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1 **Original Paper**

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4 **NA Beresford and J Vives i Battle**

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6 **Estimating the biological half-life for radionuclides in homoeothermic**
7 **vertebrates: A simplified allometric approach**

8

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20 **Abstract** The application of allometric, or mass dependent, relationships within
21 radioecology has increased with the evolution of models to predict the exposure of organisms
22 other than man. Allometry presents a method of addressing the lack of empirical data on
23 radionuclide transfer and metabolism for the many radionuclide-species combinations which
24 may need to be considered. However, sufficient data across a range of species with different
25 masses are required to establish allometric relationships and this is not always available. Here
26 an alternative allometric approach to predict the biological half-life of radionuclides in
27 homoeothermic vertebrates which does not require such data is derived. Biological half-life
28 values are predicted for four radionuclides and compared to available data for a range of
29 species. All predictions were within a factor of five of the observed values when the model
30 was parameterised appropriate to the feeding strategy of each species. This is an encouraging
31 level of agreement given that the allometric models are intended to provide broad
32 approximations rather than exact values. However, reasons why some radionuclides deviate
33 from what would be anticipated from Kleiber's law need to be determined to allow a more
34 complete exploitation of the potential of allometric extrapolation within radioecological
35 models.

36

37 **Keywords:** Allometry, biological half-life, metabolic rate, radionuclide, environmental
38 assessment

39

40

41 **Introduction**

42

43 Size affects rates of all biological structures and processes from cellular metabolism to
44 population dynamics (Peters 1983; Hoppeler and Weibel 2005). The dependence of a
45 biological variable (Y) on body mass (M) is typically characterised by an allometric scaling
46 law of the form:

$$47 \quad Y = aM^b \quad (1)$$

48 where a and b (the allometric exponent) are constants.

49 In the 1930's Kleiber (1932) found that basal metabolic rate (measured as heat production)
50 across 13 groups of mature animals ranging from a ring dove (<200 g body mass) to a steer
51 (about 680 kg body mass) was proportional to mass to the power 0.74. Following further
52 analyses which demonstrated similar exponents Kleiber suggested that 'metabolic body size'
53 (now generally referred to as metabolic liveweight) could be determined as $M^{0.75}$ where M is
54 the mass of the animal (Kleiber 1947); this has since become known as *Kleiber's law*. There
55 have been many compilations of allometric relationships for biological parameters across
56 large mass ranges and a multitude of animal and plant species (e.g. Peters 1983; Hoppeler
57 and Weibel 2005; Higley 2010).

58 In this paper the use of allometric relationships in radioecological models is explored and in
59 particular a simple solution is suggested to enable their more widespread application to
60 homoeothermic vertebrates.

61

62 Allometry in radioecology

63

64 Many of the reported allometric relationships are useful in radioecological modelling, for
65 instance, dry matter food ingestion rates, water ingestion rates, inhalation rates, etc. and these
66 have been used in a number of models of the radionuclide transfer to wildlife (e.g. Beresford
67 et al. 2008; Johansen et al. 2012) including the US Department of Energy's RESRAD-Biota
68 model (USDOE 2002).

69 Moreover, there are specific radioecological parameters which have been shown to scale
70 allometrically, with relationships for biological half-life across species having been reported

71 in the 1970's (e.g. Stara et al. 1971; Kitchings et al. 1976). In more recent years, the
72 application of allometry to radioecology has received revived attention during the
73 development of models to predict the exposure of wildlife to radionuclides in both terrestrial
74 (Higley et al. 2003; Higley 2010; Beresford et al. 2008; Sheppard 2001) and aquatic
75 ecosystems (Vives i Batlle et al. 2007; 2009; Brown et al. 2004). The reason for this attention
76 is the potential of allometry to help address the lack of data for the large number of organism-
77 radionuclide combinations which may need to be assessed (Beresford et al. 2004; Higley et
78 al. 2003; IAEA in-press).

79 In the marine environment, allometric relationships have been found across plankton,
80 seaweed, fish, crustaceans and molluscs (Vives i Batlle et al. 2007; 2009) for the
81 concentration ratio (CR) of activity concentrations in organisms to those in water ($M^{-0.26\pm0.09}$)
82 and also the biological half-life of elimination ($M^{0.16\pm0.03}$). The CR scaled better allometrically
83 for particle seeking radionuclides, mainly lanthanides and actinides. A relationship between
84 the independent term of the allometric power function (a) and the sediment-water partition
85 coefficient (k_d) was also observed. This was strongest for particle seeking radionuclides,
86 suggesting the importance of particle-reactive material sorbed onto food and ingested in
87 particulate form relative to conservative radionuclides which tend to stay largely in the
88 aqueous phase.

89 For terrestrial organisms, allometric relationships have also been suggested for the dietary
90 transfer coefficient (i.e. the ratio of the activity concentration of a radionuclide in an
91 organism to the daily intake of that radionuclide) (MacDonald 1996). However, Beresford et
92 al. (2004) demonstrated that this was the consequence of the dependence of daily dry matter
93 intake on mass and that the ratio between the activity concentration in the animal and that in
94 feed is independent of mass.

95 USDOE (2002) presents allometric relationships for the biological half-lives of 16 elements
96 in terrestrial/riparian vertebrates. Many of these have an exponent of approximately 0.25,
97 which can be explained on the basis of the relationship between the biological half-life and
98 the metabolic rate as described below.

99 Taking a simple model, adapted from Sazykina (2000) of intake versus elimination for an
100 adult organism of total mass M then the radionuclide activity concentration y (Bq kg^{-1} , fresh
101 mass) of the organism changes according to:

102

103
$$\frac{dy}{dt} = -\varepsilon_a \frac{B_r}{M} \left[y - \frac{Q_1^A A_f}{Q_0^A} \right]$$
 (2)

104

105 where B_r is the metabolic rate (kg d^{-1}); ε_a is a proportionality constant between the rate of
 106 biological loss of a radionuclide from the organism and the metabolic rate of the organism; A_f
 107 is the radionuclide activity concentration in food (Bq kg^{-1} dry matter); and Q_1^A, Q_0^A are the
 108 total element concentrations in the organism (mg kg^{-1} fresh mass) and in food (mg kg^{-1} dry
 109 matter) respectively (here, isotopic equilibrium is assumed, *i.e.* that the ratio of the
 110 radionuclide concentration in the organism to that in the diet is the same as the concentration
 111 ratio for the total element). This gives the solution:

112
$$y = y_0 e^{-\varepsilon_a \frac{B_r}{M} t} + \frac{Q_1^A A_f}{Q_0^A} \left(1 - e^{-\varepsilon_a \frac{B_r}{M} t} \right)$$
 (3)

113 Where y_0 is the activity concentration of the organism at $t = 0$, *i.e.* at the beginning of
 114 depuration. If $A_f = 0$ and $y_0 \neq 0$ (representing a depuration process) Eq. 3 becomes reduced to
 115 a simple exponential, and applying the definition of biological half-life (ie $y = y_0 e^{-\frac{\ln 2}{T_{B1/2}} t}$)
 116 yields:

117
$$T_{B1/2} = \frac{M \ln 2}{\varepsilon_a B_r}$$
 (4)

118 If Kleiber's law is now applied (*i.e.* $B_r = aM^{0.75}$) then:

119
$$T_{B1/2} = \frac{\ln 2}{a \varepsilon_a} M^{0.25}$$
 (5)

120 This is in agreement with the exponent values quoted by USDOE (2002) for many
 121 radionuclides (note, however, that some radionuclides within USDOE do not scale as
 122 approximately 0.25 as discussed later).

123 The application of allometric biological half-life relationships allows broad approximations to
 124 be made to help address the limitations of the current empirical data for wildlife. However, to
 125 derive such relationships, adequate data are required for a given element and for a number of
 126 species across a range of masses. Sheppard (2001) proposed that, if it is accepted that there is

127 an approximation of the exponent applicable for all elements (i.e. in the case of biological
 128 half-life, 0.25), then only an estimation of the multiplicand is needed for any given element.
 129 In the following section, a method of estimating this multiplicand is derived and, hence, the
 130 applicability of allometric approaches to estimating biological half-life is extended.

131

132

133 **Materials and methods**

134

135 Extending the application of allometry in radioecology

136

137 If one starts by considering a simple first-order linear retention model with constant input:

$$138 \quad \frac{dy}{dt} = \frac{f_1 A_f I_r}{M} - \frac{\ln 2}{T_{B1/2}} y \quad (6)$$

139 where y is the fresh mass activity concentration in the whole organism (Bq kg^{-1}), I_r is the dry
 140 matter ingestion rate (kg d^{-1}), f_1 is the fractional gastrointestinal absorption coefficient and
 141 other terms have been defined above.

142 Equation 6 implies a single component release which is not always observed. However,
 143 current allometric relationships predict the long component of loss only (USDOE 2002). At
 144 equilibrium ($t=\infty$), Eq. 6 equals zero and the equilibrium activity concentration in the
 145 organism (y_{eq}) is given by:

$$146 \quad y_{eq} = \frac{A_f f_1 I_r T_{B1/2}}{M \ln 2} \quad (7)$$

147 This can be rearranged to give the ratio between the activity concentrations in the whole
 148 organism (fresh mass) and the diet (dry matter) ($CR_{org-diet}$):

$$149 \quad CR_{org-diet} = \frac{f_1 I_r T_{B1/2}}{M \ln 2} \quad (8)$$

150 If it is assumed that the biological half-life scales allometrically to body mass to the power of
 151 0.25 and that intake rate, which is proportional to metabolic rate, scales allometrically to
 152 body mass to the power of 0.75 (see Nagy 2001), then:

153 $T_{B1/2} = a_B M^{0.25} \quad Ir = a_I M^{0.75}$

154 This gives:

155 $CR_{org-diet} = a_B a_I \frac{f_1}{\ln 2} \frac{M^{0.75} \times M^{0.25}}{M}$ (9)

156 Therefore, mass cancels out and:

157 $CR_{org-diet} = a_B a_I \frac{f_1}{\ln 2}$ (10)

158 If it is accepted that $CR_{org-diet}$ approximates to a constant for a given element across all
 159 species as suggested in Beresford et al. (2004) (and later accepted for farm animals in IAEA
 160 (2010)) then a solution to a_B can be proposed:

161 $a_B = \frac{\ln 2}{a_I f_1} CR_{org-diet}$ (11)

162 Hence an estimate of $T_{B1/2}$ can be derived for an element if $CR_{org-diet}$ and f_1 are known:

163 $T_{B1/2} = \frac{\ln 2}{a_I f_1} CR_{org-diet} M^{0.25}$ (12)

164 Values of a_I are relatively well documented for terrestrial vertebrates (e.g. Nagy 2001). If the
 165 ingestion rate is known, then a_I can be substituted by: $(I_r \times M^{0.75})$

166

167 Testing the hypothesis

168

169 For this test the primary source of $T_{B1/2}$ values was Whicker and Shultz (1982), who tabulated
 170 estimates from the literature for a number of radionuclides and terrestrial organisms. For Cs,
 171 data were supplemented by values presented in Battison et al. (1991) and Gaare and Staaland
 172 (1994). Observed $T_{B1/2}$ values from these sources for Cs, I, Sr and Co are given Table 1. The
 173 $T_{B1/2}$ values are for the long component of loss, consistent with the allometric $T_{B1/2}$
 174 relationships suggested for use in environmental assessment models (USDOE 2002).

175 Nagy (2001) fitted allometric relationships to predict dry matter intake rates of terrestrial
 176 vertebrates presenting these on the basis of, for example, taxonomic grouping or feeding
 177 strategy and a_I values from this source were used here. Reflecting the species for which $T_{B1/2}$

178 data are available, the a_I values from Nagy (2001)¹ were used for ‘all mammals’ ($a_I=0.057 \text{ d}^{-1}$
179 $\text{kg}^{0.25}$), carnivorous mammals ($a_I=0.027 \text{ d}^{-1} \text{ kg}^{0.25}$) and herbivorous mammals ($a_I=0.15 \text{ d}^{-1}$
180 $\text{kg}^{0.25}$); the a_I value for rodents ($a_I=0.059 \text{ d}^{-1} \text{ kg}^{0.25}$) is similar to that of ‘all mammals’.
181 Estimates of f_I have been taken from IAEA (2010) which cites values from ICRP (2006) for
182 monogastric animals and additionally presents f_I for ruminants.

183 To estimate values of $CR_{org-diet}$ $CR_{meat-diet}$ values presented by IAEA (2010) were used which
184 relate the fresh weight activity concentration in meat (i.e. muscle) to the dry matter activity
185 concentration in the diet of farm animals (Table 1). Whilst IAEA (2010) presents these
186 parameter values for Co, Cs and I, it does not include a $CR_{meat-diet}$ value for Sr. Dietary
187 transfer coefficients (i.e. the ratio of the activity concentration of Sr in meat to the daily
188 intake of Sr) presented in IAEA (2010) have been used together with typical dry matter
189 intake rates from IAEA (1994) to estimate the average $CR_{org-diet}$ across all five species for
190 which data are available (cattle, goat, sheep, poultry and pig) in IAEA (2010) (Table 1).

191 Yankovich et al. (2010) present tissue to wholebody radionuclide activity concentration
192 conversion factors for a range of wildlife groups which could be used to derive wholebody
193 $CR_{org-diet}$ estimates from $CR_{meat-diet}$ values. However, Cs is the only element of interest here for
194 which Yankovich et al. (2010) report a conversion factor for mammals. Therefore, for Sr and
195 Co, conversion factors were estimated using data presented in Barnett et al. (2013) for wood
196 mice and roe deer; a conversion factor for I has been estimated from information presented in
197 Coughtrey et al. (1983) (Table 1).

198

199 **Results and Discussion**

200

201 The a_I for ‘all mammals’ was used to predict $T_{B1/2}$ values for all available comparisons (Table
202 2). All predictions were within an order of magnitude of the observed values with most being
203 within a factor of three. This can be considered to be satisfactory, given that the allometric
204 models are designed to give a broad approximation rather than an exact value. For Cs and I
205 there is a tendency to under-predict, whereas for Co all estimates are over-predictions. If the
206 a_I suggested for carnivorous mammals by Nagy (2001) is used there is a marked
207 improvement in predictions for Cs and I for carnivorous species (Table 2). However, if the a_I

¹ Nagy (2001) presents relationships based upon mass in units of grammes, we have converted these to kilogrammes

208 applicable to herbivorous mammals is applied, then the predictions for the relatively few
209 herbivores for which there were data are underestimated with the exception of the estimates
210 for Co in laboratory rabbit, and Sr in mule deer (Table 2).

211 A linear regression of $T_{B1/2}$ values predicted using a_I values appropriate to the feeding type of
212 each species with the measured data (from Table 2) yields an R^2 value of 0.58 with a slope of
213 1.4 and an intercept which is not significantly different from zero ($p < 0.001$).

214 As both mule deer and reindeer are ruminants, predictions for these animals were also made
215 using the ruminant specific f_I values from (IAEA 2010) of 0.8 and 0.11 for Cs and Sr
216 respectively. This made little difference to the predictions for Cs (an increase by 25 %) but in
217 the case of mule deer the Sr $T_{B1/2}$ predicted using the herbivorous mammal a_I and ruminant f_I
218 values was 1,000 days compared with the observed value of 228 days.

219 Our ability to obtain reasonable predictions is in part dependent upon the quality of data
220 available for the required input parameters. For many elements in IAEA (2010), $CR_{\text{meat-diet}}$ are
221 based upon few observations (e.g. I is based upon six studies and Co on three) and the value
222 for Sr had to be estimated as described above. Similarly, the correction factors to convert
223 from $CR_{\text{meat-diet}}$ to $CR_{\text{org-diet}}$ are based on relatively few data as exemplified by the need to
224 derive them for Co, I and Sr. Investigation of the data used by Nagy (2001) to derive the
225 allometric dry matter intake relationship for herbivores shows that they are dominated by
226 relatively small species with many of the larger species being marsupials.

227 It should also be acknowledged that the dry matter intake relationships presented by Nagy
228 (2001) are for animals under field and not laboratory conditions and that field metabolic rates
229 are generally higher than basal metabolic rates determined for housed animals (Nagy 2005).
230 This may result in a tendency to under-prediction of $T_{B1/2}$ for housed (i.e. experimental)
231 animals as was observed for Cs and I (Table 2).

232 An assumption of the approach developed here is that $T_{B1/2}$ scales to the power of 0.25. Of the
233 allometric expressions derived for $T_{B1/2}$ for 16 radionuclides by USDOE this is true for eight
234 (Cs, Co, Ra, Sb, Sr, U, Zn and Zr). The mass scaling functions for I and H reported by
235 USDOE are 0.55 and 0.13 respectively. However, other sources suggest that the scaling
236 function for the $T_{B1/2}$ for these two radionuclides should be *circa* 0.25 (Galeriu et al. 2003;
237 MacDonald 1996).

238 For five elements in USDOE (2002) (Am, Ce, Eu, Pu and Th) biological half-life scales to
239 the power of 0.8. For all of these ICRP Publication 30 (ICRP 1979; 1981; 1988) is quoted as

240 the data source but unfortunately it not possible to find the data within this publication to
241 independently verify the allometric equations presented by USDOE (2002). None of these
242 elements play an active biological role and hence it could perhaps be suggested that there is
243 no reason for them to follow a metabolically driven uptake process (i.e. as signified by a mass
244 scaling function of 0.25). However, it is noted that some of the elements which do scale as
245 mass to the power of 0.25 are not essential elements either (e.g. U). The assumption that
246 $CR_{org-diet}$ is independent of mass for any elements for which $T_{B1/2}$ is proven to not scale
247 allometrically with a value approximating to 0.25 will be invalid (i.e. see Eq. 9). Therefore, it
248 is recommended that the reasons for the deviation of some elements from the mass scaling
249 function of 0.25 be explored and/or the relationships presented by USDOE (2002) be
250 independently verified.

251 It should be acknowledged that there is considerable debate with regard to the numerical
252 values for the allometric exponent, in particular whether it should be 0.75 or perhaps 0.67 for
253 basal metabolic rate (e.g. West et al. 1997; Hoppeler and Weibel 2005; Isaac and Carbone
254 2010; Agutter and Tuszynski 2011). It has also been suggested that the scaling exponent may
255 itself be dependent upon body mass (Savage et al. 2008). In discussing this issue with respect
256 to radioecological models, Higley and Bytwerk (2007) suggested that given other
257 uncertainties in radioecological modelling, the exact value of the allometric scaling exponent
258 ‘may not be of critical importance’ for practical (rather than theoretical) purposes, and this
259 suggestion is supported here.

260

261 **Conclusions**

262

263 Based upon the above evaluation, Eq. 12 could be applied to make predictions of $T_{B1/2}$ values
264 for application in wildlife assessment models expanding upon the limited range of
265 radionuclides for which allometric $T_{B1/2}$ equations are currently available (USDOE 2002).
266 The approach presented requires that values of $CR_{org-diet}$ and f_1 are available for the
267 radionuclide of interest. These parameters are presented in, or can be estimated from, existing
268 compilations for many radionuclides (e.g. IAEA 2010); a basic premise of the suggested
269 model is that the two parameters are not species specific. However, reasons why some
270 radionuclides deviate from what would be anticipated from Kleiber’s law (see Eq. 5) need to

271 be determined to enable more complete exploitation of the potential of allometric
272 extrapolation within radioecological models.

273 The current assumption of a single long-component of loss in some wildlife assessment
274 models (e.g. USDOE 2002; Avila et al. 2004) should yield estimates of the equilibrium
275 activity concentration in organism which are conservative (i.e. they should be overestimated
276 compared to a model assuming more than one loss component). However, if used in dynamic
277 models this assumption will predict slower changes in organism activity concentrations than
278 would be observed in reality as a result of changes in activity concentrations in environmental
279 media. Theoretically it is possible to generalise an expression to suggest that both the short
280 and long-term biological half-lives have an allometric exponent of 0.25 although this requires
281 validation with suitable data.

282 Although not tested here it is recommend that the application of Eq. 12 to make
283 approximations of $T_{B1/2}$ for edible tissues of farm animals, a relatively poorly studied
284 parameter for many radionuclides, be tested against available data.

285

286

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291

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398 **Table 1** Values used to parameterise Eq. 12; conversion factor is defined as ratio of the fresh
399 mass wholebody activity concentration to that of muscle (meat) (Barnett et al. 2013;
400 Coughtrey et al. 1983; IAEA 1994, 2010; Yankovich et al. 2010).

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Element	f_i	$CR_{meat-diet}$	Conversion factor	$CR_{org-diet}$
Co	0.1	3.1×10^{-1}	3	9.3×10^{-1}
Cs	1	3.9×10^{-1}	1	3.9×10^{-1}
I	1	9.4×10^{-2}	5	4.7×10^{-1}
Sr	0.3	2.2×10^{-2}	400	8.9

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Table 2 Comparison of reported $T_{B1/2}$ values with estimates from Eq. 12 assuming different a_I values.

Speices	Mass (kg)	$T_{B1/2}$ reported	Predicted $T_{B1/2}$ using a_I for:			Reference ID
			All mammals	Carnivores	Herbivores	
<i>Radiocaesium</i>						
Harvest mouse	1.0×10^{-2}	3.7	1.5			1
Laboratory mouse	2.0×10^{-2}	5.1	1.8			1
Whitefooted mouse	2.1×10^{-2}	3.5	1.8			1
Cotton rat	1.3×10^{-1}	8.4	2.8			1
Laboratory rat	1.9×10^{-1}	6.3	3.1			1
Rabbit	1.6	11	5.3		2.0	2
Arctic fox	4.9	17.5	7	15		3
Silver fox	5.3	25.3	7.1	15		3
Coyote	9.5	26	8.3	17		3
Red fox	10	29	8.4	18		1
Coyote	12	22	8.7	18		3
Dog	19	28	9.8	21		1
Wolf	31	23	11	24		3
Mule deer	55	14	13		4.8	1
Reindeer	80	14	14		5.3	1
<i>Radiocobalt</i>						
Whitefooted mouse	2.0×10^{-2}	5.2	42			1
Laboratory mouse	2.5×10^{-2}	4.8	45			1
Laboratory rat	4.0×10^{-1}	11	89			1
Guinea pig	4.7×10^{-1}	21	93			1
Laboratory rabbit	3.0	13	148		56	1
<i>Radioiodine</i>						
Laboratory mouse	2.1×10^{-2}	5.2	2.2			1
Cotton rat	1.1×10^{-1}	8	3.3			1
Laboratory rat	2.1×10^{-1}	2.5	3.8			1
Guinea pig	5.0×10^{-1}	26	4.8			1
Jack rabbit	1.9	5	6.7		2.5	1
Laboratory rabbit	3.7	13	7.9		3.0	1
Dog	12	17	10	22		
<i>Radiostrontium</i>						
Laboratory mouse	3.0×10^{-2}	43	140			1
Laboratory Rat	2.0×10^{-1}	590	240			1
Dog	1	530	640	1,300		1
Mule deer	65	190	1,000		380	1

407 References: (1) Whicker and Shultz (1982); (2) Battiston et al. (1991); (3) Gaare and Staalnd (1994).

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