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Radon dose conversion coefficients and their use in the Nordic countries

Report

The Radiation Safety Authorities in Denmark, Finland, Iceland, Norway and Sweden

Radon dose conversion coefficients and their use in the Nordic countries

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Summary

The dose conversion coefficients for radon published by the ICRP in 2018[1] caused some puzzlement among many radiation protection authorities, as doses for the same radon exposure would be twice as high, and in some cases even higher. This may lead to an increased number of workplaces being considered as a planned exposure situations and requiring a safety license under the EU-BSS directive. Furthermore, the credibility of the authority may suffer in the eyes of those workplaces with elevated radon levels if a concentration level previously considered safe enough is no longer acceptable. A further complication factor is that the ICRP and UNSCEAR each have their own, different dose conversion coefficients.

The problem is not confined to workplaces. Radiation protection authorities often publish dose pie charts of the mean effective doses received by the public annually. In these, radon typically accounts for a large proportion, but with the latest dose conversion coefficients from the ICRP, radon can account for the majority of the total dose. At the same time, the effective dose to the population can almost double. How should this change in effective dose be explained to the public and the media?

This report emphasizes that the effective dose is not a measure of risk, but a tool used in radiation protection work to monitor compliance with dose limits or dose constraints when radiation exposure comes from different sources. In addition, the effective dose is a useful tool for optimizing radiation protection in order to target measures to reduce radiation exposure in a cost-effective way. It should also be noted that in the case of radon, there is an exposure-response relationship[2] for long-term *exposure* to different radon concentrations (time integral of radon concentration) and risk of lung cancer. Therefore, it is not necessary to make a risk assessment based on effective dose, but to use data directly from epidemiological studies. It is also emphasized that in the case of radon exposure, smoking is particularly important in assessing the risk to an individual, so that the effective dose is a particularly poor tool for assessing the health risk due to radon exposure to an individual.

This report summarises the current approaches in Finland, Sweden and Norway for estimating the effective dose from indoor radon in workplaces and dwellings, and for radon in drinking water. So far, Denmark and Iceland have not had the need for dose assessment for radon exposure and are therefore not covered in this report.

For occupational exposure to radon in indoor air, the working group recommends that all Nordic countries, including non-EU member states, adopt the effective dose assessment method outlined in ICRP 137 from the radiation protection point of view. The current monitoring practices and reference values specified in existing Finnish, Swedish and Norwegian legislation allow for the application of the dose conversion coefficient from ICRP 137 with minimal impact.

For managing radon exposure in the home, effective doses are not recommended. Instead focus should remain on radon activity concentration, as risk assessment for radon exposure is based on epidemiological evidence. If a "dose pie chart" is published to compare different sources of radiation, it is essential to highlight the three points outlined in the previous paragraph. In addition, the caption should clearly state that the risk assessment for radon is not based on the effective dose.

For ingested radon, the working group recommends that the latest ICRP dose conversion coefficients, based on recent scientific findings, be used in the future.

[1] The ICRP 137 part 3 bibliographic reference is for 2017, but the actual publication date was 13 February 2018.
[2] Usually, in epidemiology, this is referred to as a dose-response relationship. However, in this report, we use the term exposure-response to clarify that the dependence is specifically on radon exposure, not on effective dose.

Content

1 Introduction

In February 2018, the International Commission on Radiological Protection (ICRP) published Publication 137: *Part 3: Occupational intake of radionuclides*, in which new dose conversion coefficients (DCCs) for radon exposure were given. The new DCCs for radon inhalation, to be used in most exposure situations, were twice (for work) or three times (for dwellings) the old ones from 1993 and 1990 (ICRP 65 and 60). The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) completed a review of the report on lung cancer from exposure to radon and the applicable DCCs in 2019. The DCCs currently recommended by these two organisations differ by a factor of 1.8. For example, exposure to 200 Bq m^{-3} in dwellings results in a dose of 9 mSv per year according to ICRP but only 5.0 mSv according to UNSCEAR, assuming 7000 h of radon exposure and an equilibrium factor of 0.4.

This lack of clarity prompts the following questions:

- Which DCC should be used for assessing doses from radon exposure in homes and workplaces?
- Is radon more harmful than previously considered?
- How should these sudden changes in dose assessments be communicated to the public?
- What are the implications of the new DCCs on the workplaces?

The effective dose is a central feature of radiation protection. It summarises any number of different exposures into a single number that generally reflects the overall risk. The effective dose, expressed in millisieverts (mSv), is the sum of equivalent doses to all organs, each adjusted to take account of the organ's sensitivity to radiation, averaged over the whole body. The effective dose primarily serves the purpose of planning and optimising radiation protection, ensuring the protection of individuals through dose limitation.

The effective dose, however, is also widely used to compare contributions of different radiation sources to the public in the so called "dose pie charts". In this sense, the effective dose is often understood as a measure of risk by the public. Nevertheless, in the case of radon, there exists an exposure-response relationship for long-term *exposure* to different radon concentrations (time integral of radon concentration) with the risk of lung cancer. The effective dose is not intended as a replacement for epidemiologically derived risk estimates.

When comparing the effective dose estimates for the population provided by the three Nordic countries, it becomes evident that Finland, Sweden, and Norway have each utilized distinct methods or dose conversion coefficients to estimate the effective dose for their respective populations (Table 1). The estimated average effective doses range from 0.8 to 4 mSv per year, despite very similar radon concentrations in dwellings across all three Nordic countries.

Table 1. Assessment of annual effective doses caused by radon exposure to the public in the Nordic Countries.

Country	Year	Mean radon activity concentration	Dose conversion coefficient	Mean effective dose
Finland	2020	94 Bq m^{-3}	10 mSv WLM^{-1}	4 mSv
Norway	2015	90 Bq m^{-3}	5.7 mSv WLM^{-1}	2.5 mSv
Sweden	2007	108 Bq m^{-3}	Conversion from assessed number of lung cancers and according to epidemiological data from Darby et al. (2005)	0.8 mSv (all) 0.2 mSv (never smokers) 1.5 mSv (smokers and ex-smokers)

ICRP Publication 137 also includes the DCC for ingested radon (from drinking water). Previously, the age-specific DCCs given by the National Academy of Science (NAS, 1999) were widely supported by the scientific community. The new DCC value published by the ICRP for ingested radon by workers ($6.9 \cdot 10^{-10}$ Sv Bq^{-1}) is only a fifth of the value recommended by the NAS for adults ($3.5 \cdot 10^{-9}$ Sv Bq^{-1}). The draft document for consultation by ICRP in

May 2024[3] suggests a DCC of $7.7 \cdot 10^{-10}$ Sv Bq^{-1} for adult members of the public, also much lower than the DCC by the NAS.

This report summarises the Nordic approaches to the assessment of doses due to radon. Occupational and domestic exposures are dealt with separately, as well as airborne and waterborne radon. Experiences in communicating the new dose assessments to the public are also discussed.

2 Recommendations by international organisations

The unit of DCC for inhalation of radon is sievert (Sv) per exposure to potential alpha energy concentration (PAEC) of the radon progeny[4]. The PAEC can be expressed as J h m^{-3}, BqEEC h m^{-3} (equilibrium equivalent concentration) or WLM (working level month), which makes direct comparison of DCCs difficult. Therefore, in this report we have converted the DCC values into unit mSv WLM^{-1} to facilitate comparison, even though it is not an SI-unit.Table 2 presents the values issued or recommended by different organisations.

Table 2. Summary of the available/recommended dose conversion coefficients for exposure to airborne and waterborne radon.

Exposure	UNSCEAR 1988–2019	ICRP 2017	IAEA 2014	ICRP 1993	NAS 1999	European Commission recommendation 2024
Homes (mSv WLM^{-1})	5.7	10	8*	3.9		10
Sedentary work (mSv WLM^{-1})	5.7	10	8*	5.1		10
Physically active work (mSv WLM^{-1})		20	8*	5.1		20
Drinking water (Sv/Bq)		$6.9 \cdot 10^{-10}$			$3.5 \cdot 10^{-9}$	

* IAEA has not issued a DCC for radon but gives an example of conversion from exposure to effective dose. The value is calculated by the authors.

2.1 ICRP recommendation

The review of dosimetric computations of DCCs was already given in ICRP Publication 115. Including the most recent computations using the latest Human Respiratory Track model introduced in ICRP publication 130, the ICRP recommends the use of a DCC of 3 mSv (mJ h m^{-3})$^{-1}$ (equivalent to 10 mSv WLM^{-1}) for exposure to radon in indoor workplaces without heavy physical activity in Publication ICRP 137. This is considered to be applicable to most circumstances (including dwellings) without adjustment for aerosol characteristics. However, for indoor workplaces where workers are engaged in substantial physical activitiy, and for workers in tourist caves, the Commission recommends a DCC of 6 mSv (mJ h m^{-3})$^{-1}$ (corresponds to 20 mSv WLM^{-1}). The ICRP stresses that the DCC for indoor radon is given to one significant digit and the dose cannot be more precisely estimated than that.

Table A.3 in ICRP 137 gives reference aerosol charasteristics for general indoor workplaces, mines and tourist caves. In cases where the aerosol characteristics differ significantly from typical conditions, where sufficient and reliable aerosol data are available, and where the estimated doses require more detailed consideration, it is possible to calculate site-specific dose conversion coefficients using the data provided in the annex to the publication (Section A.8.2).

[3] https://www.icrp.org/page.asp?id=642

[4] Most of the lung dose from radon is due to the radon progeny, which due to their metallic nature adhere more effectively to the respiratory tract either attached or unattached to solid particles (aerosols). The dose from inhaling radon gas is only a small component of the total effective dose; less than 2% and 5% for indoor workplaces and mines, respectively. (ICRP 137).

In addition, the ICRP is currently (May 2024) preparing a new publication entitled Dose Coefficients for Intakes of Radionuclides by Members of the Public: Part 1, which will include DCC for radon exposure in dwellings[5]. The draft report proposes a dose conversion coefficient of 3 mSv (mJ h m^{-3})$^{-1}$ (equivalent to 10 mSv WLM^{-1}) for dwellings and all age groups. Age-dependent dose conversion coefficients will also be published for inhaled radon progeny for the members of public.

The recommended DCC for ingested radon via drinking water is $6.9 \cdot 10^{-10}$ Sv Bq^{-1} for workers (ICRP 137). The ICRP concluded that the experimental data support the assumption that absorption of radon occurs primarily or completely in the small intestine, with little diffusion across the stomach wall. The 1999 NAS model assumed partial diffusion of radon into the stomach wall and the DCC for adults was then estimated to $3.5 \cdot 10^{-9}$ Sv Bq^{-1}. Age-dependant dose conversion coefficients will be also published of ingested radon by the members of the public.

2.2 UNSCEAR recommendation

UNSCEAR (2019) reviewed 16 dosimetric assessments of the DCCs for dwellings. The arithmetic and geometric mean values were 18 and 16 nSv (h BqEEC m^{-3})$^{-1}$, respectively. The range was 7–34 nSv (h BqEEC m^{-3})$^{-1}$. Using WLM units, these values would be 11 and 10 mSv WLM^{-1} and the range would be 4–21 mSv WLM^{-1}.

In the UNSCEAR review (2019) on 5 dosimetric assessments of the DCCs in workplaces, the arithmetic and geometric mean values were 25 and 23 nSv (h BqEEC m^{-3})$^{-1}$, respectively. The range was 9–38 nSv (h BqEEC m^{-3})$^{-1}$. Using WLM units, these values would be 16 and 15 mSv WLM^{-1} and the range would be 6–24 mSv WLM^{-1}.

The UNSCEAR recommended, when estimating the impact of radon exposure levels in a population, the use of a general dose conversion coefficient of 9 nSv (h BqEEC m^{-3})$^{-1}$, which corresponds to 5.7 mSv WLM^{-1}. This is similar to the old value recommended by UNSCEAR back in 1988. As this value was within the range obtained in the review, UNSCEAR did not consider that there was not sufficient evidence to change the previous recommendation (Table 2).

The UNSCEAR DCCs is applicable for dose assessments of the public and workers exposed to radon, both indoor and outdoor. UNSCEAR stresses that it should *not* be used for radiation protection purposes (e.g. for evaluation of compliance with dose constraints), but that in such cases the ICRPs recommendations should be followed. The UNSCEARs coefficient DCC can also be used for comparison of contribution to annual effective dose from different sources of exposure.

2.3 IAEA recommendation

The IAEA General Safety Requirements Part 3: Work and Homes (2014) establishes reference levels (in activity concentration) for occupational and public exposure to radon, based on an annual effective dose limit 10 mSv. Although not explicitly stated, these reference levels appear to be derived the from ICRP Publication 115 (2010), which adjusted the previous detriment-adjusted nominal risk coefficient ($2.8 \cdot 10^{-5}$ WLM^{-1}) to $5.0 \cdot 10^{-5}$ WLM^{-1}. In tandem with the new risk coefficient there was ongoing preparations for new DCCs for both occupational and public radon exposure. The ICRP publication 115 recommended the continued use of existing DCCs from ICRP Publication 65 until new dose coefficients are available. Nevertheless, it was indicated that this adjustment may lead to approximately twofold increase in effective dose per unit exposure[6].

The IAEA recommends a maximum concentration of 300 Bq m^{-3} for the public in homes and high occupancy buildings. The publication explains that with an assumed "equilibrium factor for ^{222}Rn of 0.4 and an annual occupancy of 7000 h, the value of activity concentration due to ^{222}Rn of 300 Bq m^{-3} corresponds to an annual

[5] https://www.icrp.org/page.asp?id=642

[6] There has been some misunderstanding as to whether the ICRP gave a new dose conversion coefficient in its publications 115 and 126. Indeed, the ICRP did not issue new conversion coefficients but stated that the old so-called dose conversion convention method is obsolete, and that dose conversion should be based on dosimetric models, not epidemiology. At the same time, the ICRP reminded that the old conversion coefficients will be used until the new factors are published.

effective dose of the order of 10 mSv". Similarly, for workplaces, the IAEA suggests a maximum radon concentration of 1000 Bq m^{-3}. According to the report, assuming an equilibrium factor for ^{222}Rn of 0.4 and an annual occupancy of 2000 hours, this concentration translates to an annual effective dose of approximately 10 mSv. These conversions translate to approximately 8 mSv WLM^{-1}.

IAEA hosted a Technical Meeting on the Implications of the New Dose Conversion Factors for Radon (Oct 2019). The experts concluded that there is no immediate need to change the current reference levels, expressed in activity concentration of 1000 Bq m^{-3} and 300 Bq m^{-3}, for managing radon exposure in existing exposure situation. The experts also concluded to recommend the use of a DCC of 10 mSv WLM^{-1} (ICRP Publication 137) as a single default DCC for workplaces in existing and planned exposure situations, unless different DCC is justified by specific aerosol characteristics of the case (IAEA, 2019 and 2020).

2.4 IARCS recommendation

In July 2020, the Inter-Agency Committee for Harmonisation of Radiation Safety (IARCS) published an overview of radon-related information for radiation protection authorities and adopted the revised ICRP 137 dose conversion coefficients for radon exposure in the workplace (IARCS, 2020).

The key messages highlight that "control of radon to protect people in homes and most workplaces is guided by reference levels for radon concentrations in air. However, in planned exposure situations, where dose limits are used, protection of workers requires calculation of the radiation dose due to radon exposure using a dose coefficient or conversion factor (DCF)."

"It is up to individual national authorities to decide if and when to implement the new ICRP DCC for radon[7]. This could be carried out immediately, but it may be practical to do so once the full set of revised ICRP DCCs for workers are available to ensure a consistent approach for all radionuclides. All revised occupational DCCs are expected to be available within a year."

"The IACRS supports the continued implementation by national authorities of the approaches reflected in the IAEA General Safety Requirements Part 3 (GSR Part 3, also referred to as the International Basic Safety Standards or simply the BSS) [IAEA 2014] for managing exposure due to radon in homes and workplaces, with emphasis on optimisation of protection and the use of a graded approach."

According to IARCS (2020), the revised DCC for radon exposure in dwellings and for the public will be the same value as for workplaces by the ICRP. The ICRP, however, has not yet (June 2024) published it as discussed in section 2.1.

2.5 WHO recommendation

According to the World Health Organization (WHO), an exposure-response relationship has been demonstrated for radon, so radon should be regulated through reference levels that are expressed as annual average activity concentration. WHO recommends a reference value for radon concentration in buildings of 100 Bq m^{-3}. If this level cannot be reached under the prevailing country-specific conditions, the reference level should not exceed 300 Bq m^{-3}. WHO also notes that radon gas concentration is generally considered a good surrogate for the radon decay product concentration, and radon gas measurements are usually preferred to decay product measurements because of their relative simplicity and cost effectiveness (WHO, 2009). WHO give no recommended dose conversion coefficient.

2.6 European Commission recommendation

According to Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom (in short: EU-BSS), the calculation of doses from measurable quantities should rely on scientifically established values and relationships. The Commission recognises that the compendium of dose coefficients for internal exposure in ICRP Publication

[7] This refers to ICRP Publication 137 part 3 (2017).

119 is being updated on the basis of the radiation and tissue weighting factors and phantoms laid down in ICRP Publication 103. The EU-BSS also provides that the Commission shall invite the group of experts referred to in Article 31 of the Euratom Treaty to continue to monitor scientific developments and that the Commission shall make recommendations on any updated values, relationships and coefficients, including those for exposure to radon, taking relevant opinions of the group of experts into account.

After having consulted the group of experts referred to in Article 31 of the Euratom Treaty, the Commission recommended that Member States should use the ICRP Publications on Occupational Intakes of Radionuclides: Part 1-5 (ICRP Publications 130, 134, 137, 141 and 151), and all the dose coefficients therein, in the estimation of the effective dose and equivalent dose from internal exposure for the purposes of Directive 2013/59/Euratom (Official Journal L, 2024/440). In practice, this means that for occupational exposure, Member States will have to use the ICRP 137 dose conversion coefficient for radon.

3 The use of dose conversion coefficients in the Nordic Countries

In this section, the use of radon dose conversion coefficients in the Nordic Countries is summarised. The following issues are reported:

- Is the dose assessment method presented in the legislation?
- In which situations are doses from radon assessed in workplaces and how?
- In which situations are doses from radon assessed in homes and how?
- In which situations are doses from radon assessed in drinking water and how?

3.1 Finland

3.1.1 Regulatory basis

Finland has adopted the DCCs for inhalation of radon recommended by the ICRP 137. Annex 3 of the 2018 Government Decree on Ionising Radiation (1034/2018) (GDIR, 2018) introduces the dose assessment methods to be used for regulatory oversight exercised under Radiation Act (1034/2018 12 §). The following equation is given for the assessment of effective doses from radon in air:

$E = h\, t\, C(AE)$

where

h is the dose conversion coefficient

t is exposure time

$C(AE)$ is the alpha energy concentration.

The unit of exposure time (t) is hours, and the unit of alpha energy concentration $C(AE)$ is J m^{-3}. The alpha energy concentration is the total potential alpha energy per unit volume that arises in from the short-lived decay products in the decay chain of radon.

The $C(AE)$ can be assessed based on radon activity concentration, $C(Rn)$, expressed in the unit (Bq m^{-3}):

$C(AE) = F \cdot C(Rn) \cdot 5.56 \cdot 10^{-9}\ J/Bq$

in which the equilibrium factor F is 0.4 unless specifically measured. Other values for equilibrium factor may be used if justified by studies carried out or by international recommendations.

The dose conversion coefficient is 3 mSv mJ^{-1} h^{-1} m^{3} for homes and workplaces. Other value for the DCC may be used if there are supportive studies or international recommendations show that it is justified.

The ICRP recommendation of 6 mSv mJ^{-1} h^{-1} m^{3} (20 mSv/WLM) for physically active work is not included in the GDIR (2018). No dose assessment method for thoron (Rn-220) exposure is given. No dose conversion coefficient for ingested radon is given.

3.1.2 Use of the dose conversion coefficients for workplaces

According to EU-BSS, if a workplace cannot reduce the radon concentration below the reference level, an assessment of effective the dose is required. If the effective dose from radon exceeds 6 mSv per year, the exposure must be regarded as planned exposure, and below this level, exposures must be kept under review.

The Finnish legislation is stricter in this respect and the reduction of radon exposure is the key[8]. If the reference value of 300 Bq m^{-3} is exceeded in workspaces with more than 600 hours of occupancy per year, or if the total annual exposure exceeds the reference value of 500 000 Bq h m^{-3}, the employer shall reduce radon exposure in accordance with the Radiation Act (859/2018). There is therefore no need for dose assessment. Only if it is not possible to reduce radon exposure must the workplace apply for a safety licence.

Dose assessments are carried out in the following two cases:

- Workplaces applying for a licence must provide a reliable dose assessment as a part of the optimisation of radiation protection (ALARA, As Low As Reasonably Achievable, and dose constraint).
- Licensed workplaces will regularly report effective doses to the dose register at STUK. Licensees may take into account the use of respiratory masks when assessing doses and comparing them with the dose constraint (in-house Guide STO 5.1 annex 10).

In May 2024, only one workplace has a licence for exceeding the reference levels for radon exposure.

The use of the new DCC has had little impact on the regulatory oversight exercised in workplaces, including underground excavations and mines.

3.1.3 Use of the dose conversion coefficients for dwellings

Every few years, STUK publishes pie charts of effective dose to the population. These pie charts exclude occupational doses which are reported elsewhere. The two most recent population dose pie charts are from 2012 (Muikku et al., 2014) and 2018 (Siiskonen, 2020) shown in the Figures 1 and 2 respectively. In the 2012 chart, the mean annual effective dose from radon exposure of the Finnish population was calculated using the DCC of 3.88 mSv WLM^{-1} given in the ICRP Publication 65. In the 2018 chart, the DCC of 10 mSv WLM^{-1} from ICRP 137 was used.

3.1.4 Use of the dose conversion coefficients for drinking water

Doses from radioactivity in drinking water have been indirectly included in the dose pie charts of 2012 and 2018. According to theses assessments, about 160 000 Finns permanently use water from drilled wells. The mean radon concentration in drilled well water is 460 Bq l^{-1} or 311 Bq l^{-1}, depending on the survey. Therefore, the doses to this group of users have been discussed separately.

The 2012 assessment used the NAS dose conversion coefficient, and the 2018 assessment used the ICRP coefficient (Table 3). Therefore, the doses are lower in the 2018 assessment, although the concentrations and intakes have remained the same (Table 3). Only the DCC for radon has changed.

[8] The EU BSS is a minimum harmonisation directive. Member States thus have the right to set stricter requirements than those laid down in the directive.

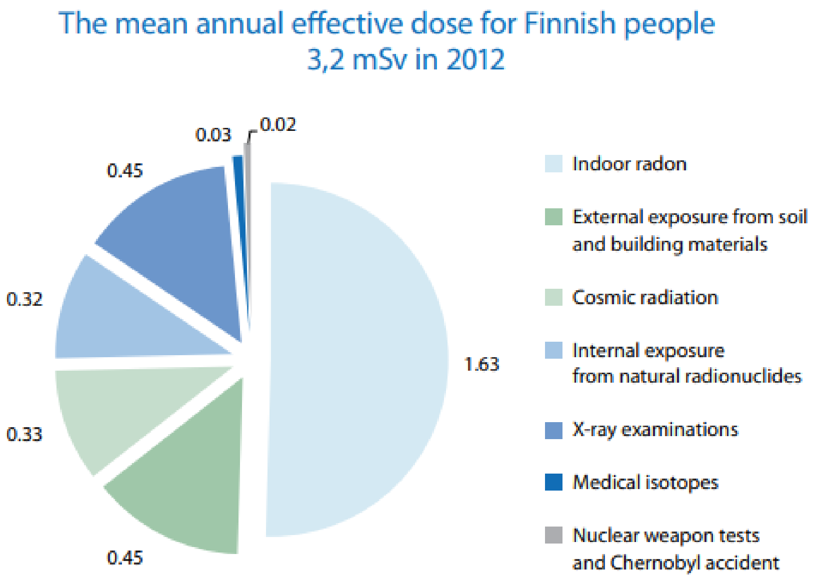

Figure 1. Mean effective doses from ionising radiation for the Finnish population in 2012 (Muikku et al., 2014). The contribution of man-made sources to the total effective dose is estimated at 16 %. The effective dose from exposure to radon accounts for 51 % of the total dose.

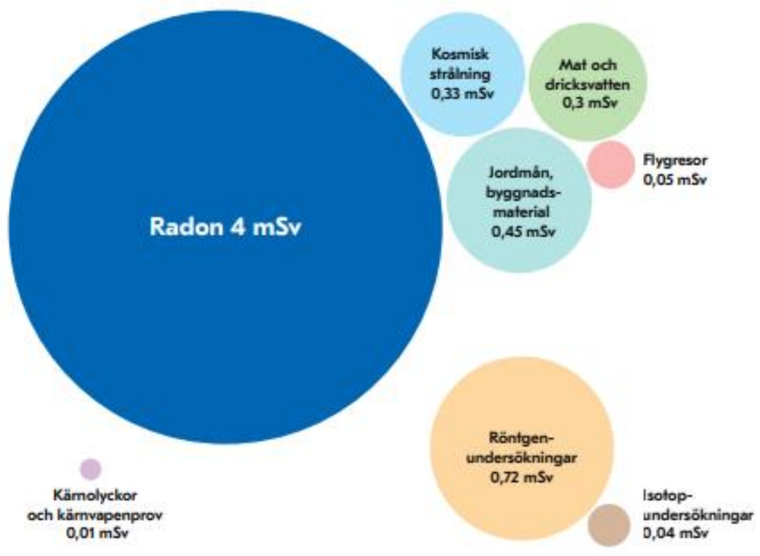

Figure 2. In 2018, the mean effective dose from ionising radiation for the Finnish population was estimated at 5.9 mSv (Siiskonen, 2020). The proportion of man-made radioactive substances, 13%, is a minor part of the total effective dose. The effective doses originating from exposure to radon comprises 68 % of the total dose, which is 12 % higher than that in 2012 due to the higher DCC associated with radon exposure.

Table 3. Assessment of annual effective doses caused by uranium series radionuclides (U, Ra-226, Rn-222, Pb-210 and Po-210) and Ra-228 in drinking water in Finland.

User group	Eff. dose in 2012 (mSv/y)	Eff. dose in 2018 (mSv/y)
Water works	0.03	0.02
Dug well	0.08	0.05
Drilled well	0.55	0.28
All users	0.05	0.03
Total	0.71	0.38

Another situation in which DCC for radon is needed is the regulatory control of drinking water by the municipal health authority. For small waterworks and cooperatives, the quality recommendation for radon is less than 300 Bq l^{-1} (decree 401/2001). For larger commercial water suppliers, the quality objective is below 300 Bq l^{-1} and the quality requirement is below 1000 Bq l^{-1} (decree 1352/2015). The need for corrective measures must be considered on the basis of a risk assessment if the quality objective is not met. Corrective action must always be taken if the quality requirement is not met.

The mean transfer factor for radon released from water to indoor air in Finnish dwellings has been assessed to be $0.39 \cdot 10^{-4}$ (Turtiainen and Salonen, 2010). This means that if the water used in a household contains 1000 Bq l^{-1} of radon, it increases the radon concentration in the indoor air by 39 Bq/m^3. It can, therefore, be calculated that more than 90 % of effective dose from waterborne radon is due to inhalation of radon.

In the present situation, the 300 Bq l^{-1} appears to be an unnecessarily stringent requirement, as it will only result in a dose of 0.04 mSv per year for the average user (ingestion of 0.5 l of cold tap water per day). A dose of 0.1 mSv only occurs if the radon concentration in water is 800 Bq l^{-1}. However, we know that there is large variation in the water-to-air transfer factor. It can be one order of magnitude higher if the ventilation of the dwelling is inefficient and the volume of the air in the dwelling is small relative to the water consumption. The risk assessment, therefore, should pay particular attention to indoor radon concentrations. One approach is to measure dwellings that have not yet been measured and decide upon countermeasures based on the results.

3.2 Sweden

3.2.1 Regulatory basis

It follows from the EU-BSS that the Member States are required to bring into force the laws, regulations, and administrative provisions necessary to comply with the directive. In Sweden, this has been accomplished by a new Radiation Protection Act (RPA) (SFS 2018:396) and a new Radiation Protection Ordinance (RPO) (SFS 2018:506), as well as by the Swedish Radiation Safety Authority's (SSM) regulations concerning radon at workplaces (SSMFS 2018:10). The new RPA, RPO and SSM's regulation came into force on 1 June 2018. Sweden has not implemented DCC for radon in the regulations. In most cases, the radon activity concentration, expressed in Bq·m^{-3}, or the radon exposure (integrated radon activity concentration), expressed in Bq h m^{-3}, are used for radon management.

In accordance with chapter 3, section 6 of the RPO, the national reference level for radon activity concentration is 200 Bq m^{-3} in indoor air in dwellings, premises to which the public has access and in workplaces, expressed as an annual average activity concentration. This complies with article 74, item 1 of the EU-BSS (2013), where the reference level is set at 300 Bq/m^3 for indoor radon activity concentration. The assessment of effective doses from indoor radon in dwellings in Sweden is described below in section 3.2.3.

In distinction to dwellings, where the annual average radon activity concentration is only recommended to be compared with the reference level in accordance with chapter 3, section 6 of RPO (which implies no dose calculations), radon exposure in workplaces is also regulated by comparison with maximum permissible *annual* *radon exposure* levels. It should be noted that the optimisation principle ALARA (As Low AS Reasonably Achievable) is always required in relation to dwellings, premises to open to the public and workplaces, regardless of the level of the radon activity concentration according to chapter 3, section 5 of the RPO.

Radon exposure at workplaces is regulated in Sweden by the SSM (regulation SSMFS 2018:10) and the Swedish Work Environment Authority (AV) (regulation AFS 2018:1).

According to section 4 of the regulation SSMFS 2018:10, workplaces shall notify to and be registered by SSM if the annual average radon activity concentration during working hours exceeds the reference level of 200 Bq m^{-3}

- either because measures to reduce the radon activity concentration are not expected to reduce the radon activity concentration below the reference level, or
- because the reference level is exceeded despite the measures taken.

Normally, the employer is responsible for this type of notification.

For workplaces that are subject to registration in accordance with section 4 of the regulation SSMFS 2018:10, the radon exposure of the employees concerned shall be established by measurement or calculations to the extent necessary for the control and monitor radon exposure in accordance with section 8 of the regulation (SSMFS 2018:10). These radon exposure values must then be compared with the national maximum permitted levels, known as hygienic limit values, which are established in the AV's regulations (AFS 2018:1). According to items 41 and 42 in the AV regulations (AFS 2018:1), there are three hygienic limit values depending on the type of workplace:

- For underground work, the annual radon exposure must not exceed 2.1 MBq·h m^{-3}. Underground work is defined as mining work, underground construction work and similar work, as well as temporary work in underground premises, rock chambers, tunnels and similar.
- For other types of underground work, such as work in completed and furnished rock chambers and rock facilities, basements and the like, the annual radon exposure must not exceed 0.72 MBq·h m^{-3}.
- For work other than underground work, the annual radon exposure shall not exceed 0.36 MBq·h m^{-3}.

Where the estimated annual radon exposure exceeds the relevant maximum permitted level, appropriate measures shall be taken to reduce the exposure below the limit values.

According to section 5 of the regulation SSMFS 2018:10, a workplace where workers may be exposed to more than 0.72 MBq h m^{-3} per year during working hours shall be notified to and registered with SSM by the party in control of the workplace. These workers must be identified in accordance with section 9 of the same regulation and their radon exposure must be determined annually and individually, either by measurement or by calculation in accordance with section 8.

If a worker may have received an annual radon exposure of more than 2.1 MBq·h m^{-3}, this must be reported to SSM as soon as possible according to section 16 of SSMFS 2018:10.

For most workplaces, it is not necessary to calculate effective doses from radon to workers in order to ensure that national effective dose limits are not exceeded (see section 3.2.2 for more details). However, for workers employed in a workplace with ionising radiation that is a subject to a permit or notification requirement (according to Chapter 1, Section 7 of the RPA), the annual effective doses from indoor radon and from other radioactive sources related to the workplaces with ionising radiation shall be summed up when comparing with the effective dose limits (section 7 of SSMFS2018:10). The assessment of effective doses from radon at workplaces in Sweden and the associated dose conversion coefficients are described in section 3.2.2.

The Swedish Food Agency is the authority responsible for drinking water quality in Sweden, and the corresponding requirements are given in the regulations SLVFS 2022:12 on drinking water. The regulation states that the radon activity concentration in drinking water must not exceed 100 Bq l^{-1}.

If the result of an investigation shows that there are deviations from the limit value, an operator who produces drinking water or supplies it from a distribution facility or tank must immediately investigate the cause of the deviation, assess whether the deviation poses a risk to human health and take the necessary measures as soon as possible. When assessing the measures to be taken, the extent of the deviation and the risk to human health shall be taken into account. This regulation applies to operators producing or supplying at least 10 m^3 of water intended for human consumption per day, or supplying at least 50 persons with water intended for human consumption.

According to the Food Agency's advice on water from private wells, water that contains more than 1000 Bq l^{-1} should not be used for drinking or cooking.

The situation in Sweden regarding the assessment of effective doses from radon in water is described in more detail in section 3.2.4.

3.2.2 Use of the dose conversion factors/coefficients for workplaces

Assessment of the dose to the lung/respiratory tract from radon exposure is a complex task and depends on many model parameters and assumptions, which introduce relatively large uncertainties.

No specific Dose conversion coefficient (DCC) is officially used in Sweden. SSM has not yet formally decided which DCC should be used for the assessment of effective dose from occupational exposure to radon. SSM is investigating the various DCCs established by the ICRP, in addition to UNSCEAR, and what consequences they have for the assessment of the effective dose due to occupational radon exposure, but also due to radon exposure of the general population. However, no formal conclusion has yet been reached (June 2024).

Nevertheless, a DCC based on the ICRP Publications 103 (2007) and 115 (2010) is applied in the SSM's regulation on radon at workplaces (SSMFS 2018:10). This has been done to compare the annual effective dose of 6 mSv (as stated in the EU-BSS) with the annual radon exposure (or integrated activity concentration) of 0.72 MBq·h m^{-3}, which is one of the values for notification and registration in Sweden.

According to the EU-BSS, exposure to radon exceeding 6 mSv per year shall be handled as a planned exposure situation. With the (occupational) DCC based on ICRP Publications 103 and 115[9], it is estimated that an annual effective dose of 6 mSv, using an equilibrium factor (F) of 0.4, results in an approximate annual radon exposure of slightly more than 0.72 MBq·h m^{-3}. Thus, an annual radon exposure of 0.72 MBq·h m^{-3} was conservatively estimated to result in an effective dose from radon slightly less than 6 mSv per year. This value for radon exposure was adopted as the limit value for additional notification to SSM in accordance with section 5 of the regulation SSMFS 2018:10.

It should be noted that the SSM's regulations on workplaces with elevated radon activity concentrations primarily require that the annual radon exposure (integrated activity concentration) of workers as the quantity to be determined and used for the control and limitation of radon exposure, instead of the annual effective dose, which involves a more complex assessment. The main reason for using the concept of radon exposure instead of effective dose is that the concept is already used, known and applied by most workplaces where the annual average radon activity concentrations are higher than the reference level. The Swedish Work Environment Authority also uses this approach. This makes the regulatory system for radon in workplaces more predictable and easier to adapt to practices.

Only in one specific situation (workplaces with ionising radiation, see section 3.2.1) it is mandatory to calculate effective doses from radon exposure so that this contribution can be added to the total annual effective dose. The SSM's regulation SSMFS 2018:10 states that the dose from radon can be assessed in several ways. However, there is neither a requirement nor a recommendation as to which DCC should be used, nor how the effective dose should be assessed from radon exposure. Dose assessment should be carried out by the party in control of the workplace using ionising radiation.

[9] Similarly to ICRP 65, where the radon DCC was derived by conversion convention, the ICRP103 detriment-adjusted nominal risk coefficient for adults of 0.042 Sv^{-1} and a lifetime excess absolute risk of $5 \cdot 10^{-4}$ per WLM (ICRP 113) for radon exposure among workers results in DCC of 12 mSv WLM^{-1}.

3.2.3 Use of the dose conversion coefficients/ coefficients for dwellings

SSM's assessment of the annual mean effective dose to the Swedish general population from exposure to indoor radon *(*Andersson et al. 2007*)* is based on epidemiological studies in which the linear relationship between residential radon activity concentration and the risk of lung cancer has been estimated (Darby et al. 2006).

Based on the average indoor radon activity concentration in Sweden and the exposure-response relationship found in the study by Darby et al. (2006), the number of annual lung cancer cases in Sweden attributable to indoor radon in dwellings, both in small houses and apartment buildings, has been assessed. SSM estimates that approximately 14% of the total number of lung cancer cases diagnosed annually in Sweden can be attributed to exposure to indoor radon.

From this estimate, a corresponding effective dose to the general population due to radon exposure was calculated based on the size of the Swedish population, the annual exposure time and the detriment per effective dose to the general population taken from ICRP Publication 103 (ICRP 103). The annual effective dose to the general population from indoor radon was thereby estimated to be approximately 1 mSv (Andersson et al. 2007).

It could be a potential problem that the ICRP 137 Dose conversion coefficient does not seem to be consistent with the number of lung cancer cases in Sweden, if the number of cases would be estimated from the total exposure (population size multiplied by mean indoor radon activity concentration) and ICRP detriment per effective dose.

When dealing with risk for the general population associated with indoor radon, SSM currently prefers to keep to *risk*, and not to involve dose calculation based on DCC. This is because in the case of radon, in contrast to most other radiation exposure situations, we have direct information on the risk through epidemiological studies, and do not need to calculate effective dose using DCC.

Therefore, regarding dwellings there is currently no DCC applied for converting measured indoor radon activity concentration into effective dose.

3.2.4 Use of dose conversion coefficients for drinking water

The regulation concerning drinking water quality (section 3.2.1) sets a limit value of 100 Bq l^{-1} for the radon activity concentration. A limit is also set for the parametric value of indicative dose (0.1 mSv y^{-1}), but radon is not included in this parameter and thus there is no DCC for radon in the drinking water quality regulation. In the most recent compilation of effective doses assessed for the *general public* (Andersson et al. 2007), the dose from radon in drinking water was based on a mean radon activity concentration of 38 Bq l^{-1}, a water consumption of 60 l y^{-1} (cold water straight from the tap) and a dose conversion coefficient of 0.0035 µSv Bq^{-1}, i.e. the NAS DCC mentioned above (NAS, 1999), resulting in an effective dose of 0.008 mSv y^{-1}.

3.3 Norway

3.3.1 Regulatory basis

Norway has not implemented DCCs for radon in the regulations. In most cases, the radon activity concentration, expressed in Bq m^{-3}, is used for radon management. The DSA's general reference levels as well as the legally binding limit values for new buildings and for schools, kindergartens and rental accommodation are given in Bq m^{-3} (100 Bq m^{-3} and 200 Bq m^{-3} are the action and maximum levels, respectively).

3.3.2 Use of dose conversion coefficients for workplaces

The EU-BSS sets requirements for workplaces in the EU. Norway is not a member of the EU, and is therefore not bound by the directive.

In Norway, radon in workplaces is regulated in general terms in the Working Environment Act, which is administered by the Norwegian Labour Inspection Authority. The employer shall ensure a fully satisfactory working environment. In general, there are no legally binding limit values, but the DSA's general recommendations should be taken into account when considering radon exposure in the working environment. This advice is given in guidelines from the Labour Inspection Authority.

Some workplaces are unable to meet the general reference levels, and for such workplaces, typically underground workplaces, the guidelines from the Labour Inspection Authority gives recommended radon limits, expressed as radon exposure limits in Bq h m^{-3}. The guidelines propose a graded approach system of action: If the radon level is above the general recommendation, 100 Bq m^{-3} and 200 Bq m^{-3}, despite measures to lower the activity concentration, the actual radon exposure of the workers should be calculated. If this is above 0.36 MBq h m^{-3}, the employer should inform the employees, the workplace should be measured more regularly to ensure updated exposure calculations, and there should be routines and measures in place to ensure the lowest possible exposure. If a worker is exposed to 0.72 MBq h m^{-3} or more, the workplace should be managed as a planned exposure situation, according to the guidelines. Using the DCC of 10 mSv WLM^{-1} given in ICRP 137 and assuming an equilibrium factor F=0.4, the exposure of 0.72 MBq h m^{-3} corresponds approximately to the 6 mSv limit given in the EU-BSS (in fact 6 mSv corresponds to a slightly higher exposure). Norway is in line with the ICRP 137 DCC for radon in workplaces.

The radon exposure value on 2.1 MBq h m^{-3} is the recommended upper limit for workplaces and should never be exceeded.

3.3.3 Use of dose conversion coefficients for dwellings

When comparing doses from different types of radiation sources, typically in a dose pie-chart, it is necessary to use dose conversion coefficients (DCCs) for radon. The dose pie chart for Norway was last updated in 2015 (Komperød et al. 2015) using the UNSCEAR radon DCC of 9 nSv Bq^{-1} h^{-1} m^{-3}, EEC (5.7 mSv WLM^{-1}). With an average radon level in dwellings of about 90 Bq m^{-3} (and assuming F=0.4 and an indoor occupancy of 90 %) this resulted in radon contributing about half of the total mean effective dose to the Norwegian population, about 2.5 mSv annually (Figure 3). It will be decided which DCC Norway will use when updating the dose pie chart in the future. Figure 4 has been created to illustrate that some people will receive effective doses that are far above the average (Komperød et al. 2015).

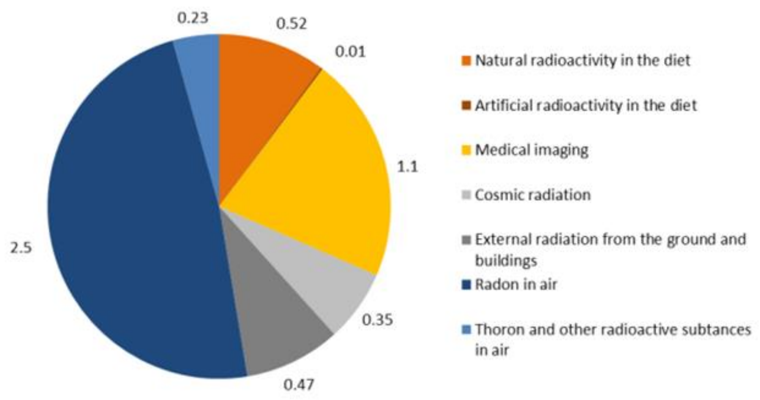

Figure 3. Summary of the average radiation dose (mSv/year) received by the Norwegian population from various sources (Komperød et al. 2015).

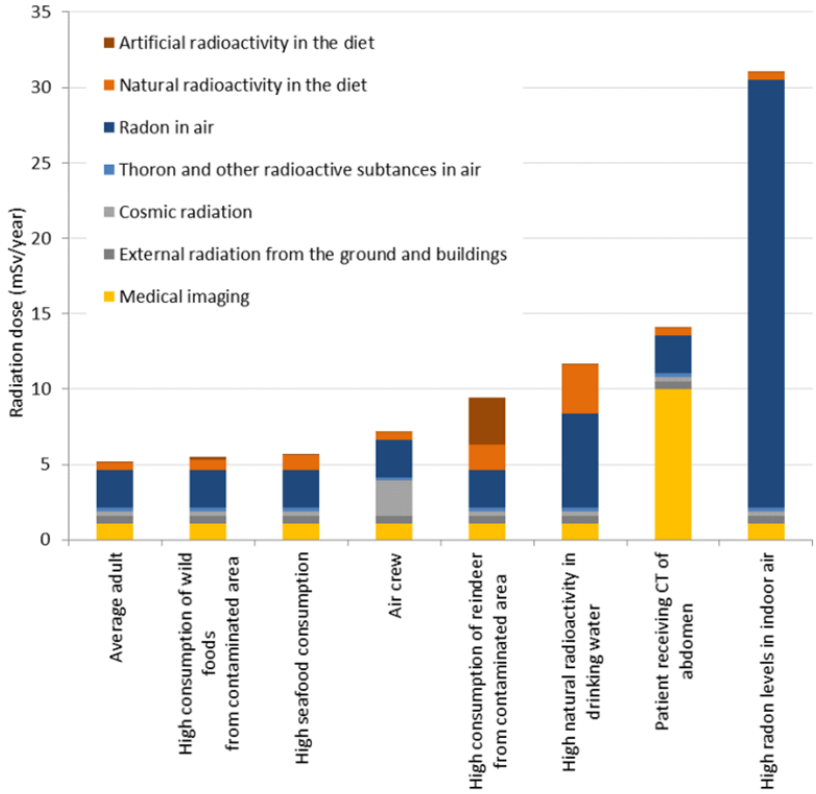

Figure 4. Comparison of radiation doses received by an average Norwegian and persons representing the various examples of elevated exposure. (The assumptions and estimations are described in Komperød et al., 2015:11). This comparison is only meant to illustrate the point that different population groups receive different doses depending on e.g. diet, residence or occupation.

3.3.4 Use of the dose conversion coefficient for drinking water

Approximately 20% of Norwegians obtain their drinking water from a ground water supply. Roughly half of these are private wells. Most private wells are drilled into the bedrock. A survey carried out by the DSA and the Norwegian Geological Survey in the 1990's found a mean radon activity concentration of 400 Bq l^{-1} in private wells drilled in bedrock. The mean intake of tap water (excluding use for other beverages, such as tea and coffee) for an adult Norwegian is approximately 1 liter daily (Totland et al. 2012).

Norway has until recently used the DCC published by the NAS for the intake of radon from drinking water, e.g. for the assessment of public exposure in 2015 (Komperød et al. 2015). Using this factor, the mean effective dose from private bedrock wells was estimated at 0.5 mSv y^{-1}. Using a weighted mean for different types of drinking water sources, the mean effective dose from ingestion of radon was estimated at 0.05 mSv y^{-1}.

In future assessments, Norway is expected to use the new ICRP DCC for drinking water, resulting in lower dose estimates (Table 2).

4 Discussion

Even though the effective dose is not intended to be a quantity of risk, it is often regarded as such, especially in situations where no exposure-response relationship is available from epidemiological studies. However, in the case of radon, there is sufficient epidemiological data supporting lung carcinogenicity of inhaled radon. In Europe, lung cancer risk from domestic exposure is generally assessed using an excess relative risk of 16% per 100 Bq m^{-3} in a 30-year exposure (Darby et al., 2006). Since smokers have a much higher baseline risk of lung cancer, this excess relative risk translates to a higher absolute risk for smokers at the same effective dose.

The ICRP reassessed the lifetime excess *absolute* risk in 2010, establishing a risk coefficient of $5 \cdot 10^{-4}$ per WLM for workers, compared to the 1993 assessment of $2.8 \cdot 10^{-4}$ per WLM. However, this risk coefficient does not recognize smoking habits. This is only natural, as the standard of occupational health and safety should not be affected by the smoking habits of employees. It is always worth bearing in mind whether you are dealing with risk assessment, radiation protection or epidemiology.

STUK published the 2018 dose pie-chart in April 2020. The chapter on radon stated, "The effective dose poorly describes the risk of lung cancer caused by radon because the effective dose does not take smoking into account. In other words, the same effective dose causes a clearly different risk for smokers and non-smokers. [...] The new dose conversion coefficient has no effect on the risk assessment, i.e., the estimated number of radon-related cancer deaths."

The media widely published the new dose assessments, but the validity of these assessments (or the entire system of radiological protection) was not questioned, contrary to previous anticipation. This may be because the report clearly explained what the new dose assessment method means in terms of risk. Another equally plausible explanation is that the coronavirus epidemic at that time diverted the press's attention.

If choosing to publish a dose pie-chart, it is crucial to emphasize the disparity between effective dose and the risk associated with radon exposure, considering the influence of smoking habits. Structuring the pie chart to separate radon from other radiation exposures, perhaps through a distinct colour of a column, sphere, or similar element, could be beneficial. This approach could help to distinguish radon from other radiation exposures within the "pie", facilitating a clearer explanation in the caption regarding the disparity between the effective dose from radon and the associated risk. It is also useful to compare radon with other environmental pollutants, such as fine particles, passive smoking or environmental noise, as typically these exposure situations are also "existing". In this case, the comparable quantity could be e.g. DALY per year[10].

According to the EU-BSS (2013), workplaces where the annual radon exposure exceeds 6 mSv should be treated as a planned exposure situation. As mentioned earlier, the EU-BSS is a minimum harmonisation directive, so Member States can also set more stringent requirements. Both Sweden and Norway have a reference value for occupational radon exposure of 0.72 MBq h m^{-3}, above which work is defined as a planned exposure situation. An annual effective dose in accordance with ICRP 137 at a radon exposure of 0.72 MBq h m^{-3} and an equilibrium factor of 0.4 results in an annual effective dose of approximately 5 mSv for a sedentary indoor worker. Thus, the requirement of the Directive is met among sedentary workers and is even slightly more stringent than required.[11] The use of the dose conversion coefficient given in ICRP 137 does not require any changes to existing regulatory practices.

In Finland, if the annual radon exposure exceeds the reference value of 0.5 MBqh m^{-3} and the workplace is unable to reduce the radon exposure despite efforts, the work should be treated as a planned exposure situation. In other words, in Finland, a safety license is already required for annual effective doses above 3 mSv using ICRP 137 DCC. Dose assessment is only required when applying for a safety licence and during the period of its validity. The method of dose assessment is specified in the legislation and is in accordance with ICRP 137.

The Nordic approach to radon risk management in the workplace has attracted attention elsewhere in Europe, since in the Nordic Countries radon exposure above reference level rarely leads to a cumbersome assessment of effective dose. Many European countries are still debating the best method for assessing effective doses, since in addition to the site-specific dose conversion coefficient, other information is needed, such as working hours in different workspaces, total annual working hours and information on the temporal (daily, weekly, seasonal) variation of radon concentrations.

In the Nordic countries, radon risk management is based on radon exposure assessment (time-integral radon concentration) and effective radon remediation. It is important to recognize that dose assessment does not reduce occupational radiation exposure, but radon remediation and the use of alternative workspaces do.

The Nordic measurement protocol in the workplace has also attracted attention. The requirement for energy efficiency in buildings has brought ventilation systems operated according to working hours to all parts of

[10] Disability-adjusted life years. One DALY represents the loss of the equivalent of one year of full health.
[11] For physically active work (DCC of 20 mSv WLM^{-1}) compliance with the 6 mSv limit is not fulfilled. This issue needs to be addressed in the future.

Europe, so the Nordic approach to measure radon exposure at work is potentially spreading to other European countries. Thus, harmonisation of the assessment of occupational exposure is well advanced in the Nordic countries, but common procedures should be agreed upon in the light of free labour movement across the borders. This is particularly important for the protection of workers in companies that operate in two or more Nordic countries and whose radon exposure is monitored by authorities in more than one country.

In Finland, Sweden and Norway, the latest estimates of the effective dose to the population from radon exposure are completely different, basically due to different methodologies used. The most recent Finnish assessment in 2020 used the dose conversion coefficient according to ICRP 137 and Norway used the dose conversion coefficient recommended by UNSCEAR in 2015. In Sweden, the effective dose was estimated in 2007 on the basis of the number of lung cancers caused by radon, based on the excess relative risk defined by Darby et al. (2006). Thus, the Swedish estimate also took into account the effect of smoking on the effective dose and presented different effective doses for non-smokers and smokers (Table 1).

Although radon levels in homes are similar in the three Nordic countries, the estimated and reported effective doses differ significantly. In this situation, it would obviously be a good idea to harmonise a Nordic approach. However, the authors of this report concur that the utilisation of the effective dose for assessing radon exposure in the population is problematic due to:

1. The effective dose is, in principle, a quantity of radiation protection that is used to manage exposures via different exposure pathways and to optimise dose reduction measures.
2. For radon exposure in the dwellings, the exposure-response relationships exist from three pooled epidemiological studies (Asia, America and Europe) and their results are consistent. Therefore, the risk associated with radon is best assessed based on epidemiological studies.
3. The individual risk associated with radon exposure is strongly dependent on the smoking habits of the individual. The effective dose is a radiation protection parameter, which does not consider smoking.

5 Recommendations

The Commission Recommendation (EU) 2024/440 regarding the value of dose conversion coefficient in the assessment of occupational dose is clear. It explicitly recommends that Member States should henceforth estimate doses according to ICRP 137. Consequently, for occupational exposure to radon in indoor air, it is recommended that all Nordic countries, including non-EU member states, adopt the effective dose assessment method outlined in ICRP 137. The current regulatory oversight and reference values stipulated in existing Finnish, Swedish and Norwegian legislation allow for the application of the dose conversion coefficients from ICRP 137 with minimal impact.

For managing radon exposure in the home, effective doses are not recommended to be assessed. Instead focus should remain on radon activity concentration, as risk assessment for radon exposure is based on epidemiological evidence. If a "dose pie chart" is published to compare different sources of radiation, it is essential to highlight the three points outlined in the previous paragraph. In addition, the caption should clearly state that the risk assessment for radon is not based on the effective dose.

For ingested radon, the working group recommends that the latest ICRP dose conversion coefficients, based on recent scientific findings, be used in the future.

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