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Review

Estimating the Annual Average Dose to the Public from Ionizing Radiation in Ireland

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The public is constantly exposed to radiation from a variety of sources, both natural and artificial. Natural sources of radiation include cosmic radiation; external radiation from radioactivity in the earth's crust; the radioactive gases radon and thoron released from radioactivity in the earth's crust; and radioactivity transferred to foodstuffs. There are also sources of artificial radioactivity in the environment. The testing of nuclear weapons, nuclear accidents and authorised releases from nuclear facilities abroad have all resulted in radioactivity reaching Ireland. Radioactivity is also released in small amounts into the Irish marine environment from hospitals and research facilities located along the Irish coastline. As with sources of natural radioactivity, artificial radioactivity can give an external radiation exposure and also be transferred through the food chain to give an internal radiation exposure.

This work outlines the methodologies used to evaluate the dose received to members of the Irish public from the exposure pathways outlined above. The average annual effective dose to a person in Ireland from all sources of radiation is now estimated as 4037 µSv. Natural sources of radioactivity account for 86% of the total effective dose in Ireland with the remainder attributed to artificial sources and are dominated by radiation in medicine.

Key words: Dose Assessment, Radon, Public population dose, effective dose

1. Introduction

The Environmental Protection Agency (EPA) in Ireland has responsibility for the protection of members of the public and the environment from the harmful effects of ionising radiation. This work includes the provision of advice on matters related to radiological safety and informing members of the public of the levels of radioactivity in the Irish environment[1)].

The EPA provides advice to members of the public on the exposure and dose received from all sources of ionising radiation (both natural and artificial) though the publication of dose assessment reports that are compiled an published every 6 – 8 years[2, 3)].

The dose assessments are conducted by the EPA to gain a better understanding of the levels of radioactivity for members of the public are exposed to and to estimate the health effects of such exposure. The dose assessments also assist in identifying significant pathways of exposure

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and investigating temporal trends in exposure levels from both natural and artificial radioactivity. The EPA is also under a legal obligation to undertake such assessments as it has been written into Irish legislation[4].

The compilation of exposure and dose data typically takes two years and involves a number of national collaborators in addition to the EPA. These collaborators include the Health Service Executive (HSE), the Central Statistics Office (CSO) relevant government Departments and research institutions.

The radiation doses investigated, and methods used to determine dose are closely aligned, to the extent practicable, to the United Nations Scientific Committee on the Effects of Atomic Radiation methodology for dose assessment[5].

The sources of radiation dose investigated as part of this study are as follows:

- Cosmic radiation
- Terrestrial gamma radiation
- Radioactivity in food and drinking water
- Radon
- Thoron
- Medical exposure and
- Occupational exposure

This paper presents a summary of the dose assessments conducted to date by the EPA and outlines the approaches that will be taken for the next dose assessment report that is due to be published in the near future.

2. Cosmic Radiation

Cosmic radiation consists of primary particles, mainly protons, and secondary particles that are produced through the interactions of primary particles with the upper atmosphere. The primary particles are quickly attenuated by the earth's atmosphere so, at sea level, the cosmic rays that irradiate the humans are mainly secondary particles such as muons, electrons and neutrons. Cosmic radiation can be categorised into two components: a directly ionising component and a neutron component.

To determine the annual effective dose a member of the public for cosmic radiation at sea-level the following formula, derived from UNSCEAR[6], was used:

$$E_{Cosmic} = D_{Total} \times 8760 \times [(1 - I_{In}) + (I_{In} \times SF)] \quad (1)$$

Where
E_{Cosmic} is the average annual effective dose from cosmic radiation at ground level (Sv/year)
D_{Total} is the total effective dose rate (Sv/h)
I_{In} is the Indoor Occupancy Factor
SF is the building Shielding Factor for cosmic rays indoors

Irelands is located at a latitude of approximately 54°N. According to UNSCEAR[6] the effective dose rate at sea level at this latitude is 32 nSv/h for the directly ionising component and 9 nSv/h for the neutron component, giving a total of 41 nSv/h. Applying the UNSCEAR recommended values of 0.8 for Indoor Occupancy Factor and 0.8 for average building shielding factor[5] the effective dose from exposure to cosmic radiation at ground level is approximately 302 µSv/year.

An additional component of cosmic ray exposure that also needs to be considered is the dose members of the public receive through air travel. Cosmic ray exposure on any flight is dependent upon the flight path, the duration of the flight and solar activity at the time of the flight. A number of computer programs have been developed to estimate cosmic radiation received by air crew. These programs, used in conjunction with appropriate travel data of members of the public, can be used to derive the annual effective dose to members of the public from air travel. The EPA used the European Package for Calculation of Aviation Dose (EP-CARD), that is available online and as a stand-alone software package to determine annual effective dose from air travel. This software has been approved and tested by the European Commission for use in estimating exposure to air-crew[7].

To determine the estimated doses to the public, the frequency of air travel for the Irish public was collated from data compiled by the Irish Central Statistics Office, that compiles the frequency and destination of air trips abroad each year by Irish residents[8]. A typical destination for each country or region was selected, this was normally a capital city or a well-known destination popular with Irish tourists. The average individual dose for each of these typical routes were then estimated using the EP-CARD software and the collective dose was derived based on the number of return trips for each destination. The results can be seen in Table 1.

The total collective dose from air travel is estimated to be 187 manSv per year. The total average annual effective dose from airline travel is calculated by dividing this collective dose by the total population of 4.59 million giving 41 µSv per year. The total annual effective dose from cosmic radiation is 343 µSv.

3. Terrestrial Gamma Radiation

An individual's annual exposure to terrestrial gamma radiation is largely determined by underlying soil and parent geological material, the location of their home and the places they visit and the amount of time they spend indoors and outdoors.

Two national surveys of outdoor gamma dose rates have been conducted in Ireland[9, 10]. These two national surveys were weighted accordingly resulting in an

Table 1. Annual collective effective doses of air travel by Irish residents.

Country/Region	Representative Destination	No. of Return Trips	Return Trip Dose (μSv)	Collective Dose (man Sv)
Austria	Vienna	58,000	30	1.7
Belgium/Lux/Netherlands	Amsterdam	181,000	15	2.8
Denmark/Finland/Sweden	Stockholm	53,000	32	1.7
France	Paris	601,888	13	7.9
Germany	Berlin	164,000	26	4.2
Italy	Rome	354,000	30	10.2
Other EU	Warsaw	229,000	32	7.4
Portugal	Faro	358,000	24	8.7
Spain	Madrid	703,500	22	15.6
Spain	Tenerife	703,500	36	25.2
United Kingdom	London	1,992,625	8	15.9
Other Europe	Dubrovnik	202,000	33	6.6
All Europe		**5,591,513**		**107.8**
North America Northeast	New York	266,000	102	27.2
North America Southeast	Atlanta	44,000	135	5.9
North America Midwest	Chicago	41,000	125	5.1
North America West	Los Angeles	19,000	174	3.3
All North America		**370,000**		**41.6**
Central, South and Other Americas	Buenos Aires	69,000	89.7	6.2
Asia and Middle East	Bangkok	165,000	113.2	18.7
Africa	Nairobi	58,000	58.0	3.4
Australia, New Zealand and Oceania	Sydney	64,000	150.9	9.7
All Other		356,000		37.9
TOTAL		**6,317,513**		**187**

average outdoor gamma dose rate of 37 nGy/hr.

Gamma dose rates outdoors tend to be lower than gamma dose rates indoors as a result of the presence of the gamma emitting radionuclides Ra-226, Th-232 and K-40 in commonly used building materials. McAuley and Colgan[11] estimated that the gamma dose rates indoors in Ireland is 1.38 times higher than that outdoors, which is comparable to the UNSCEAR average of 1.4 worldwide[6].

The average individual dose arising from exposure to terrestrial gamma radiation can be determined using:

$$E_{Gamma} = D \times 0.7 \times 8760 \times [(1 - I_{In}) + (I_{In} \times R)] \quad (2)$$

Where
E_{Gamma} is the average annual individual dose from terrestrial gamma radiation (μSv/year)
D is the terrestrial gamma dose rate outdoors (μGy/h)
0.7 is the UNSCEAR recommended conversion factor to convert from ambient dose rate (μGy/h) to effective dose rate (μSv/h)
I_{In} is the UNSCEAR recommended indoor occupancy factor of 0.8
R is the ratio of gamma dose rate indoors to outdoors in Ireland, which is 1.38
Using this formula, the exposure from terrestrial gamma radiation to an individual was estimated to be 297 μSv/year.

The surveys used to estimate the external gamma dose rate in Ireland were conducted prior to the accident in Chernobyl in 1986[9] and investigated natural radioactivity in soil samples[10]. Therefore, the dose component arising from the fallout in Ireland from the Chernobyl nuclear accident in 1986 is not included. Ryan[12] investigated the deposition of Cs-137 in Irish soils and estimated annual effective dose of 4 μSv arising from this fallout.

The total annual effective dose from terrestrial gamma radiation is 301 μSv.

4. Radioactivity in Food

The sources of radioactivity in food are primordial, cosmogenic and artificial radioactivity. With the exception of large-scale nuclear accidents, the majority of the dose from ingestion of food and drinking water is as a result of naturally occurring radionuclides, with a very small contribution from artificial radioactivity.

The dose arising from ingestion of food is dominated by the naturally occurring radionuclides K-40 and the decay products of the U-238 and Th-232 series. C-14 produced as a result of interactions of cosmic rays with

Table 2. Estimated annual effective dose (committed dose) from naturally occurring and artificial radionuclides in food.

Radionuclides/ Ingestion pathway	Dose (μSv/year)	
	Natural	Artificial
C-14	8	
K-40	170	
Po-210	47	
Pb-210	26	
Rb-87	2	
Ra-228	7	
Ra-226	4	
Nuclear discharges		0.07
Radioactivity in milk		0.5
Cs-137		2.7
TOTAL	**267**	

the upper atmosphere also contribute to the dose along with the naturally occurring Rb-87.

The dose from both K-40 and Rb-87 remains relatively constant in healthy individuals as the content of both of these elements in the human body are held constant by normal metabolic processes. Approximately 0.012% weight of natural potassium is K-40 and UNSCEAR[6] has estimated the dose from K-40 in health adults to be 170 μSv/year. Rb-87 represents just under 30% of the total abundance of rubidium in the earths crust and individuals typically contain approximately 300 mg of rubidium in tissues throughout their body. Watson[13] estimated that this represents an annual average dose of 2 μSv/year from Rb-87 in the human body.

Of the radionuclides in the U-238 and Th-232 decay series, Pb-210, Po-210, Ra-226 and Ra-228 provide the main contribution to ingested dose. The contribution from other radionuclides in these series is negligible by comparison.

To assess the dose contribution from Pb-210, Po-210, Ra-226, Ra-228 and C-14 the EPA conducted a diet survey. This survey was a duplicate-diet survey where samples of complete meals were collected from a large restaurant facility over a one-week period in line with EU recommendations[14] and analysed in the EPA's radiation monitoring laboratory for the radionuclides of interest.

The annual average dose resulting from the ingestion of these radionuclides was estimated using the following formula:

$$E_R = A_R \times B \times C_R \tag{3}$$

Where

E_R is the average annual individual effective dose (committed effective dose) ingested from the radionuclide of interest (Sv/year)

A_R is the activity concentration of the radionuclide of interest in the food analysed (Bq/kg)

B is the amount of food consumed per year by adults (kg/y)

C_R is the ingestion dose coefficient for the radionuclide of interest for adults[15] (Sv/Bq)

The average amount of food consumed by Irish adults has been estimated by the Irish Universities Nutrition Alliance to be 440 kg/year[16].

The sources of artificial radioactivity in the Irish diet are as a result of discharges from nuclear facilities, fallout from nuclear weapons testing and large-scale nuclear accidents, such as the Chernobyl accident in 1986. The EPA has a comprehensive radioactivity in food monitoring programme in place for the monitoring of artificial radionuclides in complete, meals and individual foodstuffs such as milk, meat, fish, shellfish and grain samples[17]. The radionuclides of interest in these samples are Cs-137, Sr-90, Tc-99, Pu-238, Pu-239, Pu-240 and Am-241. Results of the EPA's ongoing monitoring programmes have estimated the doses arising from these artificial radionuclides are negligible when compared to those from natural sources (Table 2).

5. Radon and Thoron in Homes

Between 1992 and 1999 the EPA's predecessor, the Radiological Protection Institute of Ireland (RPII), conducted a National Radon Survey (NRS)[18]. The NRS measured radon in Irish homes on a geographical basis using a 10 km x 10 km national grid of Ireland. Contemporary twelve-month radon gas measurements were made in approximately 11,000 homes, representing approximately 1 in 116 of the national housing stock at the time, using solid-state nuclear track detectors. The results of the survey estimated an average population weighted indoor radon concentration of 91 Bq/m^3. Using a population of 4.59 million[19] and an indoor occupancy factor of 0.8[6], this corresponds to a collective dose of

Table 3. Effective dose from medical exposures.

Modality	Collective Dose (man Sv)	Average annual dose (μSv/year)
CT	1368	298
Dental	6	1.3
General X-Ray	259	56.4
Nuclear Medicine	112	24.4
PET-CT	130	28.3
Interventional radiology and cardiology	630	137.3
TOTAL	**2505**	**546**

10,210 manSv. However, this collective dose needs to be corrected to take into account the time spent indoors in the workplace. The collective dose from radon in the workplace is estimated to be 1,052 manSv (See OCCUPATIONAL EXPOSURE). Therefore, the collective dose arising from radon in the home is (10,210 – 1,037) manSv corresponding to 1,995 μSv/year.

A thoron survey was conducted in 205 homes in Ireland between 2007 and 2009[20]. The average indoor air concentration of thoron and its decay products was 0.47 Bq/m^3 EETC. Dose coefficients for thoron and its decay products have been calculated using Human Respiratory Tract Models[21, 22]. Assuming a typical breathing rate of 0.78 m^3/h and an indoor occupancy factor of 0.8 the estimated exposure to thoron and its decay products at 1 Bq/m3 EETC results in a dose of 750 μSv. Using this dose coefficient and an average indoor thoron concentration of 0.47 Bq/m^3 the dose due to thoron exposure in the home is estimated as 350 μSv/year.

6. Occupational Exposure

Occupational exposure occurs as a result of exposure to ionising radiation in the workplace. These include exposure to air crew as a result of cosmic radiation, radon in the workplace, and staff working with radioactive sources and x-rays in medicine, industry and research.

Irish legislation requires that all airlines holding an Air Operators Licence issued by the Irish Aviation Authority have to evaluate the extent of exposures of their air crew to cosmic radioactivity[4]. This is in instances where air crew are likely to receive doses greater than 1 mSv in any twelve-month period. Air crew who fly exclusively below 8000 m are unlikely to receive doses greater than 1 mSv and are exempt from these regulations. Doses to air crew are assessed by airlines using the EP-CARD software and are reported to the EPA on an annual basis. A total of 12,036 air crew workers were assessed and the average dose per air crew worker was estimated to be 2,326 μSv/year.

This gives an annual collective effective dose for aircrew workers of:

$$2{,}326\ \mu\text{Sv} \times 12{,}036 = 28\ \text{manSv}$$

The contribution this makes to the average annual effective dose for the whole population is:

$$\frac{28\ \text{manSv}}{4.6 \times 10^6} = 6\ \mu\text{Sv/year}$$

The EPA's predecessor, the RPII, conducted a radon in workplace survey that consisted of over 18,000 measurements in approximately 2,600 workplaces. Additional radon workplace surveys were also conducted by other radon measurement services and this data, in conjunction with the RPII survey, was used to determine the dose in Irish workplaces.

The RPII also conducted a large-scale survey of radon in schools, which are also workplace for the teaching staff and other staff working there. This survey took place between 1998 and 2004 and over 41,000 radon measurements in more than 3,000 schools were made[24]. This data was also used to derive the exposure for radon in the workplace.

To estimate the collective dose from radon in the workplace the following was used:

$$D_{RW} = A_{Rn} \times DEC \times WP \qquad (4)$$

Where:

D_{RW} = The collective dose in the workplace of interest (manSv)

A_{Rn} = The average radon activity concentration (Bq/m^3)

DEC = The dose exposure co-efficient

WP = The working population

The dose exposure coefficient used was 1 mSv per 130 Bq/m^3 for a typical working year of 2,000 hours[25]. The working population was taken from CSO employment statistics[26]. A summary of the surveys conducted and the dose as a result of exposure in the workplace can be seen in Table 3.

Other exposure pathways investigated as part of this study were radon exposures to workers in show

Table 4. Survey results and effective dose to Irish workers from radon in workplaces

Survey	Schools	Other Workplaces
No. of Measurements	41,096	24,819
No. of workplaces	3000	> 3000
Average Radon Concentration (Bq/m^3)	75	84
No. of workers	57,736	1.6 x 10^6
Collective Dose (man Sv)	20.6	1037
Average dose to the population (μSv/year)	3.3	226
TOTAL (μSv/year)	**229**	

caves and mines and occupational exposure to artificial radiation.

Radon exposure in mines and show caves were assessed over a three-month period using solid state nuclear track detectors, similar to those used to conduct radon gas measurements in homes. The average dose assessed for a guide in a show cave was 2000 μSv for eighteen workers resulting in a collective dose of 0.038 manSv. The contribution to the overall average dose to the whole population is approximately 0.008 μSv/year. Similarly for mines, the average annual effective dose for each worker is 7,000 μSv for 27 workers resulting in a contribution to the overall average dose to the population of 0.004 μSv/year.

Workers who are deemed liable to receive a dose above 1 mSv per year from occupational activities must be provided with personal dosimeters that assess the radiation dose while they work[4]. This dose data is collated by the EPA on an annual basis and the total average annual collective dose for the 195 workers in the medical, industrial and education sectors is 0.1 manSv, resulting in a contribution to the overall annual average dose of less than 0.02 μSv/year. Therefore the total annual effective dose from occupational exposure is 235 μSv, comprising 235 μSv from above ground workplaces, 6 μSv from exposure to aircrew and 3.3 μSv from radon in schools.

Table 5. Estimated average annual dose in Ireland

Exposure Pathway	Dose (μSv/year)
Cosmic radiation	343
Terrestrial gamma radiation	301
Radioactivity in food	267
Radon in homes	1995
Thoron in homes	350
Occupational exposure	235
Medical exposure	546
TOTAL	**4037**

7. Medical Exposures

The Irish Health Service Executive (HSE) has a legal obligation to determine the dose to the Irish population from the use of medical ionising radiation[23]. To comply with this legislation, in 2010 the HSE's National Radiation Safety Committee conducted a national survey of a number of diagnostic imaging modalities and a further pilot survey for interventional radiology (including cardiology) was also conducted in 2013.

The dose assessment for diagnostic imaging modalities was based on international best practice[27–29] and consisted of a subset of examinations for each modality being investigated being surveyed. To assess the dose arising from the various imaging modalities the dose per investigation was determined along with the frequency of each investigation.

Surveys were conducted on the following:

- Computerised Tomography (CT): Adult CT examinations including Brain, C Spine, High resolution Thorax, Thorax, Abdomen/Pelvis, Thorax/abdomen/pelvis.
- Dental radiology: Intraoral, Occlusal, Panoramic, Cone Beam Computed Tomography, Lateral cephalometry
- General radiology: Chest, Spine, Thorax, Lumbar spine, Full spine, Skeletal survey, Abdomen, Pelvis, Hips, Femur, Mammography, Feet/Ankles, Wrist/Hand, Knees.
- Nuclear Medicine: Fourteen nuclear medicine examination types involving Tc-99m, I-131, I-123 and In-111.
- Positron Emission Tomography – Computed Tomography
- Interventional radiology and cardiology: Fluoroscopy, Orthopaedics, Radiology/Cardiology (cerebral, thoracic, abdominal, pelvic, pacemaker etc.)

A summary of the average annual effective dose received from these procedures are outlined in Table 4.

8. Summary and Discussion

Compiling all of the exposure pathways outlined above the average annual effective dose to a member of the Irish public is estimated to be 4,033 μSv/year (Table 5

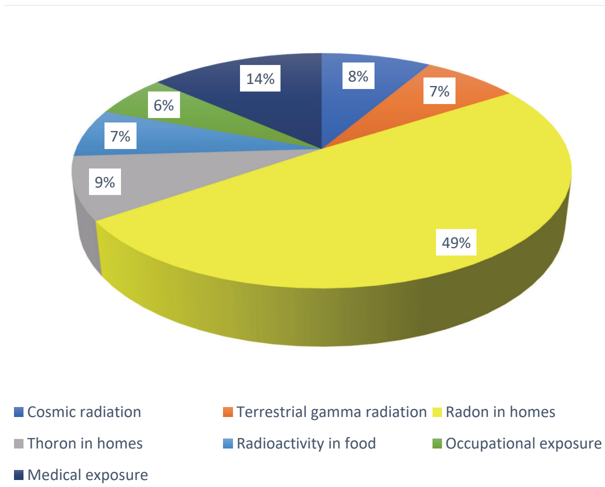

Fig. 1. Distribution of sources of radiation dose in Ireland (μSv)

and Figure 1). Radon exposure in the home continues to be the principal source of radiation exposure in Ireland, representing approximately half of the radiation dose received by the Irish population (1,995 μSv/year). The second largest contributor to dose and the largest man-made contributor to dose is medical exposure of patients (546 μSv/year). Other exposure pathways of artificial radioactivity such as fallout from nuclear accidents and weapons tests or discharges of nuclear or radioactive waste to the environment are very low. The average dose to a member of the Irish public is larger than the worldwide average, UNSCEAR[5] has estimated that the worldwide average exposure due to all sources of radiation is 3,030 μSv/year. The main difference between the Irish value and the worldwide value is as a result of the above average indoor radon concentration in Ireland.

The EPA will be conducting their next comprehensive dose assessment in the near future. To further refine and improve the exposure assessments considered as part of future dose assessments a number of improvements will be considered.

The exposure assessment for cosmic radiation can be investigated further by taking into consideration the altitude at which the Irish population are living. The directly ionising and neutron components of cosmic radiation are dependent upon both latitude and altitude. Bouville and Lowder[30] have derived equations to calculate the increase in cosmic radiation exposure with altitude for both of these components. These equations could be used to further refine the estimated dose rates to members of the public based on the altitude of their homes. However, the overall estimated dose is not expected to change significantly as the majority of Irish residents live at or near the Irish coast and hence at or close to sea-level.

The terrestrial dose to the Irish public as a result of exposure to terrestrial gamma radiation is based on a number of surveys from the 1980's and 1990's. Since then there have been no significant surveys of terrestrial gamma radiation and the methodology used to determine the dose is not in line with the UNSCEAR approach[5]. The UNSCEAR approach is to conduct a comprehensive soil sampling survey and to determine the activity concentrations of K-40, Ra-226 (U-238) and Ra-228 (Th-232) in the soil samples. A gamma dose rate 1m from the ground can be derived from the measured activity concentrations. A comprehensive soil survey and measurements can provide a more up to date assessment of the dose arising from terrestrial gamma radiation. In addition, there could also be a scope to include results from a recent airborne gamma survey of Ireland conducted by the Geological Survey of Ireland[31].

The dose to the public arising from radon exposure in the home and in workplaces will also require significant updating as a result of the recently revised indoor radon activity concentration from 91 Bq/m^3 to 97 Bq/m^3 [32]. The revised radon dose conversion factors recently published by the ICRP[33] could have an even greater impact on the estimated dose due to radon exposure. The revised dose conversion factor has been revised upwards from 2.52 nSv/Bqm^{-3}.h to 6.7 nSv/Bq.m^{-3}.h. If adopted, this could result in the dose due to radon exposure in the home to more than doubling. Discussions are currently ongoing as to whether this revised conversion factor will be adopted for future dose assessments.

The dose estimated from radioactivity in food will be updated as the EPA is currently conducting a more comprehensive survey of natural radioactivity in food. In addition, as a result of recently introduced drinking water legislation[34] a national monitoring programme for radioactivity in drinking water will assist in the estimation of dose arising from exposure to natural radioactivity in public water supplies in Ireland.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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