Quantifying exposure from radionuclides for environmental receptors

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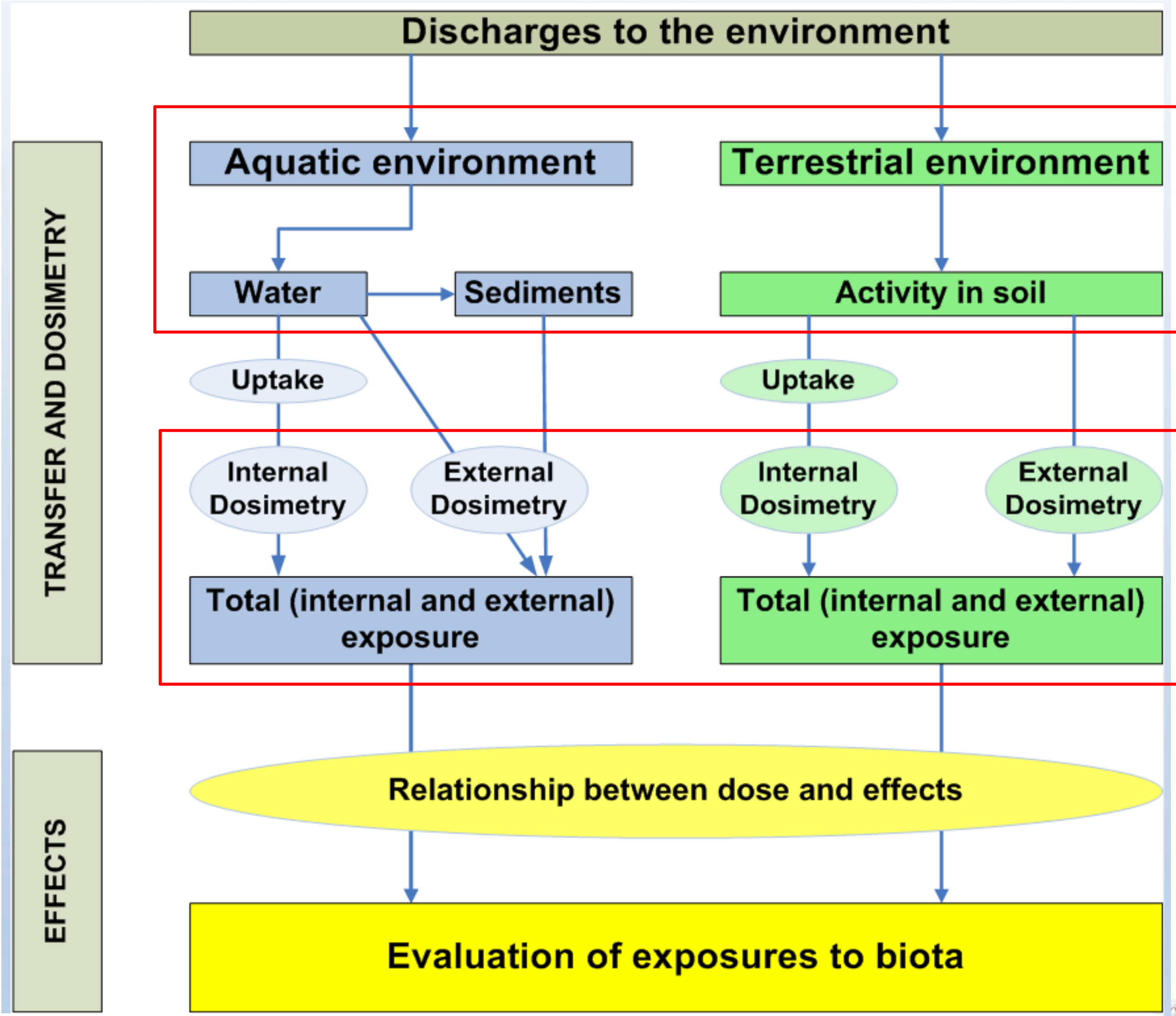
Talk Contents

- Will focus on environmental exposure estimation especially in relation to ERICA ““Environmental risks from ionising contaminants: assessment and management”
  - Close similarities with the approach adopted by ICRP
- Underlying methods
- Environmental dose calculations
- Limitations in existing approaches wrt field study application

Exposure in environmental assessment



The chart is reproduced from Jordi V. Batlle (2010).

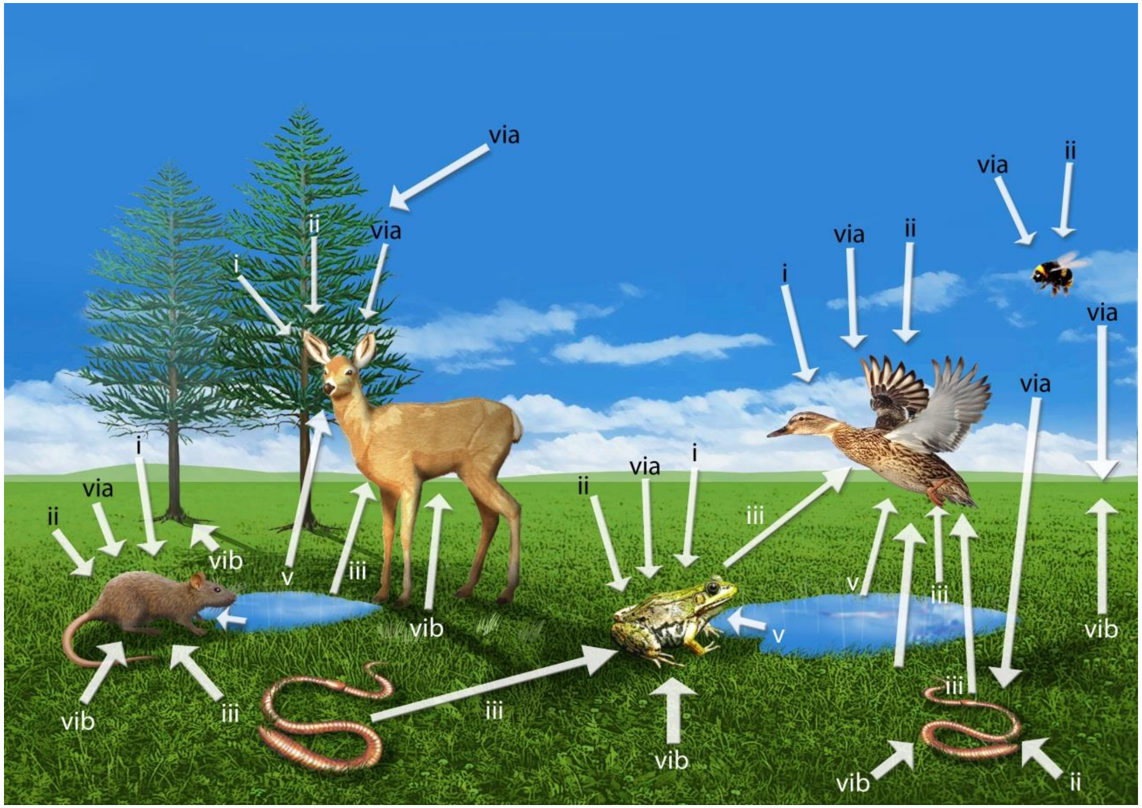
Standard application for ERICA :

- Planned, screening

2 Components :

- Transfer
- Dose

Environmental Exposure pathways



- Terrestrial exposure pathways; i) Inhalation of particles or gases ii) Contamination of fur/feathers/skin iii) Ingestion lower trophic levels v) Drinking contaminated water vi) External exposure through a) air or b) soil

Transfer - Equilibrium based model

For the terrestrial ecosystems the CRs are defined as:

$$CR_{b,i}\ (dimensionless) = C_{b,i}/C_{soil,i}$$

where,
$CR_{b,i}$ = Concentration ratio for reference organism b and radionuclide i;
$C_{b,i}$ = Activity concentration of radionuclide i in whole body of reference biota (Bq kg^{-1}, fresh weight);
C_{soil} = Activity concentration of radionuclide i in surface soil (Bq kg^{-1} d.w.)

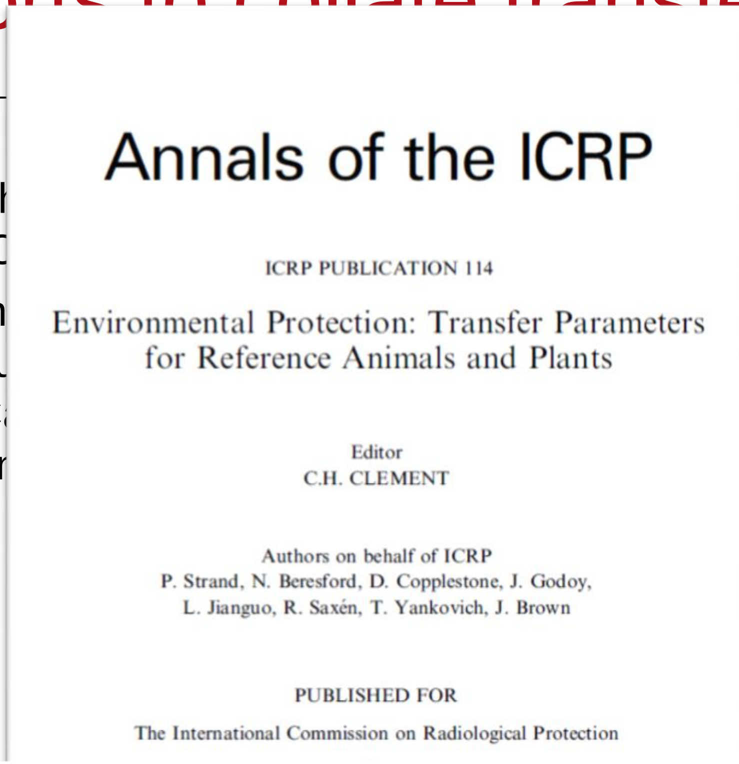
For the aquatic ecosystems the CR, commonly also known as Concentration Factors (CF), are defined as:

$$CR_{b,i}\ (dimensionless\ or\ l\ kg^{-1}) = C_{b,i}/C_{aq}$$

Where
$CR_{b,i}$ = Concentration Factor for reference organism b and radionuclide i;
C_b = Activity concentration of radionuclide i in whole body of reference biota (Bq kg^{-1}, fresh weight);
C_{aq} = Activity concentration of radionuclide i in aqueous phase (Bq l^{-1} or Bq kg^{-1}) - normally filtered water.

Collation of data based around generic organism groupings (e.g. Reference organisms) and commonly encountered radionuclides

Efforts to collate transfer information



Annals of the ICRP

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Environmental Protection: Transfer Parameters for Reference Animals and Plants

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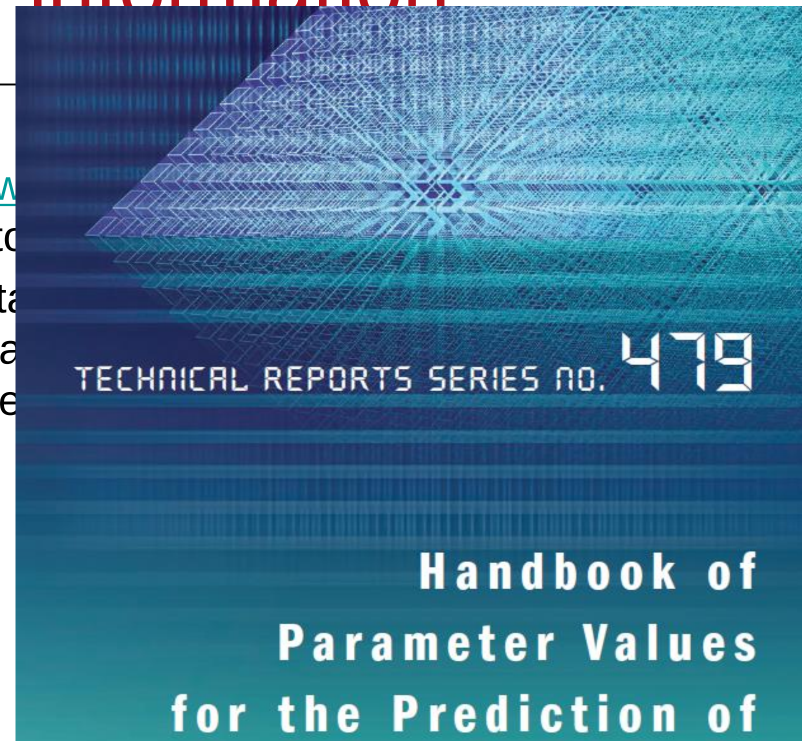

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- At the time the WTD was used to prepare the IAEA and ICRP reports, it contained information from 523 references. There were more than 50,000 lines of data entered into the WTD representing 86,979 CR values for 1438 species and 71 elements.
- Between 2011, when the WTD was used to provide values for the ICRP and IAEA reports, and the end of 2013, *c.* 17,000 additional $CR_{wo\text{-}media}$ values were added.

Considerations in environmental dosimetry

The dose-rate is the result of a complex interaction of energy, mass and the source – target configuration. In calculating, an approach is to:

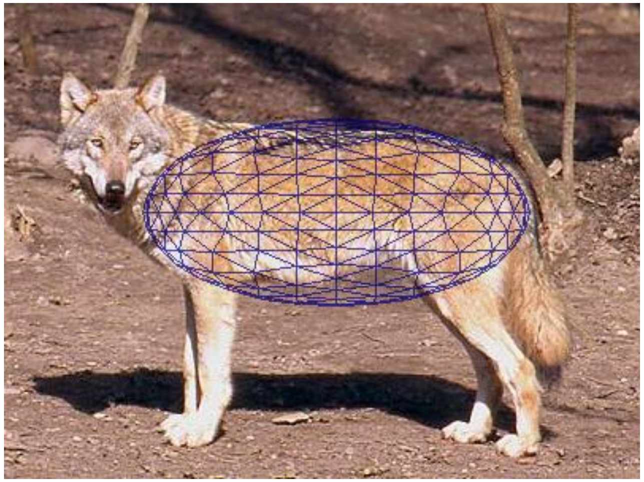
- *Define organism mass and shape*
- *Consider exposure conditions (internal, external)*
- *Derive absorbed fractions: Simulate radiation transport for mono energetic photons and electrons.*
- *Calculate Dose Conversion Coefficients: Link calculations with nuclide-specific decay characteristics*

Only a few organisms with simple geometry can be simulated explicitly- Reference organisms

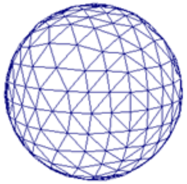
In all other cases interpolation has to be applied

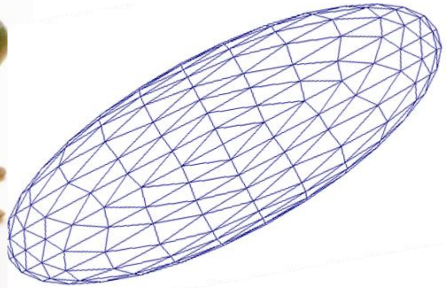
Reference organisms (ERICA approach)

The enormous variability of biota requires the definition of reference organisms that represent:



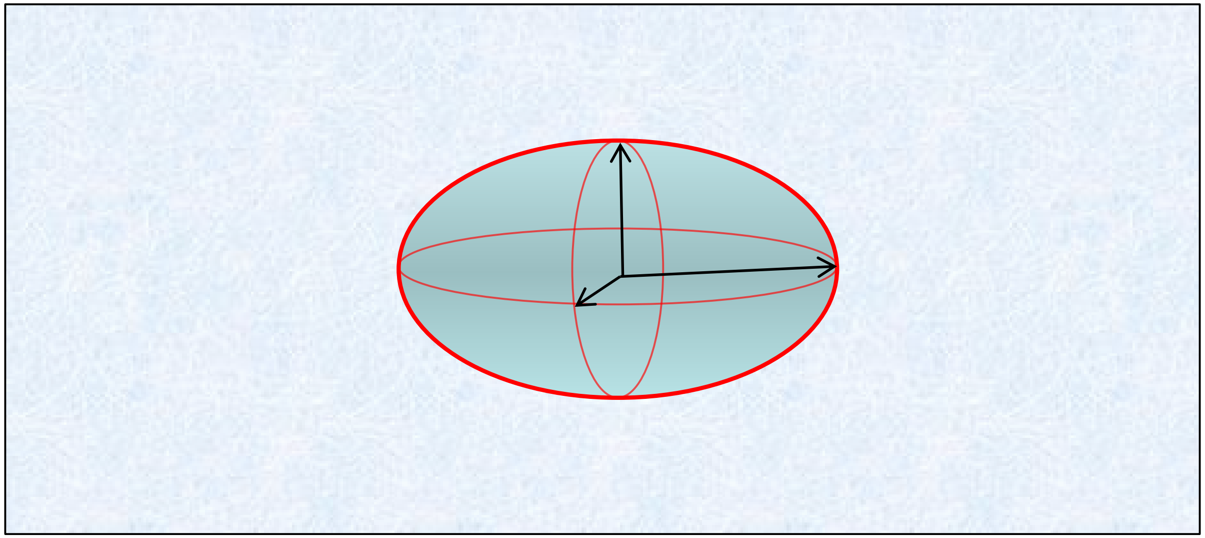
- ❖ Plants and animals
- ❖ Different mass ranges
- ❖ Different habitat





Reference organism: dosimetric assumptions

- Can be suitably represented as ellipsoids
- Homogeneous distribution of radionuclides within the organism
- Organism immersed in uniformly contaminated medium (aquatic)



- Organs are not considered
- Dose rate averaged over organism volume

Absorbed dose,dose-rate and Kerma

- Absorbed dose is the amount of energy deposited by the ionising radiation to the material being irradiated.
  - Units in Gray (Gy) = one joule of absorbed energy per kg of material.

- Environmental impact assessment approaches (e.g. ERICA) tend to apply equilibrium based models. This coupled to the wish to normalize exposures, spanning many species with greatly differing life spans led to the common application of dose-rates (using short time intervals)
  - ERICA uses µGy/h

- KERMA: Kinetic Energy Released per unit Mass = Sum of the initial kinetic energies of all the charged particles liberated by uncharged particles from ionizing radiation (e.g. protons, neutrons) in a unit of mass :
  - same unit as absorbed dose but absolute quantities differ.

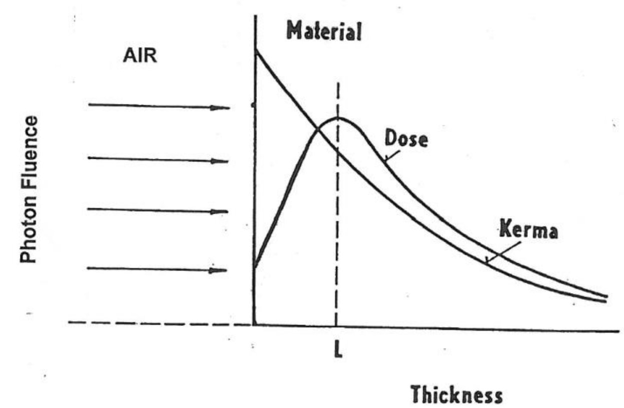
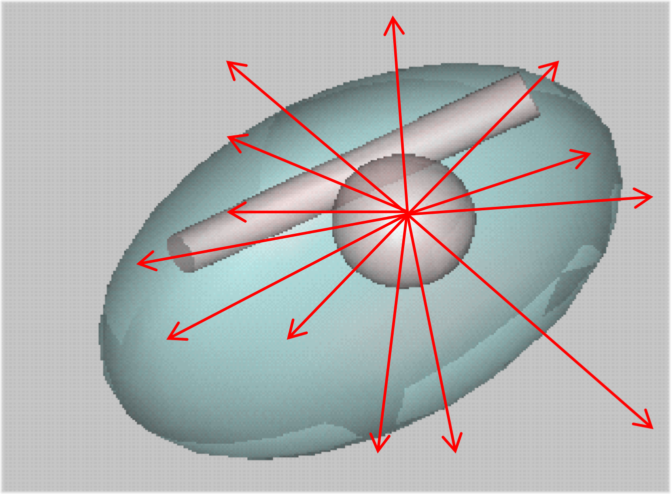


Fig. 6 Kerma and dose profiles at a boundary between air and a solid material. L represents the maximum range of recoil electrons.

Absorbed Fraction (AF)

$$\phi = \frac{\text{Energy absorbed by target}}{\text{Energy emitted by source}}$$



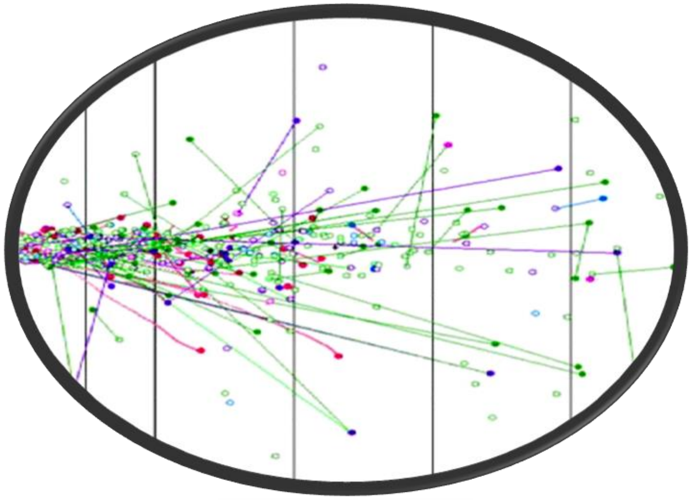
The calculations for ERICA default geometries cover:

- Energies in the range from 10 keV to 5 MeV
- Masses in the range from 1 mg to 1 tonne

Monte Carlo approach

Simulations of photon and electron transport through matter

- Materials differing in composition and density can be considered;
- Complex geometries of sources and targets can be simulated;
- All relevant physical processes that control radiation transport are precisely treated;



- Self-absorption of radiation is considered.
- Typically radiation tranport codes, e.g. Monte Carlo N-Particle (MCNP-6, MCNP-X), used.

Interpolation: Photon sources in spheres

ϕ is a function of

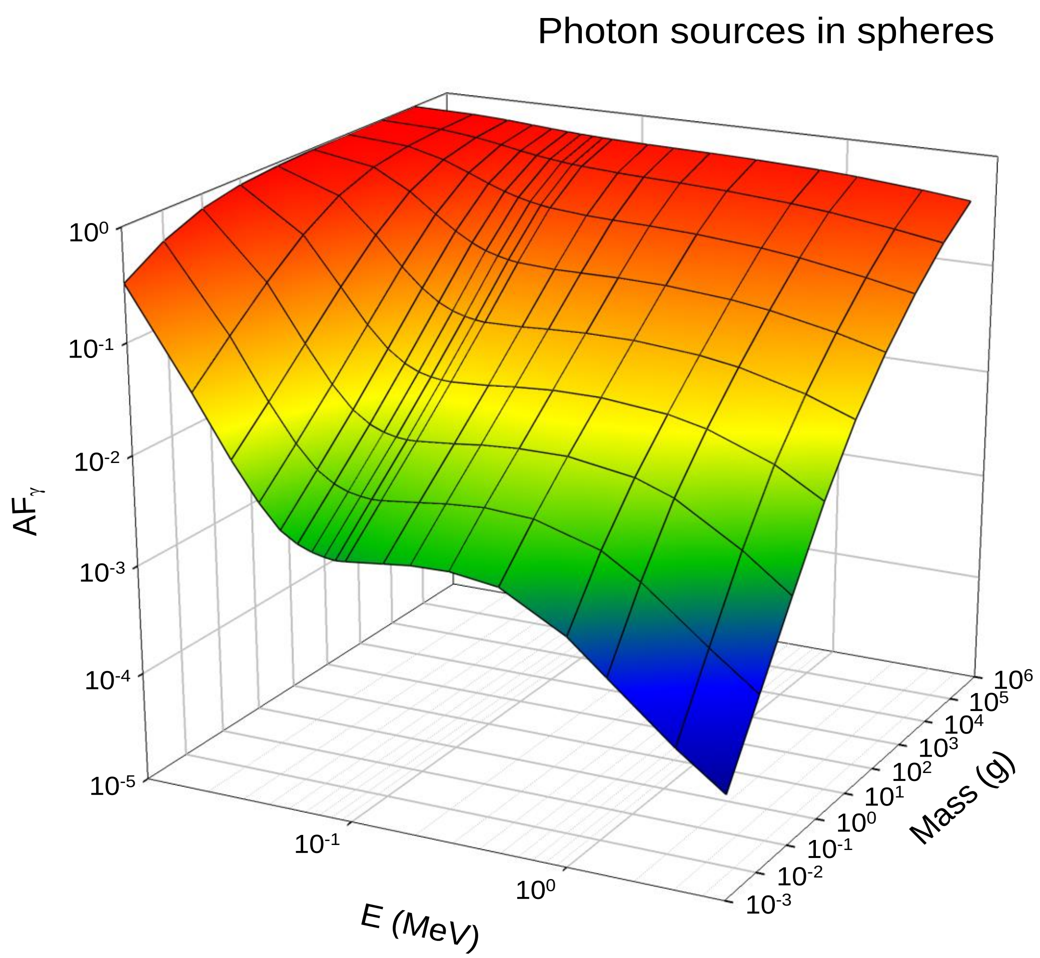
- Energy
- Mass

Large mass and low energy

$\phi \rightarrow 1$

Small mass, and High energy,

$\phi \rightarrow 0$



Dose Conversion Coefficient (DCC)

- Defined as the ratio of dose rate per unit activity concentration in organism or the medium:

$$DCC_{int} = \frac{\dot{D}_{int}}{A_{org}} \qquad DCC_{ext} = \frac{\dot{D}_{ext}}{A_{env}}$$

Units of µGyh^{-1} per Bq kg^{-1}

Internal dose rates
Homogeneous distribution in organism

Dose rates for internally incorporated radionuclides. The dose rates delivered to organisms are evaluated from the concentration of each internally incorporated radionuclide.

For each radionuclide data for the energy and yield of β particle, photon and α particle emissions have been extracted from the literature (ICRP, 1983).

$$\dot{D}_{int} = k \times A_{org} \cdot \sum_{i} \Phi_T(E_i) \cdot E_i \cdot y_i$$

$$k = 5.76 \times 10^{-4} \frac{\mu Gyh^{-1}}{MeV.Bq.kg^{-1}}$$

where:

A_{org} is the activity concentration in organism (Bq kg-1 w.w.);

E_i is the energy of component <i> of emitted radiation (MeV);

y_i is the yield of emitted radiation of energy E_i (dis^{-1});

$\Phi_T(E_i)$ is the absorbed fraction in the target for energy E_i;

K is the factor to account for conversions of MeV to Joules and seconds to hours.

External dose rates (<u>aquatic</u>)

Homogeneous distribution in environmental media

- <u>*Dose rates for external exposure*</u> from radionuclides present in the water column are calculated using a variant of the simple formula for uniformly contaminated isotropic infinite absorbing medium:

$$\dot{D}_{Ext} = k \times A_{env} \cdot \sum_i (1 - \Phi_T(E_i)) \cdot E_i \cdot y_i$$

$$k = 5.76 \times 10^{-4} \frac{\mu Gyh^{-1}}{MeV.Bq.kg^{-1}}$$

A_{env} is the activity concentration in the environment (e.g. in Bq kg^{-1})

Representative situations (ERICA approach)

- The number of possible (target-source) situations is enormous; therefore a limited number of representative situations have been selected for detailed calculations:

❖ In soil/ on soil/ in air
❖ In water/ interface water-air
❖ In sediment/ interface water-sediment

Exposure target	Radiation source			
	Air	Soil	Water	Sediment
Air	×	×		
Soil surface	×	×		
Soil	×	×		
Water			×	×
Sediment surface			×	×
Sediment			×	×

- Similarly, the density of materials and their elemental composition have an important impact on the radiation transport and need to be specified

- Where density and compositional differences are large such as those occurring in the terrestrial environment (between soil and air), explicit MC calculations are required.

Biota living on the ground (ERICA)

- A volume source uniformly distributed to a depth of 10 cm has been assumed
- It is assumed that only photon sources contribute to external exposure of the animals.
- The external DCCs have been calculated here as a product of free-in-air kerma, K_a, in a place occupied by the animals' body and pre-computed dose-to-kerma ratios, $R(E_i,M)$:

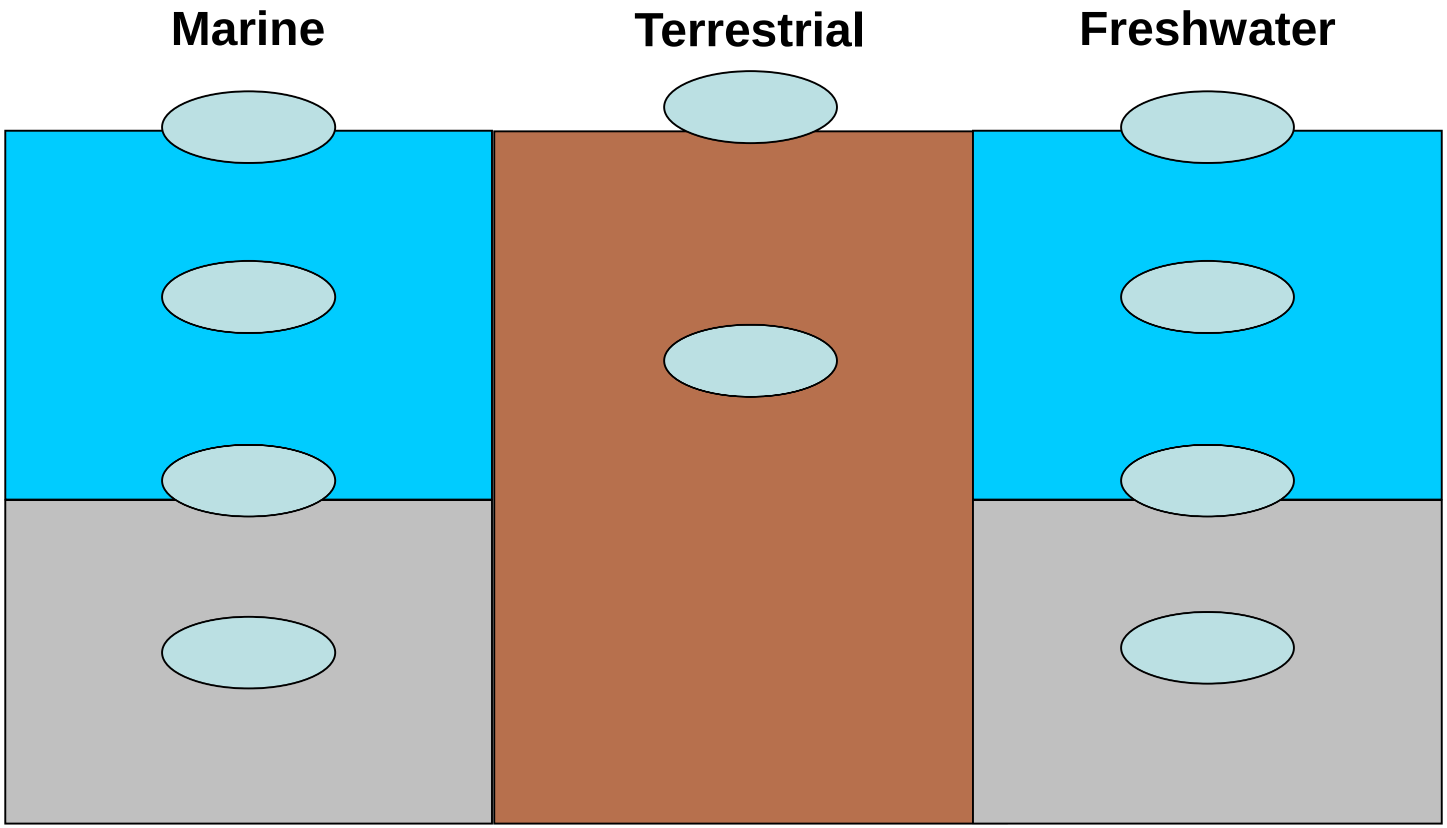
$$DCC_{ext} = \sum_i K_a(E_i) \times R(E_i, M) \times y_i$$

E_i is the energy , y_i is the yield of specific photon (per decay), and M is the mass of the animal (kg).

The Monte Carlo calculations were performed for 19 energies in the range from 10 keV to10 MeV.

Taranenko, V., Pröhl, G., Gómez-Ros, J.M., 2004. Absorbed dose rate conversion coefficients for reference biota for external photon and internal exposures. J. Radiol. Prot. 24, A35–A62.

Locations within habitat for dose-rate calcs.



Fraction of time spent by organism at different locations within its habitat

Calculation of dose rates

- Internal exposure:

$$\dot{D}_{\mathrm{int}} = (C_{medium} \times CR_{medium-organism}) \times DCC_{\mathrm{int}} = C_{organism} \times DCC_{\mathrm{int}}$$

- External exposure (e.g. terrestrial ground dwelling organism):

$$\dot{D}_{ext} = C_{soil} \times DCC_{on-soil} \times f_{on-soil} + C_{soil} \times DCC_{in-soil} \times f_{in-soil}$$

Note on DCCs

We also normally interested in **weighted total dose rates** (in µGy/h)

Need to apply : **Radiation weighting factors** (dimensionless):

$$DCC_{\text{int}} = wf_{\alpha} * DCC_{\text{int}\alpha} + wf_{low\beta} * DCC_{\text{int},low\beta} + wf_{\beta+\gamma} * DCC_{\text{int},\beta+\gamma}$$

$$DCC_{ext} = wf_{low\beta} * DCC_{ext,low\beta} + wf_{\beta+\gamma} * DCC_{ext,\beta+\gamma}$$

Where:
wf = weighting factors for various components of radiation (low beta, $\beta + \gamma$ and alpha)
DCC = Dose Conversion Coefficient in µGy/day per Bq/L or kg

Limitations in application to research

- ERICA – regulatory tool
  - Designed to have in-built conservatism
  - Simple, generic but robust
- Research requirements (Dose response relationships)
  - High level of realism, avoid conservatism
  - Accuracy and reproducibility

Characterising transfer –(internal) dynamics

- Following a deposition event, transfer can change dramatically with time
- Internal dose (for animals) - Function of (*inter alia*)
  - Physicochemical form of the radionuclide (AE)
  - Where the animal is and what it is eating
  - Metabolism- depuration rate (linked to internal biokinetics)

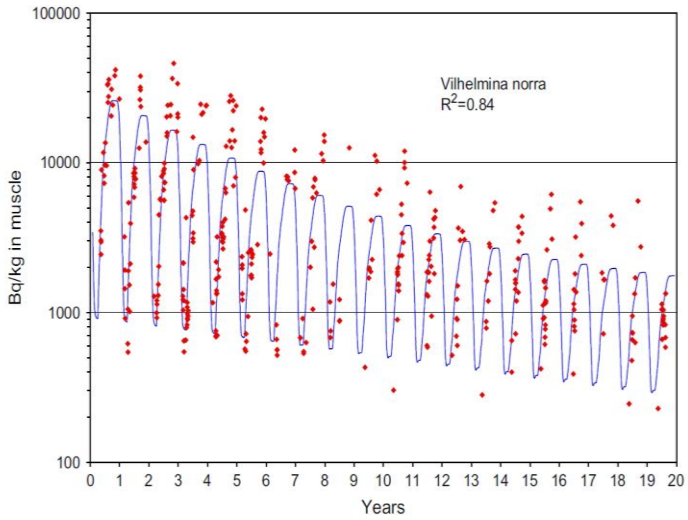


Fig. 1. Comparison of simulated and observed activity concentrations of ^{137}Cs in reindeer from Vilhelmina norra reindeer herding district. Dots are observed values (each representing 10 or more, mostly ≥30, individual reindeer) and the line is the simulated curve given by the model.

Åhman, B. (2007). Modelling radiocaesium transfer and long-term changes in reindeer. Journal of Environmental Radioactivity, 98, 153-165.

Inhomogeneous distributions

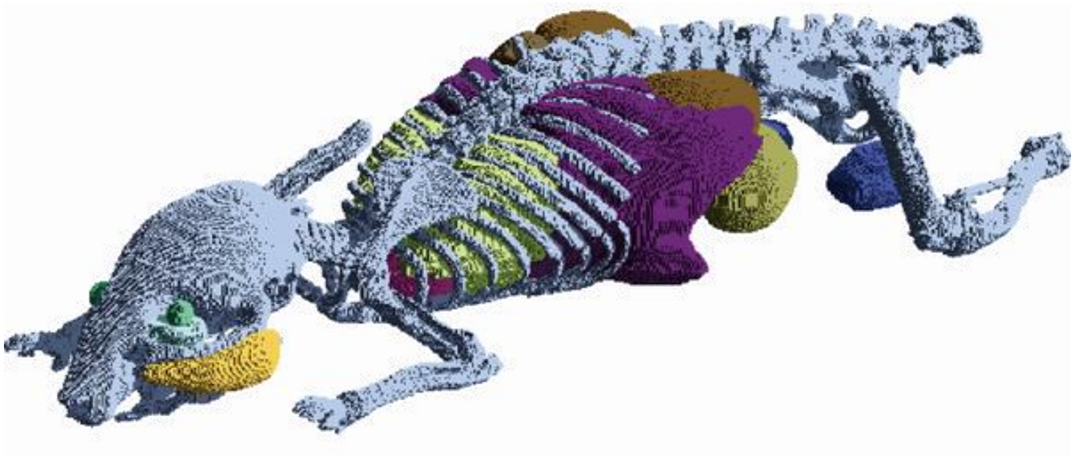
- To study the effect of inhomogeneous distributions, internal DCCs have been calculated assuming both a central and an eccentric point source (J.M. Gomez-Ros et al., 2008).
  – When the radionuclide is concentrated in a given organ, organ dose rate can be substantially higher than the whole body dose rate but we still have few data to infer what this might mean

- We know that concentrations of radionculdies in pariticular organs or body parts can be the critical factor in terms of effects observed :
  - Iodine-131 (and 132) in thyroid of animals. After Chernobyl this was a primary pathway for grazing animals :
  - For plants we would expect doses to the meristems to be important.

J.M. Gomez-Ros et al. (2008). Journal of Environmental Radioactivity, **99**, 1449 -1455

Voxel phantoms

Progression in human dosimetry towards *voxel phantoms* provides a possible way forward for improving the dosimetry for animals.



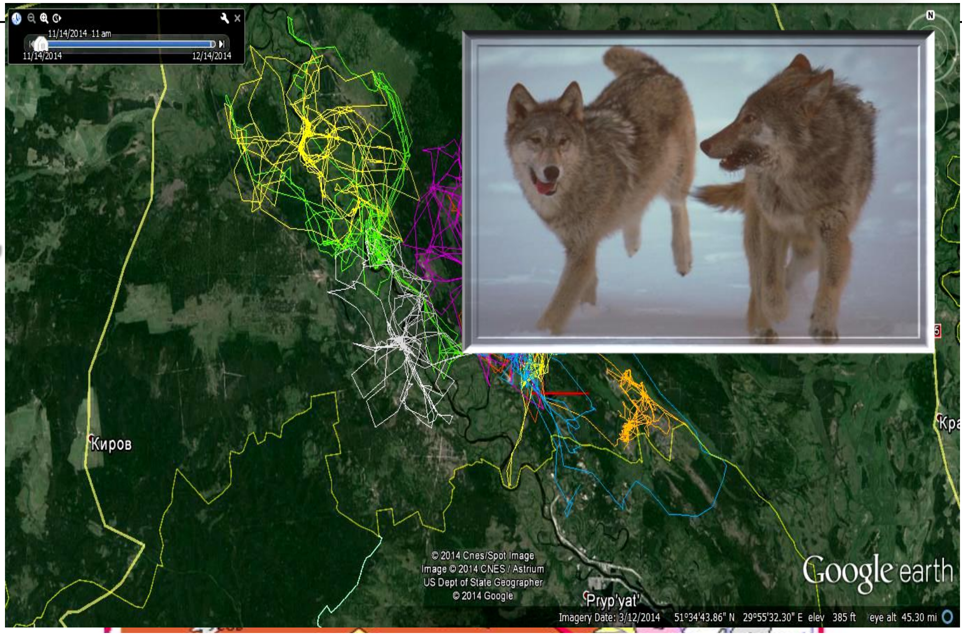
Provides a more realistic representation of the organism including internal structure ➔ more accurate dose estimates

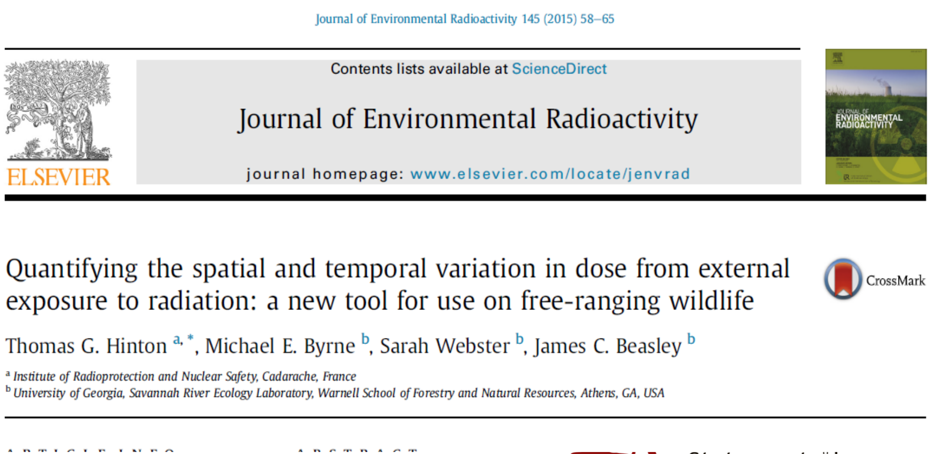
http://nsed.jaea.go.jp/ers/radiation/en/rpro/mouse-e.htm

External exposure – spatial variability

- Current models do not consider an animal's spatial and temporal use of habitats, or the habitat's large heterogeneity in levels of radioactive contamination

- Work is underway to explore this issue
  – Large mammals :GPS collar and link to electronic dosimeter





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Quantifying the spatial and temporal variation in dose from external exposure to radiation: a new tool for use on free-ranging wildlife

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[a] Institute of Radioprotection and Nuclear Safety, Cadarache, France
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Radiation weighting factors (w_r)

- For humans, α-w_r= 20 but this value is specific to stochastic effects
- For plants and animals more emphasis placed upon 'endpoints' that are relevant for the integrity of the population – mortality, morbidity, reproduction effects
- Based upon (Relative Biological Effectiveness) RBE studies –

$$RBE = \frac{D_{ref\_radiation}}{D_{high\_LET}}$$

ratio of dose required to cause a specific biological effect from a standard radiation (typically gamma rays) to the dose required to cause the same effect in the same end point from different types of radiation

- RBE is dependent upon dose-rate, species, endpoint studied etc.
- Subject for protracted discussion
  - Chambers et al. (2006) – nominal alpha radiation weighting factor of 5 but up to 10 for deterministic, population relevant endpoints.
  - ERICA = 10 for α (non stochastic effects in the species); 3 for low energy (≤ 10 keV) β radiation; 1 for γ and high energy (> 10 keV) β radiation.
- ICRP C5 taskgroup currently working on this issue

Chambers D, Osborne R, Garva A. 2006. Choosing an alpha radiation weighting factor for doses to non-human biota. J. Environ. Radioactivity, 87(1):1-14.

Conclusions

- We have well established methods for application in a regulatory context (often planned, screening)
- For quantification of exposure for research purposes some of the methods might be applicable BUT adaptations are required to account for :
  - The dynamics of transfer, especially in the first few months after a pulsed release,
  - The heterogeneity in deposition and hence external irradiation (account for home ranges etc.)
- Other factors may need to be accounted for when interpreting data
  - The heterogeneity of radionuclides on plants and within animals
  - The radiation quality : appropriate weighting factors