IDAC-Radon, an internal dosimetry code for radon and its progenies using the new ICRP biokinetic models and specific absorbed fractions

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Abstract. The Swedish Public Health Authority estimates that the number of homes in Sweden with radon levels above the guideline value of 200 Bq/m3 is at least 400,000, which means one in twelve homes. The US environmental protection agency (EPA) estimates that nearly one in 15 homes in the United States has a radon level that should be reduced. After smoking inhalation of radon (Rn-222) is the second leading cause of lung cancer. Radon forms when uranium in water, rocks, and soil begins to break down, releasing radon gas into the ground beneath buildings. Radon can enter through e.g. cracks in foundation walls and floors, or fireplaces and furnaces. International Commission on Radiological Protection (ICRP) have in ICRP Publication 137 revised both their biokinetic models and absorbed dose calculations for acute intake of radon. The ICRP dose coefficients includes progenies of the radon once the radon is inhaled and inside the body. However, the progenies will also be inhaled as these also occur in the air. The progenies will have different air flow rates leading to different activity concentration than radon once they are inhaled. The software performs absorbed dose calculations based on the full biokinetic transfer, and including inhalation of progenies. As the biokinetic calculations are solved numerically, all parameters and data connected to the radon calculations can be built-in to a complex biokinetic system. This allows for continuous inhalation at different breathing rates e.g. continuous inhalation 9 hours a day, 5 days a week and add the activity concentration, the integration period, the type of continuous inhalation and the inflow and outflow transfer rates in air for the different progenies. Parameters which all affects the number of radioactive particles inhaled. IDAC-Radon is a code created to facilitate more realistic absorbed dose calculations from exposure of radon.

KEYWORDS: ICRP, Internal dosimetry calculations, Radon

1 INTRODUCTION

There is strong epidemiological evidence that inhalation of radon and its daughter products can cause lung cancer [1-4]. After smoking inhalation of radon is the second leading cause of lung cancer. The Swedish Public Health Authority estimates that the number of homes in Sweden with radon levels above the guideline value of 200 Bq/m3 is at least 400,000, which means one in twelve homes. The US environmental protection agency (EPA) estimates that nearly one in 15 homes in the United States has a radon level that should be reduced.

There are tree isotopes of radon: Radon-222, Radon-220 (thoron), and Radon-219. Due to their origins, the isotopes are commonly known as radon, thoron, and actinon, respectively. The two isotopes Radon-222 and Radon-220 are the main sources of exposure from radon of importance for radiation protection.

The International Commission on Radiological Protection (ICRP) has revised both their biokinetic models and absorbed dose calculations for acute intake of radon [5]. The ICRP dose coefficients includes progenies of radon once the radon is inhaled and inside the body. However, the progenies will also be inhaled as they occur in the air. The flow rate of the progenies will differ from that of radon gas giving rise to different distributions in the airways. The aim of this work is to develop a software (IDAC-Radon) dedicated for internal radon dose calculations and based on the full biokinetic transfer of radon and its progenies created in or outside the body. This will allow for dose estimates at continuous inhalation at different breathing rates, activity concentrations, integration periods, types of continuous inhalation, inflow and outflow rates in air for radon and for the different progenies.

1.1 Originate of Radon

Radon-222 is the decay product of radium-226. Radon-222 and its parent, radium-226, are part of the long decay chain for uranium-238. Since uranium and thorium are everywhere in the earth's crust, radium-226 and radon-222 are present in almost all rock and all soil and water. Radon-222 gas is released from a few meters' depth in ground soil and reach the ground beneath buildings and can enter buildings through e.g. cracks in foundation walls and floors, or fireplaces and furnaces. Radium rich building material is another source of indoor radon-222.

Radon-220 (thoron) is produced in the earth's crust at rates comparable to that of radon. As the physical half-life of thoron is short, most indoor thoron comes from the outermost centimeters of the building materials in the room. Even with a small thoron source, a significantly high concentration might be obtained. As thoron dosimetry studies are limited and the absence of thoron epidemiological studies, the evaluation covering dose conversion coefficients etc. solely deals with radon (Radon-222) exposure.

1.2 The risk of radon

Inhalation of radon (Radon-222) and its daughter products as well as thoron (Radon-220) is cancerogenic mainly for the lungs. Doses to other organs and tissues are at least an order of magnitude smaller than the doses to the lung.

Two approaches for deriving radon dose conversion coefficients are in use to express health effects from exposure to radon. These are a "dosimetric approach", estimating the dose from a given exposure based on atmospheric conditions, breathing characteristics and lung modelling relevant for radon and its decay products; and an "epidemiological approach", based on using the ratio of the risk of lung cancer per unit radon exposure studied mostly in miners and the nominal risk related to effective dose of all cancers derived mostly from survivors of the atomic bombings. The range of the assessed effective doses per unit of exposure of equilibrium equivalent concentration (EEC) of Radon-222 are from 7 to 34 nSv per (h Bq m^{-3}) for exposures in homes, indoor workplaces and mines and found for exposures in homes with an arithmetic mean of 18 nSv per (h Bq m^{-3}), and a geometric mean of 16 nSv per (h Bq m^{-3}). For a reference worker with an average breath rate of 1.2 m3 h^{-1}, the effective dose coefficient is estimated to 13 nSvper (h Bq m^{-3}) [5]. UNSCEAR recommends the continued use of the dose conversion coefficient of 9 nSv per (h Bq m^{-3}) EEC of Radon-222, which corresponds to 1.6 mSv (mJ h m^{-3}) $^{-1}$ for estimating radon exposure levels to a population [6].

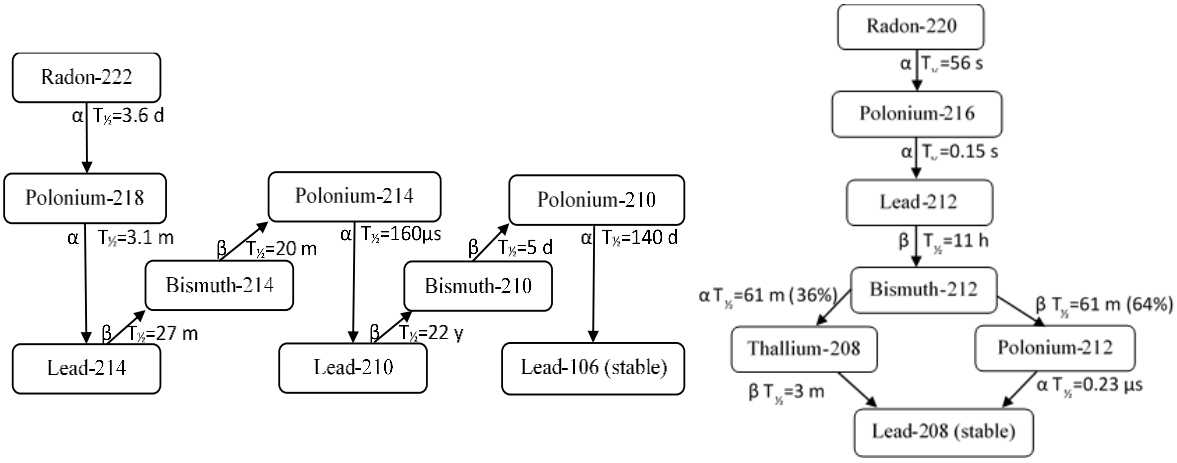
These values are consistent with those previously estimated by the UNSCEAR for average indoor conditions on the basis of dosimetric evaluations. This Committee also reviewed articles reporting on epidemiological studies (residential and occupational) of lung cancer risk from radon exposure published since 2006. For the residential studies, the excess relative risk estimates for lung cancer varied from −0.13 to 0.73 per 100 Bq m^{-3} for exposure to radon gas, with the mean excess relative risk of 0.13 per 100 Bq m^{-3} [6]. The ICRP updated its guidance on radiological protection against radon exposure in 2014 [7].

1.3 Decay chain

The decay chains of Radon-220 and Radon-222 are shown in Fig. 1. The decay chain of Radon-222 is based on 8 decays. It starts with a α-decay of Radon-222 to Polonium-218 with a half-life of 3.8 days. Polonium-218 decay with α-decay to Lead-214 with a half-life of 3.1 minutes. Lead-214 decays with β-decay to Bismuth-214 with a half-life of 27 minutes. Bismuth-214 decays with β-decay to Polonium-214 with a half-life of 20 minutes. Polonium-214 decays with α -decay to Lead-210 with a half-life of 160 microseconds. Lead-210 decays with β-decay to Bismuth-210 with a half-life of 22 years. Bismuth-210 decays with β-decay to Polonium-210 with a half-life of 5 days. Polonium-210 decays with α -decay to the stable isotope Lead-206 with a half-life of 140 days.

The decay chain of Radon-220 is based on 7 decays. It starts with an α-decay of Radon-220 with a half-life of 56 seconds to Polonium-216. Polonium-216 decay with α-decay and a half-life of 0.15 seconds to Lead-212. Lead-212 decays with a half-life of 11 hours through β-decay to Bismuth-212. Bismuth-212 decays in 64 % through β-decay to Polonium-212 and in 36 % via α-decay to Thallium-208 both ways with a half-life of 61 minutes. Thallium-208 decays with a half-life of 3 minutes via β-emission to stable Lead-208. Polonium-212 decays with a half-life of 0.23 microseconds wia α–emission also to Lead-208.

Figure 1: The decay chain from Radon-222 and Radon-220



2 MATERIALS & METHODS

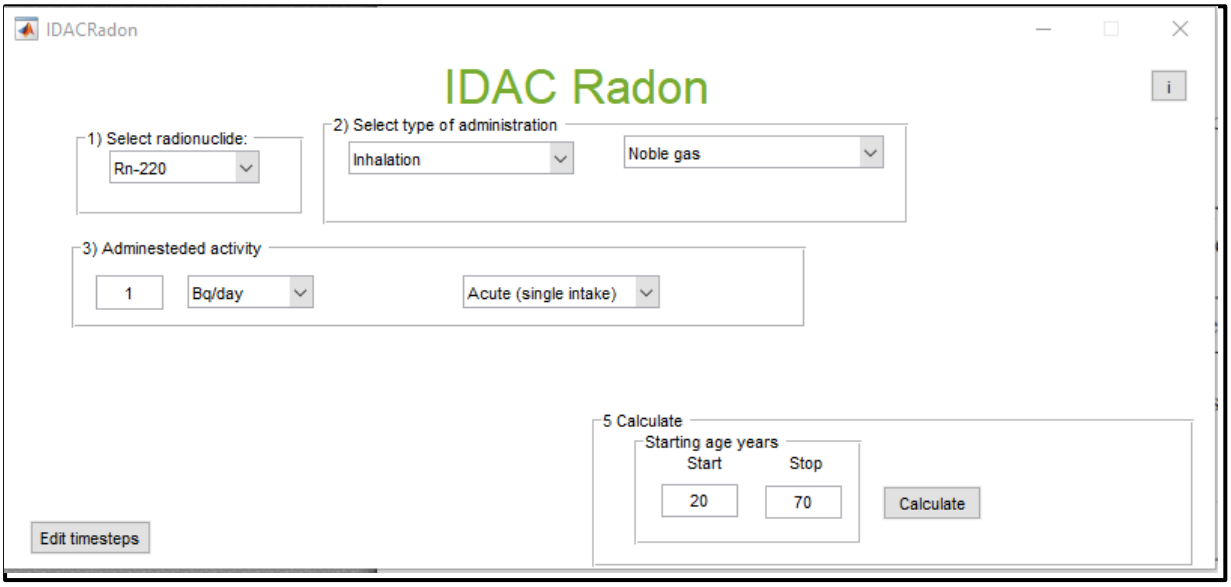
A computer code in MATLAB (MathWorks, Natick, MA, USA) has been developed. It assesses the absorbed dose to different organs and tissues using the biokinetic models for radon published in ICRP Publication 137 [5]. The calculations are based on previously published radon methodology [8].

2.1 Biokinetic

For an acute single intake of Radon-222 or Radon-220, the activity is assumed to be completely inhaled or ingested and no progenies present in air are included in the biokinetic calculations. These calculations follow that the ICRP computational framework for internal dose assessment for occupational intake. The graphical interface of input data of the software is shown in Fig. 2 and illustrates a calculation of dose estimates for inhalation of 1 Bq of Radon-220 and an integration time of 50 years.

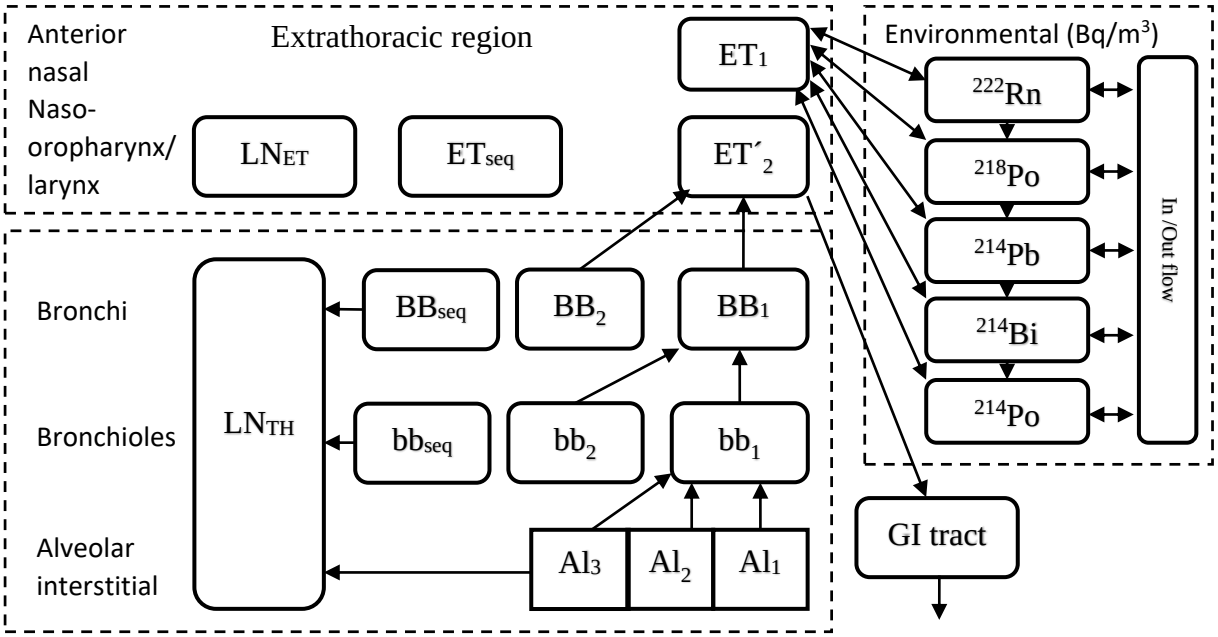
For the continuous intake, a modification of the ICRP human respiratory tract model (HRTM) has been made and is shown in Fig. 3. Inhalation of Radon-222 and its four first progenies is included in the biokinetic calculations. The fifth progeny is Lead-210, with a half-life of 22 years. The inhaled activity of Lead-210 and all progenies thereafter is negligible. Once the activity is inhaled and has entered the human body, all progenies will be included in the calculations for both acute and continuous intakes.

Figure 2: Graphical interface of acute intake of Radon-220



For the air activity in the environment Radon-222 and its first four progenies shave been given individual transfer coefficients. If there is lack of steady state for Radon-222 and its first four progenies this can be included into the biokinetic calculations. The graphical interface of continuous intake of Radon-222 is shown in Fig. 4.

Figure 3: The compartment model for inhalation of continuous intake of Radon-222 [11].



2.2 Dosimetry

The absorbed dose will be calculated by using a dedicated version of IDAC-Dose2.1 [9] generated for this specific project. The graphical interface is shown in Fig. 2 and 4. IDAC-Dose2.1 follows the computational framework of internal dose assessment given for reference adults in ICRP Publication 133. The program uses the radionuclide decay database of ICRP Publication 107 and considers 79 different source regions irradiating 43 target tissues, defining the effective dose as presented in ICRP Publications 60 and 103. The computer program has been validated against another ICRP dosimetry program, Dose and Risk Calculation (DCAL, United States Environmental Protection Agency). IDAC-Dose2.1 is written in MATLAB which enables a direct integration when creating absorbed dose calculations for occupationally exposed workers and members of the public. Currently, a new version of IDAC-Dose is under development which will also include absorbed dose calculations for preadults.

IDAC-Radon uses the biokinetic compartment models of ICRP Publication 137, the nuclear decay data of ICRP Publication 107 [10]and the specific absorbed fraction data of ICRP Publication 133 [11] to calculate organ absorbed doses and the effective dose defined in ICRP Publication 103 [12].

2.3 Absorbed dose and effective dose

To estimate the effective dose the mean absorbed dose to a target region was calculated by [13]:

$$D(r_T, T_D) = \sum_{r_s} \int_0^{T_e} A(r_s, t) * S\left(r_T \longleftarrow r_{s,t}\right) dt \text{ [Gy]} \quad (1)$$

where $A(r_s, t)$ is the time dependent activity at time t, in source region r_s from exposure to the arbitrary stopping time T_e. $S(r_T \longleftarrow r_s)$ is the mean absorbed dose in target r_T per nuclear transformations in source region r_s. The $S(r_T \longleftarrow r_s)$ is generated with radionuclide decay scheme and Monte Carlo simulated specific absorbed fractions by simulate every source-target combination

$$S(r_T \longleftarrow r_s) = \sum_i \Delta_i \Phi(r_T \leftarrow r_s, E_i) \text{ [Gy/Bq]} \quad (2)$$

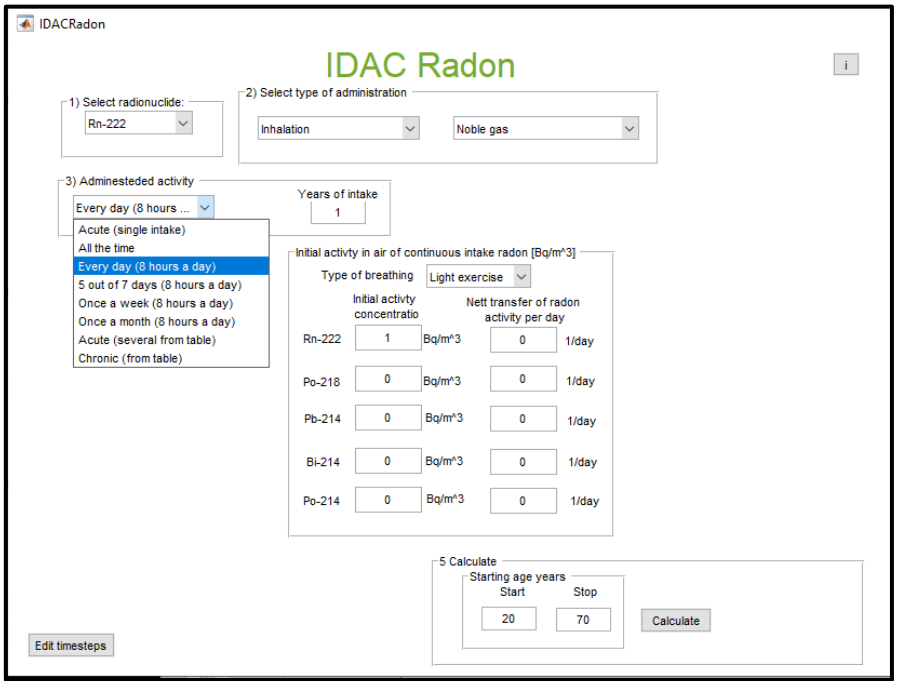
where $\Phi(r_T \leftarrow r_s, E_i)$ is the specific absorbed fraction from the source region r_s to the target region r_T of the *i*th components in the decay scheme and $\Delta_i = E_i Y_i$ is the energy yield there Y_i is the yield and E_i is the mean energy of the *i*th nuclear transition of the radionuclide in Joule. For each radiation type in equation 2 needs to have an additional summation running over electrons, alpha, and photons plus an additional term as an integral over the beta spectrum.

The effective dose (E), which is the sum of sex average radiation weighted equivalent dose from radiosensitive organs is calculated by:

$$E = \sum_T w_T H_T = \sum_R \frac{w_R D_{T,R_{Ref.male}} + w_R D_{T,R_{Ref.female}}}{2} \ [Sv] \quad (3)$$

where $w_R$is the radiation weighting factors of radiation R, $w_T$is the tissue weighting factor representing the relative organs and tissues detrimental effects. $D(r_T, T_D)_{Male}$ and $D(r_T, T_D)_{Female}$ is the mean absorbed dose of target region T of the reference male and female person , respectively.

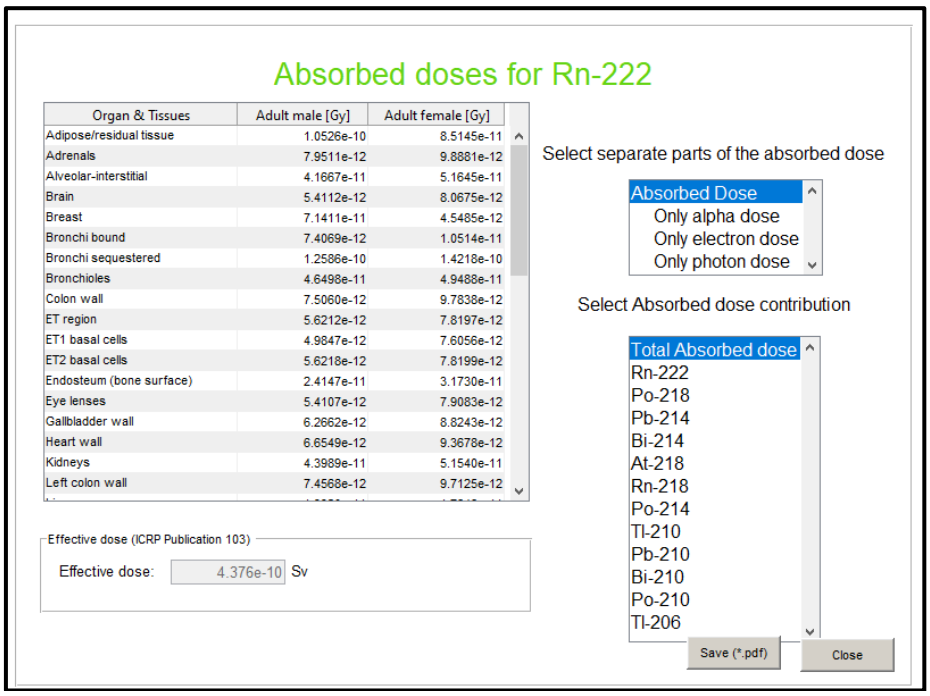
Figure 4: Graphical interface of continuous inhalation of Radon-222



3 RESULTS AND DISCUSSION

The effective dose coefficient for an acute inhalation of Radon-220 is calculated to 1.778e-10 Sv/Bq, and for Radon-222 to 4.376e-10 Sv/Bq, which is in agreement with what is published in ICRP publication 137 [3]. The absorbed dose to various organs and tissues and the effective dose for Radon-222 are given in Fig. 5. In

Figure 5: Graphical interface of the results of a calculation of organ absorbed doses and effective dose from 1 Bq inhaled activity of Radon-222.



4 CONCLUSION

Radon levels in outdoor air are generally low, but can be considerably higher inside buildings, and especially underground such as in caves and mines. After smoking inhalation of Radon-222 is the second leading cause of lung cancer. For radon, dose limits are often given in activity concentration in air (Bq/m3) and ICRP has published effective dose coefficients (mSv/Bq). IDAC Radon gives possibilities to estimate organ absorbed doses as well as effective doses from both acute and continuous intake. This simplifies radon dosimetry and provides an opportunity to more easily add radon contributions to contributions from other sources in radiation risk assessments.

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