanners.

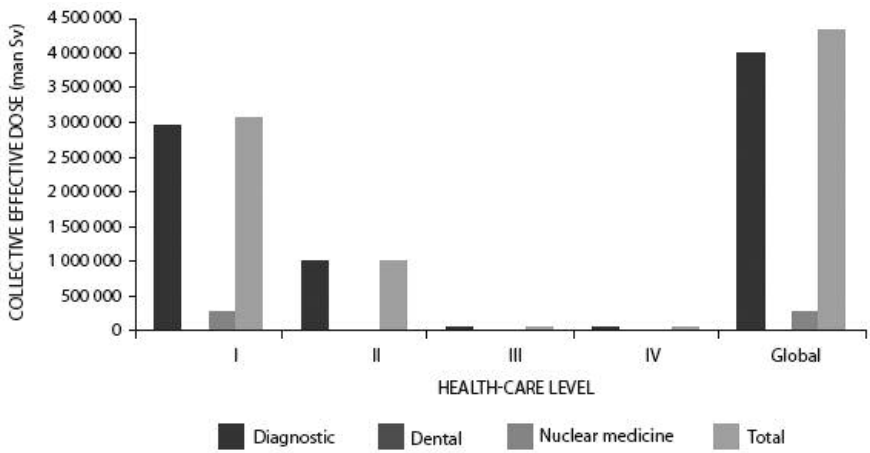

Fig 2. Annual collective effective dose (manSv) from all diagnostic exposures for each health care level and the global totals (1997-2007). Copied from the UNSCEAR 2008 report, Annex A [1].

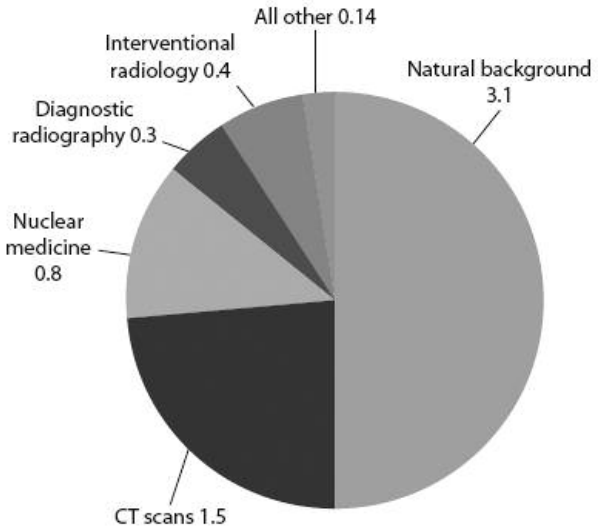

Fig 3. Per caput effective dose in the USA in 2006. Copied from the UNSCEAR 2008 report, Annex A [1].

Doses range widely among different centers. It is also agreed that especially interventional procedures are very patient specific. Literature review confirms large spread in doses. Mean effective doses for various interventional procedures in health care level 1 countries are shown in figure 4. They range from typically 5 mSv for cerebral procedures to more than 11 mSv for PTCA. Effective doses from CT are also in the mSv range.

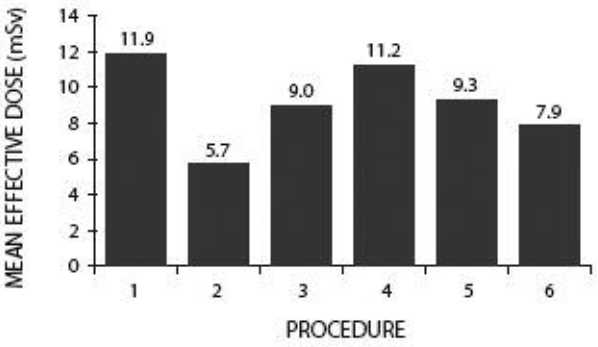

Fig 4. Mean effective doses of interventional radiology in health care level 1 countries. Copied from the UNSCEAR 2008 report, Annex A [1].

3. **Discussion**

All dose values should be considered with great caution, for several reasons.

(1) The calculation of effective dose, a necessity in order to be able to add the detriment of all examinations, is controversial. It requires conversion factors from measured values to the effective dose. These coefficients have not been standardized or may not be available for the measured quantity that has been obtained.

(2) There are not many conversion coefficients available that take into account the patient size. There is an intrinsic error related with this, as, like in other non-medical exposures, the relationship between the radiation source and effective dose for the patient largely depends on factors such as patient weight.

(3) Data collection was performed by different people and individual data points have not been controlled by UNSCEAR. Whereas some data have been published in peer reviewed journals, most of the data are not.

(4) There are several extrapolations included in all tables, as the assumption that the ratio between number of pacemakers and cardiac angiographic exams is more or less constant among countries with similar health care level. This however allows to estimate the number of cardiac angiographies if only the number of pacemakers is known.

UNSCEAR recognizes several trends and refers to Belgian scientific literature to support some of the statements.

(1) The switch from film-screen radiology to film-less digital radiology is no guarantee for lower patient dose.

(2) The spread in doses from mammography is very low. This is due to strict Quality Assurance programs in a lot of countries.

(3) Doses in interventional radiology are increasing. This is mainly due to an increasing complexity of the exams, with smaller lesions being treated percutaneously.

(4) Modern CT systems allow to scan faster, to acquire more easily large number of images, larger parts of the body and with more scan-phases per exam. More patients can be scanned per day. The power of the tube is no longer a limiting factor.

(5) Dental radiology remains a small part in terms of effective dose. The introduction of cone beam CT must be carefully supervised here as this

new modality will take over many of the panoramic exams for orthodontic planning in children.

UNSCEAR draws special attention for dose data collection in children. Although the number of pediatric exams is increasing, data collection is often insufficient for the calculation of useful percentiles or averaged doses. Similar difficulties and concerns account for fetal dosimetry.

Current Belgian data support many of the UNSCEAR statements. Generalized mammographic QA in the late 90-ies has been the trigger for the first dose surveys in our country [2]. It is an example of the effect of the implementation of European Guidelines in the regional legislation. At present screening mammography is probably most explored in terms of dose, quality and treatment results. With the support of the FANC, three projects have been performed to investigate patient doses in interventional radiology [3-6] and cardiology [7], in pediatric CT and in high dose interventional procedures [8]. This research was the trigger for more targeted investigations in the cath-lab [8-9] and on prematurely born children [10].

Our interventional procedures are indeed often associated with high effective doses and high peak skin doses. Since the 'picture of the dose levels' has now been taken, time has come for optimization and the work out of procedures for continuous patient dose monitoring. The large spread in doses suggests that large dose savings can be achieved without loss of diagnostic and/or therapeutic efficacy. The input from clinical specialists (radiologists) is essential to achieve these goals. How to get to the optimal working point requires more studies and a new project supported by the authorities. (European) Guidelines on this topic do not yet exist.

The 2007 MIRA T Milieurapport Vlaanderen [11] confirmed the increasing number of the examinations with the highest dose. CT accounted for 60.4% of the medical exposures in 2006. On most of the scanners, there are specific protocols set for pediatric exams. A recent Belgian study has shown that a 2-step procedure is required in this respect: (1) verification whether the pediatric protocols are as low as reasonably achievable for the particular scanner and (2) verification whether the protocols are being used in practice [12]. A future evolution is the monitoring of image quality.

Today, cone beam CT is being introduced in many domains to obtain 3D images (dental applications, surgery, cath lab, angiography rooms, head and neck CT, image guided radiotherapy, orthopedic 'imaging in 3D', …). This modality is often, not only commercially, presented as 'low dose CT', yet this is only correct for particular applications. Recent measurements in and around Belgium showed large variations in dose settings for the dental applications [13]. Given the potential application of cone beam CT on a growing fraction of the pediatric population, e.g. all children facing orthodontic treatment, this topic must be investigated in more detail. It could be that dental radiology will transit from a specialty with neglectable doses to a significant contributor. Application of the ALARA principle is an essential prerequisite that the somewhat higher doses are related with better medical information and treatment (evidence based).

4. Conclusion

Medical exposures represent a significant fraction of the exposure of the population and this trend is increasing also in Belgium. Application of the ALARA principle in medical exposures should focus on continuous dose monitoring, reporting and optimization of the procedures.

References

[1] Sources and effects of ionizing radiation. UNSCEAR 2008. Report to the general assembly with scientific annexes. Vol 1, Annex A: Medical Radiation Exposures.

[2] Smans K, Bosmans H, Xiao M, Carton AK, Marchal G. Towards a proposition of a diagnostic (dose) reference level for mammographic acquisitions in breast screening measurements in Belgium. Radiat Prot Dosimetry. 2005;117(1-3):321-6.

[3] Bleeser F, Hoornaert MT, Smans K, Struelens L, Buls N, Berus D, Clerinx P, Hambach L, Malchair F, Bosmans H. Diagnostic reference levels in angiography and interventional radiology: a Belgian multi-centre study. Radiat Prot Dosimetry. 2008;129(1-3):50-5.

[4] Smans K, Struelens L, Hoornaert MT, Bleeser F, Buls N, Berus D, Clerinx P, Malchair F, Vanhavere F, Bosmans H. A study of the correlation between dose area product and effective dose in vascular radiology. Radiat Prot Dosimetry. 2008;130(3):300-8.

[5] Struelens L, Hambach L, Buls N, Smans K, Malchair F, Hoornaert MT, Vanhavere F, Bosmans H. Image quality assessment using the CD-DISC phantom for vascular radiology and vascular surgery. Eur J Radiol. 2008 Aug;67(2):348-56.

[6] Clerinx P, Buls N, Bosmans H, de Mey J. Double-dosimetry algorithm for workers in interventional radiology. Radiat Prot Dosimetry. 2008;129(1-3):321-7.

[7] Bogaert E, Bacher K, Thierens H. A large-scale multicentre study in Belgium of dose area product values and effective doses in interventional cardiology using contemporary X-ray equipment. Radiat Prot Dosimetry. 2008;128(3):312-23.

[8] Struelens L, Bosmans H, Bacher K, Bleeser F, Hoornaert MT, Malchair F. How to prevent skin injuries for interventional procedures: the use of trigger levels to follow-up patient skin dose. Submitted for publication to JBR-BTR, Oct 2011.

[9] Dragusin O, Gewillig M, Desmet W, Smans K, Struelens L, Bosmans H. Radiation dose survey in a paediatric cardiac catheterisation laboratory equipped with flat-panel detectors. Radiat Prot Dosimetry. 2008;129(1-3):91-5.

[10] Bogaert E, Bacher K, Lemmens K, Carlier M, Desmet W, De Wagter X, Djian D, Hanet C, Heyndrickx G, Legrand V, Taeymans Y, Thierens H. A large-scale multicentre study of patient skin doses in interventional cardiology: dose-area product action levels and dose reference levels. Br J Radiol. 2009 Apr;82(976):303-12.

[11] Vanmarcke H. Milieurapport Vlaanderen MIRA. Achtergronddocument. Thema ioniserende straling. 2007
http://www.milieurapport.be/Upload/main/miradata/MIRA-T/02_themas/02_06/AG_ioniserende_straling.pdf

[12] Jacobs J, Marchal G, Bosmans H. Automated patient dose evaluation for pediatric CT. Annual meeting of the radiological society of North America (RSNA), Chicago, Nov 2010.

[13] Pauwels R, Beinsberger J, Collaert B, Theodorakou C, Rogers J, Walker A, Cockmartin L, Bosmans H, Jacobs R, Bogaerts R, Horner K; The SEDENTEXCT Project Consortium. Effective dose range for dental cone beam computed tomography scanners. Eur J Radiol. 2010 Dec 31.

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OVERVIEW OF INTERNATIONAL FRAMEWORKS FOR DERIVING BENCHMARKS FOR ENVIRONMENTAL PROTECTION

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1. Introduction

A framework for the protection of humans has been in existence for a very long time. Protection of the environment, however, has only recently begun to be addressed in a structured manner, and is still an evolving subject[1]. In the past, it was generally accepted that if humans were adequately protected, then "*other living things are also likely to be sufficiently protected*"[2] or "*other species are not put at risk*"[3]. This view has been questioned over the last decade, partly because of increasing world-wide interest in environmental sustainability and partly because of recognition of situations where non-human biota may be exposed but exposure to people is limited because of different occupancy, by restricted access to an area or by other protective measures.

The need for a system able to demonstrate that the environment is adequately protected from the effects of radioactive substances has been recognised by international organisations (e.g. [4]-[6]), a number of regulators (e.g. [7-9]) and the scientific community[10-13]. In part, this has been in response to new regulatory drivers, for example those associated with conservation[14]. As a result, there has been considerable international and national effort on this issue over the last decade with environmental protection now being referred to in the IAEA Fundamental Safety Principles[5] as well as in the Recommendations of ICRP[6,15].

In comparison with the protection of human beings, there is no simple or single universal definition of environmental protection. The concept differs from country to country and from one circumstance to another. Nevertheless, there is clearly a need to address the issue directly and transparently, not only to allay public concern, should it arise, but also increasingly to comply with various forms of regional and national legislation that requires that protection of the environment be explicitly demonstrated, irrespective of the protection of human beings[1].

To date, the focus has been on collating relevant information and developing assessment methodologies and more latterly comparing approaches to enable regulatory assessments[16]. The approaches need to be practicable, credible to stakeholders and fit for purpose in any regulatory context. Clearly, estimated dose rates need to be compared with some form of criteria to judge whether there is an unacceptable risk. There is thus a need for establishing protection goals, predefined dose rate values, or benchmark values to be proposed and agreed. Also, there is a need to share better knowledge on the transfer of radionuclides to biota and provide authoritative collections of the available data.

The published information on the effects on biota of ionising radiation or radionuclides in the environment[4,7,17-22] has been reviewed and a data compilation was accomplished. The methodology of derivation of the proposed benchmark, the interpretation/meaning of the benchmark, and the level of protection (individuals, populations, ecosystems) targeted, varies between the studies.

2. Protection goals

Protection goals can be set at different levels, the extremes being, on the one hand, protection of all individuals of all species and, on the other hand, maintenance of the ecosystem function generally through protection of ecological structures. Protection of individuals is commonly only used in environmental legislation for rare and endangered species. Protection of ecosystem functions may only need to focus on the most (radio)sensitive species which perform critical ecosystem functions. This approach may raise questions about our ability to identify these critical species, their dependency on other species and the ability of the environment as a whole to react against these challenges[21].

Current scientific developments in the field of radiological protection aim at designing an assessment methodology; based on a bottom-up, individual-based approach, usually referred to as the "reference organism" approach. The approach tackles the high complexity of the ecosystem by selecting a small set of representative organisms; the radiation dose to individual members of these reference organisms is then calculated and from the effects at the individual level, the effects on higher levels of organisation (e.g. population, ecosystem) are extrapolated. The approach is pragmatic in that it reduces the complexity of the ecosystem to consideration of a few representative species, chosen so that they take into account a range of environments and taking into account the availability of appropriate scientific data.

International agreements that deal with protection of the environment often refer to it in a general or holistic way. A holistic approach suggests one that considers ecosystem structure and functions. It considers the environment in an integrated manner that better reflects the actual complexity of nature. Thus such a top-down approach is to be favoured as it will address the limitations of the "reference organisms" approach whilst integrating its achievements[23].

The most commonly used approach for environmental regulation is protection at the population level. As long as the viability of the population is not threatened, it could be acceptable that individuals are affected. In this key aspect, environmental protection differs from the protection of humans. Protection of all populations will ensure ecosystem integrity. Though most existing numerical values or benchmarks are intended to protect populations, this does not mean that the values are necessarily derived from observed effects on populations or even that the whole population is assumed to be exposed at the given dose rate. Most data address measurement endpoints at the individual level. To derive numbers that are relevant at the population level, only data for measurement endpoints that are directly relevant to population dynamics should be used in approaches to derive numerical values[21]. However, most of the numerical benchmarks to protect animals and plants at the population level are derived from studies on small groups of individuals.

3. Benchmark values

In this section, the frameworks developed by different international organisations (UNSCEAR, IAEA, ICRP) or under EURATOM projects for the protection of the environment from radioactive substances are summarized and their methodology to derive and apply endpoints of protection are briefly described. There is no international agreement on numerical limits for environmental protection and how they are derived for radioactive substances. As well as being a key part of environmental risk assessment, numerical limits that define the interface between an acceptable and an unacceptable stressor level can also be used as triggers within a tiered risk assessment, or as standards.

3.1. UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation

Prior to its 1996 report and scientific annex on the *"Effects of radiation on the environment"*[4], the Committee had not specifically addressed the effects of radiation on plant and animal communities. Living organisms had been considered primarily as part of the environment, in which radionuclides are present from natural sources or from human activities, as resources that, if they take up radionuclides from their environment, might contribute to human exposures. Like man, however, organisms are themselves exposed to internal irradiation from radionuclides that have been taken up into the organism from its environment and externally to radiation in the organism's habitat.

The UNSCEAR 1996 report[4] reviewed and summarized information onexposures of organisms in their natural habitats to the natural radiation background, to radionuclides released into the environment in a controlled manner from industrial activities, and to radionuclides released as a consequence of accidents. It also reviewed information on the responses to acute and chronic irradiation of plants and terrestrial and aquatic animals. In general terms, the Committee considered that population level effects were of primary interest and of those, that reproductive effects were the most sensitive indicator. UNSCEAR considered as effect endpoints mortality, fertility, fecundity, vigour and chromosome damage.

UNSCEAR suggested that "*Chronic dose rates $<400\ \mu Gy\ h^{-1}$ would have effects, although slight, in sensitive plants but would be unlikely to have significant deleterious effects in the wider range of plants present in natural*

plant communities". For the most sensitive animal species, mammals, there is little indication that dose rates of 400 μGy h^{-1} to the most exposed individual would seriously affect mortality. For dose rates up to an order of magnitude less (40-100 μGy h^{-1}), the same statement could be made with respect to reproductive effects. For aquatic organisms, maximum dose rates of 400 μGy h^{-1} to a small proportion of the individuals, and, therefore, a lower average dose rate to the remaining organisms would not have any detrimental effects at the population level. The Committee hence concluded that it was unlikely that radiation exposures causing only minor effects in the most exposed individual would have significant effects at the population level.

The UNSCEAR 2008 report[17] reviewed additional effects information obtained following its 1996 review which included a review of effects literature from the Chernobyl accident. The more important conclusions from the Chernobyl effects data were the following. Numerous acute adverse effects were observed in the biota located in areas of higher exposure (up to few tens of km from the release point) and both individual and population effects were found caused by radiation-induced cell death observed in plants and animals. These effects were: increased mortality of coniferous plants, soil invertebrates and mammals; reproductive losses in plants and animals; chronic radiation sickness of animals (mammals, birds, etc.). Beyond the exclusion zone, no acute radiation-induced effects on biota were reported. No adverse radiation effect were reported in plants and animals exposed to a cumulative dose <0.3 Gy during the first month after accident (i.e. <10 mGy d^{-1}). By the next growing season following the accident, population viability of plants and animals substantially recovered as a result of the combined effects of reproduction and immigration. A few years were needed for recovery from major radiation induced adverse effects in plants and animals.

Considering scientific information developed since 1996, the UNSCEAR 2008 report[17] concluded that: "*...chronic dose rates of less than 100 μGy h^{-1} to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities and that maximum dose rates of 400 μGy h^{-1} to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level"*. These conclusions refer to the effects of low-LET radiation. Where a significant part of the incremental radiation exposure

came from high-LET radiation (alpha particles), the Committee concluded that it was "*necessary to take account of the different relative biological effectiveness of the radiations*".

These benchmarks are derived following a literature review and expert judgement on selection of scientific studies and assignment of protection limits. There is no information on which criteria were used to select effects data, on how the benchmarks are derived from the available data and on how they compare to them and what the degree of conservatism is. There is limited transparency on how the benchmarks were derived from the collected data and it is not so clear how these benchmarks may be applied in a regulatory context.

3.2. IAEA - International Atomic Energy Agency

The IAEA has a long history of engagement with the topic of the protection of biota from ionising radiation[19, 24]. One of the objectives of the IAEA Technical Report Series No. 332[19] was to determine whether or not radiation protection standards for aquatic and terrestrial biota are warranted. The report dealt primarily with potential effects on natural plant and animal populations exposed to routine, chronic releases of radionuclides that are controlled to limit exposure of humans in compliance with specified safety standards. Accidental releases and releases to areas where human access would be controlled were not specifically considered. The IAEA report specifically evaluated situations in which environmental releases are limited to levels that protect the most highly exposed humans. The biota of the natural environment share the same environment as the most exposed humans.

IAEA[19] evaluated data related to terrestrial plants, mammals, birds, reptiles, amphibians, and invertebrates. The objective of the data review was to identify acute doses and chronic dose rates "*below which the likelihood of observing population level effects is remote*". Effects on mortality, fertility, fecundity, growth rate, vigour and mutation rate were included in their consideration of data. A detailed evaluation of data relating to effects of ionizing radiation on aquatic biota was not performed because the IAEA believed that the existing comprehensive reviews of these data were adequate (e.g. [25]). They concluded that irradiation at chronic dose rates of 1 mGy d^{-1} (40 μGy h^{-1}) to even the most radiosensitive species does not appear likely to cause observable changes in terrestrial animal

populations. IAEA found that reproduction is likely the most sensitive radiological marker. Sensitivity varies markedly among different taxa; certain mammals, birds, reptiles, and a few tree species appear to be most sensitive. For invertebrates, it was concluded that indirect responses caused by radiation-induced changes in vegetation appear to be more critical than direct effects of radiation on the organisms themselves. For aquatic biota, they found that a chronic dose rate of 10 mGy d^{-1} (400 μGy h^{-1}) would be unlikely to adversely affect populations.

The approach to derive numerical benchmarks is largely based on 'expert judgement'. There is no information on which criteria were used to select effects data, on how the benchmarks are derived from the available data and on how they compare to them and what the degree of conservatism is. The derived benchmarks do not explicitly refer to the whole population. Statements as "*It would appear that there are unlikely to be any detrimental long-term effects on plant communities in which the maximum dose rate is in the order of 400 μGy h^{-1} or less*"; "*Chronic dose rates of 40 μGy h^{-1} or less do not appear likely to cause observable changes in terrestrial animal populations*", "*Limitation of the dose rate to the maximally exposed individuals in the population to <400 μGy h^{-1} would provide adequate protection of the population*" are little transparent in respect of how some of these benchmarks may be applied. Furthermore, such statements are not consistent between the biota categories. These radiological protection guidelines seem to be based on the assumption that populations of organisms possess compensatory capabilities, such that impacts on a few individuals should not affect the integrity of a population or community[26]. It is, presumably, assumed that the dose rate to the general population is less than to the specified more highly exposed individuals. However, it is unclear how much less the typical dose rate in the population should be to conclude that the population is protected. NCRP[18] stated that such guidelines must be used carefully if substantial proportions of the population are exposed.

3.3. ICRP – International Commission on Radiation Protection

In the absence of any clear definition of environmental protection, the ICRP has adopted the overarching aim of preventing or reducing the frequency of deleterious effects of radiation to a level where they would have a negligible impact on the maintenance of biological diversity, the

conservation of species, or the health and status of natural habitats, communities and ecosystems. The achievement of such aims implies the need to protect animals and plants at the population level[1].

The ICRP position on the protection of the environment has slowly changed over the last decades: ICRP[2] stated: "*Although the principle objective of radiation protection is the achievement and maintenance of appropriately safe conditions for activities involving human exposure, the level of safety required for the protection of all human individuals is thought likely to be adequate to protect other species although not necessarily individual members of those species. The Commission therefore believes that if man is adequately protected then other living things are also likely to be sufficiently protected."* In 1991, ICRP[3] added a clarification of the original statement *"Occasionally, individual members of non-human species might be harmed but not to the extent of endangering whole species or creating imbalance between species*." In 2003, ICRP[27] writes "*...ICRP therefore needs to revise its current system of protection, and particularly, develop a comprehensive approach to the study of the effects on, and protection of, all living matter with respect to the effects of ionising radiation…*". Here, ICRP suggests a framework, based on scientific and ethical-philosophical principles, by which a policy for the protection of non-human species could be achieved.

ICRP[15] has recently issued a report on protection of the environment, considering that numerical guidance should be based on a sound scientific system similar to that which had been developed for human protection. Therefore, the ICRP suggests an approach based on a (small) set of Reference Animals and Plants (RAPS) whereby the reference organisms are intended to be representative of the range of habitat occupancies, radionuclide uptake behaviours, and sizes and shapes (affecting dosimetric calculation) characterising a real ecosystem.

The ICRP suggests that, in considering the potential effect of ionizing radiation, context should be provided by comparing estimated dose rates to the dose-rates experienced by the various biota in their natural environment. In this regard, the ICRP proposed Derived Consideration Levels Reference Levels (DCRLs) intended to serve as points of reference for assessing the potential effects of ionizing radiation on non-human biota. A DCRL can be considered as a band of dose rates within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals

of the Reference Animal or Plant. The DCRL can be used as a point of reference to optimise the level of effort expended on environmental protection, dependent upon the overall management objectives and the exposure situation. For deriving those DCRL, the ICRP compiled available information for various biota categories. The endpoints considered were mortality, morbidity, reproduction (fertility, fecundity) as well as DNA damage (chromosome aberrations and mutations). Data are summarized into bands of dose rates from less than 0.1 mGy d^{-1} (4 μGy h^{-1}) to more than 100 mGy d^{-1} (4000 μGy h^{-1}) covering the level where the dose rates compel a more detailed evaluation of the situation.

The range of dose rates for various biota categories summarized by ICRP is defined as follows:

1- For 'higher vertebrates' (reference mammals: deer and rat), it was suggested that at dose rates in the region of 4-40 μGy h^{-1}there was only a very low probability of certain effects occurring that could result in reduced reproductive success or morbidity. At the band below that range (0.4-4 μGy h^{-1}), such effects have not been observed;

2- For birds (reference bird = duck), there was no information available in either of these band and the ICRP suggested that based on metabolism, longevity, and reproductive behaviour, it was reasonable to assume that the dose rate band of 4-40 μGy h^{-1} would similarly serve as sensible level of DCRL;

3- For the 'lower' poikilothermic vertebrates (reference organisms: frog, trout and flatfish), data are generally lacking below about 40 μGy h^{-1}. Though considering the general lack of physiological data on amphibians, the ICRP suggested a lower DCRL dose rate band of 40-400 μGy h^{-1} for frogs as for the two types of fish. For such dose rates, the ICRP suggested a possible reduction in reproductive success in the fish species, while no positive "effect" information could be retrieved for frogs;

4- For invertebrates (reference organisms: bee, crab, earthworm), ICRP indicated again a complete lack of data, but suggested that invertebrates are less sensitive and recommended a DCRL of 400-4000 μGy h^{-1}.

5- For trees, plants and seaweeds (reference organisms: pine tree, wild grass and brown seaweed), the data are highly variable across species with the best data for pine trees. The ICRP suggested DCRLs of 400-4000 μGy h^{-1} for seaweeds with potential effects on growth rate and

reproductive success. A 10 times lower value was suggested for wild grass, and the lowest DCRL of 4-40 μGy h^{-1} was suggested for pine trees, which they attribute in part to the potential for very long periods of exposure.

For the derivation of DCRLs, expert judgement was used. ICRP recognizes that this derivation was based on "*informed opinion and not on statistically derived, or rigorously reviewed analysis of all the available data*". The ICRP report stated that "*The DCRLs are not intended to be regarded as dose limits, or 'substitute' values for them. They are zones of dose rates at which, with respect to the Reference Animals and Plants, or similar types, a more considered level of evaluation of the situation is warranted."* The ICRP report intends to provide high-level guidance and advice, and the Commission recommends the development of applied and specific numerical approaches by national and other bodies.

3.4. EURATOM

3.4.1. EC-ERICA - Environmental Risks from Ionizing Contaminants Assessment and Management

The EC-FASSET (Framework for Assessment of Environmental Impact)[28] started in 2000. Its objective was to develop a framework for the assessment of environmental impact of ionising radiation in European ecosystems. The FASSET project developed a database (FASSET Radiation Effects Database – FRED) on radiation effects on non-human biota under four broad effects categories, referred to by FASSET as 'umbrella effects'. These included: (1) morbidity (including growth rate, effects on the immune system, and the behavioural consequences of damage to the central nervous system from radiation exposure of the developing embryo); (2) mortality (including stochastic effect of somatic mutation and its possible consequence for cancer induction, as well as deterministic effects in particular tissues or organs that would change the age-dependent death rate); (3) reproductive success (including fertility and fecundity); (4) mutation (induced in germ and somatic cells). An overall summary of the effects due to chronic exposure on plants, fish and mammals identified by FASSET was reported by Real et al.[29] for the different endpoint classifications (morbidity, mortality, reproductive capacity and mutation). The authors concluded that for chronic exposure conditions "*the reviewed effects data give few indications for readily observable effects at dose rates*

below 100 μGy h^{-1}". However, it was advised that "using this information for establishing environmentally 'safe levels' of radiation should be done with caution, considering that the database contains large data gaps for environmentally relevant dose rates and ecologically important wildlife groups"[13].

The EC-ERICA (Environmental Risks from Ionizing Contaminants Assessment and Management) project, the successor to the EC-FASSET project, expanded the FASSET effects database and carried out extensive quality assurance to produce an expanded effects database (referred to as FREDERICA)[30].

The EC-ERICA project (Environmental Risks from Ionizing Contaminants Assessment and Management) has derived screening values for environmental protection[20]. The approach followed by ERICA to derive screening values is similar to what is applicable for chemicals[31]. The screening value proposed by ERICA is supposed to screen out situations of no regulatory concern. A screening value of 10 μGy h^{-1} incremental dose rate to be applied for all ecosystems and all organisms is suggested by ERICA. This screening value was derived on the basis of data taken from the FREDERICA database[30] using a Species Sensitivity Distribution (SSD) approach. A three-step methodology was used[20]. Firstly, a coherent data sub-set was extracted from each experiment, covering endpoints related to mortality (including stochastic effects like cancer formation and deterministic effects which altered mortality and life expectancy), morbidity (including growth, effects on the immune system, effects on behaviour) and reproduction (including fertility, fecundity and embryo development). Secondly, a systematic mathematical treatment was applied to reconstruct dose (rate) - effect relationships and to estimate critical toxicity endpoints. For chronic exposure, the critical toxicity endpoint is the estimated Effective Dose Rate (EDR_{10}), that is the 'Effect Dose Rate' (expressed in μGy h^{-1}) giving rise to a 10 % change in observed effect. Thirdly, these estimated critical toxicity data are used to derive a Predicted No-Effect Dose Rate (PNEDR) using the SSD method which is defined as the hazardous dose rate affecting 5 % of the species (HDR_5). For chronic exposures, there was no difference between the radiosensitivity of species from marine (SW), freshwater (FW) and terrestrial (TER) ecosystems, which allowed the construction of a unique SSD for generic ecosystems (SW+FW+TER) chronically exposed to external gamma irradiation.

ERICA established that, for chronic exposure situations, the HDR_5 and associated 95 % confidence interval were 81.8 μGy h^{-1} [range = 23.8 – 336 μGy h^{-1}]. To derive the screening value, an assessment factor (AF) of 5 was applied to maintain a high degree of conservatism as required for the screening assessments. Rounding down the value and expressing it with one significant digit resulted in a chronic exposure screening value for incremental exposure of 10 μGy h^{-1} for all ecosystems (Figure 1).

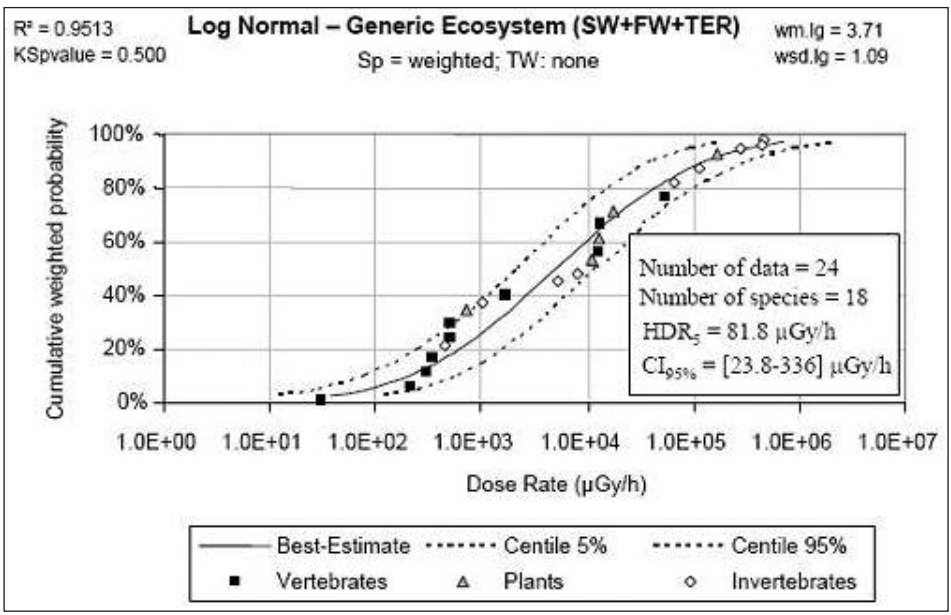

Figure 1. SSDs for generic ecosystems (FW+SW+TER) and chronic external gamma irradiation exposure conditions. The log normal distribution with its associated 95 % confidence interval is fitted to geometric means per effect category for each species calculated on critical ecotoxicity data (EDR_{10}). The trophic-level weight reflects the trophic diversity of the primary data sets (after[20]*).*

Several stages of the derivation of this benchmark required expert judgement, but these decisions were documented and there was transparency throughout the process. The generic screening value of 10 μGy h^{-1} derived by ERICA is considered protective of the structure of generic ecosystems (including all organism groups), whereas in the other approaches different dose rate values are assigned to different organism groups. At the ecosystem level, the ERICA Integrated Approach screening

dose rate value lies in the dose range giving rise to minor effects[13,20]. The authors suggest such effects are not expected to be directly relevant at higher organizational levels, such as the structure and functioning of ecosystems.

The ERICA benchmark is defined to be used only as screening dose rate (for use in lower assessment tiers (see further)) applicable to incremental (above background) exposures. The use of this value is to screen out situations of no regulatory concern.

The ERICA Environmental Risk Assessment approach is a tiered approach that requires risk assessment benchmark values for risk characterisation within Tiers 1 and 2. These benchmark values guide the environmental assessment at various decision points in the tiered approach.

3.4.2. EC-PROTECT - Protection of the Environment from Ionising Radiation in a Regulatory Context

The EC-project PROTECT (Protection of the Environment from Ionising Radiation in a Regulatory Context)[32], a follow up project of ERICA, used a similar approach for the derivation of a screening value. The derivation of the benchmark under PROTECT followed a three-step approach:

(1) as starting point, a compilation of quality assessed exposure-effects data using the FREDERICA database[30] was made. Only data from papers considering chronic exposures and for which it was possible to derive the Effective Dose Rate resulting in 10 % effect (EDR_{10}) values were included. The approach was similar to that of Garnier-Laplace and Gilbin[20] except that there were more data in the FREDERICA database and that also hormetic effects were considered.

(2) In a second step the critical ecotoxicity values were estimated by derivation of the EDR_{10} from the dose rate-effect curves.

(3) Finally, the EDR_{10} values are used to derive the HDR_5 (Hazardous Dose Rate giving 10% effect to 5% of species) by applying the SSD method. The predicted no effect dose rate (PNEDR) is then obtained by applying a relevant assessment factor to the HDR_5 to account for any residual uncertainties (e.g. lack of data for certain taxa or endpoints).

PROTECT addressed several considerations during this third step which may have a direct and potentially considerable influence on the final benchmark value, such as the selection of data to include in the SSD, the precise methodology of fitting a distribution to these data, and the value of

the assessment factor applied to the HDR_5. In this section, only the issue of data selection is treated in some detail. As the goal is to protect populations from ionising radiation, the selection of which EDR_{10} should be included in the SSD needs to consider each endpoint's relevance for population sustainability. The approach used within PROTECT was to select the most sensitive (lowest EDR_{10}) endpoint for any given species; cytogenetic endpoints were not considered to be relevant to population sustainability. Reproduction endpoints were most often amongst the more sensitive and are generally accepted as being population relevant. 20 EDR_{10} values were obtained, comprising 4 plants, 2 annelids, 3 crustaceans, 2 molluscs, 2, birds, 4 fish and 3 mammals. As the EU Technical Guidance Document (TGD) for risk assessment[31] does not give guidance on the assessment factor to be applied to the derived HDR_5 value in order to estimate a PNEDR value (other than specifying a range of 1-5), PROTECT used their own selection criteria and considered an assessment factor of 2. The resulting generic HDR_5, when all 20 EDR_{10} values are used to produce a generic SSD as described above, is 17 μGy h^{-1}. The application of an assessment factor of 2 results in a generic screening value of 10 μGy h^{-1}, same as for ERICA. This screening value is supposed to screen out situations of no regulatory concern and pose no potential detrimental impact on all ecosystems.

In many cases, the most exposed species may not necessarily be the most sensitive. Because a generic screening value is applied to all species, its use may result in either: (i) overly conservative assessments which lead to more detailed site-specific assessments which may not be scientifically justified; or (ii) assessments which do not identify the need for more detailed consideration of the more radiosensitive organism groups. Different organism group screening values may, therefore, be more appropriate than a single generic value. Within PROTECT, consideration was therefore given to deriving values for three broad organism categories, namely plants, vertebrates and invertebrates recognising that these groups each contain organisms which are likely to have a range of radiosensitivities. The estimated screening values were:

(i) vertebrates 2 μGy h^{-1};
(ii) plants 70 μGy h^{-1};
(iii) invertebrates 200 μGy h^{-1}. The vertebrate and invertebrate values were generated using the SSD methodology whereas, because of fewer

available data, the plant value was generated using the assessment factor approach. Taking into account the limited data and uncertainty associated with these estimates, they should be considered as illustrative and indicative of the order of magnitude of values only. The organism group values are broadly compatible with the lower end of the derived consideration reference level (DCRL) band for comparable organisms as proposed in the ICRP[15] Report. The conceptual difference between the types of screening value is that the generic value should protect 95 % of all species whereas the organism specific values should protect 95 % of species within each organism group.

While using a screening value is helpful in identifying if further environmental assessment is required (or not), problems may arise when a refined exposure assessment has been completed but the calculated dose rates remain above the screening value. In these circumstances, it cannot easily be stated with confidence that there will be negligible or no impact on biota. Currently there is limited advice on what should be done if the screening value is exceeded. PROTECT further elaborated on the issue of a second, higher, benchmark which identifies, for example, when the risk of impact is 'significant' or 'severe'. This could aid decision making by highlighting where, on the scale of no effect to significant effect, the calculated dose rate is. Although it was not possible to reach consensus on the need for this second benchmark, PROTECT explored potential approaches which could be used to provide the scientific input to help determine such a level.

3.5. Comparison of benchmarks

Table 1 gives an overview of the numerical benchmarks discussed above. The numbers are difficult to compare as they are stated to be indicative for different organism groups and inherently have different protection goals. The ERICA and PROTECT generic screening values are intended to protect entire generic ecosystems (all organism groups) whereas the ICRP approach suggests values for smaller groups such as fish. Some of the values suggested by IAEA and UNSCEAR refer to the most exposed individual rather than the population as a whole. Also ICRP[15] states that " *Care should be taken in using such values* (DCRL) *to make decisions with*

regard to populations of animals and plants, as opposed to small groups of individuals."

The lowest dose rates quoted by each approach are broadly comparable: 4-40, 10, and 40 μGy h^{-1} as suggested by ICRP, ERICA/PROTECT and IAEA/UNSCEAR, respectively. However, the different approaches do not indicate similar organism groups as being the most radiosensitive and the protective dose rates for similar organism groups differ between the approaches.

Table 1: Overview of the numerical benchmarks for environmental protection proposed by international organisations and projects or national authorities. Dose rates in μGy h^{-1}.

	UNSCEAR 1996-2008	IAEA 1992	ICRP 2008	ERICA 2006	PROTECT 2008
Terrestrial					10
Plants	400	400		10	70
Reference Pine tree			4-40		
Reference Wild grass			40-400		
Animals	40	40		10	
Mammals					2
Reference Deer			4-40		
Reference Rat			4-40		
Birds					2
Reference Duck			4-40		
Invertebrates					200
Reference Bee			400-4000		
Reference Earthworm			400-4000		
Aquatic	400	400		10	10
Freshwater organisms					
Macrophytes					200
Algae					200
Benthic invertebrates					200
Reference Frog			40-400		
Fish					2
Reference Trout			40-400	10	
Marine organisms					
Reference Brown Seaweed			400-4000		
Reference Crab			400-4000		
Reference Flatfish			40-400		

Since the publication of the reports mentioned above, a great deal of additional work has been done to investigate and improve data and methods for evaluating pathways through which biota are exposed to radiation and there have been many improvements in dose assessment methods. Many

opportunities remain for improving current understanding and methods. An improved understanding of such aspects will improve the overall understanding of the relationship between levels of radiation in the environment and the potential effects on biota [24]. Appropriate field and laboratory studies will also furnish the required data to propose more robust benchmarks. Under the IAEA-EMRAS II Biota transfer and Effects Working groups, for example, transfer factors to non-human biota are collected and assembled to allow for improved assessments of biota exposures. Furthermore, recent dose-effects data are being introduced in the FREDERICA database. Including the new data that passed the QA/QC procedure did not result in an altered ecosystem benchmark. Only the organism group specific benchmark for plants changed from 70 to 120 μGy h^{-1}.

4. Conclusions

It is clear that at the moment, there is not one general system for protection of the environment from ionising radiation and that there is no complete and comprehensive set of data and methodologies available to carry out an impact assessment of a radioactive waste disposal on the environment. Significant knowledge gaps exist regarding the radionuclide uptake by biota and radiation effects on biota, especially in the case of chronic exposure. There is therefore a clear need for effects research and assessment for realistic, chronic low dose exposure conditions emphasizing population level effects in order to be able to derived robust benchmarks protective of populations and ecosystems.

5. References

[1] Pentreath; R.J., 2009. Radioecology, radiobiology, and radiological protection: frameworks and fractures, Journal of Environmental Radioactivity 100, pp. 1019-1026.

[2] ICRP - International Commission on Radiological Protection, 1977. Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Annals of the ICRP Vol. 1 No. 3.

[3] ICRP - International Commission on Radiological Protection, 1991. Recommendations of the International Commission on Radiological Protection. Publication 60. Annals of the ICRP 21. Oxford Pergamon Press (Oxford)

[4] UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation, 1996. Sources and effects of ionizing radiation. Report to the General Assembly, with scientific annex. United Nations sales publication E.96.IX.3. United Nations, New York, 1996.Fifty-first Session, Supplement N° 46 (A/51/46).

[5] IAEA - International Atomic Energy Agency, 2006. Fundamental safety principles – Safety Fundamentals, IAEA Safety Standards No. SF-1, IAEA, Vienna, November 2006.

[6] ICRP - International Commission on Radiological Protection, 2007. Recommendations of the ICRP, ICRP Publication 103, Annals of the ICRP Vol. 37, No. 2-4.

[7] Environment Canada/Health Canada, 2003. Second priority substances list assessment report (PSL2). Releases of radionuclides from nuclear facilities (Impact on non-human biota). Environment Canada and Health Canada, Ottawa.

[8] US-DOE - United States Department of Energy, 2002. A graded approach for evaluating radiation doses to aquatic and terrestrial biota, Technical Standard DOE-STD-1153-2002, Washington DC.

[9] Copplestone D., Bielby S., Jones S.R., Patton D., Daniel P. and Gize I. 2001. Impact assessment of ionising radiation on wildlife, Environment Agency R&D Publication 128, 222 pp, updated March 2003, ISBN: 1 85705590 X.

[10] Pentreath R.J. and Woodhead D.S., 2001. A System for Protecting the Environment from Ionising Radiation: Selecting Reference Fauna and Flora, and the Possible Dose Models and Environmental Geometries that Could be Applied to Them. The Science of the Total Environment, 277(1- 3), 33-43.

[11] IUR - International Union of Radioecology, 2002. Protection of the environment – Current status and future work, IUR Report 03, Osteras, Norway.

[12] Bréchignac F., Polikarpov G, Oughton DH, Hunter G, Alexakhin R, Zhu YG, Hilton J, Strand P, 2003. Protection of the environment in the 21st century: radiation protection of the biosphere including humankind - Statement of the International Union of Radioecology, Journal of Environmental Radioactivity, 70 (3): 155-159.

[13] Woodhead D. and Zinger, I., 2003. Framework for Assessment of Environmental Impact (FASSET). Deliverable 4: Radiation effects on plants and animals (D. Woodhead and I. Zinger, eds.).

[14] Copplestone D., Wood M.D., Bielby S., Jones S.R., Vives J. and Beresford N.A. 2003. Habitat regulations for Stage 3 assessments: radioactive substances authorizations, Environment Agency R & D Technical Report P3-101/SP1a, 100pp.

[15] ICRP - International Commission on Radiological Protection, 2008. Environmental protection: the concept and use of reference animals and plants. ICRP-108. Volume 38, Issues 4-6, 1-242.

[16] Vives i Battle J., Barnett C.L., Beaugelin-Seiller K., Beresford N.A, Copplestone D., J. Horyna D., Hosseini A., Johansen M., Kamboj S., Keum D.-K., Newsome L., Olyslaegers G., Vandenhove H., Vives Lynch S., Wood M., 2011. Absorbed dose conversion coefficients for non-human biota: an extended inter-comparison of data, Radiation and Environmental Biophysics 50(2), pp. 231-251.

[17] UNSCEAR - United Nations Scientific Committee on the Effects of Atomic Radiation, 2008. Effects of ionizing radiation on non-human biota, Fifty-sixth session, Vienna, 10 to 18 July 2008, A/AC.82/R.672, pp. 134.

[18] NCRP - National Commission on Radiological Protection. 1991, Effects of ionising radiation on aquatic organisms. NCRP Report 109, Bethesda, MD, USA.

[19] IAEA - International Atomic Energy Agency, 1992. Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards, Technical Reports Series No. 332

[20] Garnier-Laplace J. and Gilbin R. (Eds), 2006. Derivation of Predicted No Effect Dose Rate values for ecosystems (and their sub-organisational levels) exposed to radioactive substances, Deliverable D5, European Commission, 6th Framework, Contract N°FI6RCT-2003-508847.

[21] Andersson P., Garnier-Laplace J., Beresford N.A., Copplestone D., Howard B.J., Howe P., Oughton D.H. and Whitehouse P. 2009. Protection of the Environment from ionising radiation in a regulatory context (protect): proposed numerical benchmark values. Journal of Environmental Radioactivity, 100, 1100-1108.

[22] Howard B.J., Beresford N.A., Andersson P., Brown J.E., Copplestone D., Beaugelin-Seiller K., Garnier-Laplace J., Howe P.D., Oughton D., Whitehouse P. 2010. Protection of the environment from ionising radiation in a regulatory context-an overview of the PROTECT coordinated action project, Journal of Radiological Protection, 30 (2), 195-214.

[23] NEA - Nuclear Energy Agency, 2007. Scientific issues and emerging challenges for radiological protection – Report of the expert group on the implications of radiological protection science, NEA No. 6167, Organisation for Economic Co-operation and Development, OECD/NEA, Paris.

[24] IAEA - International Atomic Energy Agency, 1988. Assessing the impact of deep sea disposal of low level radioactive waste on living resources. International Atomic Energy Agency, Technical Report Series Nº 288

[25] IAEA - International Atomic Energy Agency, 1979. Methodology for Assessing Impacts of Radioactivity in Aquatic Ecosystems. IAEATechnical Reports Series No. 190, IAEA, Vienna.

[26] Barnthouse, L.W., 1997. Extrapolating ecological risks of ionizing radiation from individuals to populations to ecosystems. In: Symposium on Radiological Impacts from Nuclear Facilities on Non-Human Species, Ottawa, Ontario, December 1–2, 1996. Canadian Nuclear Society, Toronto, Ontario. pp 53–60.

[27] ICRP - International Commission on Radiological Protection, 2003. A Framework for Assessing the Impact of Ionising Radiation on Non-human Species, Annals of the ICRP 33:3.

[28] FASSET - Framework for Assessment of Environmental Impact, 2004. Framework for assessment of environmental impact of ionising radiation in major European ecosystems. Deliverable 6. Euratom, Contract N°FIGE-CT-2000-00102, EC 5th Framework Programme, Larsson CM (Eds).

[29] Real A., Sundell-Bergman S., Knowles J.F.et al., 2004. Effects of ionising radiation exposure on plants, fish and mammals: relevant data for environmental radiation protection. Journal of Radiological Protection, 24(4A), 123-137.

[30] Copplestone D., Hingston J. and Real A. 2008. The development and purpose of the FREDERICA radiation effects database. Journal of Environmental Radioactivity, 99, 1456-1463.

[31] European Chemicals Bureau, 2003. Technical Guidance Document in Support of the Commission Directive 93/67/EEC on Risk assessment for new notified substances, Commission Regulation (EC) N° 1488/94 on Risk assessment for existing substances, Directive 98/8/EC of the European Parliament and of the Council concerning the placing of biocidal products on the market. Part II. EUR 20418 EN/2. Office for Official Publication of the European Communities, Luxemburg.

[32] Andersson P., Beaugelin-Seiller K., Beresford N.A., Copplestone D., Della Vedova C., Garnier-Laplace J., Howard B.J., Howe P. and Oughton D.H. 2008. Numerical benchmarks for protecting biota against radiation in the environment: proposed levels and underlying reasoning, Deliverable 5B (draft) of the EC EURATOM PROTECT project (Contract Number: 036425 (FI6R)).

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Annex B of the UNSCEAR 2008 report

EXPOSURES OF THE PUBLIC AND WORKERS FROM VARIOUS SOURCES OF RADIATION

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Abstract

The dose estimates from natural radiation sources in the UNSCEAR 2008 report are unchanged from those of the 2000 report. The worldwide average effective dose is estimated at 2.4 mSv per year, with radon accounting for about half of the exposure.

Occupational exposures in nuclear power plants have decreased by about a factor of 4 from the late 70s to the early 2000s. The collective effective dose of the workers at the nuclear power station of Doel in the period 2000-2002 was 0.5 manSv/GWy, much lower than the worldwide average for pressurized water reactors over the same period of 2.2 manSv/GWy.

The public exposure to the various stages of the nuclear fuel cycle is assessed per unit of electrical energy generated. The collective effective dose for local and regional population groups is estimated at 0.72 manSv/GWy. Using this coefficient, with an average of 278 GW per year produced in the 1998-2002 period, an annual collective dose of about 200 manSv is estimated for all operations related to nuclear energy production. Nuclear accidents are the biggest threat, but these small risks with far-reaching consequences are not included in the UNSCEAR figures.

Attention on occupational exposure focused until the 1990s on artificial sources of radiation. Now however it is realized that a very large number of workers are occupationally exposed to enhanced natural sources of radiation and the current estimate of their collective dose is about 3 times higher compared to that of the UNSCEAR 2000 report. The total number of workers exposed to ionizing radiation is estimated to be about 22.8 million, about 13 million exposed to natural sources of radiation and about 9.8 million exposed to artificial sources of radiation; 75% of them are medical workers.

1. Introduction

The publication of annex B "Exposures of the public and workers from various sources of radiation", which is part of volume I of the UNSCEAR 2008 report, has been delayed because of funding and staffing problems at the UNSCEAR secretariat until 20 July 2010 [1].
There is not enough time to discuss the 245 pages and 31 excel tables of the comprehensive annex in detail. In my presentation, I will keep to the structure of the annex and present some highlights of the report.

2. Natural radiation sources

The UNSCEAR 2008 values for the average doses and ranges of exposure from natural sources are summarized in table 1. The values are unchanged from those of the UNSCEAR 2000 report [2]. The worldwide average effective dose is estimated at 2.4 mSv/y and is equally divided among the natural background radiation and the inhalation of radon decay products. The typical ranges are rounded off to 1 mSv/y for cosmic radiation, ingestion and external terrestrial radiation (soil and buildings) and to 10 mSv/y for exposure to radon decay products.

Table 1. Population exposure to natural sources of ionizing radiation from the UNSCEAR 2008 report [1] (*the average dose in Belgium in italic and within brackets* [3]).

Natural source of exposure	**Average dose (mSv/y)**	**Typical range (mSv/y)**	**Comments**
Inhalation (radon)	1.26 *(1.45)*	0.2 - 10	Much higher in some dwellings
Soil and buildings	0.48 *(0.4)*	0.3 - 1	Dose is higher in some locations
Ingestion	0.29 *(0.3)*	0.2 - 1	
Cosmic radiation	0.39 *(0.35)*	0.3 - 1	Dose increases with altitude
Total	2.4 *(2.5)*	1 - 13	Sizeable population groups receive 10 to 20 mSv/y

3.1. Cosmic radiation

Cosmic radiation is an important component of natural background radiation. It is caused by a continuous stream of energetic particles hitting

the upper atmosphere. High-energy cosmic rays come from outside the solar system, while some relatively low energy cosmic rays originate in the Sun.

Cosmic radiation may broadly be divided into two categories, primary and secondary. The primary radiation consists of particles, mainly protons that reach the earth, but not the earth's surface because they are blocked by the atmosphere. Their interactions in the upper atmosphere create secondary radiation that can reach the earth's surface. The dose rate from cosmic radiation is a function of both altitude and geomagnetic latitude.

The cosmic ray interactions also produce a range of radioactive nuclides known as cosmogenic radionuclides. The most important are carbon-14 and tritium.

Cosmic-ray exposure approximately doubles with every 1500 m of altitude. The exposure at flight altitude is about 100 times greater than at sea level. The dose rate at an altitude of 11 km is at the magnetic poles about 6 μSv/h, two to three times higher than for the equatorial region. The most intense solar flares *(huge explosions that occur on the sun)* can significantly increase the cosmic radiation at flight altitude for several hours. Fortunately they are rare phenomenon.

The two components of the external exposure to cosmic radiation in Belgium at sea level are:

- photons and the directly ionizing component: 32 nSv/h *(1.02)*;
- the neutron component: 9 nSv/h *(1.1)*.

(As Belgium is a country near sea level, the altitude correction *(in italic and within brackets)* is small).

This results in a total effective dose rate outdoors of: 32 x 1.02 + 9 x 1.1 = 42.5 nSv/h.

Applying an indoor shielding factor of 0.8 and assuming indoor occupancy to be 80% (of time or 7000 h per year) the average annual dose is: 42.5 (1760 + 7000 x 0.8) 10^{-6} = 0.31 mSv.

The internal exposure by cosmogenic radionuclides is much smaller. The largest contribution comes from carbon-14, whose activity in the environment and consequently in the human body amounts to 230 Bq per kg carbon resulting in an effective dose of 0.012 mSv per year.

Radiocarbon dating uses the naturally occurring carbon-14. As soon as a living organism dies, it stops taking in new carbon. Carbon-14 has a half-life of 5730 years, so that the age can be determined from the C-12 to C-14 ratio. Note that the atmospheric nuclear weapon tests almost doubled the concentration of C-14 in the Northern Hemisphere in the early 60s.

Including a small contribution from air travel and holidays (for instance winter sports) the average exposure to cosmic radiation in Belgium can be estimated at: 0.31 + 0.012 + ... = 0.35 mSv/y. This corresponds to three to four return flights from Europe to North America.

3.2. Natural radioactive substances

With the exception of cosmic radiation, the natural radioactivity results from the decay of radioactive nuclides with half-lives of more than 500 million years. Important nuclides are the uranium-238 and 235 isotopes, thorium-232 and potassium-40. Exposures arising from these sources are indicated in table 1 as "inhalation (radon)", "soil and buildings" and "ingestion".

3.2.1. Radon (^{222}Rn) and thoron (^{220}Rn) exposure

The above-mentioned long-lived radionuclides, except for potassium-40, form the beginning of natural decay series: the uranium series (U-238), the thorium series (Th-232) and the actinium series (U-235). The stable isotope formed at the end of the three decay series is an isotope of lead. Each of the three decay series has an isotope of the noble gas radon. Traditionally these isotopes are called radon (Rn-222), thoron (Rn-220) and actinon (Rn-219). As they are chemically inert, they can move in the earth's crust and in building materials and may eventually reach the atmosphere. This characteristic gives rise to the radon and thoron issue. The half-life is important for the amount of noble gas capable of reaching the atmosphere. Actinon has the shortest half-life and the lowest abundance of the three natural decay series. That is why the isotope's concentration in the air is negligibly low. Radon and thoron on the other hand are present in indoor air. The much longer half-life of radon (3.82 days) in comparison with thoron (55.6 seconds) makes the contribution of radon to the radiation exposure of the population more significant than that of thoron.

Radon is present in the air, and is thus inhaled. Being a noble gas, it is again exhaled. At first glance: no problem. However radon is radioactive, thus its short-lived decay products are also present in the air. These are solids that can deposit in the lungs. Since the biological half-life of the decay products in the lungs exceeds a few hours, there is time for decay to lead-210. In this process, two alpha particles are emitted, originating from polonium-218 and polonium-214. These alpha particles can damage the secretory and basal cells of the respiratory tract, through which a lung cancer may develop after many years. In fact, the radon problem is actually a polonium problem.

Radon measurements in thermometer shelters in Belgium gave an average value of 10 Bq/m³ in outdoor air [4]. The radon concentrations indoors are higher. The average concentration in Belgium is estimated at 48 Bq/m³ with a geometric mean of 38 Bq/m³ and a geometric standard deviation of 2.0 [5]. The highest values, up to several thousands of Bq/m³, are found in the Ardennes. The FANC has recently revised its estimate of the average indoor radon concentration in Belgium to 53 Bq/m³ (website FANC, 2011).

Direct measurements of the concentrations of the short-lived decay products of radon are difficult and limited. That is why they are mostly estimated from considerations of equilibrium *(disequilibrium would be a better term)* with radon. The equilibrium factor is the ratio of the Equilibrium Equivalent radon Concentration (C_{EEC}) to the radon concentration (C_{Rn}).

$$F = C_{EEC}/C_{Rn} \quad \text{with} \quad C_{EEC} = 0.105\, C_{218Po} + 0.515\, C_{214Pb} + 0.380\, C_{214Bi}$$

where C_{218Po}, C_{214Pb} and C_{214Bi} are the concentrations of the short-lived radon decay products in air. UNSCEAR suggests a rounded value of 0.6 for the equilibrium factor for the outdoor environment and 0.4 indoors.

It is important to mention that there is currently no scientific consensus on the value of the dose conversion factor for radon. UNSCEAR uses in its 2006 [6] and 2008 [1] reports for radon exposure its long-established conversion factor of 9 (nSv/h)/(Bq/m³) radon progeny exposure, which is 50% higher than the ICRP 65 conversion convention of 1993 for members of the public of 6 (nSv/h)/(Bq/m³) [7]. ICRP, however, has issued in 2009

a statement on their website to increase its dose conversion factors in the near future by about a factor of 2.

For the representative radon concentrations in Belgium, equilibrium and occupancy factors (80% indoors), and the dose coefficient of UNSCEAR in terms of radon progeny exposure, the following annual effective doses are derived:

Indoors: $48 \times 0.4 \times 9 \times 7000 \times 10^{-6} = 1.2$ mSv/y

Outdoors: $10 \times 0.6 \times 9 \times 1760 \times 10^{-6} = 0.1$ mSv/y

Total = 1.3 mSv/y

For completeness, the contribution from a minor pathway of exposure to radon has to be added, namely dissolution of radon gas in blood with distribution throughout the body. The dose estimate for the representative radon concentrations in Belgium with the method given in the UNSCEAR 2000 report is 0.06 mSv/y [2].

The short half-life of thoron (55.6 seconds) limits the thoron exhalation of soil and building materials and thus the contribution of thoron to the radiation exposure of the population. UNSCEAR estimates the average concentration of thoron outdoors at 10 Bq/m³ and approximately the same indoors. The determination of a dose conversion factor as a function of the thoron concentration has little meaning. Indeed, the half-life of thoron is shorter than the time a gas needs to spread homogeneously over a room, so that the thoron concentration strongly depends on the location of the measurement. With the estimated equilibrium equivalent concentrations of thoron indoors of 0.3 Bq/m³ and outdoors of 0.1 Bq/m³, and the UNSCEAR dose conversion factor of 40 (nSv/h)/(Bq/m³), the annual effective doses are:

Indoors: $0.3 \times 40 \times 7000 \times 10^{-6} = 0.084$ mSv/y

Outdoors: $0.1 \times 40 \times 1760 \times 10^{-6} = 0.007$ mSv/y

Total (rounded) = 0.1 mSv/y

This value also includes a minor contribution from thoron gas dissolved in blood.

Note that the UNSCEAR dose conversion factor of 40 (nSv/h)/(Bq/m³) [2] is close to the value given in the European Basic Safety Standards for thoron at work [8] of 0.5 Sv per J h/m³, which is equivalent to 37.5 (nSv/h)/(Bq/m³).

The average exposure to radon, thoron and their short-lived decay products in Belgium is (rounded): 1.3 (radon decay products) + 0.06 (radon in blood) + 0.1 (thoron) = 1.45 mSv/y.

3.2.2. External terrestrial exposure (soil and buildings)

External exposures arise from terrestrial radionuclides present at trace levels in soil and building materials. Irradiation is mainly by gamma radiation from radionuclides in the uranium and thorium series and from potassium-40. Hundreds of soil samples from all over Belgium were measured in the eighties by SCK and WIV [9]. The average values of the spectrometric analyses of the soil samples, the dose conversion coefficients from UNSCEAR and the calculated absorbed dose rates in air are given in table 2 and compared to the worldwide average values from the UNSCEAR 2000 report [2].

Table 2. External exposure rates derived from the average radionuclide concentrations in soil in Belgium *(UNSCEAR worldwide averages in italics and between brackets).*

	Concentration in soil Bq/kg	**Dose conversion coefficient (nGy/h)/(Bq/kg)**	**Absorbed dose rate nGy/h**
^{40}K	380 *(420)*	0.0417	16 *(18)*
^{226}Ra (uranium series)	26 *(33)*	0.462	12 *(15)*
^{232}Th (thorium series)	27 *(45)*	0.604	16 *(27)*
Total absorbed dose rate outdoors from soil measurements:			44 *(60)*

The three components of the external radiation field make approximately equal contributions to the gamma radiation dose. Direct measurements of absorbed dose rates in air were carried out at the same locations where the soil samples were taken. Excluding cosmic ray exposure, an average value of 43 nGy/h *(59)* was found, which is close to the value calculated in table 2 from the soil concentration measurements.

In the same study indoor measurements were performed at hundreds of locations all over Belgium [9]. A somewhat higher average value of the absorbed dose rate of 60 nGy/h *(84)* was found indoors, due to the change in source geometry from half-space to a more surrounding configuration indoors.

To estimate effective doses, account must be taken of the conversion coefficient from absorbed dose in air to effective dose. The smaller body size of children and infants results in higher dose conversion coefficients (adults: 0.7, children: 0.8 and infants: 0.9). The average annual effective dose assuming an occupancy factor indoors of 0.8 is:

- adults: $(43 \times 1760 + 60 \times 7000) \times 0.7 \times 10^{-6} = 0.35$ mSv *(0.48)*;
- children: $(43 \times 1760 + 60 \times 7000) \times 0.8 \times 10^{-6} = 0.40$ mSv *(0.55)*;
- infants: $(43 \times 1760 + 60 \times 7000) \times 0.9 \times 10^{-6} = 0.45$ mSv *(0.62)*.

The average effective dose to the whole population, including children and infants, from external terrestrial radiation in Belgium is estimated at 0.4 mSv/y.

3.2.3. Internal exposures other than radon and thoron

Ingestion is the main route of intake of the population with significant contributions from potassium-40, and from the uranium and thorium decay series. An adult person consumes about 4 grams of potassium per day containing more than 100 Bq of K-40. Potassium is more or less uniformly distributed in the body and its concentration is under homeostatic control:

- adults: 55 Bq K-40 per kg body weight ⇨ 0.165 mSv/y;
- children: 61 Bq K-40 per kg body weight ⇨ 0.185 mSv/y.

There are no control mechanisms to keep the concentration of the radionuclides from the uranium- and thorium-series in the body at a fixed level, so that the doses are dependent on the intake. The main contributor to the dose is polonium-210, a member of the natural uranium-238 decay series:

- adults: 0.11 mSv/y (^{210}Po contribution = 0.07 mSv/y);
- children: 0.20 mSv/y (^{210}Po contribution = 0.10 mSv/y);
- infants: 0.26 mSv/y (^{210}Po contribution = 0.18 mSv/y).

The total effective dose from internal exposures other than radon and thoron is assessed at 0.3 mSv/y (rounded value).

3. Nuclear fuel cycle

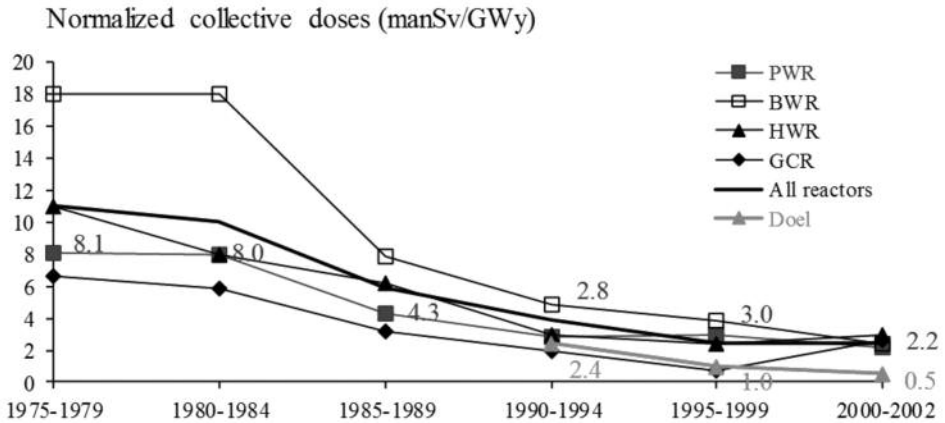
3.3. Occupational exposure in nuclear power plants

The reactor types used for electrical energy generation are characterized by their coolant system and moderator *(material used to slow down the fast fission neutrons so that they can be captured by a uranium-235 nucleus)*.

The Belgian nuclear power plants are light water *(this is ordinary water)* moderated and cooled reactors of the type Pressurized Water Reactor (PWR). Half of the reactors in the world are PWRs.

The collective doses of the main reactor types are summarized in figure 1. The data have been averaged over five-year periods, except for the last period, and expressed per unit electrical energy generated [1]. The collective doses have decreased by a factor of 4 from the late 70s to the early 2000s. The average collective dose of the workers at the 4 reactors of Doel *(15 km north-west of Antwerp)* in the period 2000-2002 was 0.5 manSv/GWy, much lower than the worldwide average for PWR reactors over the same period of 2.2 manSv/GWy.

Since the early 2000s the doses at Doel have remained at about the same level: 0.6 manSv/GWy in 2009. Most of the dose is received by external workers during the refueling *(replacing spent or irradiated fuel)* and maintenance activities conducted every 12 to 18 months at the nuclear reactors.



PWR, BWR: light-water-moderated and cooled reactors (75% of all reactors)
HWR: heavy-water-moderated and cooled reactors (Canada, Argentina)
GCR: gas-cooled, graphite-moderated reactors (United Kingdom)

Fig 1. Trends in occupational radiation exposures in nuclear power plants [1]. The average collective doses at Doel are given from 1990 on [10].

Nuclear power plants supplied in 2009 about 30% of the electricity in the EU, with the highest percentage in Lithuania (76.2%) and France (75.2%). The share of nuclear energy in the Belgian electricity production amounted to 51.6% in 2009; 24.3% of this electricity was produced in Doel. The high investment costs and the low fuel costs make nuclear power plants particularly suitable for base-load production, so that the reactors, with the exception of maintenance outages, run almost continuously throughout the year. The average load factor of the Belgian nuclear power plants in 2009 reached 87.6%.

3.4. Population exposure from the nuclear fuel cycle

The estimated doses to members of the public due to the nuclear fuel cycle are given in table 3 per unit of electrical energy generated [1]. For local and regional population groups a normalized collective effective dose of 0.72 manSv/GWy is determined. Using this coefficient, with an average of 278 GW per year produced in the 1998-2002 period, an annual collective dose of about 200 manSv is estimated for all operations related to nuclear energy production. The individual doses to the local population in normal operation are low. Typical values for the most exposed members of the public are in the μSv range: the highest values for mining and milling: 25 μSv/y and the lowest values for reactor operation 0.1 μSv/y.

Nuclear accidents are the biggest threat but these small risks with far-reaching consequences are not included in the UNSCEAR figures. The collective dose from the Chernobyl accident has been estimated by UNSCEAR to 275 000 manSv, corresponding to 1500 years of normal operation.

Table 3. Collective effective doses to the local population due to radionuclides released in effluents of the nuclear fuel cycle (world average, 1998-2002) [1]. *The large Belgian nuclear power plants have an electrical capacity of 1 000 MW or 1 GW.*

Part of the nuclear fuel cycle	**Collective dose manSv/GWy**
Mining of uranium ore	0.19
Milling of uranium ore	0.008
Mine and mill tailings (releases of radon over five years)	0.008
Enrichment and fuel fabrication	0.04
Reactor operation: atmospheric discharges	0.22
Reactor operation: aquatic discharges	0.05
Reprocessing: atmospheric discharges	0.028
Reprocessing: aquatic discharges	0.081
Transportation	< 0.1
Total (rounded)	**0.72**

Radionuclides that are long-lived and easily dispersed in the environment give rise to doses to people across the whole planet. Radionuclides of specific interest are: ^{3}H (T½: 12.26 years), ^{14}C (T½: 5730 years), ^{85}Kr (T½: 10.7 years) and ^{129}I (T½: 16 million years). The collective doses due to globally dispersed radionuclides are delivered over very long periods. If the current practice of nuclear power production is continued for 100 years at its present capacity of about 300 GW per year, the maximum annual effective dose to the global population would be about 0.18 μSv/y. This dose rate is low compared to that due to natural background radiation (see table 1).

The UNSCEAR estimate of the radiological impact of the disposal of solid low- and intermediate-level waste is relatively low: 0.5 manSv/GWy.

No figures are given for the geological disposal of high-level radioactive waste because of the highly site specific nature of the calculations.

3.5. Radioactive liquid and atmospheric releases of nuclear power plants

Table 4 gives an overview of the radioactive discharges from the nuclear power plants of Doel into the Scheldt and the air [10].

The liquid discharges in 2009 were only a fraction of the discharge limits authorized by the FANC and have a negligible dose impact on the local population. A control measurement can easily be disturbed by discharge into the same waterway of iodine-131 by an ambulatory patient treated with radioiodine (eg for thyroid cancer). The non-nuclear waste processor Indaver, located on the opposite site of the Scheldt in Doel releases equivalent amounts of iodine-131 as the nuclear power station. This radioiodine comes from municipal and medical waste from nuclear medicine patients.

Atmospheric discharges of noble gases greatly reduced by the smaller number of leaking fuel rods. The noble gases emitted are mainly short-lived. The seemingly increase of atmospheric releases in 2006 is due to a change in reporting. From 2006 also measurement results below the detection limits have to be reported to the FANC.

The monitoring programme of the FANC *(environmental samples taken near the nuclear power station)* shows that there is no measurable increase of the radiation exposure to the local population. By far most of the radioactivity remains trapped in the fuel rods and is only partially released after disposal (in a geological repository) after a very long period of time.

Table 4. Yearly releases of radionuclides in liquid and airborne effluents from the nuclear power station of Doel.

	Liquid effluents		Atmospheric effluents			
	Tritium (GBq)	Other (eg I-131) (GBq)	Noble gas (GBq)	Tritium (GBq)	I-131 (GBq)	Parti-culates (GBq)
Autho-rization	103 600	1480.0	2 960 000	88 800	14.8	148.0
1990	63 000	15.5	15 600	752	0.485	0.162
1991	38 100	30.1	31 300	548	0.657	0.100
1992	45 200	4.5	26 400	774	0.193	0.075
1993	34 300	23.6	5 190	553	0.097	0.008
1994	33 900	9.3	970	846	0.010	0.000
1995	47 000	37.8	4 120	613	0.032	0.004
1996	31 300	18.9	2 050	288	0.009	0.003
1997	38 400	26.4	74	227	0.006	0.002
1998	47 100	16.1	3 310	52	0.014	0.002
1999	48 400	27.8	2 660	60	0.003	0.000
2000	30 900	15.0	95	17	0.009	0.000
2001	37 500	6.7	33	329	0.004	0.001
2002	27 500	7.8	331	1 026	0.009	0.005
2003	34 300	8.4	775	710	0.003	0.010
2004	42 100	5.2	25	30	0.006	0.001
2005	39 900	4.5	71	476	0.018	0.0006
2006	46 100	1.7	115	1 975	0.036	0.052
2007	53 733	2.5	14	2 927	0.034	0.0039
2008	41 705	3.1	22	2 070	0.059	0.0033
2009	53 097	3.5	16	2 940	0.062	0.0085

Source: Electrabel 2010 [10]

Tritium is the heavy hydrogen isotope with a half-life of 12.3 years. It is a weak beta emitter, dealt with separately in table 4 because of its low radiotoxicity. Tritium ends up in the hydrogen-containing compounds present in the environment and can penetrate into the biological cycle (organically bound tritium). Iodine-131, with a half-life of 8 days, is also mentioned separately because of its property to accumulate in the human thyroid.

The liquid and airborne releases of radionuclides from the nuclear power stations of Doel and Tihange are compared in table 5 to the average UNSCEAR values from all pressurized water reactors (PWRs). There are some minor differences between the data in table 4, received directly from Electrabel [10], and the data in table 5 from the UNSCEAR 2008 report [1]. The releases from the Doel and Tihange PWRs in the 1998-2002 period are less than the UNSCEAR values, except for tritium in airborne effluents released from Tihange (2500 compared to 2100 GBq/GWy).

Table 5. Releases of radionuclides in the 1998-2002 period from Doel and Tihange, compared in the last column to the values of the UNSCEAR 2008 report from all PWRs (between brackets) [1].

	1998	1999	2000	2001	2002	Total	Normalized
	Noble gases in airborne effluents (GBq)					**(GBq)**	**(GBq/GWy)**
Doel 1-4	3 310	2 660	95	26	331	6 400	**510** (11 000)
Tihange 1-3	8 040	4 320	3 520	4 650	8 460	29 000	**2 200** (11 000)
	Tritium released in airborne effluents (GBq)					**(GBq)**	**(GBq/GWy)**
Doel 1-4	52	5 670	17	326	1 030	7 200	**570** (2 100)
Tihange 1-3	6 350	7 170	7 560	5 650	5 260	32 000	**2 500** (2 100)
	Iodine-131 released in airborne effluents (MBq)					**(MBq)**	**(MBq/GWy)**
Doel 1-4	14	3	9	4	9	39	**3.1** (300)
Tihange 1-3	5	6	0.6	8	0.8	20	**1.6** (300)
	Tritium released in liquid effluents (GBq)					**(GBq)**	**(GBq/GWy)**
Doel 1-4	47 000	48 000	30 900	38 000	27 500	191 000	**15 000** (20 000)
Tihange 1-3	32 900	66 600	33 100	41 000	56 600	233 000	**18 000** (20 000)
	Energy generated (GWy)					*(GWy)*	
Doel 1-4	*2.545*	*2.572*	*2.543*	*2.557*	*2.492*	*12.709*	
Tihange 1-3	*2.473*	*2.760*	*2.686*	*2.474*	*2.650*	*13.043*	

4. Worldwide overview of occupational radiation exposures

Occupational radiation exposures have been evaluated for six broad categories of work. Figure 2 shows the relative share (percentage) of the global occupational exposures associated with man-made and natural sources of ionizing radiation for the period 2000-2002 [1].

The worldwide average annual collective dose to workers exposed to radiation is estimated for the period 2000-2002 to be around 42 000 manSv. The largest contribution is due to exposure to natural sources *(in excess of the average levels of natural background)* of 37 260 manSv, which represents about 89% of the total collective dose.

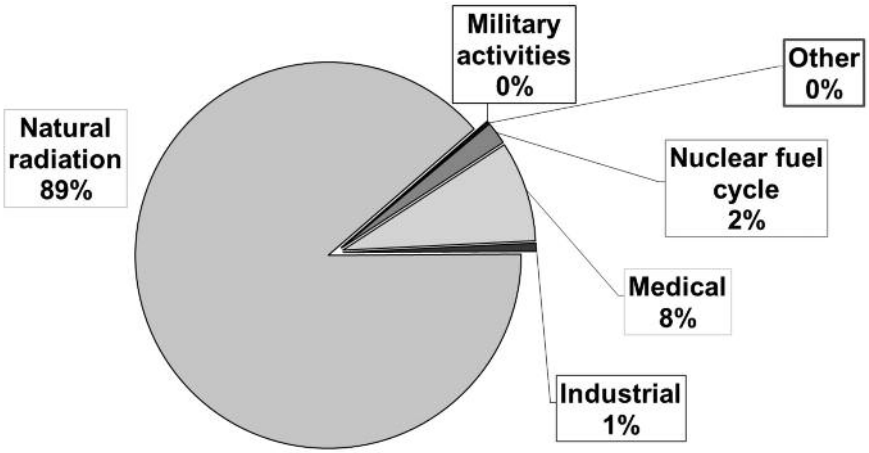


Fig 2. Relative contributions of the different work categories to the worldwide occupational exposures [1].

The occupational exposure to enhanced natural sources of radiation is about three times higher than the value estimated in the UNSCEAR 2000 report [2]. The largest component of this, 30 360 manSv, comes from mining (16 560 manSv due to coal mining and 13 800 manSv due to other mining operations, excluding uranium mining). 6000 manSv is due to "workplaces other than mines" and 900 manSv is due to the exposure of aircrew to cosmic radiation. The large difference with respect to the UNSCEAR 2000 report comes from the level of exposure in coal mines. For the current period, the estimate is based on an assessment of exposure in Chinese mines, which represents a very large number of workers. The relative share of the natural sources of radiation for the period 2000-2002 is shown in figure 3. The trends (1990-2002 period) are illustrated in figure 4.

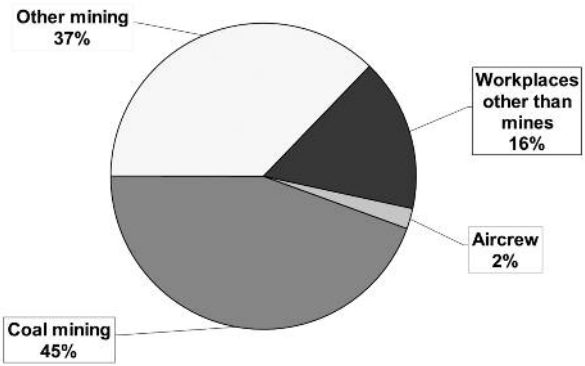
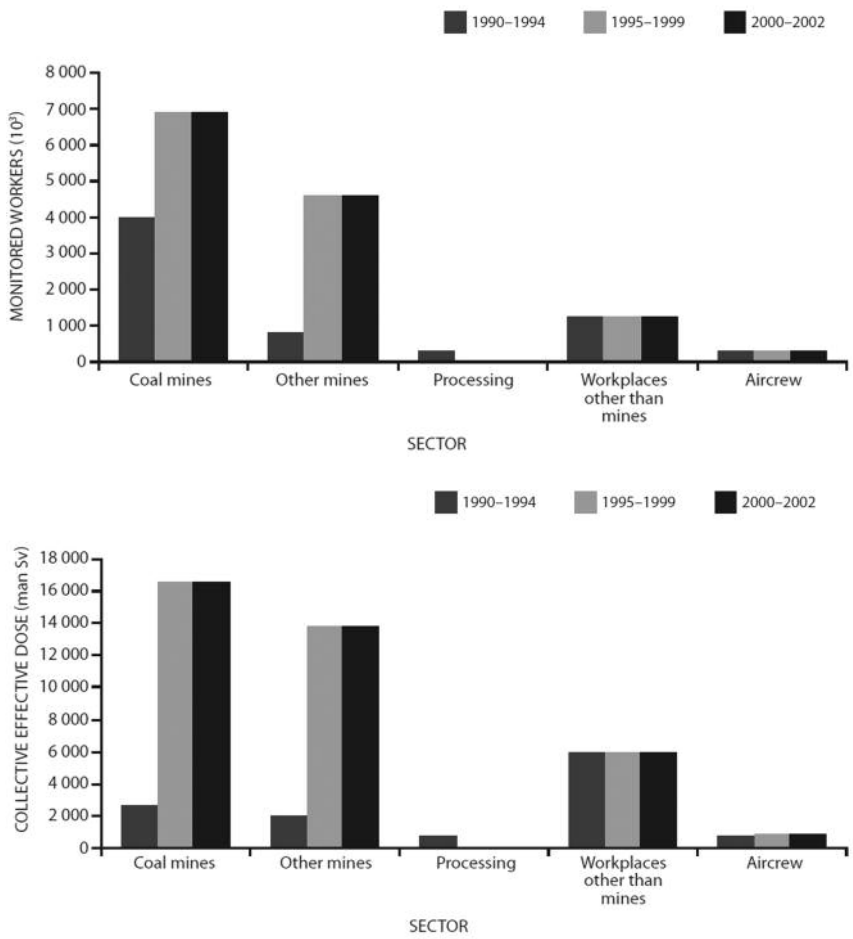


Fig 3. Relative contributions of the different work categories to the worldwide occupational exposures from various natural sources of radiation [1].



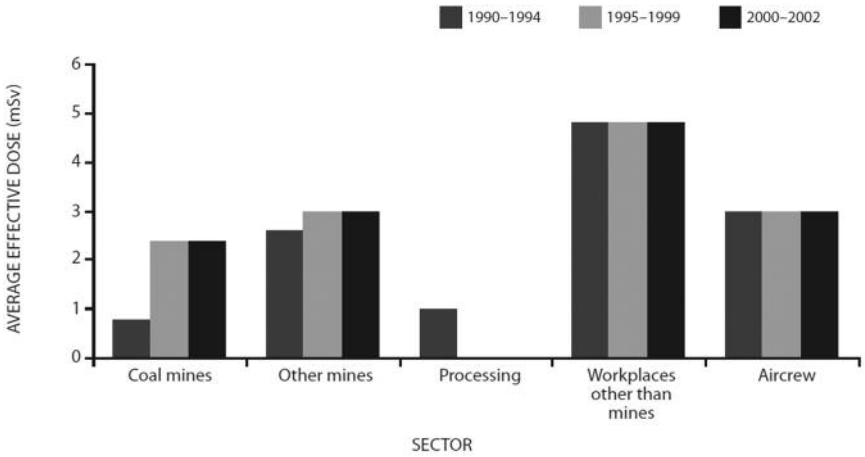


Fig 4. Worldwide trends in numbers of monitored workers, in collective effective doses and in effective doses to monitored workers due to natural sources of radiation [1].

The collective effective dose to workers in practices using man-made sources of radiation has in the past been dominated by practices in the nuclear fuel cycle, but the current estimate has shown that occupational exposure in the medical field has become dominant. The collective effective dose in practices using man-made sources of radiation for the 2000-2002 period may be around 4730 manSv. The exposure data has been divided into five categories of work:

- 800 manSv in the nuclear fuel cycle;
- 3540 manSv to workers in medical uses;
- 289 manSv to workers in industrial uses;
- 45 manSv from military activities;
- 56 manSv from miscellaneous uses.

Medical uses of radiation contribute about 75% of the collective effective dose due to occupational exposure to man-made sources of radiation.

The relative share of the man-made sources of radiation for the period 2000-2002 is shown in figure 5, while the trends (1975-2002 period) are illustrated in figure 6.

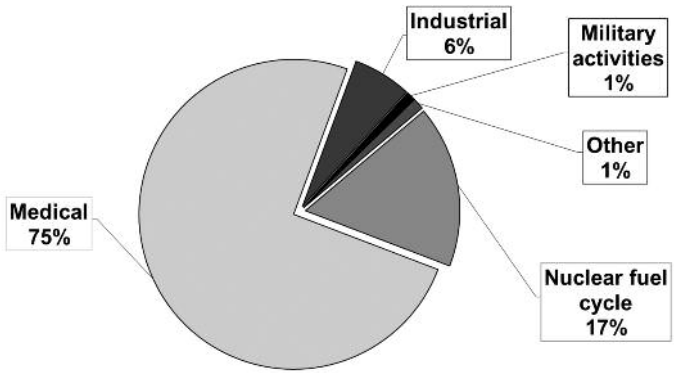
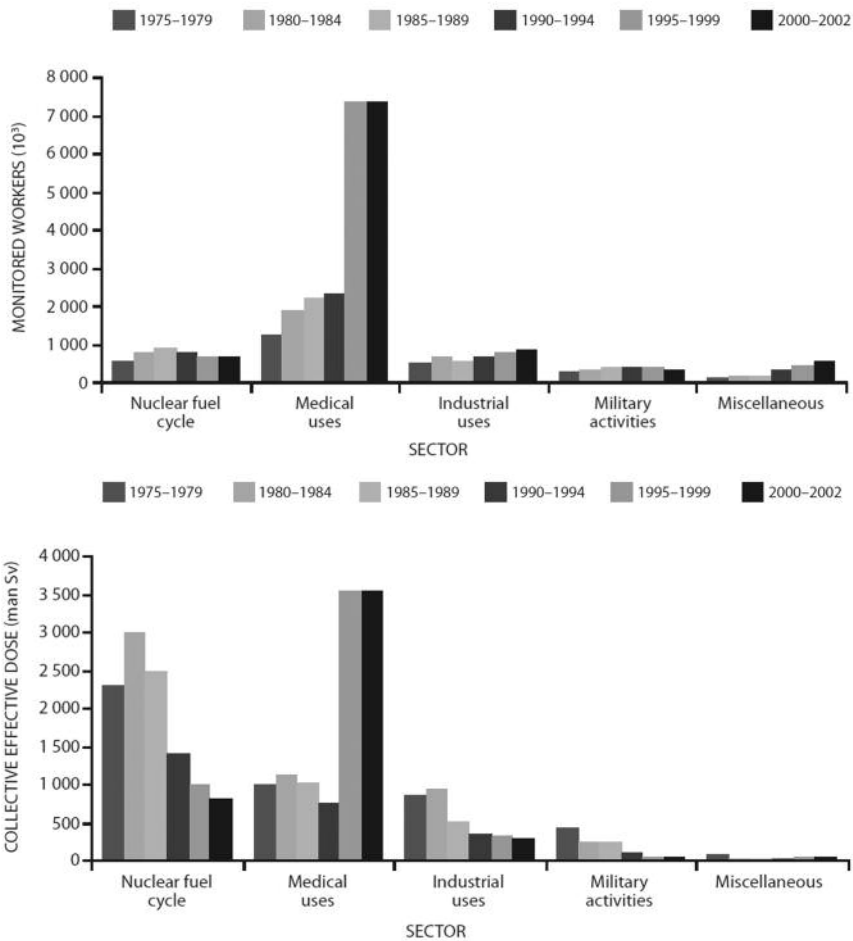


Fig 5. Relative contributions of the different work categories to the worldwide occupational exposures from various man-made sources of radiation [1].



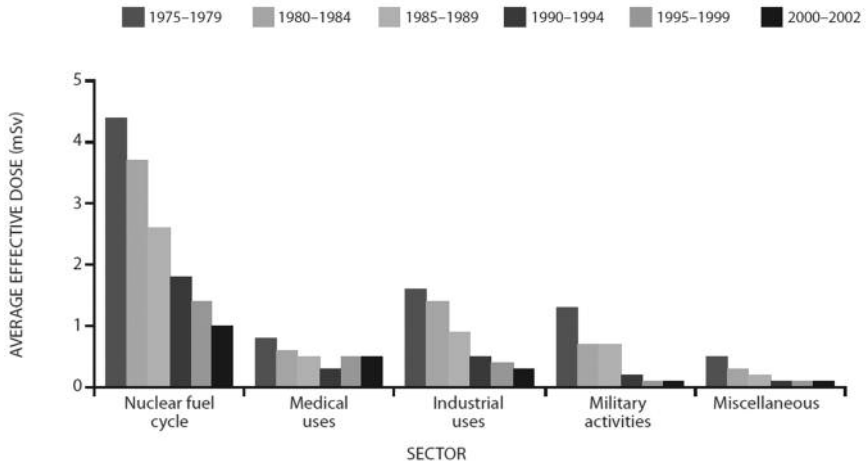


Fig 6. Worldwide trends in numbers of monitored workers, in collective effective doses and in effective doses to monitored workers due to man-made sources of radiation [1].

References

[1] UNSCEAR (2008) Sources and effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes, United Nations sales publication, Volume I on sources: E.10.IX.3, Volume II on effects: E.11.IX.3, New York.

[2] UNSCEAR (2000) Sources and effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes, United Nations sales publication E.00.IX.3, New York.

[3] Vanmarcke H., Mol H., Paridaens J., Eggermont G. (2004) Exposure of the Belgian population to ionizing radiation, IRPA 11 conference in Madrid of 2004, 6d20, http://www.irpa11.com

[4] Poffijn A. (2001) Personal communication in the framework of the UNSCEAR survey on exposures to natural radiation sources.

[5] Poffijn A., Charlet J.M., Cottens E., Hallez S., Vanmarcke H., Wouters P. (1991) Radon in Belgium: the current situation and plans for the future, in Proceedings 1991 International Symposium on Radon and Radon Reduction Technology, Philadelphia, VI-7.

[6] UNSCEAR (2006) Effects of ionizing radiation. Report to the General Assembly of the United Nations with Scientific Annexes, United Nations sales publication, Volume I: E.08.IX.6, Volume II: E.09.IX.5, New York.

[7] International Commission on Radiological Protection (1993) Protection against radon-222 at home and at work. ICRP Publication 65, Ann. ICRP 23.

[8] 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, Official Journal of EC, Series L, No. 159.

[9] Gillard J., Flémal J.M., Deworm J.P., Slegers W. (1988) Measurement of the natural radiation of the Belgian territory, Report of SCK•CEN, BLG 607.

[10] Electrabel (2010) Personal communication in the framework of the MIRA report, Report on the Environment and Nature in Flanders, Vlaamse Milieumaatschappij (VMM).

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SYMPOSIUM ON HEALTH IMPACT OF PRE- AND EARLY POST-NATAL IRRADIATION, BRUSSELS, OCTOBER 7, 2011

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Résumé

Le 7 octobre 2011, le SCK•CEN et l'Agence fédérale de Contrôle nucléaire (FANC-AFCN) ont organisé un symposium consacré aux risques d'une irradiation prénatale ou postnatale précoce. Ce symposium a rassemblé 125 participants belges ou étrangers: chercheurs, médecins radiologues, physiciens d'hôpitaux et autres utilisateurs des rayonnements ionisants, médecins du travail, experts en contrôle physique, régulateurs,… Le texte qui suit a pour but de donner un aperçu fidèle des différents exposés donnés à cette occasion, dont certains n'ont pas manqué d'interpeller les scientifiques présents. D'autre part, cet aperçu est suivi d'un *addendum* synthétisant de façon quelque peu plus détaillée les recherches entreprises au SCK•CEN dans ce domaine depuis plus de 20 ans, ainsi que leurs principales conclusions. Par rapport au texte publié dans un numéro précédent, les résultats obtenus ces deux dernières années sur un nombre accru d'animaux nous ont conduits à reconsidérer certaines de ces conclusions.

But du symposium et synthèse des différentes communications

Le premier objectif du symposium était de dresser un bilan aussi exact que possible des connaissances actuelles dans le domaine des risques liés à une exposition de l'embryon ou du jeune enfant aux radiations ionisantes. Certains traitements requièrent en effet une irradiation prénatale ou postnatale précoce qui, dans certains cas, n'est pas sans conséquences. Il était donc capital que de tels risques soient examinés de manière approfondie. Des recherches dans ce sens ont entre autres lieu au Centre d'Etude de l'Energie Nucléaire (SCK•CEN) de Mol. Avec l'Agence Fédérale de Contrôle Nucléaire, les chercheurs de Mol ont donc convié leurs collègues étrangers à venir commenter avec eux les dernières

recherches épidémiologiques et radiobiologiques dans ce domaine. Le symposium a eu lieu le 7 octobre 2011, à l'Académie Royale des Sciences, des Lettres et des Beaux-Arts de Belgique, située dans le centre de Bruxelles.

Au cours du premier exposé de la journée, **Hanane Derradji**, du SCK•CEN de Mol, a résumé les effets "classiques" d'une irradiation au cours du développement prénatal. Ces effets diffèrent selon la période au cours de laquelle a lieu l'exposition: période "pré-implantatoire" (première semaine), "période de l'organogenèse" (de la 2e à la 8e semaine) et "période foetale" (de la 8e semaine à la naissance). L'irradiation au cours du développement prénatal peut ainsi induire de la mortalité embryonnaire, des retards de croissance, des malformations congénitales, un retard mental léger ou sévère, la leucémie ou différents types de cancer.

Paul Jacquet, qui travaille depuis plus de 30 ans au laboratoire de Radiobiologie du SCK•CEN, a enchaîné en brossant une synthèse des nombreuses recherches réalisées à Mol dans ce domaine. Les recherches du laboratoire de Radiobiologie de Mol se sont notamment concentrées sur l'influence des caractéristiques génétiques de l'embryon sur sa sensibilité à l'induction d'anomalies du développement par des doses modérées de radiation. Une attention particulière a été accordée à la période préimplantatoire, durant laquelle la femme ne peut savoir si elle est enceinte. Selon un dogme de la Tératologie, l'irradiation au cours de cette période ne peut qu'entraîner la mort de l'embryon ou sa survie sans anomalies (loi du "tout ou rien" de Russell, 1960). Or, des études réalisées en Allemagne et au Japon sur deux races de souris ont mis en évidence la présence de certaines malformations après irradiation d'embryons pré-implantés. En dépit de certains problèmes notés dans ces études et des résultats rassurants obtenus à Mol et dans la plupart des autres études avec des doses supérieures à celles normalement utilisées dans les procédures radiologiques, la possibilité d'une radio-induction de malformations fœtales chez certains individus ne peut donc être exclue, notamment dans le cas d'une irradiation survenant très peu de temps après la fécondation de l'ovocyte (premier jour de la grossesse). Cette possibilité est également supportée par les résultats positifs obtenus avec des agents chimiques après exposition d'embryons pré-implantés, bien que les mécanismes responsables de ces malformations puissent être totalement différents.

D'autre part, les changements dans l'expression d'une série de gènes notés dans les études de Mol après irradiation de jeunes embryons, en l'absence même d'effets phénotypiques, invitent également à une certaine prudence et nécessiteront des recherches complémentaires à plus long terme. Si les risques potentiels d'une irradiation au cours de la première semaine de la grossesse paraissent relativement faibles par rapport aux risques "spontanés" accompagnant toute grossesse, ceci ne constitue bien sûr pas une raison pour ne pas appliquer certains principes de précaution, lorsque cela s'avère possible….d'autant plus que de nombreuses études ont suggéré que le risque de cancer ou leucémie infantile associé à une irradiation aux premiers stades du développement, aussi faible soit-il, n'est probablement pas non plus égal à zéro.

Outre les études sur la radiosensibilité de l'embryon au cours des premiers stades du développement, le SCK●CEN poursuit également des recherches sur les mécanismes du retard mental radio-induit par une exposition prénatale aux rayonnements ionisants. Celles-ci ont été résumées par **Rafi Benotmane**. On sait que les survivants d'Hiroshima et Nagasaki exposés *in utero* aux bombardements entre la 8^{e} et la 15^{e} semaine de la grossesse et, dans une moindre mesure, entre la 15^{e} et la 25^{e} semaine, ont montré des retards mentaux parfois sévères et accompagnés ou non de microcéphalie (périmètre crânien inférieur à la norme). Les recherches en cours au SCK●CEN s'efforcent de préciser les mécanismes de tels retards, en collaboration avec d'autres laboratoires belges et étrangers. Différentes souches de souris sont soumises à une irradiation à des stades du développement embryonnaire correspondant à la radiosensibilité maximale pour de tels effets dans l'espèce humaine. Après la naissance, ces souris sont soumises à une batterie de tests cognitifs. Les effets notés sont mis en relation avec ceux obtenus par d'autres méthodes, telles que l'imagerie médicale (MRI ou molecular resonance imaging), la microscopie en fluorescence (développement des neurites au cours de la maturation des neurones,….) ou la biologie moléculaire (expression de certains gènes peu après l'irradiation). Grâce à son expertise développée depuis de nombreuses années dans ce domaine, le SCK●CEN vient de se voir nommé coordinateur d'un nouveau projet européen (CEREBRAD) centré sur les effets des faibles doses sur le système nerveux central. Ce projet a pour but

d'accroître le pouvoir statistique des données épidémiologiques sur les effets cognitifs et cérébrovasculaires causés par les radiations.

Ce sont précisément les résultats d'une étude épidémiologique dans ce domaine qui ont été présentés par l'orateur suivant, **Marten Palme**. Celui-ci, économiste à l'Université de Stockholm, a fait état de certains effets cognitifs constatés parmi la population scolaire de Suède qui avait été exposée *in utero* au nuage radioactif de Tchernobyl, entre la 8e et la 25e semaine de la grossesse. Comme signalé ci-dessus, les études menées sur les survivants d'Hiroshima et Nagasaki ont montré que cette période de la grossesse est sensible à l'induction de retards mentaux. Mais, contrairement à Hiroshima et Nagasaki, il s'agissait ici d'une exposition chronique à des doses de radiations beaucoup plus faibles…..Ainsi, même si la Suède a été particulièrement touchée par le nuage radioactif de Tchernobyl, la dose d'exposition maximale encourue par la population étudiée a été estimée à 4 mSv pour la première année suivant l'accident, soit une valeur comparable à la dose annuelle résultant d'une exposition à la radioactivité naturelle. Il va sans dire que l'interprétation de ces résultats pose un sérieux problème aux scientifiques et que des études additionnelles de ce type devraient pouvoir être réalisées dans d'autres régions du globe caractérisées par un taux de radioactivité excessif.

Wladimir Wertelecki de l'université de South Alabama a quant à lui fait état d'une augmentation de la fréquence de certaines malformations congénitales parmi la population d'une région d'Ukraine fortement contaminée par l'accident de Tchernobyl. De par leur mode de vie, les habitants de cette région représentent une population homogène, exposée depuis 25 ans à la radioactivité par l'ingestion de champignons et baies forestiers, de lait et produits laitiers, mais aussi par l'inhalation des fumées dues à la combustion du bois servant à cuisiner ou à chauffer leurs maisons, ou à la combustion des déchets végétaux. Les auteurs de cette étude restent toutefois prudents dans l'interprétation de leurs résultats. D'autres facteurs, comme une insuffisance en certaine vitamine (acide folique ou vitamine B9) ou une consommation exagérée d'alcool peuvent engendrer des effets semblables chez le fœtus. Il semble d'ores et déjà que, dans ce cas, l'alcool ne pourrait constituer à lui seul la cause de ces malformations, mais qu'il pourrait peut-être y contribuer en synergie avec les radiations et certaines déficiences alimentaires. Wladimir Wertelecki lance donc un appel pressant

aux chercheurs étrangers pour mettre sur pied d'autres recherches dans cette population aux caractéristiques uniques (adresse e-mail: genfir3@gmail.com).

Le premier exposé de l'après-midi a été donné par **Elisabeth Cardis**, responsable durant plus de 20 ans du Radiation Group de l'IARC (International Agency for Research on Cancer) et travaillant actuellement au CREAL de Barcelone (Center for Research in Environmental Epidemiology). Celle-ci a résumé les connaissances actuelles sur les risques de cancer infantile et adulte après exposition *in utero.* Des études à large échelle (telle que la fameuse Oxford Survey) réalisées chez des patients exposés *in utero* dans le cadre d'une pelvimétrie aux rayons-X ont montré un risque accru de développer des cancers infantiles après des doses très faibles de radiation, bien que l'importance de cet effet demeure incertaine. D'autres informations sont disponibles à partir d'études de cohorte de taille plus faible, comme celles réalisées sur les survivants d'Hiroshima et Nagasaki ou sur les habitants du nord de l'Ukraine exposés *in utero* suite aux bombardements atomiques ou à l'accident de Tchernobyl. Un risque accru de cancer à l'âge adulte a aussi été noté dans la plupart de ces études, mais on ne peut toujours pas affirmer si ce risque est supérieur, inférieur ou du même ordre de grandeur que celui qui existe pour les enfants exposés en bas âge.

Hubert Thierens, de l'université de Gand, a ensuite rapporté les résultats d'une étude importante réalisée auprès d'enfants. Comme on le sait, les enfants constituent tout comme l'embryon une population particulièrement sensible aux radiations. Du fait de l'usage largement répandu des rayons-X, l'équipe a considéré qu'il était important de connaître les risques éventuellement associés à l'usage de ceux-ci en radiologie pédiatrique. Ils ont ainsi étudié l'incidence des cassures double-brin (lésions clés de l'ADN jouant un rôle important dans la mort cellulaire radioinduite) chez de très jeunes enfants exposés aux rayons-X au cours de procédures d'intervention cardiologique. Pour ce faire, ils ont prélevé un peu de sang aux enfants immédiatement avant et après l'intervention et ils ont comparé le nombre de foyers de γ-H2AX présents dans les lymphocytes avant et après celle-ci. La γ-H2AX qui est la forme phosphorylée de l'histone H2AX constitue un biomarqueur typique des cassures double-brin induites par les radiations. Pour chaque patient, l'équipe a observé un accroissement net des foyers de γ-H2AX, représentant les cassures double-brin induites par les rayons-X

au cours de l'intervention. De plus, ils ont constaté une hypersensibilité pour ce type d'effet aux doses les plus faibles et une réponse similaire a été constatée après irradiation *in vitro* d'échantillons sanguins. Ces résultats vont dans le même sens que ceux obtenus récemment par d'autres chercheurs dans d'autres types de cellules irradiées *in vitro* par des doses faibles. Différents éléments suggèrent que l'hypersensibilité des cellules aux doses faibles résulterait d'un effet "bystander", phénomène par lequel des cellules non irradiées montrent les mêmes effets que les cellules irradiées situées dans leur voisinage immédiat, suite à la transmission par ces dernières de certains signaux. Soulignons que les recherches de l'université de Gand dans ce domaine sont actuellement poursuivies, en collaboration avec le Laboratoire de Radiobiologie du SCK●CEN et avec le support financier de l'Agence Fédérale de Contrôle Nucléaire.

Géraldine Thomas, de l'Imperial College de Londres, fait partie de l'équipe qui vient de publier un papier fort important concernant la "signature moléculaire" du cancer de la thyroïde radioinduit chez l'enfant. On sait que le cancer de la thyroïde constitue l'effet sanitaire le plus marquant de l'exposition aux radiations suite à l'accident nucléaire de Tchernobyl. Le risque de ce type de cancer touche essentiellement les personnes qui ont été exposées en tant qu'enfants (0-4 ans) aux doses élevées d'iode-131 engendrées par l'accident. Les résultats disponibles à ce jour suggèrent que les cas cliniques de cancers de la thyroïde radio-induits sont semblables à ceux observés chez les enfants non irradiés, nés plus d'un an après la catastrophe. Il est intéressant de noter que les caractéristiques moléculaires de ces tumeurs diffèrent de celles notées chez les personnes adultes atteintes du même type de cancer. Généralement, les analyses moléculaires ne montrent pas de différence entre les enfants, que les tumeurs soient dues ou pas à l'exposition aux radiations. Toutefois, les résultats que l'équipe vient de publier dans la célèbre revue PNAS (Proceedings of the National Academy of Sciences of the USA) font état de l'amplification d'une petite partie du chromosome n° 7 ainsi que de la surexpression d'un certain gène (CLIP2) chez les enfants malades qui avaient été exposés au nuage radioactif. La surexpression de ce dernier gène suggère qu'il pourrait jouer un rôle important et jusqu'ici inconnu dans les cancers radio-induits.

Simon Bouffler de l'HPA (Health Protection Agency du Royaume-Uni) a clôturé la série des exposés en présentant un bilan des connaissances concernant les effets transgénérationnels des radiations. Contrairement aux données sur animaux, il n'existe aucune preuve directe d'effets héréditaires des radiations dans l'espèce humaine. Depuis les années '90, un certain nombre d'études se sont focalisées sur les "minisatellites" ou les "ESTR" (Expanded Single Tandem Repeats) qui sont des portions d'ADN situées dans des régions non codantes des gènes et sont constituées de séquences courtes de bases répétées un certain nombre de fois (par exemple GCAATGCAATGCAAT….). Des changements dans le nombre de répétitions ont été rapportés parmi les enfants de personnes exposées aux radiations ainsi que dans la progéniture de souris irradiées. Les résultats concernant l'espèce humaine restent toutefois controversés. Des effets transgénérationnels de ce type ont encore été rapportés après exposition *in utero*, chez la souris. Les études expérimentales commencent à montrer que ces effets pourraient être liés à des changements persistants et transmissibles au niveau de l'expression de certains gènes, causés par des modifications épigénétiques du génome tels que la méthylation de l'ADN ou l'acétylation des histones.

Le symposium s'est terminé par une table ronde animée par Patrick Smeesters, conseiller en radioprotection à l'Agence Fédérale de Contrôle Nucléaire et membre de différents comités scientifiques internationaux en matière de Radioprotection. La table ronde a rassemblé certains des orateurs, des représentants de l'OMS, de l'ONE/ Kind en Gezin, un biologiste philosophe et un journaliste. Le sentiment général était qu'il restait beaucoup à étudier et qu'une attitude préventive visant à protéger l'embryon ou le jeune enfant des risques minimes mais incertains d'une exposition aux radiations devait continuer à prévaloir.

Addendum

Détail des recherches réalisées à Mol sur la radiosensibilité de l'embryon au cours des dix premiers jours de la grossesse

Le laboratoire de Radiobiologie du SCK•CEN s'est forgé une solide expérience dans le domaine de la recherche sur les effets des radiations ionisantes sur l'embryon et les cellules germinales. Ces recherches ont débuté il y a plus de 30 ans et ont bénéficié de façon pratiquement continue du support financier de la Communauté Européenne, mais aussi d'autres instances belges (dont les SSTC et la FANC-AFCN) et étrangères.
Depuis les années '90, les recherches réalisées au laboratoire de Radiobiologie du SCK•CEN se sont notamment concentrées sur l'influence des caractéristiques génétiques de l'embryon sur sa sensibilité à l'induction d'anomalies du développement par des doses modérées de radiation [1].

Une attention particulière a été accordée à la première semaine de la grossesse, période au cours de laquelle la femme ne peut savoir si elle est enceinte. Dès 1956, Russell énonçait sa fameuse loi du « tout ou rien », selon laquelle l'irradiation au cours de cette période dite "préimplantatoire" ne pouvait qu'entraîner la mort de l'embryon (si la dose était suffisante) ou sa survie sans anomalies [2]. Pour que des malformations congénitales puissent être induites, il faut donc en principe que l'embryon soit exposé à l'irradiation après son implantation dans l'utérus, au cours de la période dite "de l'organogenèse" (de la 2e à la 8e semaine de la grossesse), avec une dose-seuil estimée à 100 mGy selon les résultats des études réalisées sur animaux de laboratoire. Ce dogme de la Tératologie a toutefois été remis en question à plusieurs reprises au cours de ces dernières décennies. Des agents chimiques divers se sont en effet révélés capables d'induire des malformations congénitales chez la souris lorsque l'exposition avait eu lieu au cours de la période préimplantatoire et particulièrement au stade unicellulaire, ou stade "1-cellule" (premier jour de la gestation) [3]. En ce qui concerne les radiations ionisantes, des recherches réalisées à partir de la fin des années '80 en Allemagne ou au Japon ont de même suggéré que la période préimplantatoire et le stade unicellulaire en particulier pouvait, chez certaines races de souris, être sensible à la radio-induction de malformations congénitales, selon des mécanismes mal définis. Dans le cas de l'étude allemande, il s'agissait d'une augmentation de la fréquence d'une seule malformation ("gastroschisis", type d'hernie entraînant la saillie d'une

partie des intestins en dehors de l'abdomen) pour laquelle la race de souris Heiligenberger montrait déjà une prédisposition marquée [4]. Les chercheurs allemands ont donc suggéré que chez l'être humain également, la radio-induction de malformations congénitales par l'irradiation d'embryons préimplantés pourrait être possible s'il existait déjà une prédisposition pour de telles malformations [5]. En ce qui concerne l'étude japonaise, par contre, diverses malformations étaient observées après l'irradiation d'embryons unicellulaires et il n'existait aucune prédisposition de la race ICR pour une quelconque de ces malformations [6]. De plus, l'augmentation de la fréquence des malformations observée après de fortes doses était bien moins spectaculaire que celle observée dans l'étude allemande, et des différences significatives par rapport à la population témoin n'apparaissaient que si on additionnait toutes les malformations. D'autres études réalisées en Allemagne ont encore suggéré que l'irradiation de l'embryon unicellulaire par de fortes doses pouvait également entraîner l'apparition d'une forme d'instabilité génomique caractérisée par l'apparition d'un nombre anormalement élevé d'anomalies chromosomiques dans les cellules du fœtus, longtemps après l'irradiation [7]. La signification de ce phénomène n'est pas connue mais on sait que dans l'espèce humaine, il existe une certaine association entre une instabilité génomique et plusieurs types de cancers. Enfin, les études allemandes ont encore suggéré que les malformations congénitales et l'instabilité génomique résultant d'une irradiation par de fortes doses peu après la fécondation pourraient être transmises à la génération suivante [5,8].

Selon nous, les études allemandes et japonaises prêtent le flanc à certaines remarques ou critiques, notamment le fait qu'elles aient été partiellement ou totalement réalisées sur des races de souris constituées d'individus génétiquement différents (races outbred), que les populations témoins utilisées dans les différentes études allemandes montraient une très grande variabilité dans la fréquence spontanée de la malformation concernée, ou encore que dans les deux races de souris les effets observés après irradiation au stade unicellulaire étaient plus marqués qu'après irradiation au cours de l'organogenèse, ce qui est contraire à ce à quoi on devrait normalement s'attendre. Les études réalisées par ailleurs depuis de nombreuses années

dans le laboratoire de Radiobiologie de Mol ont notamment mené aux conclusions suivantes:

- Chez une autre race de souris (CF1) prédisposée à une malformation sévère ("exencéphalie", c'est-à-dire absence d'une voûte crânienne entraînant la saillie de l'encéphale hors de la boîte crânienne), l'irradiation de l'embryon unicellulaire par des doses croissantes allant jusqu'à 1 Gy de rayons-X n'a pas entraîné d'augmentation de la fréquence de cette malformation ou de toute autre malformation. Ces résultats obtenus dans diverses expériences réalisées au cours de la période 2007-2011 et plus particulièrement en 2010-2011 nous amènent à infirmer la conclusion que nous avions tirée il y a une quinzaine d'années, selon laquelle les embryons unicellulaires de cette race seraient sensibles à la radio-induction de malformations [9]. A l'époque, la prédisposition de cette race pour l'exencéphalie ne nous était pas non plus apparue.

- Un corollaire important de ces études récentes est que la prédisposition pour une malformation congénitale ne va pas nécessairement de pair avec un risque accru de développer cette malformation en cas d'irradiation en début de grossesse.

- Aucune instabilité génomique et aucun accroissement de la fréquence des malformations congénitales n'a de même été constatée dans la génération suivante, suite à l'irradiation d'embryons unicellulaires de races ICR et CF1 par des doses de 0,2 et 0,4 Gy [10].

- En dépit de l'absence d'effets phénotypiques, des changements dans l'expression d'une série de gènes ont été notés dans ces embryons de la génération suivante [11]. Leurs conséquences potentielles à long terme restent à définir. Toutefois, on ne peut exclure qu'ils soient le simple reflet de légères différences interindividuelles dans le développement des embryons analysés. En effet, le stade auquel l'analyse a été réalisée (gastrula) correspond au tout début de l'organogenèse et est caractérisé par une prolifération et une différentiation cellulaires marquées, logiquement accompagnées de changements considérables dans l'expression des gènes: au cours d'un tel processus dynamique, des embryons ne différant que de quelques heures dans leur évolution peuvent montrer des différences non négligeables dans leur degré de différenciation, même au sein d'une même nichée.

- Certaines mutations dans des gènes impliqués dans la réparation de l'ADN ou dans d'autres processus importants comme la régulation du cycle cellulaire ou l'apoptose (mort cellulaire programmée de la cellule) entraînent une sensibilité accrue du jeune embryon à la radio-induction d'anomalies chromosomiques par des doses élevées (0,5 ou 1 Gy de rayons-X) [12]. Lorsqu'elles sont présentes à l'état hétérozygote (un seul des deux gènes muté, cas de très loin le plus fréquent) et dans les limites des doses étudiées (jusqu'à 0,4 Gy), de telles mutations ne semblent cependant pas accroître le risque de malformations congénitales après irradiation aux stades préimplantatoires ou peu après l'implantation [13]. A nouveau, ces résultats récents obtenus sur un nombre important de fœtus nous conduisent à infirmer notre conclusion tirée à l'issue d'une étude publiée précédemment, selon laquelle la mutation hétérozygote du gène p53 semblerait entraîner une sensibilité accrue du jeune embryon à la radio-induction de malformations congénitales [14].
- Les recherches suggèrent que l'irradiation des embryons mutants pourrait toutefois s'accompagner de modifications dans l'expression de certains gènes, avec des conséquences potentielles à long terme inconnues [15]. Il convient toutefois de souligner que ces différences peuvent à nouveau résulter de très légères différences dans le développement des embryons analysés.
- En dépit de certaines particularités notées dans les études allemande et japonaise et des résultats rassurants obtenus dans la plupart des autres études avec des doses supérieures à celles normalement utilisées dans les procédures radiologiques, la possibilité d'une radio-induction de malformations fœtales chez certains individus ne peut être exclue, notamment dans le cas d'une irradiation survenant très peu de temps après la fécondation de l'ovocyte (premier jour de la grossesse).
- Cette possibilité est également supportée par les résultats positifs obtenus avec des agents chimiques après exposition d'embryons préimplantés, bien que les mécanismes responsables de ces malformations puissent être totalement différents.
- Les changements dans l'expression d'une série de gènes notés dans nos études, qu'ils soient ou non la conséquence de l'irradiation, invitent en tous les cas aussi à une certaine prudence et nécessiteront des recherches complémentaires à plus long terme, incluant notamment des animaux

porteurs de mutations dans d'autres gènes impliqués dans la réponse aux radiations.

- Le risque potentiel le plus important dans le cas d'une irradiation au cours de la première semaine de la grossesse demeure, de loin, celui de la mort de l'embryon qui disparaîtra sans laisser de traces. Selon nos recherches et celles de chercheurs japonais [16-18], le risque maximum concernerait les 6-7 premières heures du développement, la mortalité augmentant alors de 1% par dose de 10 mGy (0,01 Gy). Passé cette étroite fenêtre, la dose nécessaire pour tuer un embryon augmenterait rapidement. En effet, aux stades pluricellulaires, la mort d'une cellule peut facilement être compensée par les autres cellules.
- Ces chiffres doivent bien sûr être comparés aux risques "spontanés" accompagnant toute grossesse. Bien qu'il soit actuellement impossible de connaître précisément le taux de mortalité préimplantatoire dans l'espèce humaine, des études réalisées après fécondation *in vitro* ont suggéré que jusqu'à 50 % des fécondations pourraient être suivies de la mort de l'embryon avant l'implantation [19]. D'autre part, on estime que pas moins de 1 à 3 % des nouveau-nés sont porteurs d'anomalies congénitales, ce chiffre pouvant même atteindre 5-6 % si on inclut certaines malformations mineures [20]. Dans le domaine des doses normalement utilisées en radiologie, le risque d'induction de mort embryonnaire ou de malformation congénitale par l'irradiation d'un embryon nouvellement conçu est donc certainement faible comparé aux risques "spontanés" de tels effets.
- Ceci ne constitue bien sûr pas une raison pour ne pas appliquer certains principes de précaution, lorsque cela s'avère possible….d'autant plus que de nombreuses études ont suggéré que le risque de cancer ou leucémie infantile associé à une irradiation aux premiers stades du développement, aussi faible soit-il, n'est probablement pas non plus égal à zéro [21]. Une façon d'éviter au maximum ces différents risques consiste à appliquer la "règle des dix jours" édictée il y a plusieurs dizaines d'années. Celle-ci prévoit de limiter, lorsque cela s'avère possible, les procédures radiologiques impliquant des doses potentielles à l'embryon de plusieurs dizaines de milligray aux dix premiers jours du cycle menstruel de la femme, afin d'éviter une irradiation de l'embryon en cas de grossesse ignorée.

Références

[1] P. Jacquet, Genetic susceptibility to radiation-induced effects in embryos, *in* Effects of *in utero* exposure to ionising radiation during the early phases of pregnancy, Office for Official Publications of the European Communities, (Ed. European Communities), Luxembourg, ISBN-92 894-4536-X, pp. 17-36, 2002.

[2] L.B. Russell, X-ray-induced developmental abnormalities in the mouse and their use in the analysis of embryological patterns. II. Abnormalities of the vertebral column and thorax. *J. Exp. Zool*., 131, 329-395 (1956).

[3] J.C. Rutledge, Developmental toxicity induced during early stages of mammalian embryogenesis. *Mutation Res*. 36, 113-127 (1997).

[4] S. Pampfer and C. Streffer, Prenatal death and malformations after irradiation of mouse zygotes with neutrons or X-rays. *Teratology* 37, 599-607 (1988).

[5] C. Streffer, Genetic predisposition and genomic instability in preimplantation mouse embryos, *in* Effects of in utero exposure to ionising radiation during the early phases of pregnancy, Office for Official Publications of the European Communities (Ed. European Communities), Luxembourg, ISBN 92-894-4536-X, pp. 4-16, 2002.

[6] Y. Gu, M. Kai and T. Kusama, The embryonic and fetal effects in ICR mice irradiated in the various stages of the preimplantation period. *Radiat. Res.* 147, 735-740 (1997).

[7] S. Pampfer and C. Streffer, Increased chromosome aberration levels in cells from mouse fetuses after zygote X-irradiation. *Int. J. Radiat. Biol*., 55, 85-92 (1989).

[8] C. Streffer, Transgenerational transmission of radiation damage: genomic instability and congenital malformation. *J. Radiat. Res*., 47: Suppl., B19-B24 (2006).

[9] P. Jacquet, L. de Saint-Georges, J. Vankerkom and L. Baugnet-Mahieu, Embryonic death, dwarfism and fetal malformations after irradiation of embryos at the zygote stage: studies on two mouse strains. *Mutation Res.*, 332, 73-87 (1995).

[10] P. Jacquet, J. Buset, M. Neefs, J. Vankerkom, M.A. Benotmane, H. Derradji, G. Hildebrandt and S. Baatout, Transgenerational developmental effects and genomic instability after X-irradiation of preimplantation embryos: studies on two mouse strains. *Mutation Res*., 687, 54-62 (2010).

[11] R. Benotmane, P. Jacquet and S. Baatout, Transgenerational changes in gene expression after irradiation of mouse preimplantation embryos with moderate doses of X-rays, *in preparation.*

[12] P. Jacquet, P. van Buul, J. Buset, M. Neefs, A. van Duijn-Goedhart, A. Michaux, S. Baatout and P. de Boer, Pronounced radiation sensitivity of the mouse gastrula stage

for both locus mutations and chromosome abnormalities: involvement of Non Homologous End Joining, Homologous Recombination repair and polyribosylation, *in preparation.*

[13] P. Jacquet, J. Buset, M. Neefs, J. Vankerkom, M.A. Benotmane, H. Derradji and S. Baatout, Genetic susceptibility to delayed effects following embryonic irradiation during the very early stages of pregnancy, *in preparation.*

[14] S. Baatout, P. Jacquet, A. Michaux, J. Buset, J. Vankerkom, H. Derradji, J. Yan, H. Von Suchodoletz, L. de Saint-Georges, C. Desaintes and M. Mergeay, Developmental abnormalities induced by X-irradiation in p53-deficient mice. *In vivo*, 16, 215-222 (2002).

[15] R. Benotmane, P. Jacquet and S. Baatout, Changes in gene expression after X-irradiation of mouse preimplantation embryos carrying mutations in DNA damage response genes, *in preparation.*

[16] T. Yamada, O. Yukawa, Y. Matsuda and A. Ohkawa, Changes in radiosensitivity of the in vitro fertilized mouse ova during zygotic stage from fertilization to first cleavage. *J. Radiat. Res.,* 23, 450-456 (1982).

[17] P. Jacquet, G. Kervyn and G. De Clerq, Studies *in vitro* on mouse egg radiosensitivity from fertilization up to the first cleavage. *Mutation Res*., 110, 351-365 (1983).

[18] P. Jacquet and S. Grinfeld, Influence of some methodological factors on the radiosensitivity of the mouse zygote. *Teratology*, 42, 453-462 (1990).

[19] K. Hardy and S. Spanos, Growth factor expression and function in the human and mouse preimplantation embryo. *J. Endocrinol.,* 172, 221-236 (2002).

[20] NRPB (National Radiological Protection Board), Board Statement on diagnostic medical exposures to ionizing radiation during pregnancy and estimates of late radiation risks to the UK population. *Doc. NRPB*, 4(4), 1993.

[21] HPA (Health Protection Agency), Protection of pregnant patients during diagnostic medical exposures to ionizing radiation. Advice from the Health Protection Agency, The Royal College of Radiologists and the College of Radiographers. *Documents of the HEALTH Protection Agency, Radiation, Chemical and Environmental Hazards*, RCE-9, March 2009.

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