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Dosimetric approach for biota exposure to inhaled radon daughters

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Executive summary

This study presents an approach based on allometrically derived respiration rates and target tissue masses, designed to calculate ^{222}Rn (radon) daughter dose rates to sensitive tissues and the whole body of terrestrial animals and plants. The approach is an improvement on the interim method based on plutonium dosimetry developed by the Environment Agency, which aimed to produce a conservative calculation without the need to develop a full respiratory model for radon in animals and plants.

The results of an assessment using the discharge limits listed in a selection of RSA93 authorisations suggest that there is no significant risk of deterministic effects to the populations of species studied. Further work could include additional investigation of the dosimetry for insects and plants, a review of evidence for dose rates that would cause stochastic effects in the lung and more detailed lung modelling (if appropriate). Consideration could also be given to how to extend the dose assessment for ^{226}Ra in soil to include ^{222}Rn emissions in that environment, as well as to the development of a similar approach to calculate thoron doses.

Practical calculation of ^{222}Rn dose to whole body per unit concentration in air (DPUC) for all the species used by the Environment Agency for habitats assessments is given as an appendix to this report.

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1. Radon dosimetry: an introduction

Radon is a radioactive noble gas that is formed by the decay of radium. The environmentally significant isotope is ^{222}Rn, which has a half-life of 3.8 days and decays relatively fast into ^{218}Po, ^{218}At, ^{214}Pb and ^{214}Bi (the short-lived daughters) and subsequently to ^{210}Pb, ^{210}Bi and ^{210}Po (the long-lived daughters).

Initially, products of the radon decay chain are produced in the form of bare atoms. After formation, they react very fast (in under a second) with vapours and gases, forming nanometre-sized clusters known as the "unattached fraction". These clusters become attached to aerosol particles in the atmosphere (in over one to 100 seconds), forming a radioactive aerosol of radon daughters (Porstendörfer, 1994). In general, the concentrations of radon gas and its daughters in both unattached and attached forms are not in secular equilibrium.

Organisms that inhale the aerosol mixture exhale the parent ^{222}Rn but trap the radon daughter aerosol quite efficiently. It is this radon daughter aerosol that constitutes the key to radon dosimetry in biota. What is required is to relate the concentration of radon daughters in air with internal dose to an organism. This requires knowledge of:

- transfer from air to organism, which for noble gases such as radon will be inhalation, mediated by an inhalation rate;
- respiratory tract dosimetry of radon daughters – in other words, how to calculate dose to the sensitive tissue of the lung (the walls of the tracheobronchial tree), and scale up to calculate a whole-body dose.

The information above is used to calculate a dose to whole body per unit concentration in air value (DPUC, μGy per Bq h m^{-3}). However, due consideration should be paid to the fact that plants and insects do not "breathe" in the normal sense, and so the method has to include these species in a simplified way.

1.1 Magnitudes and units

Estimating the generation of a radon daughter aerosol in partial equilibrium requires the use of special magnitudes and units in radon dosimetry. The principal variables are potential α-energy, working level (WL) and equilibrium equivalent radon (EER) (NEA, 1983 and Porstendörfer, 1994).

The potential α-energy of the ^{222}Rn daughters is the total α-energy that will ultimately be released by decay of the radon progeny. It is calculated to be 19.2 MeV per atom; hence one Bq of ^{222}Rn (and its daughters) will, through its decay chain down to ^{210}Pb, generate 9.15×10^{6} MeV. This is not dependent on equilibrium: as the decay occurs through the full chain, eventually, there must be one disintegration of each daughter product for every disintegration of the parent radionuclide ^{222}Rn.

The unit working level (WL) emanates from the above definition. It is the potential α-energy of short-lived ^{222}Rn daughters in air in equilibrium with a ^{222}Rn concentration of 3,700 Bq m^{-3} (NEA, 1983). One WL is equal to 3.70×10^{3} Bq m^{-3} EER. An individual exposure is determined by multiplying the working level by the number of 170-hour periods (known as work months), giving the exposure unit working level-month WLM.

One WLM is equal to 6.3×10^5 Bq h m^{-3} EER (ICRP, 1978). Working level-months of exposure are defined because all dose conversion factors and detriment coefficients used in estimating a dose from radon and its daughters are derived from this fundamental unit (NEA 1983), originally from assessments performed in the mining industry.

Equilibrium equivalent concentration of a mixture of ^{222}Rn and its progeny not in equilibrium is the activity concentration of ^{222}Rn in equilibrium with its daughters that would have the same potential alpha energy. It can be expressed as $F = \frac{C_{EER}}{C_0}$ with C_0 being the activity of the mother nuclide. F ranges between zero and one.

Substantial work has been carried out on radon in humans and, for this reason, the next two sections summarise briefly human radon dosimetry, for the purposes of comparison.

1.2 Principal endpoints in radon dosimetry

The key endpoints in radon dosimetry are the mean dose or dose equivalent to sensitive cells in the tracheobronchial (T-B) and pulmonary (P) regions of the lung, respectively (ICRP, 1981). For humans, these are generally calculated using two models: J-E (Jacobi-Eisfeld) and J-B (James-Birchall). What drives the dose is breathing rate. Table 2.11 of ICRP (1981) gives reference values of annual effective dose equivalent for adults, in units of Sv per equilibrium equivalent Bq (^{222}Rn) m^{-3} of 60×10^{-6} (assuming a radiation weighting factor RWF of 20 for α-energy). This table is for indoor environments as opposed to mining sites, where F and F_p for radon have different values (NEA, 1983).

Some useful data given by NEA (1983) for human dosimetry, suitable for reference or comparison, are given below:

(a) Mean dose to bronchial basal cells of adults exposed indoors = 3-9 mGy per WLM exposure (0.9-2.5 Gy per J h m^{-3}).

(b) Pulmonary doses are lower at 0.3-1.2 mGy per WLM (0.08-0.3 Gy per J h m^{-3}).

(c) Reference conversion coefficients of 4.0 mGy per WLM exposure (1.2 Gy per J h m^{-3}) for the mean bronchial dose and 0.5 mGy per WLM exposure (0.15 Gy per J h m^{-3}) for pulmonary dose are recommended.

1.3 Representative doses per unit activity concentration in humans

James (1988) deduced an effective dose of 1,200 μSv y^{-1} for humans exposed to a UK average radon level of 20 Bq m^{-3}, which gives a weighted DPUC of 60 μSv y^{-1} per Bq m^{-3}. Assuming a RWF of 20 for α-particles, this is equivalent to an unweighted DPUC of 2 μGy y^{-1} per Bq m^{-3} or 2.28×10^{-4} μGy h^{-1} per Bq m^{-3}. Dose appears to be roughly proportional to exposure (Miles and Cliff, 1992).

From James *et al*. (1988), one can extract the following formula for dose rate to ^{222}Rn "mother" activity concentration (DPUI) ratio:

$$\frac{\dot{D}}{\int \mathbf{C}_{Rn}dt} = F\left[f_p\left(D_U - D_A\right) + D_A\right]f_T \qquad [1]$$

And the following for effective dose equivalent:

$$\frac{\dot{H}}{\int \mathbf{C}_{Rn}dt} = Qw_B F\left[f_p\left(D_U - D_A\right) + D_A\right]f_T \qquad [2]$$

where:

F	is the equilibrium factor, $F = \frac{C_{EER}}{C_{Rn}}$, necessary to convert dose per unit C_{EER} to dose per unit C_{Rn};
f_p	is the non-aerosol attached radon daughter concentration fraction;
D_U	is the dose per unit exposure $\int C_{EER}dt$ to unattached Rn daughters, which is 1.23×10^{-3} Gy per Bq (EER) y m^{-3};
D_A	is the dose per unit exposure $\int C_{EER}dt$ to attached Rn daughters, which is 7.89×10^{-5} Gy per Bq (EER) y m^{-3};
Q	is the radiation quality factor for α particles = 20;
W_B	is the weighting factor applied to represent the risk of bronchial cancer = 0.06;
f_T	is fractional occupancy or exposure duration (in years) for each one year;
D and H	are dose and effective dose rates.

The conversion of 20 Bq m^{-3} to approximately 1.0 mSv y^{-1} is arrived at by using $f_p \approx 0.1$, $F \approx 0.35$ and $f_T = 0.65$ (typical dwelling occupancy fraction), which are the most representative values of a range of domestic conditions as shown in Figure 3 of James *et al.* (1988). This figure is a plot of f_p versus F for a variety of conditions, showing an inverse relationship and based on data reviewed from various sources.

For outdoor exposures in biota f_T would be unity and under an assumption of equilibrium (F equals one), extrapolation from that graph suggests that it is appropriate to use the approximation $f_p \approx 0$. Hence, $\frac{\dot{D}}{\int \mathbf{C}_{Rn}dt} = FD_a f_T$ = 0.08 mGy y^{-1} per Bq(Rn) m^{-3}, that is, a conversion of 12.5 Bq $m^{-3} \approx 1.0$ mGy y^{-1}.

The NCRP 78 Report (NCRP, 1984) provides equations for converting exposure resulting from inhalation of radon daughter products to an equivalent lung dose, treating the whole lung as the target organ for the radiation exposure. Furthermore, ICRP 66 (ICRP, 1994) gives specific tissue-weighting factors representing the localised radiation exposure to the bronchial epithelium for use in calculating equivalent doses.

2. Review of interim Environment Agency dose calculation method for radon in biota

The Environment Agency devised a method for assessing doses to biota and an associated assessment spreadsheet tool known as the EA R&D 128 methodology. This methodology is fully described in Copplestone *et al*. (2001; 2003). The problem is that this spreadsheet tool does not include radon in its suite of radionuclides.

As a method specific for radon doses to biota was not readily available, the Environment Agency developed an interim method to produce a ^{222}Rn dose per unit concentration factor (DPUC) using ^{239}Pu (also an α-emitter) as a surrogate. This "fix" was designed to be conservative. Its application therefore generated occasional dose rates above the Environment Agency screening value of 40 μGy h^{-1}, for no other reason than the unnecessarily high level of conservatism built into the calculations. The Environment Agency decided to improve on these 'first pass' calculations with the present study, designed to produce a more realistic method and reduce the unnecessary conservatism.

The Environment Agency approximation was calculated as follows. From the assessment spreadsheet, the ^{239}Pu internal DPUC (which is constant for all organisms except bacteria at 2.97×10^{-3} μGy h^{-1} per Bq kg^{-1} body mass) was taken. This was then multiplied by a radiation weighting factor (RWF) of 20 for α-particles to give a weighted ^{239}Pu internal α-DPUC of 5.93×10^{-2} μGy h^{-1} per Bq kg^{-1} body mass. The ^{222}Rn CF for air to organism was assumed to be 1.0 Bq kg^{-1} body per Bq m^{-3} air and the ^{222}Rn weighted internal dose (air exposure) was then generated by dividing the weighted ^{239}Pu internal α-DPUC by this value.

There are three fundamental problems with this calculation.

Firstly, the dose to the organism is delivered by the short-lived ^{222}Rn daughters, the ^{222}Rn gas being inert and consequentially exhaled without being deposited, unlike the highly electrostatically charged daughters that are trapped in the respiratory tract. It would be more appropriate to use a DPUC for ^{218}Po and its short-lived progeny in equilibrium than the very different ^{239}Pu internal DPUC value. Multiplication of the measured ^{222}Rn activity concentration by this DPUC would have given a better approximation for the dose from radon daughters, assumed to be in equilibrium with the parent radionuclide. Calculations using the original Environment Agency R&D 128 MonteCarlo calculation code yield a DPUC of 7.9×10^{-3} μGy h^{-1} per Bq kg^{-1} body mass for the short-lived radon daughters, that is, 2.7 times higher than for ^{239}Pu. The difference is due to the higher number of α-decays involved in the radon chain. This indicates that the "fix" is unnecessarily conservative.

Secondly, the "fix" misrepresents the transfer from medium to organism. It assumes a 1:1 equilibrium between activity concentration (Bq kg^{-1}) in body and activity concentration (Bq/m^{-3}) in air. In reality, there is a constant input of ^{222}Rn and its daughters into the body by the respiration process. As soon as the daughters enter the body, the radioactive decay is so fast that a dynamic equilibrium is rapidly achieved between the steady input and the decay. It can be calculated (set Equation 5 below to equilibrium with $\frac{dN}{dt} = 0$) that for a short-lived radionuclide, the equilibrium CF for air to organism is equal to breathing rate divided by organism mass × decay constant. For example, in humans this would be 3.33×10^{-4} m^3 s^{-1} / (70 kg × 3.73×10^{-3} s^{-1}) = 0.0013 m^3 kg^{-1}. This value is much smaller than unity and consequently the fix introduces an even higher overestimation of the dose on that count.

Lastly, owing to the fact that the dose from radon daughters arises primarily from α-emissions, and α-particles have a very short range in tissue (of around 50 μm), the depth of the irradiated tissue will be very small. The R&D 128 tool calculates doses to the whole body of the organism, assuming uniform distribution of the radionuclides. Clearly, it is necessary to be able to calculate doses per unit mass of irradiated tissue additionally to doses to whole body, in order to be able to assess the correct endpoint.

There follows the need to improve the interim "fix" developed by the Environment Agency in order to address these problems. In the sections below an improved method is set out, which can be codified into new DPUCs for internal α-irradiation arising from exposure of animals and plants to short-lived ^{222}Rn daughters. The ^{222}Rn DPUCs can be used, in the same way as the "fix", to make an assessment in the normal way, using atmospheric radionuclide versions of the standard R&D 128 formula for terrestrial ecosystems:

$$\dot{H} = \sum_i (C_i^{air} \times CF_i^{air} \times DPUC_{total,i}^{\text{int}}) + \left(\left(f_{soil} + 0.5 f_{surface}\right) C_i^{soil} \times DPUC_{total,i}^{ext}\right) \qquad [3]$$

where:

$\sum_i$ represents summation over all nuclides;

C^{air} is the activity concentration of the radionuclide in air;

C^{soil} is the concentration of the radionuclide in surface soil, calculated from the air concentration and the relevant concentration ratio;

CF^{air} is the concentration factor for the organism referenced to air;

f_{soil} is the fraction of time the organism spends under the soil surface;

$f_{surface}$ is the fraction of time the organism spends on the ground surface.

3. Development of new method

^{222}Rn is inhaled and then exhaled, resulting in no accumulation and little health risk. ^{222}Rn decay products, on the other hand, are inhaled and travel to the bronchioles and alveoles where they get trapped, and are subsequently transported to the bronchi where they deliver the dose representing the primary health risk. The target tissues in the lung for dosimetry of inhaled radon daughters are therefore bronchial stem cells. The bronchial basal cell layer is the region to which the dose posing the highest risk is delivered (three to ten times higher dose than to alveolar epithelium and the terminal non-ciliated bronchioles – NEA, 1983).

Modelling bronchial doses requires factorisation of the mucus clearance process but this is beyond the scope of this study, whose purpose is to perform an approximated calculation. Therefore, the aim at this stage is to model an average dose to the whole inner lining of the lung and, in doing so, end with a dose calculation that is greater than dose to the whole body but smaller than dose to the inner lining of the bronchi. Doses to bronchi can then be inferred using a simple mass scaling factor which will likely overestimate, as it neglects decay in transit during clearance.

3.1 Problem formulation

We model the input of a constant flow of atoms into a compartment (the inner lining of the tracheobronchial tree) compounded with fast loss of these atoms due to radioactive decay. It is assumed that the tissue is 100 per cent efficient at trapping the material, where no particles escape by exhalation and decay is the only source of removal. In other words, the tracheobronchial tree as a whole is assumed to act like a very efficient filter, by trapping both the unattached and attached fractions of the radon aerosol onto the large surface area formed by the bronchioles and alveoles.

Figure 1 summarises the situation. Under the assumption of equilibrium (equilibrium factor F = 1), the input flow I_0^i is constant and can be calculated as the specific activity × breathing rate (Bq s^{-1}) divided by the decay constant in order to convert disintegrations per unit time to particles, according to the formula activity = number of atoms × λ.

$$I_0^i = \frac{B_R A_i}{\lambda_i} \qquad [4]$$

where:

i	index labelling the radionuclide: 1 to 5 for ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po;
A_i	activity of radionuclide i [Bq m^{-3}] = A_1 (assumption of secular equilibrium);
BR	breathing rate [m^3 s^{-1}] = tidal volume (V_T) × respiratory frequency (ν_R);
λ_i	decay constant of radionuclide i [s^{-1}].

Hence the differential equation for the system is:

$$\frac{dN_i}{dt} = I_0^i - \lambda_i N_i = \frac{B_R A_i}{\lambda_i} - \lambda_i N_i \qquad [5]$$

3.2 Model solution

Equation 5 is easy to integrate and yields the following solution:

$$-\lambda_i t = \int_0^t \frac{dN_i}{N_i - \frac{B_R A_i}{\lambda_i^2}} \Rightarrow N(t) = \frac{B_R A_i}{\lambda_i^2}\left(1 - e^{-\lambda_i t}\right) \qquad [6]$$

Now we need to calculate the rate of energy per unit mass (dose rate) deposited in the lung by the each radon daughter i (i = 2-5), which is as simple as:

$$\dot{D}_i = \frac{N_i(t)\lambda_i E^{\alpha}_{i}}{M_T} \qquad [7]$$

where:

i	index for the radionuclide;
$\dot{D}_i$	absorbed dose rate [Gy s^{-1}];
$N_i(t)\lambda_i$	activity associated with $N_i(t)$, as per Equation 4 above;
M_T	mass of sensitive tissue = $\rho_T \times S_T \times h_T$ [m^3];
E_i^{α}	total energy emitted by daughter radionuclide *i* due to its own decay and the (rapid) subsequent decay of its short-lived daughters down to ^{210}Pb = $\sum_{j=i}^{5} \varepsilon_j^{\alpha}$ [J];
ε_j^{α}	alpha decay energy of emission of radionuclide k.

Substitution of the formula for the volume of sensitive tissue and Equation 6 into 7 yields:

$$\dot{D}_i = \frac{B_R A_i E_i^{\alpha}}{\lambda_i \rho_T S_T h_T}\left(1 - e^{-\lambda_i t}\right) \qquad [8]$$

where:

B_R	breathing rate [$m^3\ s^{-1}$] = 3.33×10^{-4} $m^3\ s^{-1}$ for human;
A_i	average concentration of radionuclide *i* [Bq m^{-3}];
ρ_T	tissue density = 10^3 kg m^{-3};
S_T	tracheobronchial surface area [m^2]; here, we are interested in doses received by the tracheobronchial tree excluding the trachea, which is relatively insensitive to radiation exposure, and thus need to sum the surface area of both the bronchial (generations 1-8) and bronchiolar (generations 9-15) regions = $2.9 \times 10^{-2} + 2.4 \times 10^{-1}$ m^2 = 2.69×10^{-1} m^2 for humans (from ICRP 1994);
h_T	active depth of sensitive tissue; the height (m) of the human bronchial epithelium (without cilia) is 5.5×10^{-5} m (from ICRP 1994, p16) while for the bronchioles, this is 1.5×10^{-5} m so for conservatism sake, we take the higher value which ensures 100 per cent absorption of α-energy given the range of α-particles in water (de Carvalho and Yagoda, 1952)[1].

The total dose rate is the sum of all the dose rates for the short-lived daughters:

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[1] Essentially, what is meant here is that the range of the alpha particles determines the depth of the irradiated tissue from which the mass of the critical tissue can be calculated.

$$\dot{D}=\sum_{i=2}^{5}\dot{D}_i=\frac{B_R}{\rho_T S_T h_T}\sum_{i=2}^{5}\frac{A_i E_i^{\alpha}}{\lambda_i}\left(1-e^{-\lambda_i t}\right) \qquad [9]$$

Since ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po have a very short half-lives (3.1, 26.8, 19.7 and 2.73 × 10^{-6} minutes, respectively), the decay constants are large and the product $\lambda_i t$ is very large after the first minutes, hence a relatively simple expression can be obtained under the assumption that secular equilibrium has taken place: $1-e^{-\lambda_i t}\approx 1$ and $A_1 = A_i$, i = 2-5. Hence:

$$\dot{D}_i=\frac{B_R}{\rho_T S_T h_T}\sum_{i=2}^{5}\frac{A_i E_i^{\alpha}}{\lambda_i}=\frac{B_R A_1}{\rho_T S_T h_T}\sum_{i=2}^{5}\frac{1}{\lambda_i}\sum_{j=i}^{5}\varepsilon_i^{\alpha}=\frac{B_R A_1 D_P^{\alpha}}{\rho_T S_T h_T}=\frac{F B_R EE_{Rn} D_P^{\alpha}}{\rho_T S_T h_T} \qquad [10]$$

where the sum $\dot{D}_P^{\alpha}=\sum_{i=2}^{5}\frac{1}{\lambda_i}\sum_{j=i}^{5}\varepsilon_i^{\alpha}$ is the potential α-energy per Bq activity of the short-lived radon daughters in secular equilibrium and A_1 is the activity of radon gas = F × EER (equilibrium factor per equilibrium equivalent radon concentration). The potential α-energy per Bq activity factor can be calculated from the data in Table 1.

The dose rate per unit activity concentration of radon via inhalation (Gy s^{-1} per Bq m^{-3}), or DPUC, is the above Equation 10 divided by the activity of ^{222}Rn:

$$DPUC=\frac{\dot{D}}{A_{Rn}}=\frac{B_R D_P^{\alpha}}{M_T}=5.54\times10^{-9}\frac{B_R}{M_T} \qquad [11]$$

With $M_T=\rho_T S_T h_T$. If equivalent doses are desired, this equation needs to be further multiplied by a radiation weighting factor for α-energy (R_{wf}^{α}, default = 20).

The total absorbed dose delivered to the tissue (in Gy) would then be, very approximately, D = DPUC × A_{Rn} × T where T is the time of application of the dose. This approach is compatible with that developed by MacDonald and Laverock (1998) except that these authors consider the whole lung to be the reference tissue for calculation of the dose. Therefore, in order to compare the DPUCs generated by these authors with our work, it is necessary to make a tissue weight correction:

$$DPUC_{THIS\,WORK}=\frac{Lung\ \ dose_{McD}}{Exposure\ \ time\times Rn\ \ EEC\times F}\times\frac{M_{Whole\ lung}}{M_{TB\ epithelium}} \qquad [12]$$

3.3 Allometric scaling of the relevant parameters for the lung

Deriving radon DPUCs for different species requires an ability to calculate dose factors in a simple way, using formulae that relate these factors to organism dimensions. In this study, allometric scaling is the method chosen to scale the dimensions and exchange rates of the respiratory system across different animal species.

Allometric analysis is the comparison of a given structural or functional parameter (*Y*) as a function of body weight (BW) across organisms of different species. *Y* is represented by the function $Y = A \times BW^B$ where A and B are called the base and exponent of the power function, respectively. The log-transformed version of this function, $\log Y = \log A + B \times \log BW$, is particularly useful. When the exponent B equals unity, Y increases in direct proportion to weight through the proportionality factor A (isometric scaling). Exponents higher or smaller than unity indicate that the variable under consideration increases, respectively, disproportionately more or less with the increase in body weight.

3.3.1 Tracheobronchial epithelium height and mass

The tracheobronchial epithelium target tissue is a classical case of body part susceptible of allometric scaling. In a simplified way, this tissue can be thought of as the volume between two interlocking cylinders of radii r and $r + h$, respectively, and length L (Figure 2). Henceforth, the volume of the target area is:

$$V = \pi(R+h)^2 L - \pi R^2 L = 2\pi RLh\left(1+\frac{h}{2R}\right) \approx 2\pi RLh \qquad [13]$$

We can now use the allometric scaling rule that bronchial dimensions R and L scale in proportion to one-third power of lung capacity (Hofmann, 1982). We also use the rule that lung volume is linearly related to body mass (Tenney and Remmers, 1963). Therefore:

$$S_T = 2\pi hRL = KM^{2/3} \qquad [14]$$

For the lining of the tracheobronchial tree, we calibrate this formula for a reference man[2] with $S_T = S_T^{RM} = 2.69 \times 10^{-1}$ m^2 and $M = M_{RM} = 70$ kg, hence $k = 2.69 \times 10^{-1} \times 70^{-2/3} = 1.58 \times 10^{-2}$ and $S_T = S_T^{RM}\left(\frac{M}{M_{RM}}\right)^{2/3} = 1.58\times10^{-2} M^{2/3}$; therefore, for a tissue of same density as water ($\rho_T = 10^3$ kg m^{-3}):

$$M_{TB} = 15.8 h_T M^{2/3} \qquad [15]$$

For the bronchial epithelium of the lung, the surface area would be a factor of 9.25, that is, approximately one order of magnitude below, k being 1.71×10^{-3} for bronchi:

$$M_B = 1.71 h_T M^{2/3} \qquad [16]$$

3.3.2 Lung volume and mass

Lung volume is linearly related to body mass (Tenney and Remmers, 1963), as stated previously, with tidal volume linearly related to lung volume so $V_T = k_1 M$. According to Peters (1983), $V_T = 7.69 \times 10^{-6} M^{1.04}$. This formula under-predicts the ICRP reference man tidal volume $V_T = 1.25 \times 10^{-3}$ m^3, giving 6.38×10^{-4} m^3 instead. A formula calibrated for the reference man would have $k_1 = 1.25 \times 10^{-3}$ m^3 / 70 kg, hence

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[2] Reference man is defined as being between 20-30 years of age, weighing 70 kg, is 170 cm in height, and lives in a climate with an average temperature of 10 to 20°C. He is a Caucasian and is a Western European or North American in habitat and custom.

$V_T = 1.79 \times 10^{-5} M$. A suitable compromise to cover the organism size range from small mammal to human is to average both the base and the exponent, giving $V_T = (1.28 \pm 0.72) \times 10^{-5} M^{1.02 \pm 0.03}$. The lung mass will be tidal volume times lung density (approximated to 10^3 kg m^{-3}) or:

$$V_T = (1.28 \pm 0.72) \times 10^{-2} M^{1.02 \pm 0.03} \qquad [17]$$

This is virtually identical to the formula given by MacDonald and Laverock (1998), taken from Peters (1983): $M_L = 1.13 \times 10^{-2} M^{0.986}$.

3.3.3 Breathing rate

According to Worthington *et al*. (1991), respiratory frequency ν_R (s^{-1}) for mammals correlates with body mass M (kg) according to $\nu_R = 0.84M^{-0.26}$ which, for M_{RM} = 70 kg, predicts quite accurately the breathing frequency for the reference man. In birds, ν_R scales approximately to $M^{-1/4}$ (Hempleman *et al*., 2005). It thus seems reasonable to assume that $\nu_R = k_2 M^{-1/4}$ and therefore that breathing rate for biota is $R_B = V_T \nu_R = k_1 k_2 M^{3/4}$, that is, proportional to $M^{3/4}$, at least for vertebrates.

Calibrating this formula for reference man with $R_B = R_B^{RM} = 3.33 \times 10^{-4}$ $m^3 s^{-1}$ and M = M_{RM} = 70 kg (ICRP, 1975; NEA, 1983) gives $R_B = 1.38 \times 10^{-5} M^{0.75}$. That R_B scaling is proportional to three-quarters power of the mass in mammals is confirmed by $R_B = 5.57 \times 10^{-6} M^{0.76}$, the formula for a range of terrestrial and riparian animals reported by USDOE (2002), and $R_B = 6.84 \times 10^{-6} M^{0.78}$ from Peters (1983), quoted in MacDonald and Laverock (1988).

It thus appears that the formula for humans may tend to overestimate for smaller animals. A reasonable compromise is to average the base and exponent of the above three equations to obtain:

$$R_B = (8.7 \pm 4.4) \times 10^{-6} M^{0.76 \pm 0.02} \qquad [18]$$

Table 2 shows some comparisons with breathing rates for human (70 kg), rat (300 g) and Oryzomys (75 g), the latter being two small mammals.

3.4 Allometric formula for the DPUI

Using Equation 11 in combination with Equations 15-18 gives the following formulae (expressed as simple base and exponent power functions) for the DPUC in μGy per Bq h m^{-3}:

$$
\begin{aligned}
DPUC_B &= F_U R_{WF}^{\alpha}\left(\frac{D_P^{\alpha} A_{BR}}{\rho_T h_T S_B^{RM}} M_{RM}^{2/3}\right) M^{B_{BR}-\frac{2}{3}} \\
DPUC_{TB} &= F_U R_{WF}^{\alpha}\left(\frac{D_P^{\alpha} A_{BR}}{\rho_T h_T S_{TB}^{RM}} M_{RM}^{2/3}\right) M^{B_{BR}-\frac{2}{3}} \\
DPUC_L &= F_U R_{WF}^{\alpha}\left(\frac{D_P^{\alpha} A_{BR}}{A_{LM}}\right) M^{B_{BR}-B_{LM}} \\
DPUC_{WB} &= F_U R_{WF}^{\alpha}\left(D_P^{\alpha} A_{BR}\right) M^{B_{BR}-1}
\end{aligned}
\tag{19a - d}
$$

where:

F_U	unit conversion factor (3.6×10^9 μGy h^{-1} per Gy s^{-1});
BR	gross extrapolation to the bronchial epithelium (airway generations 1-8);
TB	full tracheobronchial epithelium (generations 1-15);
L	full lung;
WB	whole body;
$A_{BR}(A_{LM})$	(also $B_{BR}(B_{LM})$) base and exponent of the allometric formulae for breathing rate and lung mass in Equations 18 and 17, respectively;
S_{TB}^{RM}, S_B^{RM}	surface area of the tracheobronchial tree or the bronchial epithelium;
R_{wf}^{α}	radiation weighting factor for α-energy (default = 20).

Substitution of actual data gives the values listed in Table 3. For tracheobronchial and bronchial epithelium, this is a smooth dependence causing only 20 per cent difference when mass varies by one order of magnitude. Smaller organisms are predicted to receive smaller doses because the breathing rate decreases more quickly than the target tissue volume, and that is driven by the increase in breathing frequency for smaller mass organisms.

3.5 Model validation

Our main validation dataset is the paper by MacDonald and Laverock (1988) which gives doses to the whole lung; these should resemble results using Equation 19c. An additional complication is that these authors consider the dose to have three components: hibernation, in burrow and out of burrow. For simplicity we use the highest component to dose, corresponding to active animal in burrow. In Table 4, the dose rates given by MacDonald and Laverock (1988) are compared with unweighted doses (here we use $R_{wf}^{\alpha} = 1$, not 20, to facilitate comparison) obtained by our method. The table shows good agreement, with differences attributable to the different breathing rate formula used in our work, which tends to underestimate for smaller organisms though differences are never more than 30 per cent.

Additional comparison with rat DPUCs for the tracheobronchial tree by Hofmann *et al.* (2006) and Harley (1988) is problematic because these sources use a full model of the tracheobronchial tree. This has the following consequences:

1. The full model predicts that a significant fraction of the radon daughters is removed by the nasal passages.

2. Such models includes lung clearance processes, resulting in transport and redistribution of the radon daughters from the alveolar region to the bronchial part of the airways, with associated decay included in transit.
3. The models consider atmospheres with various assumptions of equilibrium resulting in varying particle size, F below one and f_P values.

The net result is that doses calculated by a full respiratory model will be lower by a factor of 5.5-7.5, as shown in Table 5. Strong *et al*. (1996) estimated an absorbed dose to the whole lung of 2.4×10^{-9} Gy s^{-1} for an integrated unit exposure of one WL in mice, equivalent to 6.49×10^{-7} μGy per Bq s m^{-3}. This is again higher than our calculated DPUC for rat, for the same reason. Thus, our simplified model has built-in conservatism, fit for the purpose of the current calculations. It is recommended that future work should focus on devising an allometric fully process-based lung model to calculate respiratory doses more precisely.

3.6 Simpler organisms: eggs, insects and plants

3.6.1 Bird egg

A bird's egg is a complex structure of liquids and membranes designed to meet the needs of the growing embryo. Eggs contain a certain amount of airspace, allowing gases to be exchanged through the shell. The allantois (a membrane that spreads around the inside of the shell) contains numerous blood vessels which carry gases between the embryo and the outside.

For the purposes of this exercise, the maximising assumption is made that the breathing rate for eggs is equal to the breathing rate of a bird having the same mass as the egg. Consequently, using Equation 18 for the breathing rate is an extremely conservative assumption, because it is likely that the pores of the egg shell will trap a substantial component of the unattached and attached fractions of the radon aerosol before they reach the animal. We retain this assumption, however, because, as will be seen in Section 5.3, it does not lead to unusually high doses for eggs compared with other organisms.

3.6.2 Insects

It is a general finding that the metabolic rates of all animals scale approximately the three-quarters power of mass. However, as seen above, allometric formulae optimised to fit the more complex organisms (such as human) tend to over-predict the simpler organisms (see Section 3.3.3). In the case of insects, respiration in insects is mainly a diffusion and convection process through a network of tubes, the tracheolae, connecting the body surface to the innermost tissues. The quantity of air circulated is regulated via spiracles and the respiratory network of insects is less complex than a scaled-down version of the mammal lung. Consequently, using Equation 18 for the whole size range including invertebrates is a justifiable conservative assumption.

3.6.3 Plants

According to Higley and Bytwerk (2007), the rate of resource use in individual plants also scales as approximately the three-quarters power of vegetative mass, which is the same as the metabolic rate of animals. However, this has been disputed (Price and Enquist, 2007). Reich *et al*. (2005), using data obtained from about 500 laboratory and field-grown plants from 43 species and four experiments, propose that whole-plant respiration rates scale approximately isometrically with total plant mass.

Data from Table 2 of Reich *et al*. (2005) was used to calculate a breathing rate relationship for plants as follows. Firstly, information on the whole plant respiration (measured as net CO_2 efflux in nmol CO_2 s^{-1}) as a function of dry mass (g) was used to calculate an average base (1.19) and exponent (1.02). The whole set of data, covering a variety of plants[3], was used to obtain a "broad-brush" relationship[4] for the equation $\log_{10}$ (total respiration rate, nmol CO_2 s^{-1}) = exponent × $\log_{10}$ (dry mass, g) + $\log_{10}$ (base). Next, data were converted to appropriate units by applying: (a) a conversion factor of 2.5×10^3 mol of air per mol of CO_2[5]; (b) a generic wet:dry mass ratio of five[6]; and (c) a molar volume of 22.4 l STP. This gives the following formula for the total plant air respiration rate:

$$BR_{PLANT}(m^3s^{-1}) = 1.95\times10^{-4}M(kg)^{1.02} = A_{PL}M^{B_{PL}} \qquad [20]$$

In plants, it no longer makes sense to consider the target tissue to be the epithelium of the bronchi because plants have no such structures. Instead, one can assume the external surface area of the plant to be the system exchanging gases with the atmosphere[7]. Fractal biological models predict that the surface area of plant leaves scales proportional to $M^{3/4}$ (West *et al*., 1999; Enquist and Niklas, 2002). However, Price *et al*. (2007) have studied the problem in greater detail and aver that there is no "one size fits all" model for linking leaf surface area as a function of mass; hence, this problem is not easily tractable.

The R&D methodology considers plants (such as lichen, moss, tree, shrub, grass, germinating seed and fungal fruiting body) to be highly elongated ellipsoids, the abstracted representation of an "equivalent cylinder" representing a segment of the root rather than the whole plant. The dose is delivered from the radionuclide trapped in soil by transfer across the walls of the root. This kind of representation is inconvenient for gaseous radionuclides. However, as a crude approximation, one can coax the Environment Agency R&D 128 methodology to calculate plant doses assuming that the range of the alpha particles determines the depth of the irradiated tissue in the walls of the root.

Let us assume the reference organism to be an elongated ellipsoid with major axis L and identical minor axes a = b. The volume of the ellipsoid is $V_{ellipsoid} = \frac{1}{6}\pi La^2$ = volume of the "equivalent cylinder" $V_{cylinder} = \pi R^2 L$ so the radius of the equivalent cylinder is $R = \frac{a}{\sqrt{6}}$. The target tissue can be modelled as the volume between two interlocking

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[3] Herb and tree seedlings, and saplings from field, greenhouse and growth chambers.

[4] The authors have stated that there is no generic expression for the respiration rate versus total mass of plants because the base of the log-log scaling relationship depends on plant nitrogen. Covering all the species by averaging all the bases is a conservative assumption in respect of considering only the relatively nitrogen-poorer soils in the field.

[5] Dry air contains approximately 0.04 per cent carbon dioxide. The partial pressure of carbon dioxide in dry air at sea level is, therefore, 4×10^{-4} A. One mol of air will have 4×10^{-4} mol of CO_2 in it; hence there are $1 / 4 \times 10^{-4} = 2.5 \times 10^3$ mol of air per mol of CO_2.

[6] This is the largest potential source of uncertainty in this calculation.

[7] This assumption has a deliberate degree of conservatism because, in not modelling the inner surface of stomata, it underestimates the plant's exposed area and, consequently, it overestimates the energy deposited per unit mass, or dose.

cylinders of radii *r* and $r + h_T$, respectively, and length *L*. Henceforth, using Equation 13, the mass of the critical tissue m_T can be expressed as a function of the total mass of the organism M:

$$m_T \approx \sqrt{\frac{2}{3}}\pi\rho a L h_T = 2\sqrt{6}\,\frac{h_T}{a}M \qquad [21]$$

Consequently, substituting Equations 20 and 21 into Equation 1, we obtain the following formula for plant tissue DPUC in μGy per Bq s m^{-3}:

$$DPUC_{PLANT\ TISSUE} = F_U\,R_{WF}^{\alpha}\,\frac{A_{PL}\,a M^{B_{PL}-1}}{2\sqrt{6}h_T}D_P^{\alpha} \approx F_U\,R_{WF}^{\alpha}\,\frac{A_{PL}\,a}{2\sqrt{6}h_T}D_P^{\alpha} = 1.44\times10^{1}a \qquad [22]$$

where:

D_P^{α}	potential α-energy factor 5.54 × 10^{-9} J Bq^{-1};
A_{PL}	allometric base for breathing rate in plants, 1.95 × 10^{-4} m^3 s^{-1};
a	minor axis of the ellipsoid representing the plant in metres (if the two minor axes of the geometry are dissimilar, then the average is taken);
h_T	depth of sensitive tissue = 5.5 × 10^{-5} m;
F_U	unit conversion factor (3.6 × 10^9 μGy h^{-1} per Gy s^{-1});
R_{wf}^{α}	radiation weighting factor for α-energy (default = 20).

If we assume that the whole plant is a surface exchanging gases with the atmosphere, then we can predict DPUCs to whole plant (in μGy per Bq s m^{-3}) with a reasonable degree of approximation as being constant with mass:

$$DPUC = F_U\,R_{WF}^{\alpha}\,\frac{B_R D_P^{\alpha}}{M} = 1.99\times10^{1}R_{WF}^{\alpha}A_{PL}M^{B_{PL}-1} \approx 1.99\times10^{1}R_{WF}^{\alpha}A_{PL} = 3.88\times10^{-3}R_{WF}^{\alpha} \qquad [23]$$

Equations 22-23 can be regarded as a plausible form of calculating radon doses to plants until such time as an appropriate process model has been derived to consider these organisms[8]. An obvious limitation of the approach is that CO_2 – a gas actively taken in by the plant – is used as a tracer for radon (an unreactive gas) and its short-lived daughters. Consequently the amount of radon entering the plant is conservatively estimated. In future work, this representation could be improved by factorising the different deposition velocities of CO_2, radon and the daughter aerosol in stomata. A dynamic dose model for the plant respiratory system representing radon gas exchange through plant stomata on a species-by-species basis is the next logical improvement of this methodology. Such work transcends this study and is a recommendation for future work.

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[8] Interestingly, with the exception of germinating seed, dose rates calculated by Equations 22-23 appear to be within a factor of five of the dose rates that would have been obtained using the allometric formulae for animals.

3.7 Derivation of DPUCs for animals and plants

Based on Equations 19a-d for animals and Equations 22-23 for plants, we arrive at a set of DPUCs for different target tissues of biota as given in Table 6. To highlight the impact of the radiation quality on dose, in this table the DPUCs are multiplied by a radiation weighting factor R_{wf} of 20 for α-radiation[9].

For the assessment of internal and external exposure to low-energy β (below 10 keV) and high-energy β (above 10 keV) and γ radiation, we propose the use of standard DPUCs for these components of radiation calculated in the normal way using the Environment Agency 128 Monte Carlo DPUC calculators, as described in Section 4 below.

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[9] The R_{wf} of 20 for α-radiation, equal to the value used in human protection, is the default set in the Environment Agency 128 methodology. This may be a conservative overestimation, because it was intended to represent RBEs for stochastic effects in humans (primarily the induction of cancers), whereas in non-human biota deterministic effects will be of greater significance (Vives i Batlle *et al.*, 2004).

4. Decay chain and calculation of external exposures

According to the ICRP-38 database, ^{222}Rn has the following decay chain: ^{222}Rn (3.82 days) $\Rightarrow$ ^{218}Po (3.1 minutes) $\Rightarrow$ ^{214}Pb (26.8 minutes) $\Rightarrow$ ^{214}Bi (19.7 minutes) $\Rightarrow$ ^{214}Po (164 micro-seconds) $\Rightarrow$ ^{210}Pb (22.3 years) $\Rightarrow$ ^{210}Bi (5.01 days) $\Rightarrow$ ^{210}Po (138 days) $\Rightarrow$ ^{206}Pb (stable). There is also a one per cent ^{218}At branch from ^{218}Po to ^{214}Bi. This decay chain was examined in some detail to assess the significance of external exposures.

For the purposes of this study, we consider ^{222}Rn to be in equilibrium with the members of its progeny capable of reaching equilibrium in a relatively fast time, which excludes ^{210}Pb, ^{210}Bi and^{210}Po, leaving only ^{222}Rn, ^{218}Po, ^{218}At, ^{214}Pb and ^{214}Bi. Dose factors are calculated for this compound radionuclide. The presence of multiple α decays in the chain implies that α-DPUCs for radon and its daughters are larger than plutonium, as discussed in Section 2.

The ^{222}Rn and short-lived daughters combined decay chain comprises 93 electron, 75 γ- and six α-lines. Table 7 lists all the relevant decays, from the ICRP-38 (ICRP, 1983) database (decays of the parent ^{222}Rn nuclide are highlighted in bold and italic). The table shows, for β- and γ-rays, a combination of medium-to-low energies and quantum yields.

For β-particles, the whole body dose rate is proportional to 1 – AF, where AF is the absorbed fraction, calculated with the semi-empirical formula $AF = \frac{1}{1 + aE^n}$. Here, *a* and *n* are constants that depend on the organism (Vives i Batlle *et al.*, 2004). It can be easily demonstrated that this only becomes significant (AF $\geq$ 0.1) for $E_{avg} \geq 0.5$ MeV, which could happen only in plants. There are only three β-transitions of potential importance here, with E_{avg} = 0.525, 0.539 and 1.239 MeV and yields of 0.176, 0.179 and 0.177 respectively. Due to the low yields, only the latter transition is significant, and even this will have an external dose proportional to (1 – AF) × yield = 0.099 for a single organism (lichen) compared with AF = 1 for internal α-dose. Consequently, the external dose contribution from β-particles is basically negligible and the approach to calculate skin doses as in previous work for Ar and Kr (Vives i Batlle and Jones, 2003) is not warranted.

For γ-rays, there are five contributors of potentially more importance, with energies of 0.295, 0.352, 0.609, 1.12 and 1.77 MeV and yields of 0.192, 0.371, 0.461, 0.150 and 0.159 respectively. Thus, the main contributor to external dose is the aforementioned γ-rays.

Estimating the weight of this contribution is possible by calculating external exposure DPUCs for the low-energy β (below 10 keV) and high-energy β and γ emissions of the short-lived ^{222}Rn daughters, assumed in secular equilibrium, using the Environment Agency 128 Monte-Carlo DPUC calculators. It was necessary to convert the Monte Carlo DPUC spreadsheet-generated factors from μGy h^{-1}/Bq kg^{-1} of air to μGy h^{-1}/Bq m^{-3} of air, and to this effect division by an air density of 1.2 kg m^{-3} under standard conditions was assumed in the calculations. Additionally, the DPUCs are weighted using RWFs of three for low-energy β (below 10 keV) and one for high-energy β and γ emissions, consistent with the Environment Agency 128 methodology. This information is given in Table 8.

The following conclusions are evident from the data:

1. Low-energy β DPUCs are, as foreseen, negligible compared to high-energy β + γ.
2. For animals, the DPUCs for internal exposure to α-irradiation drive the dose, so external exposure can be neglected. The worst case is carnivorous mammal, where the external DPUC can be 30 per cent of its internal equivalent.
3. Only in plants will the external radon daughter dose become significant, ultimately owing to the low respiration rates in plants.

For risk assessment, it is thus justified to neglect external irradiation for all animal species.

5. Dose assessment

The Environment Agency derived three radon concentrations (lowest, typical and highest) in air for trial assessment of seven organisations with set ^{222}Rn authorisation limits under the UK Radioactive Substances Act (RSA) 1993. The range of concentrations was from 183 MBq y^{-1} to 10 TBq y^{-1}. The Environment Agency calculated a dispersion factor of 2.79×10^{-12} Bq m^{-3} per Bq y^{-1} (R. Allott, Environment Agency, personal communication). Hence, the ^{222}Rn concentration in air ranges from 5.11×10^{-4} to 2.79×10^{1} Bq m^{-3}, with a median of 1.40×10^{1} Bq m^{-3}. The highest air concentrations are much lower than those reported by MacDonald and Laverock (1992) in artificial burrows from radon-rich soils (5×10^{3} Bq m^{-3}) and are not considered to be excessively high. For comparison, a typical concentration of ^{222}Rn in indoor air is in the range 2-500 Bq m^{-3} and in outdoor air 1-10 Bq m^{-3} (ICRP, 1987).

5.1 Assessment set up

Three assessments were run, corresponding to the air concentrations calculated above. A concentration factor of 10^{-4} was specified as a default for converting concentration in air (Bq m^{-3}) to soil (Bq kg^{-1} wet), arising from migration into the soil pores. This assumes a free air space of 0.15 volume:volume in soil and a bulk density of 1,500 kg m^{-3} (Vives i Batlle and Jones, 2003). Occupancy factors (listed in Table 9) were set as per Vives i Batlle and Jones (2003), with f_{air} for plants redefined to 0.5. Clearly, a total occupancy of 1.5 is pessimistic. Use of a factor of 0.5 for air effectively calculates the dose from air immersion to foliage close to the ground surface.

The following formulae were used, applicable to all radionuclides whose concentration is referenced to air - that is, ^{3}H, ^{14}C, ^{32}P, ^{35}S, ^{41}Ar, ^{85}Kr and ^{222}Rn:

$$\begin{aligned}
&(\text{Internal dose}, \mu\text{Gy h}^{-1})_{nuclide,organism} = \left(\text{Air conc, Bq m}^{-3}\right)_{nuclide} \times \\
&\qquad\qquad \times (DPUC, \mu\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{internal}}_{nuclide,organism} \\
&(\text{External dose})_{nuclide,\ organism} = (Soil\ dose + Immersion\ dose) \\
&(Soil\ dose) = (\text{Air conc, Bq m}^{-3})_{nuclide} \times (CF,\ m^{3} kg^{-1})^{\text{soil}}_{nuclide} \times \\
&\qquad \times (DPUC, \mu\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{external}}_{nuclide,organism} \times \\
&\qquad 1.2\ kg\, m^{-3} \times \left[\begin{pmatrix} \left(fsoil_{organism} + fsoilsur_{organism}/2 \right) \\ + fair_{organism} \times (\text{reduction factor})_{\text{radiation type}} \end{pmatrix} \right] \\
&(Immersion\ dose) = (\text{Air conc, Bq m}^{-3})_{nuclide} \times (DPUC, \mu\text{Gy Bq}^{-1}\text{ h}^{-1}\text{ m}^{3})^{\text{external}}_{nuclide,organism} \times \\
&\qquad \times (fair_{organism} + fsoilsur_{organism}/2)
\end{aligned} \tag*{[24]}$$

where the reduction factor is the modifier for dose to organisms in air received from exposure to soil: zero for α and low-energy β radiation and 0.25 for high-energy β and γ radiation.

This assessment is only relevant to radon concentrations in air (atmospheric pathway); it does not consider radon emanation from soil. If the soil contained ^{226}Ra, then there would be ^{222}Rn emanation, potentially important for doses to earthworms and burrowing animals.

5.2 Assessment results

Assessment results for the three cases considered are given in Tables 10-12. Dose rates are given for all organisms of the terrestrial Environment Agency 128 methodology except bacteria and bird eggs. External exposure α dose rates are not explicitly given, as these are zero in all cases. A number of findings are evident from the data:

1. Air immersion is the principal contributor to external dose; hence, the low external dose rates to earthworm.
2. As expected (see Section 4), low-energy β internal irradiation is always negligible compared with high-energy β and γ and α internal irradiation (typically two orders of magnitude lower for internal and six to seven for external exposure).
3. For both animals and plants, α-irradiation is the principal contributor to whole body (in the range of 80 to 100 per cent) internal dose.
4. Internal α-dose rates to plants and eggs are comparable with those to the smallest animals. This clearly indicates that assumptions for plants and eggs are conservative.
5. For all three cases, all whole-body dose rates and all target tissue doses to plants (multiplied by the appropriate radiation weighting factors) are well below the level of 40 μGy h^{-1}. This is the level below which effects of ionising radiation on terrestrial organisms are unlikely to lead to observable effects in populations (IAEA, 1992; UNSCEAR, 1996).
6. In comparison, target tissue dose rates are not always negligible. This is especially noticeable as the target tissue becomes smaller and doses become progressively higher.
7. On the basis of published risk coefficients for small mammals, McDonald and Laverock (1998) concluded that for exposure rates of 300 mGy y^{-1} (35 μGy h^{-1}) 17 cancers would occur in 1,000 animals. No mammals exceed this level in our assessment.

5.3 Discussion

Weighted whole body dose rates are of a magnitude unlikely to lead to observable effects in populations. The dose rates to target tissues are higher, but are likely to be conservative. Target tissue dose rates calculated by a process-based respiratory model are, in all likelihood, lower by a factor of 5.5-7.5. A further layer of conservatism is the overestimation of breathing rates by allometry in smaller organisms, estimated to be within a factor of two. As a result, the tracheobronchial doses estimated here are likely to be conservative by an order of magnitude. Use of a corrective scaling factor of 10 would reduce all tissue doses to acceptable levels, although the dose to bronchial epithelium may need further assessment.

Although higher doses to target tissues in the respiratory system could hypothetically be associated with an increased risk of cancer, cancer is not the endpoint of concern when considering doses to biota. The endpoint to consider would be effects on the survival of the species as a whole. The dose rates calculated here are several orders of magnitude below the levels at which this kind of effect would occur. For example, Heidenreich *et al*. (2005) concluded that radon exposure rates of 100 WL (3.70×10^5 Bq m^{-3}) constitute the turning point at which survival rates in rats cease to increase to a peak and begin to decrease with exposure. Collier *et al*. (2005) avers that elevated incidence of lung malignancy begins to occur at exposure levels of 200 WLM or more. These results should be taken with caution, as the shape of the dose response curve could not be precisely determined. However, they indicate that the kind of activity concentration of Rn at which stochastic effects occur is several orders of magnitude higher than doses resulting from the RSA authorisation levels considered here.

6. Conclusions

A dynamic approach based on allometrically derived respiration rates and target tissue masses has been designed to calculate ^{222}Rn daughter dose rates to sensitive tissues and the whole body of terrestrial animals. For plants, an equivalent approach is used to scale respiration rate and calculate doses to (operationally defined) sensitive tissues for these organisms.

This method is an improvement on the interim fix based on plutonium dosimetry developed by the Environment Agency, because the latter misrepresents the dynamic equilibrium between influx of ^{222}Rn daughters to the lung and radioactive decay, among other factors. The dose rates estimated with the interim method are over-conservative as a result.

The results of an assessment of RSA93 authorisation limits carried out here suggest that, from a whole-body dose perspective, the biota in the sites considered are protected in terms of observable effects in populations. The main exposure pathway is exposure of the target tissues of the respiratory system to α radiation arising from ^{222}Rn daughters. Only the dose to bronchial epithelium may require further assessment, should this be necessary in future.

7. Future work

The following future work is recommended:

1. Rule out potentially high doses to the bronchial epithelium of mammals by developing an allometrically scaleable lung model in line with the methodology used by Hofmann *et al*. (2006) and Harley (1988).
2. Improve the dosimetry of radon to plants and insects by providing a more process-orientated model for the plant respiratory system explicitly representing radon gas exchange through plant stomata and insect spiracles.
3. Improve characterisation of the source term (the concentration of ^{222}Rn in air) by defining meaningful values of the equilibrium factor F and the unattached fraction f_P for typical atmospheres relevant to the species of biota considered in this assessment (open air, burrow in Rn-rich soil, and so on).
4. Review causative links between exposure to radon and stochastic/non-stochastic effects in biota (particularly rodents), in order to arrive at a more meaningful comparison threshold than the "blanket" value of 40 μGy h^{-1} derived from IAEA (1992) and UNSCEAR (1996).
5. Consider how dose assessments for ^{226}Ra in soil should be modified to take account of ^{222}Rn emanation, in order to assess the relative importance of the soil pathway with respect to the atmospheric pathway in radium-rich soils.
6. Consider the development of a similar approach to calculate thoron doses[10].

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[10] Thoron, that is, ^{220}Rn, is a natural decay product of thorium.

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Table 1: Calculation of potential α-energy per Bq activity for ^{222}Rn daughters

i	Isotope	λ_i (s^{-1})	ε_i (J)	$\sum_{j=i}^{5}\varepsilon_i^{\alpha}$ (J)	$\frac{1}{\lambda_i}\sum_{j=i}^{5}\varepsilon_i^{\alpha}$ (J Bq^{-1})
1	^{222}Rn	2.10E-06	8.78E-13	3.07E-12	1.46E-06
2	^{218}Po	3.73E-03	9.60E-13	2.19E-12	5.87E-10
3	^{214}Pb	4.31E-04	0.00E+00	1.23E-12	2.85E-09
4	^{214}Bi	5.86E-04	0.00E+00	1.23E-12	2.10E-09
5	^{214}Po	4.23E+03	1.23E-12	1.23E-12	2.91E-16
				$\sum_{i=2}^{5}\frac{1}{\lambda_i}\sum_{j=i}^{5}\varepsilon_i^{\alpha}$ =	5.54E-09

Table 2: Breathing rate comparison using different allometric formulae

Organism	Reference	Measured BR (m^3 s^{-1})	Predicted BR (m^3 s^{-1})			
			Ref. man	USDOE (1992)	Peters (1983)	Eq. 18
Man	Reference man	3.34E-04	3.33E-04	1.41E-04	1.88E-04	2.20E-04
Rat	Hofmann *et al.* (2006)	3.90E-06	5.58E-06	2.23E-06	2.76E-06	3.49E-06
Oryzomys	Drew & Eisenbud (1966)	6.67E-07	1.97E-06	7.78E-07	9.07E-07	1.22E-06

Table 3: Base and exponent of the allometric formulae for ^{222}Rn daughter DPUCs (internal α irradiation)

Parameter	B	TB	L	WB
Base A	5.14E-04	5.55E-05	3.77E-06	4.83E-08
Exponent B	9.63E-02	9.63E-02	-2.57E-01	-2.37E-01

Table 4: Model validation with data from MacDonald and Laverock (1998)

Organism	Mass (kg)	DPUC (μGy Bq^{-1} s^{-1} m^3)				Dose rate (mGy h^{-1})		% diff.
		B	TB	L	WB	Calculated	From paper	
Mole	4.00E-02	3.77E-04	1.85E-05	8.63E-06	1.04E-07	596	451	32
Pocket gopher	2.00E-01	4.41E-04	2.05E-05	5.71E-06	7.07E-08	854	702	22
Ground squirrel	5.00E-01	4.81E-04	2.17E-05	4.51E-06	5.69E-08	311	268	16
Ground hog	3.00E+00	5.72E-04	2.44E-05	2.85E-06	3.72E-08	132	125	6
Badger	8.00E+00	6.29E-04	2.59E-05	2.21E-06	2.95E-08	90	89	1

Table 5: Additional comparison with Hofmann *et al*. (2006) and Harley (1988)

Organism	M (kg)	Source	DPUC (nGy Bq^{-1} h^{-1} m^3)[a]	
			Reported	Calculated
Rat	0.3	Hofmann *et al*. (2006)	13.5 ± 12.5	76
Rats	0.35	Harley (1988)	10.3 ± 2.5	76

[a] Using the conversion 1 WLM = 6.3×10^5 Bq h m^{-3} (ICRP, 1978)

Table 6: Weighted ^{222}Rn daughter DPUCs (internal α-irradiation) for different target tissues of biota

Organism	Ellipsoid axes (cm)			M (kg)	DPUC (μGy Bq^{-1} h^{-1} m^3)			
	a	b	c		B	TB	Resp[a]	WB
Lichen	1.00E+01	5.00E-01	5.00E-01	1.31E-03	N/A	N/A	1.44E+00	7.75E-02
Moss	1.00E+01	2.00E+00	5.00E-01	5.24E-03	N/A	N/A	3.60E+00	7.75E-02
Tree	1.00E+01	2.00E-01	2.00E-01	2.09E-04	N/A	N/A	5.77E-01	7.75E-02
Shrub	1.00E+01	2.00E-01	2.00E-01	2.09E-04	N/A	N/A	5.77E-01	7.75E-02
Grass	1.00E+01	2.00E-01	2.00E-01	2.09E-04	N/A	N/A	5.77E-01	7.75E-02
Seed	6.00E-01	1.00E-01	1.00E-01	3.14E-06	N/A	N/A	2.88E-01	7.75E-02
Fungi	3.00E+00	1.50E+00	1.00E+00	2.36E-03	N/A	N/A	3.60E+00	7.75E-02
Caterpillar	3.00E+00	7.00E-01	7.00E-01	7.70E-04	1.86E+01	2.00E+00	1.72E+00	1.90E-02
Ant	5.00E-01	3.00E-01	3.00E-01	2.36E-05	1.33E+01	1.43E+00	4.20E+00	4.35E-02
Bee	2.00E+00	1.50E+00	1.00E+00	1.57E-03	1.99E+01	2.14E+00	1.43E+00	1.61E-02
Wood louse	1.50E+00	6.00E-01	3.00E-01	1.41E-04	1.58E+01	1.70E+00	2.65E+00	2.84E-02
Earthworm	1.10E+01	7.00E-01	7.00E-01	2.82E-03	2.10E+01	2.27E+00	1.23E+00	1.40E-02
Herb. Mammal	3.00E+01	1.20E+01	1.00E+01	1.88E+00	3.94E+01	4.24E+00	2.31E-01	2.99E-03
Carn. Mammal	6.50E+01	1.50E+01	1.20E+01	6.13E+00	4.41E+01	4.75E+00	1.71E-01	2.26E-03
Small rodent	1.00E+01	2.00E+00	2.00E+00	2.09E-02	2.55E+01	2.75E+00	7.34E-01	8.69E-03
Woodland bird	3.00E+01	1.00E+01	1.00E+01	1.57E+00	3.87E+01	4.17E+00	2.42E-01	3.13E-03
Bird egg	4.00E+00	2.50E+00	2.50E+00	1.31E-02	2.44E+01	2.63E+00	8.28E-01	9.72E-03
Reptile	1.20E+02	6.00E+00	6.00E+00	2.26E+00	4.01E+01	4.32E+00	2.20E-01	2.87E-03

[a] Respiratory organ: lung (L) for animals, first 55 μm of body surface for plants.

Table 7: Examination of decay chain for ^{222}Rn and daughters in secular equilibrium

Electrons				γ-rays				α-rays	
E_{avg} (MeV)	yield	E_{avg} (MeV)	yield	E (MeV)	yield	E (MeV)	yield	E (MeV)	yield
7.048E-02	2.000E-04	8.528E-03	4.200E-05	***5.10E-01***	***7.80E-04***	1.28E+00	1.47E-02	***5.49E+00***	***9.99E-01***
4.972E-02	2.519E-02	1.126E-02	2.800E-05	***7.93E-02***	***7.88E-06***	1.30E+00	1.21E-03	6.00E+00	1.00E+00
1.448E-01	9.678E-03	1.340E-02	4.780E-06	8.37E-01	1.09E-05	1.38E+00	4.02E-02	6.66E+00	1.28E-05
2.072E-01	4.809E-01	2.883E-03	1.824E-04	5.32E-02	1.32E-05	1.39E+00	7.76E-03	6.71E+00	1.80E-04
2.274E-01	4.209E-01	3.684E-02	9.498E-02	1.08E-02	2.04E-05	1.40E+00	1.39E-02	6.76E+00	7.20E-06
3.367E-01	6.289E-02	3.751E-02	9.918E-03	1.30E-02	2.46E-05	1.41E+00	2.48E-02	7.69E+00	1.00E+00
1.617E-01	4.100E-03	5.005E-02	2.480E-02	1.55E-02	5.86E-06	1.51E+00	2.19E-02		
2.481E-01	1.040E-02	5.323E-02	8.358E-03	1.17E-02	2.12E-07	1.54E+00	4.13E-03		
2.608E-01	2.780E-02	1.514E-01	5.319E-02	9.42E-03	8.46E-07	1.54E+00	3.54E-03		
3.181E-01	5.570E-03	2.255E-01	8.298E-03	5.32E-02	1.10E-02	1.58E+00	7.17E-03		
3.503E-01	3.320E-03	2.387E-01	2.170E-03	2.42E-01	7.46E-02	1.60E+00	2.65E-03		
3.520E-01	5.480E-02	1.683E-01	3.269E-03	2.59E-01	5.50E-03	1.60E+00	3.34E-03		
3.565E-01	8.750E-03	2.046E-01	7.429E-02	2.75E-01	3.24E-03	1.66E+00	1.15E-02		
3.737E-01	4.280E-03	2.788E-01	1.160E-02	2.95E-01	1.92E-01	1.68E+00	2.36E-03		
3.850E-01	4.310E-02	2.795E-01	1.500E-03	3.52E-01	3.71E-01	1.73E+00	3.05E-02		
4.245E-01	2.480E-02	2.920E-01	3.129E-03	4.62E-01	1.67E-03	1.77E+00	1.59E-01		
4.270E-01	1.490E-02	2.952E-01	1.040E-03	4.80E-01	3.38E-03	1.84E+00	3.83E-03		
4.334E-01	1.180E-02	2.614E-01	9.478E-02	4.87E-01	4.39E-03	1.85E+00	2.12E-02		
4.748E-01	1.570E-02	3.355E-01	1.470E-02	5.34E-01	1.90E-03	1.87E+00	2.26E-03		
4.919E-01	8.280E-02	3.362E-01	1.520E-03	5.80E-01	3.64E-03	1.89E+00	8.94E-04		
5.252E-01	1.760E-01	3.487E-01	3.829E-03	7.66E-01	7.86E-04	1.90E+00	1.77E-03		
5.339E-01	2.540E-03	3.519E-01	1.270E-03	7.86E-01	1.09E-02	2.11E+00	8.75E-04		
5.393E-01	1.790E-01	8.399E-03	1.120E-01	8.39E-01	5.87E-03	2.12E+00	1.21E-02		
5.670E-01	9.550E-03	1.112E-02	7.409E-02	7.71E-02	1.07E-01	2.20E+00	4.99E-02		
6.152E-01	3.320E-02	2.990E-03	4.769E-01	7.48E-02	6.39E-02	2.29E+00	3.24E-03		
6.679E-01	1.010E-02	5.162E-01	6.920E-03	8.74E-02	2.45E-02	2.45E+00	1.55E-02		
6.836E-01	7.520E-02	1.027E+00	1.900E-03	8.99E-02	1.13E-02	2.98E-01	5.00E-07		
7.263E-01	2.090E-03	1.145E+00	6.160E-04	8.68E-02	1.28E-02	8.00E-01	1.04E-04		
1.007E+00	9.950E-03	1.323E+00	3.960E-03	1.08E-02	5.70E-02				
1.269E+00	1.770E-01	1.399E+00	6.660E-04	1.30E-02	5.81E-02				
4.169E-01	1.670E-05	1.671E+00	6.730E-04	3.89E-01	4.13E-03				
4.931E-01	2.540E-06	2.100E-01	3.329E-08	6.09E-01	4.61E-01				
4.938E-01	2.250E-06	2.821E-01	4.769E-09	6.66E-01	1.56E-02				
4.962E-01	7.770E-07	2.828E-01	9.998E-09	7.03E-01	4.72E-03				
5.067E-01	1.390E-06	2.850E-01	4.879E-09	7.20E-01	4.03E-03				
5.100E-01	4.710E-07	2.949E-01	5.049E-09	7.68E-01	4.88E-02				
6.134E-02	3.030E-07	7.117E-01	8.478E-07	7.86E-01	3.14E-03				
7.419E-02	1.710E-07	7.838E-01	1.240E-07	8.06E-01	1.23E-02				
8.652E-03	6.360E-06	7.845E-01	4.749E-08	9.34E-01	3.16E-02				
1.145E-02	4.200E-06	7.867E-01	1.400E-08	9.64E-01	3.83E-03				
3.138E-03	2.740E-05	7.966E-01	4.249E-08	1.05E+00	3.15E-03				
7.490E-01	8.140E-08	7.997E-01	1.610E-08	1.07E+00	2.85E-03				
3.681E-02	1.140E-04	5.825E-02	1.710E-08	1.12E+00	1.50E-01				
3.749E-02	1.190E-05	8.161E-03	3.219E-07	1.13E+00	2.55E-03				
3.978E-02	9.760E-07	1.079E-02	2.100E-07	1.16E+00	1.69E-02				
5.002E-02	2.980E-05	2.913E-03	1.340E-06	1.21E+00	4.60E-03				
5.320E-02	1.002E-05			1.24E+00	5.92E-02				

Table 8: Weighted ^{222}Rn daughter DPUCs (external irradiation) for different species

Organism	Internal (μGy Bq^{-1} h^{-1} m^{3})		External (μGy Bq^{-1} h^{-1} m^{3})	
	Low β	$\beta + \gamma$	Low β	$\beta + \gamma$
Bacteria	0.0E+00	0.0E+00	3.4E-06	1.3E-03
Lichen	3.4E-06	3.0E-04	1.6E-09	9.7E-04
Moss	3.4E-06	3.5E-04	1.0E-09	9.3E-04
Tree	3.4E-06	2.0E-04	3.6E-09	1.1E-03
Shrub	3.4E-06	2.0E-04	3.6E-09	1.1E-03
Grass	3.4E-06	2.0E-04	3.6E-09	1.1E-03
Seed	3.4E-06	1.3E-04	6.6E-09	1.1E-03
Fungi	3.4E-06	3.9E-04	4.0E-10	8.8E-04
Caterpillar	3.4E-06	3.4E-04	8.8E-10	9.3E-04
Ant	3.4E-06	2.3E-04	2.7E-09	1.0E-03
Bee	3.4E-06	3.8E-04	4.4E-10	8.9E-04
Wood louse	3.4E-06	2.9E-04	2.3E-09	9.8E-04
Earthworm	3.4E-06	3.4E-04	8.7E-10	9.3E-04
Herb. Mammal	3.4E-06	5.6E-04	3.5E-11	7.1E-04
Carn. Mammal	3.4E-06	5.9E-04	5.6E-11	6.9E-04
Rodent	3.4E-06	4.2E-04	3.0E-10	8.5E-04
Bird	3.4E-06	5.3E-04	3.9E-11	7.4E-04
Bird egg	3.4E-06	4.3E-04	2.7E-10	8.4E-04
Reptile	3.4E-06	5.1E-04	9.6E-11	7.6E-04

Table 9: Occupancy factors for terrestrial biota exposed to noble gases

Organism	f_{soil}	$f_{soil\ surface}$	f_{air}
Bacteria	1.00E+00	0.00E+00	0.00E+00
Lichen	0.00E+00	1.00E+00	0.00E+00
Tree	1.00E+00	0.00E+00	5.00E-01
Shrub	1.00E+00	0.00E+00	5.00E-01
Herb	1.00E+00	0.00E+00	5.00E-01
Seed	1.00E+00	0.00E+00	5.00E-01
Fungi	1.00E+00	0.00E+00	5.00E-01
Caterpillar	0.00E+00	0.00E+00	1.00E+00
Ant	5.00E-01	3.00E-01	2.00E-01
Bee	0.00E+00	1.00E-01	9.00E-01
Woodlouse	0.00E+00	1.00E+00	0.00E+00
Earthworm	1.00E+00	0.00E+00	0.00E+00
Herb. mammal	5.00E-01	5.00E-01	0.00E+00
Carn. mammal	4.00E-01	6.00E-01	0.00E+00
Rodent	6.00E-01	4.00E-01	0.00E+00
Bird	0.00E+00	5.00E-01	5.00E-01
Bird egg	0.00E+00	1.00E+00	0.00E+00
Reptile	5.00E-01	4.00E-01	1.00E-01

Table 10: Radiation dose rates from exposure to ^{222}Rn and daughter products - air concentration = 2.79 x 10^{1} Bq m^{-3}

Organism	Internal dose rate (μGy h^{-1})						External dose rate (μGy h^{-1})					
	Low β	β + γ	α				Soil		Immersion		Total	
			B	TB	Organ	WB	Low β	β + γ	Low β	β + γ	Low β	β + γ
Lichen	9.5E-05	8.5E-03	N/A	N/A	4.0E+01	2.2E+00	2.6E-12	1.6E-06	2.2E-08	1.4E-02	2.2E-08	1.4E-02
Moss	9.5E-05	9.7E-03	N/A	N/A	1.0E+02	2.2E+00	1.7E-12	1.5E-06	1.4E-08	1.3E-02	1.4E-08	1.3E-02
Tree	9.5E-05	5.6E-03	N/A	N/A	1.6E+01	2.2E+00	1.2E-11	4.0E-06	5.0E-08	1.5E-02	5.0E-08	1.5E-02
Shrub	9.5E-05	5.6E-03	N/A	N/A	1.6E+01	2.2E+00	1.2E-11	4.0E-06	5.0E-08	1.5E-02	5.0E-08	1.5E-02
Grass	9.5E-05	5.6E-03	N/A	N/A	1.6E+01	2.2E+00	1.2E-11	4.0E-06	5.0E-08	1.5E-02	5.0E-08	1.5E-02
Seed	9.5E-05	3.5E-03	N/A	N/A	8.0E+00	2.2E+00	2.2E-11	4.3E-06	9.2E-08	1.6E-02	9.2E-08	1.6E-02
Fungi	9.5E-05	1.1E-02	N/A	N/A	1.0E+02	2.2E+00	1.3E-12	3.3E-06	5.6E-09	1.2E-02	5.6E-09	1.2E-02
Caterpillar	9.5E-05	9.4E-03	5.2E+02	5.6E+01	4.8E+01	5.3E-01	0.0E+00	7.8E-07	2.5E-08	2.6E-02	2.5E-08	2.6E-02
Ant	9.5E-05	6.5E-03	3.7E+02	4.0E+01	1.2E+02	1.2E+00	6.0E-12	2.4E-06	2.7E-08	1.0E-02	2.7E-08	1.0E-02
Bee	9.5E-05	1.1E-02	5.5E+02	6.0E+01	4.0E+01	4.5E-01	7.4E-14	8.2E-07	1.2E-08	2.4E-02	1.2E-08	2.4E-02
Woodlouse	9.5E-05	8.1E-03	4.4E+02	4.7E+01	7.4E+01	7.9E-01	3.8E-12	1.6E-06	3.2E-08	1.4E-02	3.2E-08	1.4E-02
Earthworm	9.5E-05	9.5E-03	5.9E+02	6.3E+01	3.4E+01	3.9E-01	2.9E-12	3.1E-06	0.0E+00	0.0E+00	2.9E-12	3.1E-06
Herb. mml.	9.5E-05	1.6E-02	1.1E+03	1.2E+02	6.4E+00	8.4E-02	8.8E-14	1.8E-06	2.4E-10	5.0E-03	2.4E-10	5.0E-03
Carn. mml.	9.5E-05	1.6E-02	1.2E+03	1.3E+02	4.8E+00	6.3E-02	1.3E-13	1.6E-06	4.7E-10	5.7E-03	4.7E-10	5.7E-03
Rodent	9.5E-05	1.2E-02	7.1E+02	7.7E+01	2.0E+01	2.4E-01	8.0E-13	2.3E-06	1.7E-09	4.7E-03	1.7E-09	4.7E-03
Bird	9.5E-05	1.5E-02	1.1E+03	1.2E+02	6.8E+00	8.7E-02	3.2E-14	9.3E-07	8.1E-10	1.6E-02	8.1E-10	1.6E-02
Bird egg	9.5E-05	1.2E-02	6.8E+02	7.3E+01	2.3E+01	2.7E-01	4.5E-13	1.4E-06	3.8E-09	1.2E-02	3.8E-09	1.2E-02
Reptile	9.5E-05	1.4E-02	1.1E+03	1.2E+02	6.1E+00	8.0E-02	2.2E-13	1.9E-06	8.0E-10	6.4E-03	8.0E-10	6.4E-03

Table 11: Radiation dose rates from exposure to ^{222}Rn and daughter products - air concentration = 1.40 x 10^{1} Bq m^{-3}

Organism	Internal dose rate (μGy h^{-1})						External dose rate (μGy h^{-1})					
	Low β	β + γ	α				Soil		Immersion		Total	
			B	TB	Organ	WB	Low β	β + γ	Low β	β + γ	Low β	β + γ
Lichen	4.8E-05	4.2E-03	N/A	N/A	2.0E+01	1.1E+00	1.3E-12	8.1E-07	1.1E-08	6.8E-03	1.1E-08	6.8E-03
Moss	4.8E-05	4.8E-03	N/A	N/A	5.0E+01	1.1E+00	8.4E-13	7.7E-07	7.0E-09	6.5E-03	7.0E-09	6.5E-03
Tree	4.8E-05	2.8E-03	N/A	N/A	8.0E+00	1.1E+00	6.0E-12	2.0E-06	2.5E-08	7.5E-03	2.5E-08	7.5E-03
Shrub	4.8E-05	2.8E-03	N/A	N/A	8.0E+00	1.1E+00	6.0E-12	2.0E-06	2.5E-08	7.5E-03	2.5E-08	7.5E-03
Grass	4.8E-05	2.8E-03	N/A	N/A	8.0E+00	1.1E+00	6.0E-12	2.0E-06	2.5E-08	7.5E-03	2.5E-08	7.5E-03
Seed	4.8E-05	1.8E-03	N/A	N/A	4.0E+00	1.1E+00	1.1E-11	2.2E-06	4.6E-08	8.0E-03	4.6E-08	8.0E-03
Fungi	4.8E-05	5.4E-03	N/A	N/A	5.0E+01	1.1E+00	6.7E-13	1.7E-06	2.8E-09	6.2E-03	2.8E-09	6.2E-03
Caterpillar	4.8E-05	4.7E-03	2.6E+02	2.8E+01	2.4E+01	2.7E-01	0.0E+00	3.9E-07	1.2E-08	1.3E-02	1.2E-08	1.3E-02
Ant	4.8E-05	3.3E-03	1.9E+02	2.0E+01	5.9E+01	6.1E-01	3.0E-12	1.2E-06	1.3E-08	5.1E-03	1.3E-08	5.1E-03
Bee	4.8E-05	5.3E-03	2.8E+02	3.0E+01	2.0E+01	2.2E-01	3.7E-14	4.1E-07	5.8E-09	1.2E-02	5.8E-09	1.2E-02
Woodlouse	4.8E-05	4.0E-03	2.2E+02	2.4E+01	3.7E+01	4.0E-01	1.9E-12	8.2E-07	1.6E-08	6.9E-03	1.6E-08	6.9E-03
Earthworm	4.8E-05	4.8E-03	2.9E+02	3.2E+01	1.7E+01	2.0E-01	1.5E-12	1.6E-06	0.0E+00	0.0E+00	1.5E-12	1.6E-06
Herb. mml.	4.8E-05	7.8E-03	5.5E+02	5.9E+01	3.2E+00	4.2E-02	4.4E-14	9.0E-07	1.2E-10	2.5E-03	1.2E-10	2.5E-03
Carn. mml.	4.8E-05	8.2E-03	6.2E+02	6.6E+01	2.4E+00	3.2E-02	6.5E-14	8.0E-07	2.3E-10	2.9E-03	2.3E-10	2.9E-03
Rodent	4.8E-05	5.9E-03	3.6E+02	3.8E+01	1.0E+01	1.2E-01	4.0E-13	1.1E-06	8.3E-10	2.4E-03	8.3E-10	2.4E-03
Bird	4.8E-05	7.4E-03	5.4E+02	5.8E+01	3.4E+00	4.4E-02	1.6E-14	4.7E-07	4.0E-10	7.8E-03	4.0E-10	7.8E-03
Bird egg	4.8E-05	6.0E-03	3.4E+02	3.7E+01	1.2E+01	1.4E-01	2.3E-13	7.0E-07	1.9E-09	5.9E-03	1.9E-09	5.9E-03
Reptile	4.8E-05	7.1E-03	5.6E+02	6.0E+01	3.1E+00	4.0E-02	1.1E-13	9.3E-07	4.0E-10	3.2E-03	4.0E-10	3.2E-03

Table 12: Radiation dose rates from exposure to ^{222}Rn and daughter products - air concentration = 5.11 x 10^{-4} Bq m^{-3}

Organism	Internal dose rate (μGy h^{-1})						External dose rate (μGy h^{-1})					
	Low β	β + γ	α				Soil		Immersion		Total	
			B	TB	Organ	WB	Low β	β + γ	Low β	β + γ	Low β	β + γ
Lichen	1.7E-09	1.5E-07	N/A	N/A	7.4E-04	4.0E-05	4.8E-17	3.0E-11	4.0E-13	2.5E-07	4.0E-13	2.5E-07
Moss	1.7E-09	1.8E-07	N/A	N/A	1.8E-03	4.0E-05	3.1E-17	2.8E-11	2.6E-13	2.4E-07	2.6E-13	2.4E-07
Tree	1.7E-09	1.0E-07	N/A	N/A	2.9E-04	4.0E-05	2.2E-16	7.4E-11	9.2E-13	2.7E-07	9.2E-13	2.7E-07
Shrub	1.7E-09	1.0E-07	N/A	N/A	2.9E-04	4.0E-05	2.2E-16	7.4E-11	9.2E-13	2.7E-07	9.2E-13	2.7E-07
Grass	1.7E-09	1.0E-07	N/A	N/A	2.9E-04	4.0E-05	2.2E-16	7.4E-11	9.2E-13	2.7E-07	9.2E-13	2.7E-07
Seed	1.7E-09	6.5E-08	N/A	N/A	1.5E-04	4.0E-05	4.0E-16	7.9E-11	1.7E-12	2.9E-07	1.7E-12	2.9E-07
Fungi	1.7E-09	2.0E-07	N/A	N/A	1.8E-03	4.0E-05	2.5E-17	6.1E-11	1.0E-13	2.3E-07	1.0E-13	2.3E-07
Caterpillar	1.7E-09	1.7E-07	9.5E-03	1.0E-03	8.8E-04	9.7E-06	0.0E+00	1.4E-11	4.5E-13	4.8E-07	4.5E-13	4.8E-07
Ant	1.7E-09	1.2E-07	6.8E-03	7.3E-04	2.1E-03	2.2E-05	1.1E-16	4.5E-11	4.9E-13	1.9E-07	4.9E-13	1.9E-07
Bee	1.7E-09	2.0E-07	1.0E-02	1.1E-03	7.3E-04	8.2E-06	1.3E-18	1.5E-11	2.1E-13	4.3E-07	2.1E-13	4.3E-07
Woodlouse	1.7E-09	1.5E-07	8.1E-03	8.7E-04	1.4E-03	1.5E-05	7.0E-17	3.0E-11	5.9E-13	2.5E-07	5.9E-13	2.5E-07
Earthworm	1.7E-09	1.7E-07	1.1E-02	1.2E-03	6.3E-04	7.1E-06	5.4E-17	5.7E-11	0.0E+00	0.0E+00	5.4E-17	5.7E-11
Herb. mml.	1.7E-09	2.8E-07	2.0E-02	2.2E-03	1.2E-04	1.5E-06	1.6E-18	3.3E-11	4.5E-15	9.1E-08	4.5E-15	9.1E-08
Carn. mml.	1.7E-09	3.0E-07	2.3E-02	2.4E-03	8.7E-05	1.2E-06	2.4E-18	2.9E-11	8.5E-15	1.1E-07	8.5E-15	1.1E-07
Rodent	1.7E-09	2.2E-07	1.3E-02	1.4E-03	3.7E-04	4.4E-06	1.5E-17	4.2E-11	3.0E-14	8.7E-08	3.0E-14	8.7E-08
Bird	1.7E-09	2.7E-07	2.0E-02	2.1E-03	1.2E-04	1.6E-06	5.9E-19	1.7E-11	1.5E-14	2.8E-07	1.5E-14	2.8E-07
Bird Egg	1.7E-09	2.2E-07	1.2E-02	1.3E-03	4.2E-04	5.0E-06	8.2E-18	2.6E-11	6.9E-14	2.1E-07	6.9E-14	2.1E-07
Reptile	1.7E-09	2.6E-07	2.0E-02	2.2E-03	1.1E-04	1.5E-06	4.1E-18	3.4E-11	1.5E-14	1.2E-07	1.5E-14	1.2E-07

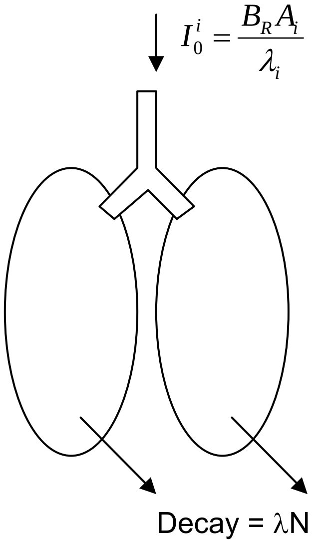

Figure 1: Schematic of simple respiratory model for ^{222}Rn daughters

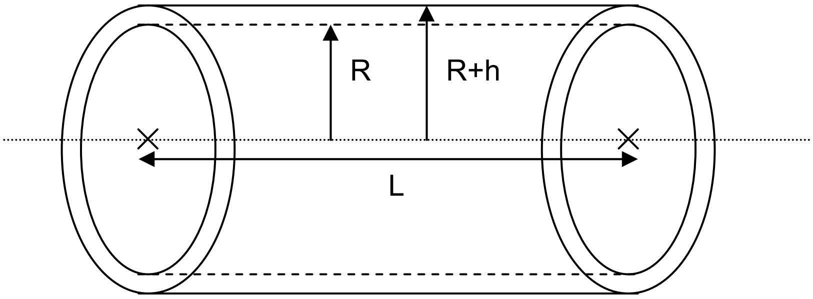

Figure 2: Conceptual representation of irradiated respiratory tissue

Appendix: Calculation of ^{222}Rn DPUCs for feature species used in habitats assessments

In order to extend the methodology developed in this report to all the feature species used by the Environment Agency for habitats assessments, an extended DPUC table, comprising all these organisms, was generated. To achieve this, dose rates were calculated for 1 Bq m^{-3} of ^{222}Rn in equilibrium with its short-lived daughters, using the methods described in this report. An "effective total" DPUC (both unweighted and weighted) could easily be generated once the concentration factors, air density and occupancy factors were factorised as part of the external dose component. Both the internal and external components of dose were then expressed as a linear function of the ^{222}Rn activity concentration, which could be left to stand out as a common factor.

After presenting the data in this convenient manner, it was possible to apply the allometric scaling procedure for the dose described in the Environment Agency SP1A report (Copplestone *et al*., 2003) using power function fittings between DPUC and area/volume for different radionuclides. Weighted and unweighted dose rates for internal, external or total exposure can be obtained directly by multiplication of the activity of ^{222}Rn in equilibrium with its short-lived daughters by the DPUCs given in Table A1 below. This method allows extension of the number of organism species considered in an assessment beyond the R&D Publication 128 reference organisms.

Table A1: Weighted and unweighted DPUCs (μGy h^{-1} per Bq m^{-3}) for exposure of SP1a feature organisms to ^{222}Rn daughters

Feature organism	**Weighted dose rates**			**Unweighted dose rates**		
	Internal	**External**	**Total**	**Internal**	**External**	**Total**
Ant	4.35E-02	1.04E-03	4.38E-02	2.17E-03	1.04E-03	2.53E-03
Bacteria	0.00E+00	1.30E-03	1.53E-07	0.00E+00	1.30E-03	1.53E-07
Bechsteins bat	9.72E-03	8.42E-04	1.06E-02	4.86E-04	8.42E-04	1.33E-03
Bee	1.61E-02	8.90E-04	1.69E-02	8.03E-04	8.90E-04	1.65E-03
Bewicks swan	2.26E-03	6.86E-04	2.71E-03	1.13E-04	6.86E-04	5.59E-04
Bird	3.13E-03	7.43E-04	3.69E-03	1.56E-04	7.43E-04	7.13E-04
Bird egg	9.72E-03	8.42E-04	1.01E-02	4.86E-04	8.42E-04	9.07E-04
Black-tailed godwit	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Brent goose	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Car. mammal	2.26E-03	6.86E-04	2.47E-03	1.13E-04	6.86E-04	3.19E-04
Caterpillar	1.90E-02	9.34E-04	1.99E-02	9.51E-04	9.34E-04	1.89E-03
Chough	2.26E-03	6.86E-04	2.71E-03	1.13E-04	6.86E-04	5.59E-04
Curlew	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Dartford warbler	2.87E-03	7.64E-04	3.44E-03	1.43E-04	7.64E-04	7.16E-04
Desmoulins whorl snail	1.90E-02	9.34E-04	1.97E-02	9.51E-04	9.34E-04	1.65E-03
Dormouse	9.72E-03	8.42E-04	1.01E-02	4.86E-04	8.42E-04	8.23E-04
Dunlin	3.13E-03	7.43E-04	3.69E-03	1.56E-04	7.43E-04	7.13E-04
Early gentian	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Earthworm	1.40E-02	9.30E-04	1.40E-02	6.99E-04	9.30E-04	6.99E-04
Fen orchid	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Fungi	7.75E-02	8.85E-04	7.79E-02	3.88E-03	8.85E-04	4.32E-03
Gadwall	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04

Golden plover	2.99E-03	1.50E-04	3.31E-03	7.14E-04	1.50E-04	1.04E-03
Great crested newt	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Greater horseshoe bat	9.72E-03	8.42E-04	1.06E-02	4.86E-04	8.42E-04	1.33E-03
Grey plover	2.99E-03	1.50E-04	3.31E-03	7.14E-04	1.50E-04	1.04E-03
Hen harrier (male and female)	2.87E-03	7.64E-04	3.44E-03	1.43E-04	7.64E-04	7.16E-04
Herb	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Herb. mammal	2.99E-03	1.50E-04	3.17E-03	7.14E-04	1.50E-04	8.93E-04
Honey buzzard	2.87E-03	7.64E-04	3.44E-03	1.43E-04	7.64E-04	7.16E-04
Kittewake	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Knot	2.99E-03	1.50E-04	3.31E-03	7.14E-04	1.50E-04	1.04E-03
Lapwing	2.26E-03	6.86E-04	2.57E-03	1.13E-04	6.86E-04	4.22E-04
Lesser black-backed gull (male and female)	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Lesser horseshoe bat	9.72E-03	8.42E-04	1.06E-02	4.86E-04	8.42E-04	1.33E-03
Lichen	7.75E-02	9.69E-04	7.80E-02	3.88E-03	9.69E-04	4.36E-03
Marsh harrier	2.87E-03	7.64E-04	3.44E-03	1.43E-04	7.64E-04	7.16E-04
Mediterranean gull	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Natterjack toad	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Nightjar	9.72E-03	8.42E-04	1.04E-02	4.86E-04	8.42E-04	1.12E-03
Otter (male and female)	2.26E-03	6.86E-04	2.43E-03	1.13E-04	6.86E-04	2.85E-04
Oystercatcher	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Peregrine	3.13E-03	7.43E-04	3.69E-03	1.56E-04	7.43E-04	7.13E-04
Petal wort	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Pink-footed goose	2.26E-03	6.86E-04	2.57E-03	1.13E-04	6.86E-04	4.22E-04
Pintail	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Redshank	9.72E-03	8.42E-04	1.01E-02	4.86E-04	8.42E-04	8.65E-04
Reptile	2.87E-03	7.64E-04	3.10E-03	1.43E-04	7.64E-04	3.72E-04
Ringed plover	9.72E-03	8.42E-04	1.01E-02	4.86E-04	8.42E-04	8.65E-04
Rodent	8.69E-03	8.48E-04	8.86E-03	4.35E-04	8.48E-04	6.05E-04
Ruff	2.99E-03	1.50E-04	3.31E-03	7.14E-04	1.50E-04	1.04E-03
Sand lizard	2.87E-03	7.64E-04	3.18E-03	1.43E-04	7.64E-04	4.49E-04
Sanderling	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Seed	7.75E-02	1.15E-03	7.81E-02	3.88E-03	1.15E-03	4.45E-03
Shore dock	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Short-eared owl	2.99E-03	1.50E-04	3.53E-03	7.14E-04	1.50E-04	1.25E-03
Shoveler	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Shrub	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
Smooth snake	2.87E-03	7.64E-04	3.18E-03	1.43E-04	7.64E-04	4.49E-04
Snipe	2.99E-03	1.50E-04	3.31E-03	7.14E-04	1.50E-04	1.04E-03
Stag beetle	8.69E-03	8.48E-04	9.07E-03	4.35E-04	8.48E-04	8.17E-04
Stone curlew	2.87E-03	7.64E-04	3.21E-03	1.43E-04	7.64E-04	4.87E-04
Teal	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Tree	7.75E-02	1.07E-03	7.80E-02	3.88E-03	1.07E-03	4.42E-03
White-fronted goose	3.13E-03	7.43E-04	3.46E-03	1.56E-04	7.43E-04	4.90E-04
Whooper swan	2.26E-03	6.86E-04	2.71E-03	1.13E-04	6.86E-04	5.59E-04
Wigeon	2.87E-03	7.64E-04	3.37E-03	1.43E-04	7.64E-04	6.40E-04
Woodlark	2.87E-03	7.64E-04	3.44E-03	1.43E-04	7.64E-04	7.16E-04
Woodlouse	2.84E-02	9.83E-04	2.89E-02	1.42E-03	9.83E-04	1.91E-03

We are The Environment Agency. It's our job to look after your environment and make it **a better place** – for you, and for future generations.

Your environment is the air you breathe, the water you drink and the ground you walk on. Working with business, Government and society as a whole, we are making your environment cleaner and healthier.

The Environment Agency. Out there, making your environment a better place.

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