HelmholtzZentrum münchen
German Research Center for Environmental Health

Department of Radiation Sciences, Institute of Radiation Protection
Research Group “Radiation risk”

Current developments in dosimetry for non-human biota

Alexander Ulanovsky

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HELMHOLTZ ASSOCIATION

Why dosimetry for animals and plants?

- We look towards protecting people and the(ir) environment from our activities resulting in additional anthropogenic radiation exposure
- What are the criteria to establish the system of radiation protection for human and the environment?
- ICRP (hopefully) knows…

ICRP system of radiological protection: the aims

Radiological protection of **human** (P103 ICRP, 2007):

"(29) The Commission's system of radiological protection aims primarily to protect human health. Its health objectives are relatively straightforward: to manage and control exposures to ionising radiation so that deterministic effects are prevented, and the risks of stochastic effects are reduced to the extent reasonably achievable."

Radiological protection of **animals and plants** (P124 ICRP, 2014):

"(7) The Commission's environmental protection aims are to prevent or reduce the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems. The biological endpoints of most relevance are therefore those that could lead to changes in population size or structure."

ICRP system of environmental protection: endpoints

ICRP Publication 124 (ICRP 2014)

"(8) The biological endpoints of interest to individuals that could have a consequence at a population level are those of:
- early mortality (leading to changes in age distribution, death rate, and population density);
- some forms of morbidity (that could reduce "fitness" of the individuals, making it more difficult for them to survive in a natural environment);
- impairment of reproductive capacity by either reduced fertility or fecundity (affecting birth rate, age distribution, number, and density); and
- the induction of chromosomal damage."

Radiation effects and reference levels

From ICRP Publication 108 (ICRP, 2008):

"(194) ... 'derived consideration reference level' (DCRL)…

(195) A DCRL can therefore be considered as a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of Reference Animal or Plant, derived from a knowledge of defined expected biological effects for that type of organism that, when considered together with other relevant information, can be used as a point of reference to optimise the level of effort expended on environmental protection, dependent upon the overall management objectives and the exposure situation."

DCRL: how to utilize?

- Probability of 'deleterious effects' of radiation is known to be defined by a total dose, which can be possibly modified by factors accounting for various effects (e.g. dose rate, saturation or non-linear response, *etc*)
- Important!
  The definition of DCRL as a 'band of dose rate' implicitly assumes a certain exposure scenario, namely, constant life-long exposure!
- To compare with DCRL, an assessor has to be capable to compute radiation doses and dose rates for various organisms assuming various exposure scenarios…
- To accomplish this task, one needs as dose responses per unit contamination (aka DCC) as exposure scenarios, including specification of the studied population, environmental contamination, and time constraints/shares

Dosimetry for non-human biota – main principles

Main challenges:

diversity and variety of living organisms in sizes, shapes, body masses and compositions, biology, biokinetic, life styles and environments

Methods to cope with those:

- Conventional dosimetry (macrolevel, not microdosimetry)
- Superposition principle: a complex exposure scenario can be split into a series of simpler ones resulting in the same integral effect
- Simplified representation of exposure geometry, body shape
- Biokinetic is not accounted for, i.e. intake is described via lumped equilibrium concentration factors
- Uniformity assumptions (media densities, activity distributions)
- Interpolation and (physically justified) extrapolations, including allometric scaling

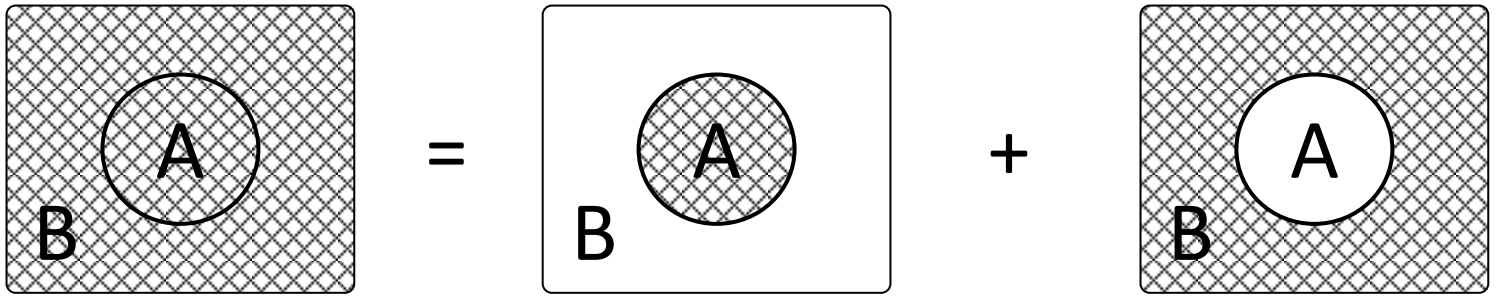
Current approach – basics

Animals and plants are characterized by:

- Body mass
- Shape (proportions)
- Ecosystems

Organism's body is approximated by simple geometric shapes:
spheres, prolate and oblate ovoids, and arbitrary ellipsoids

"Uniform isotropic model" is used:

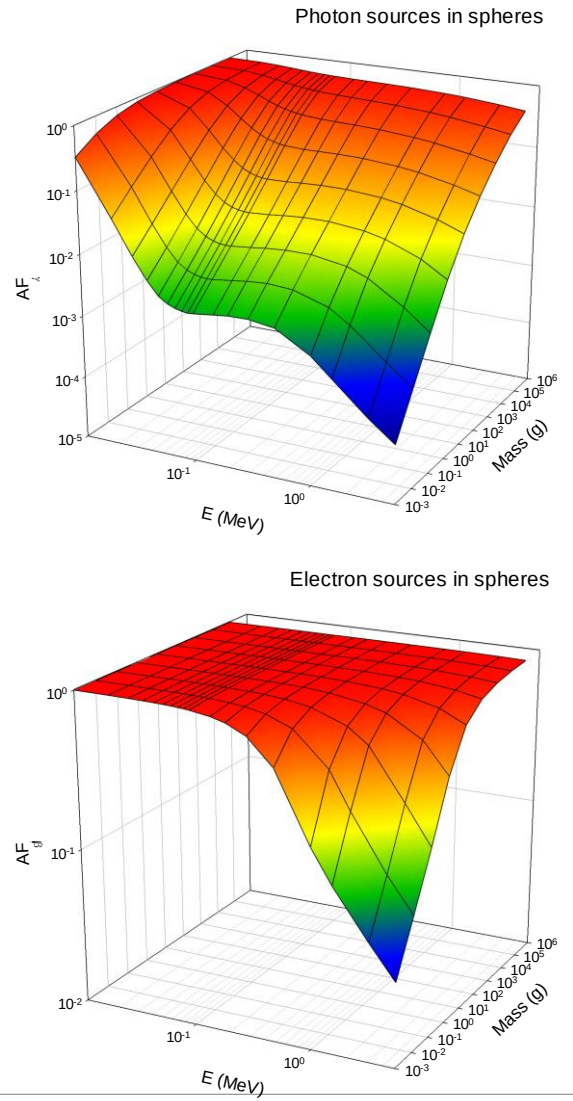


Total dose
('full absorption limit')
D_∞

Internal dose
$D(A \leftarrow A) = D_\infty \, \phi$

External dose
$D(A \leftarrow B) = D_\infty \left(1 - \phi\right)$

Current approach – absorbed fractions



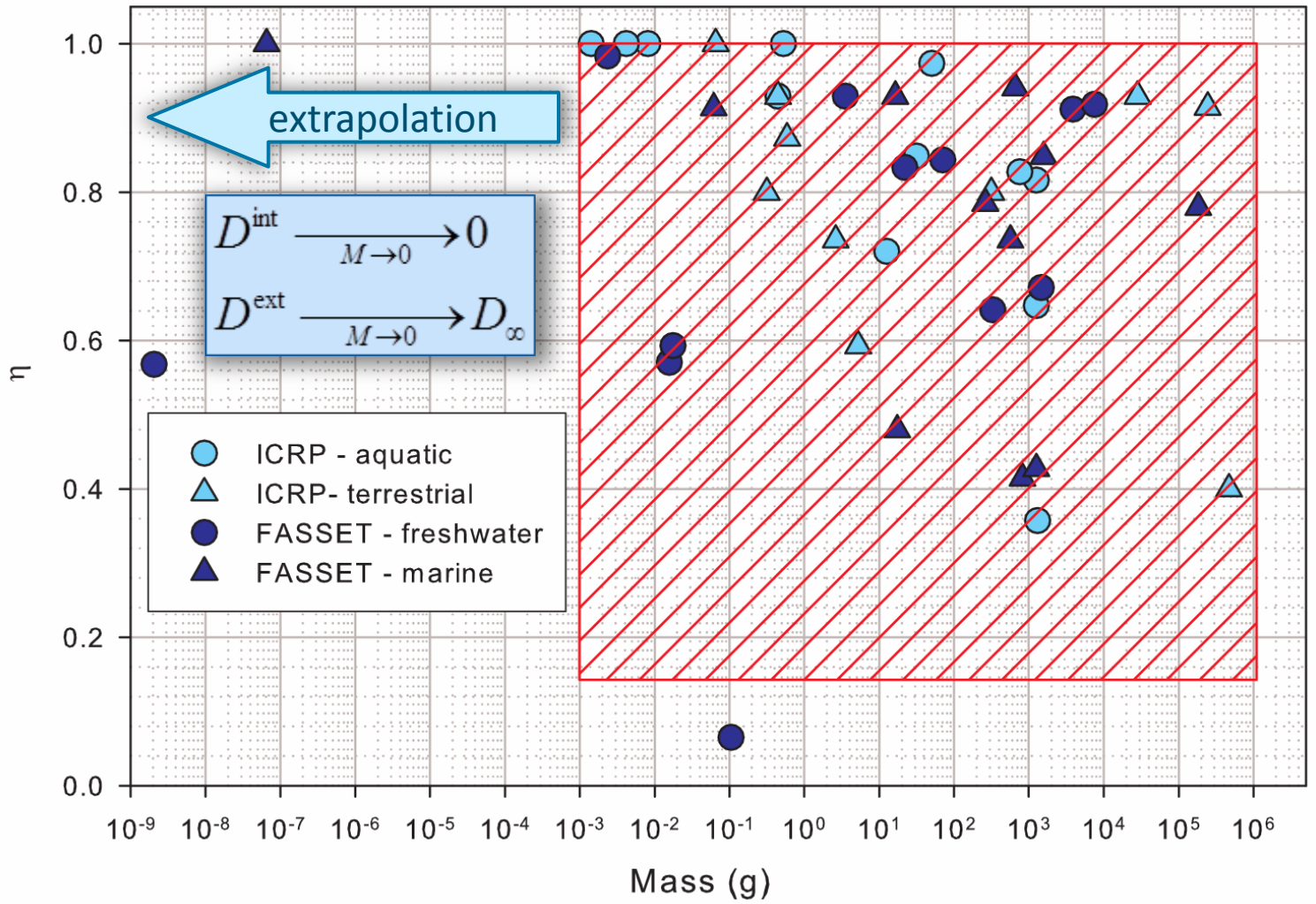
Absorbed fractions (AF) have been systematically calculated for bodies…

- with masses from 1 mg to 1 ton
- shapes from spheres to ellipsoidal shapes with non-sphericity parameter equal to 0.15
- the responses are smooth (see left) and can be easily interpolated on mass and energy

An analytical approximation (body mass and non-sphericity parameter) has been found

- to allow computation of AF for arbitrary ellipsoidal body
- uncertainties are within 10% for electrons and 15% for photons

Masses and shapes covered



Current approach – some details

Alpha-particles and fission fragments are considered as non-penetrating radiation, i.e. absorbed fractions for these particles are assumed equal to 1

An alternative to the uniform isotropic model – models with realistic elemental composition and density distributions – provide only minor improvements given other uncertainties implicit in environmental dose assessments (e.g. secondary radiation from surrounding water contributes only a few percent to internal dose)

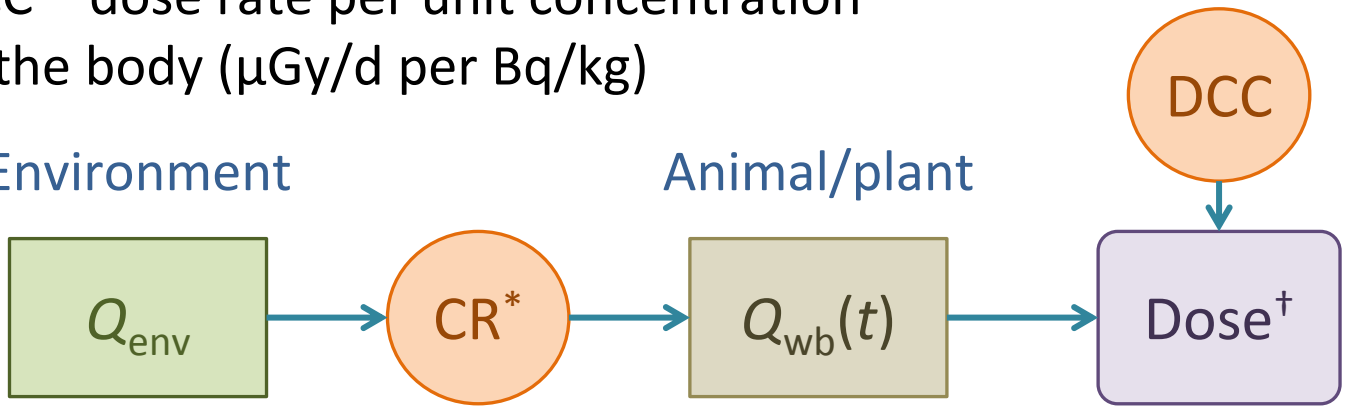
Re-scaling can help to assess organ doses in case of non-uniformly distributed radioactivity in the body (especially, for non- and low-penetrating radiations)

Still, there can be situations that might require more realistic models (e.g. internal or external exposure of skeletal tissue or heterogeneous distribution of alpha-emitting radionuclides)

Internal dose assessment – biota vs. human

Biota:

DCC – dose rate per unit concentration in the body (µGy/d per Bq/kg)

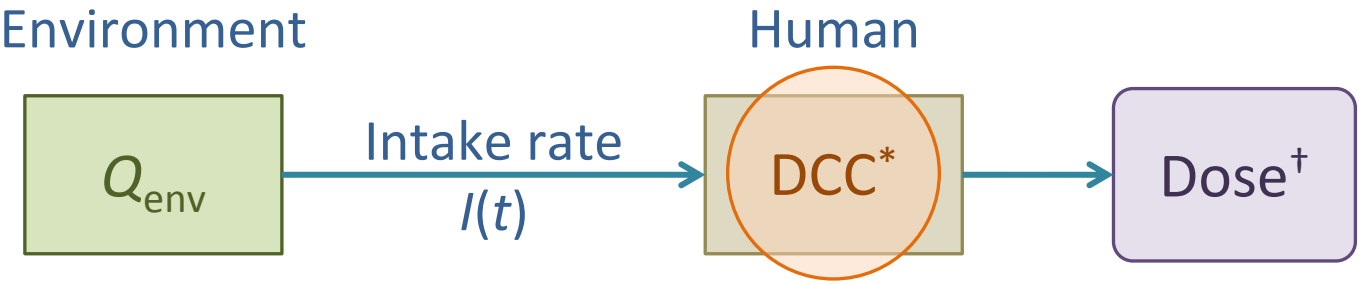


* Ecological transfer, biokinetic and decay included

† user integrates over time-dependent dose-rates

Human:

DCC – committed dose per unit intake (Sv/Bq)



* biokinetic and decay included

† user integrates over time-dependent intake

Current approach – external exposure of terrestrial animals

External exposure of terrestrial organisms is modeled differently than that for aquatic organisms:

$$D(E_0,H,M)=\sum_i \tilde{K}_i(E_0,H)\bar{R}_i(M)$$

where

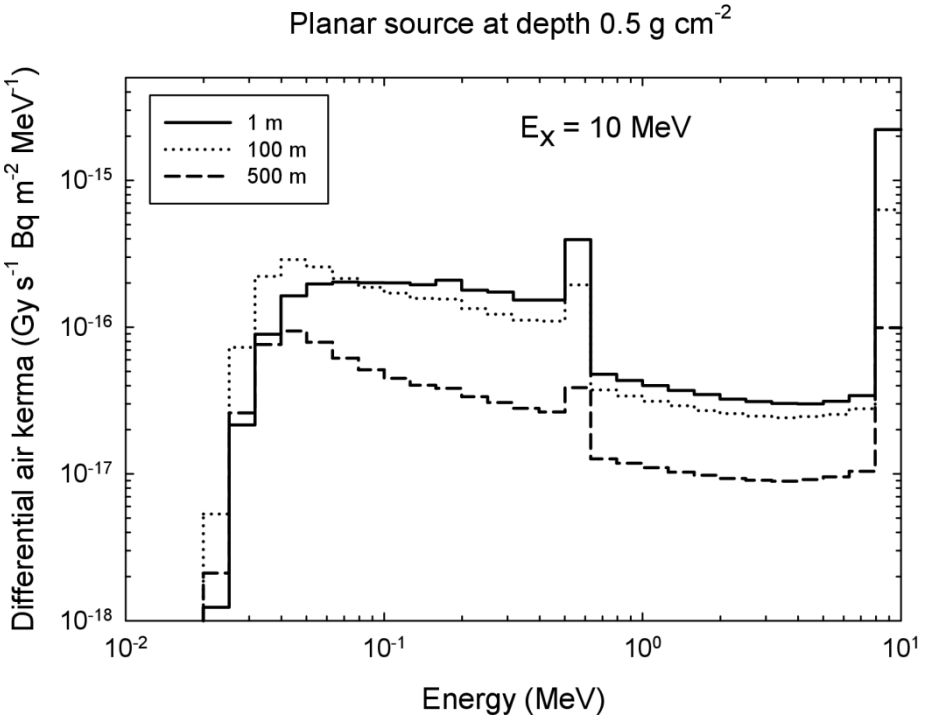
$$\tilde{K}_i(E_0,H)=\int_{\Delta_i}\frac{\mu_{tr}}{\rho}(E)E\frac{d\Phi}{dE}(E_0,H,E)dE$$

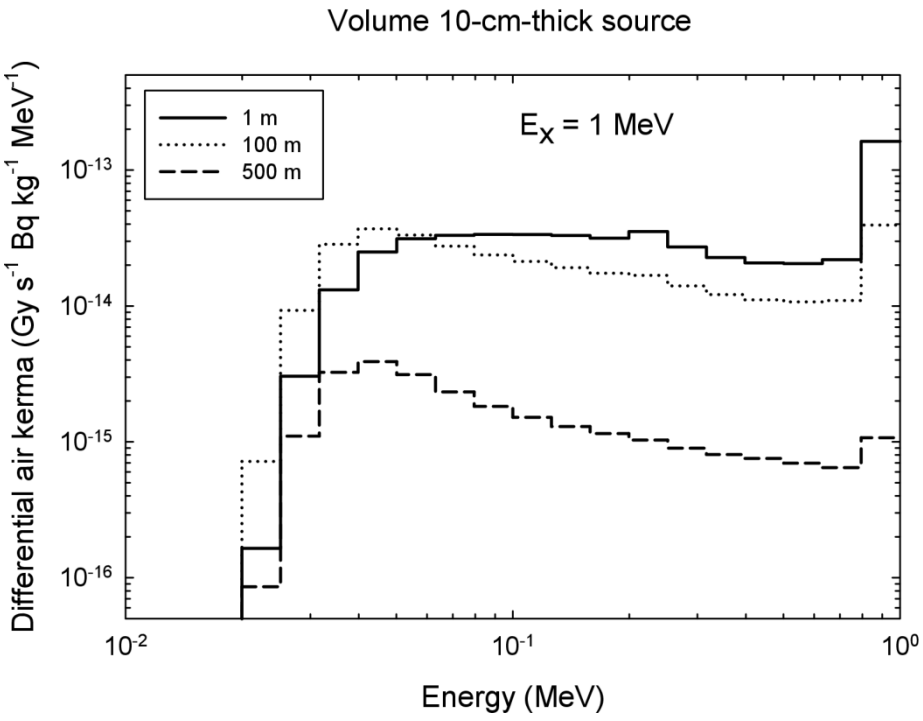
the differential air kerma is computed by Monte Carlo directly and

$$\bar{R}_i(M)=\frac{1}{\Delta_i}\int_{\Delta_i}R(E,M)dE$$

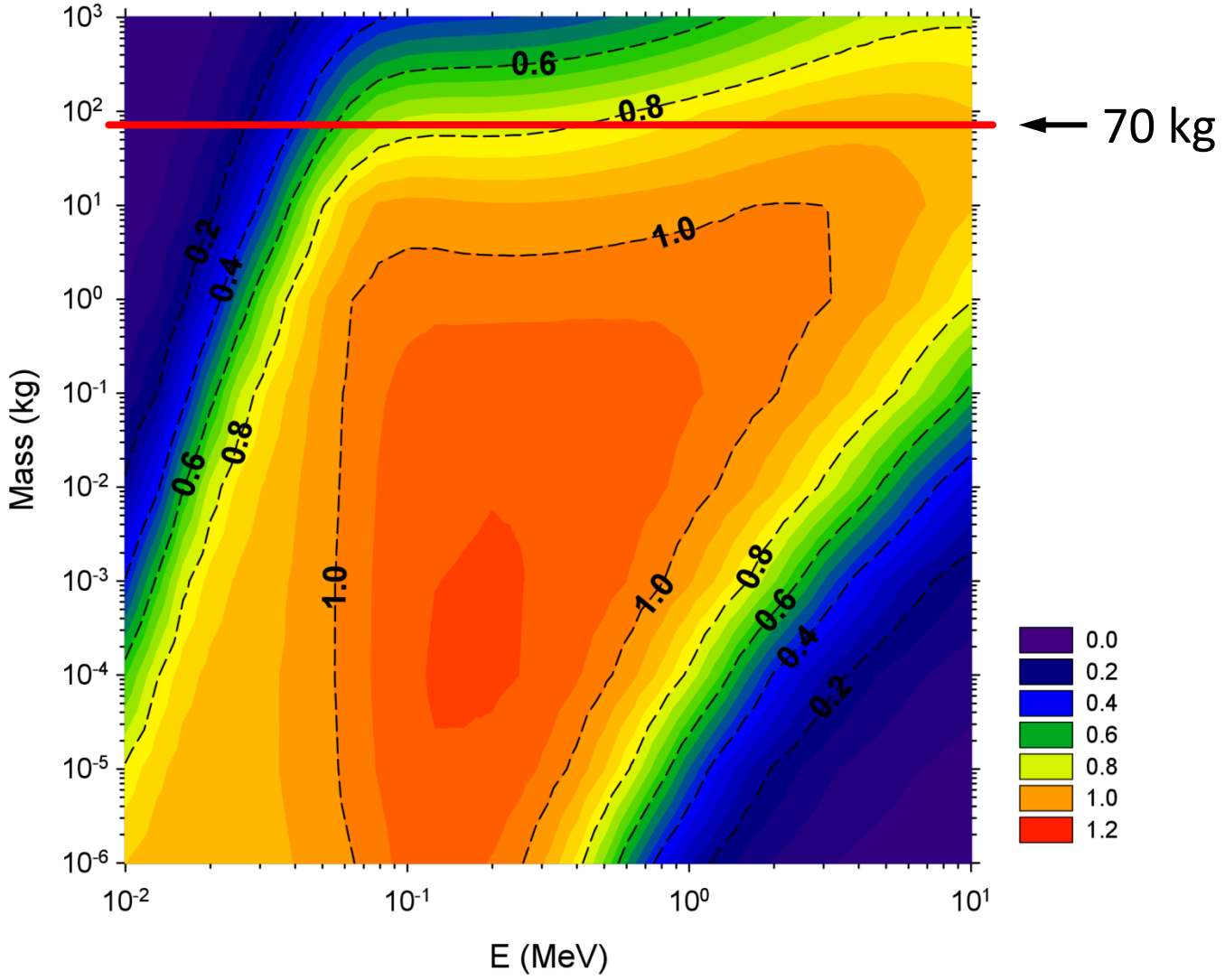
dose-per-kerma ratio is computed by integration of the values independently obtained by Monte Carlo method.

External exposure: differential air kerma (kerma spectra)





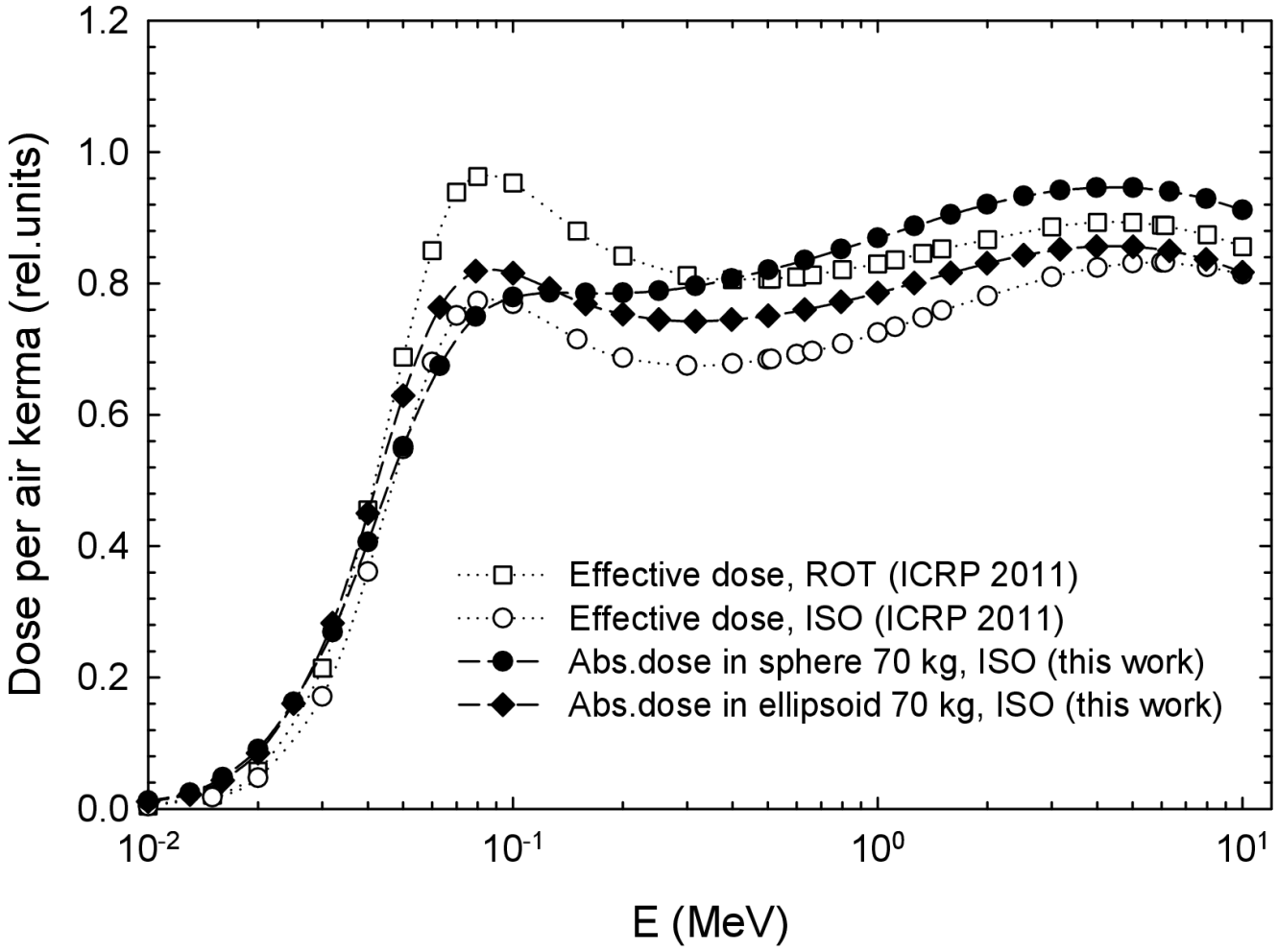
Dose-per-air-kerma ratio for spheres in isotropic photon field



Dose-per-kerma ratio for simple shapes and human phantom

Effective dose (weighted sum of equivalent organ doses) for adult human (ICRP P116, 2011)

Absorbed dose (averaged in the whole body) for 70 kg sphere and ellipsoid



Current approach – external exposure of terrestrial animals

As a result, the current method allows to compute DCC of external exposure for terrestrial animals and plants:

- for organism's body masses ranging from 10^{-6} to 10^{3} kg, thus closing the existing 'gap' in the current ICRP dosimetric approaches for terrestrial biota;
- for three environmental sources: 'effective' plane source at depth 0.5 g cm^{-2}, volume 'aged' source uniformly distributed in the upper 10 cm of soil, and volume infinitely deep uniform source in soil suitable for NORM;
- for heights above ground interface from 0.1 to 500 m;
- for energies of source photons ranging from 10 keV to 10 MeV, thus matching the range of photon energies of all nuclides included in the contemporary ICRP Publication 107 (ICRP 2008)

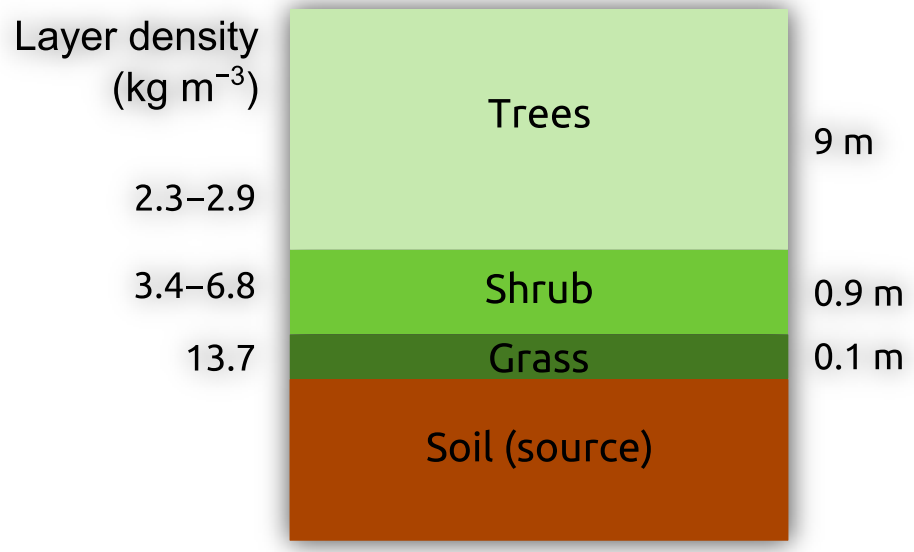
Also considered are:

- 50-cm-deep uniform volume source in soil (for 'in-soil' exposure, only)
- submersion in contaminated air (at 1-m-height above the ground)

Current approach – external exposure of terrestrial vegetation

External exposure of the terrestrial vegetation is assumed in very simplistic way; namely, for the three infinite homogeneous (biomass+air) layers, representing grasses, shrub, and trees

- Such simple models might become inadequate in a specific assessment
- Needs in reconsideration and, possibly, in an improvement



Implementation

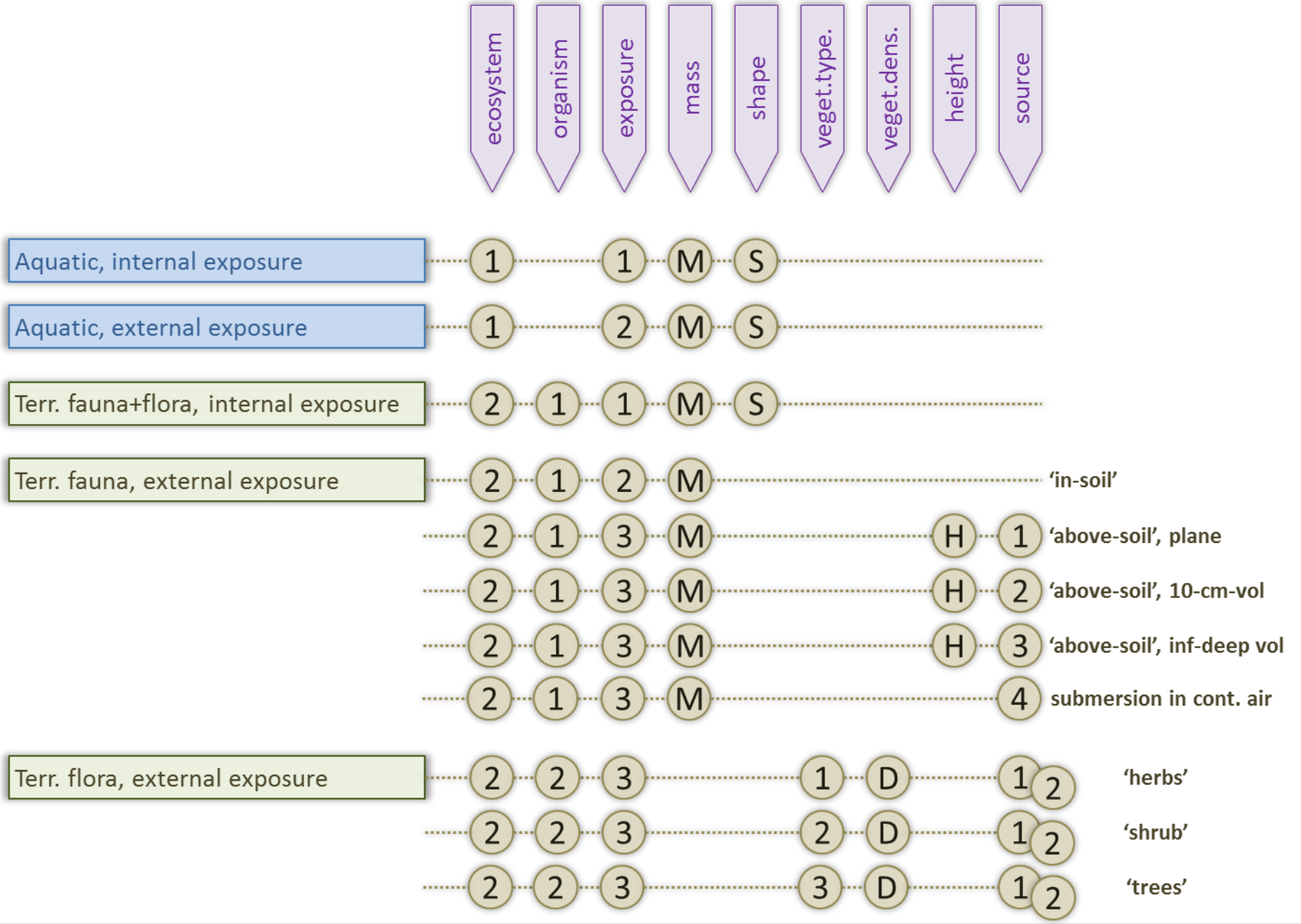
DCCs are calculated using special-purpose program, BiotaDCC

The first version of the program in the form of external library has been built in the ERICA Assessment Tool (http://www.erica-tool.com/)

The second version in the form of a stand-alone command line tool is currently under testing…

The program outputs decay chain and the whole body absorbed dose rate per unit concentration and fractions of it from different radiation types:

(a) alpha-particles and fission fragments
(b) low-energy electrons
(c) high-energy electrons and photons


ecosystem
organism
exposure
mass
shape
veget.type.
veget.dens.
height
source
Aquatic, internal exposure
1 1 M S
Aquatic, external exposure
1 2 M S
Terr. fauna+flora, internal exposure
2 1 1 M S
Terr. fauna, external exposure
2 1 2 M
'in-soil'
2 1 3 M H 1
'above-soil', plane
2 1 3 M H 2
'above-soil', 10-cm-vol
2 1 3 M H 3
'above-soil', inf-deep vol
2 1 3 M 4
submersion in cont. air
Terr. flora, external exposure
2 2 3 1 D 1 2
'herbs'
2 2 3 2 D 1 2
'shrub'
2 2 3 3 D 1 2
'trees'

Radionuclides considered

- The new version of the tool uses the electronic version of ICRP Publication 107 (ICRP, 2007) with emission data for 1252 radionuclides
- Current default approach accounts for only short-lived ($T_{½}$<10 d) progeny in equilibrium with parent nuclide (aka FASSET/ERICA approach)
- Truncation of decay chain may be inappropriate for certain exposure scenarios.
- For some radionuclides, the DCCs may depend on time (non-equilibrium conditions for parent and daughters)
- The tool offers more options to account for emissions of parent and its progeny: 'instant' and average activity ratios

Dose assessment (1)

External exposure:

Time shares in various locations = ‘life-style’

Contamination of these locations:

- Uncertainty due to spatial variability of contamination
- Uncertainty due to a scarcity of sampled data (contamination data are available only for certain locations not for the whole areal)
- Uncertainty due to approximating real exposure conditions by simplified ‘source geometries’
- Less uncertainty if contamination data are measured, higher uncertainty if they are implied or assessed from radioecological transfer models

Dose assessment (2)

Internal exposure

Activity concentration in the body

- Concentration ratios (CRs) are commonly used to derive activity concentration in the (whole) organism from activity concentration in the environment
- Estimates of CR for many elements are missing or incomplete, while available CRs often have large uncertainties
- CRs are defined for elements and equilibrium condition

Use of CR is a very approximate way to assess activity concentration in the whole organism, uncertainty of this quantity is high

Dose assessment (3)

Internal exposure

Use biokinetic modeling to assess activity concentration in the organism

Even simplest single-compartment modeling will require to define:

- Intake (depends on many environmental and biological parameters, i.e. additional uncertainty)
- Uptake and retention (many parameters like biological half-lives are not well known for many animals and plants)

Allometric ‘laws’ can be helpful to approximate biological parameters

Allometric scaling: illustration

Various organisms are diverse but similarities exist, as well

So-called 'Kleiber Law' (Rubner 1883; Kleiber 1932, 1947, 1975)

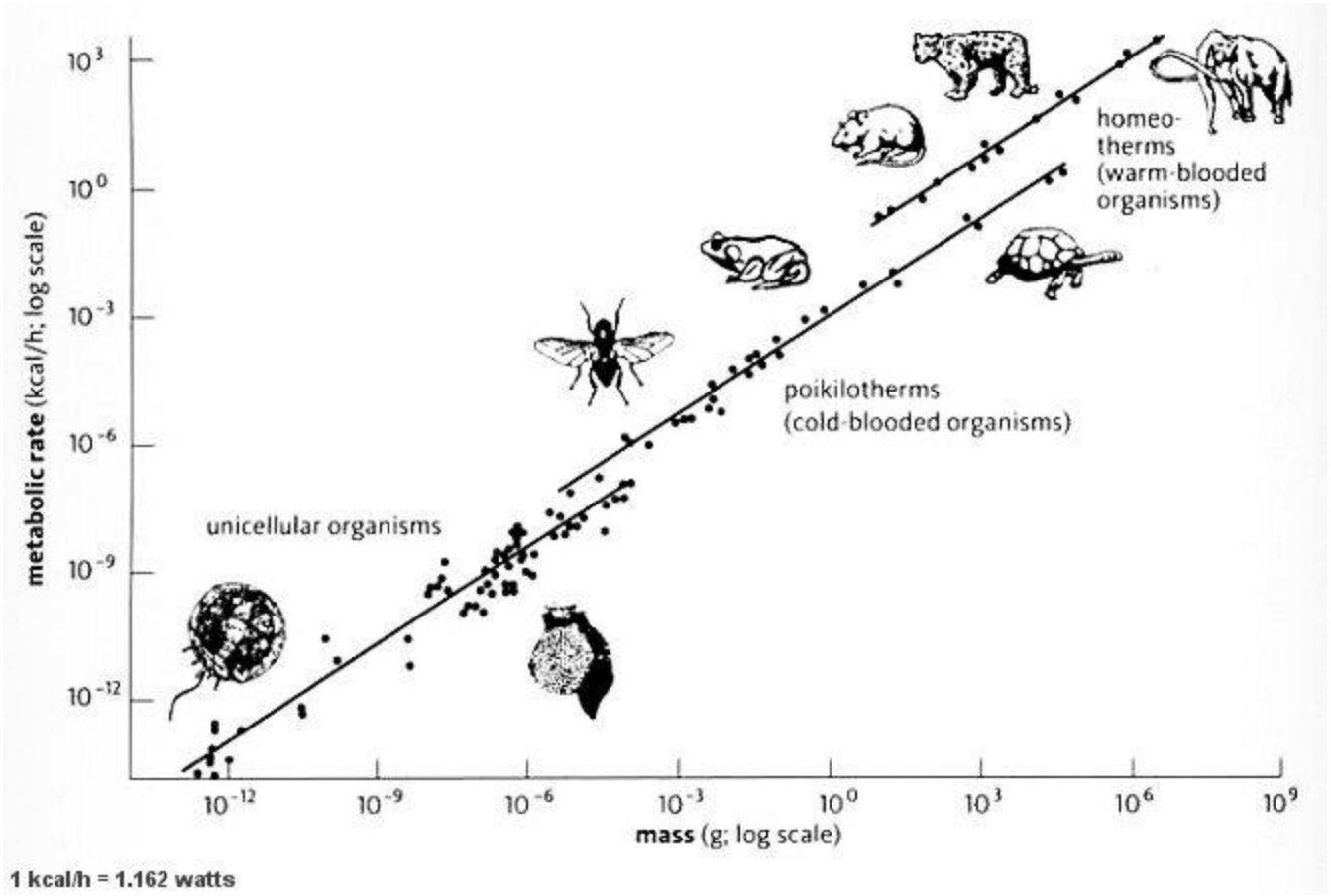


Image from: http://universe-review.ca/R10-35-metabolic.htm

Some answers to typical misbeliefs…

- One does not need a special DCC for each and every exposure scenario. Instead, a dose assessment assumes that a specific exposure scenario is modeled as a superposition of simple basic exposure scenarios
- DCCs themselves are only a part of the dose assessment. Other data used in the assessment may bring uncertainties, which considerably exceed those due to use of simplified dosimetric models
- Often, basic assumptions are forgotten or ignored. Examples are:
  - ✓ A request for bacteria's DCC – the organism is too small to be considered within assumptions of the conventional dosimetry
  - ✓ It is commonly forgotten that the DCC in the ICRP tabulations are given for parent nuclides and short-lived ($T_{½}$<10 d) daughters

Things to do…

- Consider alternative parameterizations for AFs (e.g. Amato et al, 2014)
- Effect of body shape and structure on DCC of external exposure for terrestrial organisms (fauna and flora)
- Effect of realistic terrains (non-flat landscape, heterogeneous relief, forest, vegetation) on energy- and angular distribution of air kerma
- Development of dosimetric approaches for populations of organisms, accounting for their mobility as well as inhomogeneity of the environment and its contamination
- Probabilistic analysis of uncertainties inherent to environmental dose assessments (dispersion of properties in and among biota populations, variability of environment and its contamination, …)

Thank you for attention!