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1 **Temperature-independent telomere lengthening with age in the**
2 **long-lived human fish (*Proteus anguinus*)**

3
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14 **Keywords:** Blind cave salamander, longevity, telomere

15 **ABSTRACT**

16 Despite number of studies showing negative relationship between age and telomere length,
17 the universality of this pattern has been recently challenged mainly in ectothermic animals
18 exhibiting diverse effect of age on telomere shortening. However, data on ectotherms may be
19 strongly affected by thermal history of the individuals. We thus investigated the age-related
20 changes in relative telomere length in the skin of a small but long-lived amphibian living
21 naturally in stable thermal environment over its entire life allowing the comparison with other
22 homeotherms animals like birds and mammals. The present data showed a positive relation
23 between telomere length and individual age, independent of sex and body size. A segmented
24 analysis highlighted a breakpoint in the telomere length-age relationship, suggesting that
25 telomere length reached a plateau at the age of 25 years. Further studies focusing on the
26 biology of animals that live much longer than expected based on body mass will contribute to
27 our better understanding of how ageing processes evolved and may also bring innovation for
28 extend human health span.

29

30 **INTRODUCTION**

31 The DNA repairing machinery of the cell maintains genomic integrity notably *via* the
32 recognition and reparation of DNA breaks (1). Eukaryotic telomeres, by their ability to form a
33 t-loop structure with associated proteins, are the structure allowing to distinguish the ends of
34 linear chromosomes from DNA breaks, and thus to avoid unnecessary emergency cell
35 responses (2). In the absence of active enzymatic reset by telomerase (3), telomere ends
36 inevitably erode over time in the adult soma (4), at a rate that can be accelerated by all kind of
37 stressors (5), which ultimately lead to cell senescence (6).

38 The extensive effort in studying telomere dynamics in birds and mammals confirmed, except
39 in rare cases, the age-related shortening of telomeres, and its negative link with individual
40 lifespan (e.g. 7, 8, 9). Still, telomere changes with age are supposed to be completely different
41 in ectotherms, which are animals that grow continuously and generally preserve their
42 telomerase activity in somatic cells over life (e.g. 10). Surprisingly, change in telomere length
43 with age in ectotherms was shown to be diverse, with either continuous shortening or no
44 differences between young and old individuals (11, reviewed in 12) sometimes with marked
45 sex-differences (11, 13). Such variability among ectotherm species may be attributed to intra-
46 sex differential investment in reproduction (11) but also to environmental temperature that
47 drive ectotherms' metabolism, growth and even ageing rates (14, 15). The thermal
48 performance curves, which reflect both how environmental temperatures affected individual
49 traits like early development and present performances, have been recently suggested as a key
50 framework to understand ectotherm telomere dynamics within and between species (16). Up-
51 to-date, telomere dynamics with age in ectotherm models maintained in a stable thermal
52 environment during the entire life has never been studied.

53 The olm salamander *Proteus anguinus* is an outstanding animal model to address the telomere
54 and ageing question. This animal is called “human fish” due to its extreme longevity (mean
55 and maximum lifespan estimated to 68 and more than 100 years respectively) for its body
56 mass (> 20 g) and neither the study of its basal metabolic rate or of its antioxidant capacities
57 shed lights on the nature of the mechanisms sustaining such an exceptional long life (17, 18).
58 In addition, the olm is the only obligate cave dwelling vertebrate in Europe (19), and thus live
59 in a stable thermal environment over its entire life allowing the comparison with other
60 homeotherms animals like birds and mammals without the potential confounding effect of
61 temperature variation.

62 Taking advantage of a nearly 70 years breeding program of the olm, we investigated the age-
63 related changes in relative telomere length (RTL, obtained via qPCR, see below) in a sub-
64 population of 41 individuals. This breeding program conducted in a natural cave in Moulis
65 (France) provides available living individuals kept in the dark in a controlled-temperature
66 facility (12°C) and information on their development and life cycle in a natural environment.

67

68 **MATERIALS AND METHODS**

69 - Studied species and individuals

70 All animals (n = 41) came from the Moulis captive population that is the only successful
71 programme allowing to study of the biology of this amphibian. The founder individuals of the
72 population came from successive imports from the Piuka cave river near the town of Planina
73 in Slovenia (20, 21). Reproductions has been observed since 1959 (21) with animals fed with
74 chironomid larvae ('blood worms') once a week and the aquaria kept in the dark in a
75 controlled-temperature facility (12°C). Individuals used in this study were found newly and
76 naturally dead (with yet no sign of decomposition) from 2003 to 2011. Their snout-vent
77 length (SVL) was measured (± 1 mm) for 29 individuals, which were then fixed by
78 submersion in ethanol 70°. Our sampled population was composed of 41 individuals, 17
79 males, 12 females and 12 with undetermined sex, but all with known age at death (from 4 to
80 40 years-old). No ethical authorization was needed to obtain samples.

81 - DNA extraction and PCR procedures

82 Relative telomere length (RTL) was evaluated using the qPCR methodology (22), based on
83 DNA extraction obtained from skin samples. The tissue samples (of approximately 20mg)
84 were introduced into an Eppendorf tube and mixed into 200 μ l of 10% Chelex-100 resin
85 solution. 10 μ l of proteinase K (Boehringer Mannheim) at 15 mg/ml is added to the solution
86 which is then incubated at 55° C for an hour while being shaken. The mixture is then

87 incubated further at a temperature of 90°C for 15 minutes to increase the extent of protein
88 denaturation. The tubes containing the extracted DNA and the Chelex resin, together with the
89 degraded proteins, were stored at 4° C or at -20°C. Before its use, the mixture was shaken in a
90 vortex mixer and centrifuged at 10,000 rpm for ten seconds to deposit the mass formed by the
91 resin and the proteins, and then stored at -20°C. In order to purify the gDNA, NucleoSpin
92 gDNAClean –up kits were used (Macherey Nagel, Duren Germany) and DNA quantification
93 was determined by Fluorescence (QuantiFluor® ONE dsDNA System, Promega, Madison,
94 WI, USA). Two µl of supernatant are used for each 10 µl of final volume of the PCR reaction
95 mixture. DNA quality was checked for solvents presence using a NanoDrop 1000
96 (ThermoFisher Scientific, Waltham, MA, USA) spectrophotometer (absorbance ratio
97 A260/280; A260/230) and for DNA degradation using gel migration. Two different
98 sequences of genomic DNA were amplified to obtain both a control signal accounting for
99 variation in DNA quantity (Recombinase Activity Protein 1 gene (RAG1, 287 bp, NCBI
100 number EF107303.1) and of the telomeric sequences. Forward and reverse primers were 5'-
101 CCA GGC TAT CAC CCC TTT GA - 3' and 5'- TCG CTT ACA TCT CCC ATC CC - 3' for
102 the RAG1 gene and 5'- CGG TTT GTT TGG GTT TGG GTT TGG GTT TGG GTT TGG -
103 3' and 5'- GGC TTG CCT TAC CCT TAC CCT TAC CCT TAC CCT TAC CCT - 3' for the
104 telomeric sequence. Amplifications were conducted in one plate, using one distinct control
105 gene and telomere run. qPCR conditions were 2 min at 95°C followed by 40 cycles of 15 s at
106 95°C, 30 s at 60°C and 30 sec at 72°C, or of 2 min at 95°C followed by 30 cycles of 15 s at
107 95°C, 30 s at 60°C and 30 sec at 72°C, for the control gene and telomere amplifications,
108 respectively. Reactions were done in a master mix prepared for each primer set, with 5 µL
109 GoTaq QPCR Mix (Promega, Madison, WI, USA). We used 2 ng of DNA and the telomere
110 primers at a concentration of 200 nM and the control gene primers at 7.5 nM (for a final
111 reaction volume of 10 µL in each well). All samples were run in duplicates and intra-

112 individual repeatability of RTL, evaluated using the Intra Class Coefficient (23), was of
113 0,973.

114 - Statistics

115 Statistics were done using R version 3.5.1. RTL were log transformed to obtain a normal
116 distribution of our response variable and standardized (z scores). Normality was checked
117 using the quantile – quantile function *qqnorm* both on the RTL values and model residuals
118 distributions. We investigated if RTL was related to age at death, using a Linear model with a
119 quadratic Age^2 term to control for non-linear age-related variation in ectotherms (24) and
120 controlling for sex effects. Before calculating the Age^2 variable, Age was initially scaled to
121 avoid collinearity (25), further checked using the *vif* function (“car” R package). Also,
122 because the olm salamander is an indeterminate growing organism (see results), and that
123 telomere length and growth are suspected to be interconnected (26), the individual SVL as
124 body size measurement was initially added as a fixed factor. This reduced our sample size to
125 29 individuals, including 17 males and 12 females. Duration of sample storage (range: 9-17
126 years) was also included in our model as a fixed factor (and not random factor as it did not
127 follow a Normal distribution). Our full model was therefore: $RTL \sim Age^2 + Age + Sex +$
128 $SVL + storage\ duration$. Selection of the best model was done using the *Mumin* R function,
129 based on AIC criterion. The selection was adapted to conserve the *Age* variable we were
130 interested in, and no more than 4 final variables given our sample size, and consequently
131 without including interaction terms. We choose the most complete model within a AIC
132 difference of 2 (excluding Age^2 did not change the results, see ESM). Age breaking points in
133 telomere length change over time was assessed using the *Segmented* R package, calculating
134 breakpoints in the slope of the RTL - Age relationships (27). Since our data were cross-
135 sectional (non-repeated individuals over age), we tested for selective disappearance of
136 individuals with short telomeres at adult age in two ways. First by evaluating the effect size of

137 the differences in RTL between young (<17 years) and adult individuals using the Cohen-d
138 value (“lsr” R package) and, second, by testing differences in variance among young (4-10
139 years and 11-16 years) and adults (17-30 years and 31-40 years) groups (“DescTools” R
140 package, Kruskal-Wallis test) [see (18) for data on age at sexual maturity]. $P \leq 0.05$ was
141 considered significant and effect size interpreted following Cohen (28).

142

143 **RESULTS**

144 Table 1 presents the output of the generalized linear model testing for change of RTL with
145 age at death in the olm. We found a significant and positive effect of age at death on RTL,
146 independent of sex (even if males tended to have shorter RTL) and body size (also negative
147 tendency). We also found a negative effect of storage duration on RTL values. There was no
148 indication of a quadratic relationship of RTL with age at death. However, segmented analysis
149 highlighted a breakpoint in the RTL-age relationship, suggesting that RTL reached a plateau
150 at the age of 25 years (Figure 1). Body size (SVL, 134.2 ± 4.9 mm, mean \pm S.E.M.) was found
151 to increase over age following a significant quadratic interaction with sex (GLM, Age² x sex,
152 $F_{1,24} = 14.4$, $P < 0.001$), males growing faster than females.

153 The significant increase in RTL with age at death could be due to the selective disappearance
154 of individuals with short telomeres. However, Cohen’s d effect sizes between young (<17
155 years old) and adults was of 0.312 [by convention small to medium effect (28)] and even
156 smaller when calculated from the residuals of RTL with storage duration ($d = 0.173$).

157 Variances among age at death categories were not found to be significantly different among
158 young and adult age categories (Chi-square = 3, $P = 0.392$), despite a visual tendency to
159 decrease from early-life young stage (4-10 years, var = 2.27) to the other life stages (young
160 10-16 years, 0.19; adults 17-30, 0.82; adults 31-40, 0.53).

161

162 **DISCUSSION**

163 Telomere length is commonly expected to decline with age. However, because initially most
164 studies focused on mammals and birds (29), it rapidly called into question the universality of
165 the observed patterns and proposed hypotheses. Evidences soon accumulated showed that
166 there is no single, universal pattern of telomere erosion even in endotherms (e.g. 30) but more
167 evidently in ectotherms (e.g. 31). Thus, in order to better understand ongoing selection and
168 evolution of telomeres and telomere-regulating processes, a larger panel of non-model
169 organisms presenting unusual telomere dynamics needed to be incorporated, as they lend
170 themselves better to research direct links between telomere traits and components of fitness.
171 According to the present data, the olm joins the few species exhibiting positive relationship
172 between RTL and age. Even if such positive correlation has been considered as an artefact of
173 measurement error (32), increasing arguments (both theoretical and empirical) plead for
174 considering it to be a real biological phenomenon (33, 34). Even if we cannot exclude a
175 simple TL elongation with no effect on mortality whatsoever, two hypotheses could explain
176 the present results: the "selection hypothesis" stating that the longest-lived individuals start
177 with the longest telomeres and variation in telomere length decreases with age due to the
178 selective disappearance of individuals with short telomeres. Alternatively, the "elongation
179 hypothesis" relies on the idea that the longest-lived individuals are those able to lengthen
180 telomeres with age, perhaps, due to the higher levels of telomeres maintenance pathway.
181 Since no age effect on variance has been detected, our data plead for the "elongation
182 hypothesis" but the assessment of both individual telomere dynamics and of the telomerase
183 activity would be necessary to confirm it.

184 Previous studies found that slightly negative or even positive telomere rates of change
185 (TROC) were positively linked with maximum lifespan (9) and also associated with the

186 species pace of life (*i.e.* slow-living species loose less (or even gain) telomeres per unit of
187 time than fast-living species) (35, 36, 37). Our TROC estimate is not directly comparable with
188 previously published values (ours is obtained using qPCR measurements, not in bp of
189 telomere DNA lost per year). Still, our results are in congruence with these findings since we
190 found that the very slow pace of life of *P. anguinus* is associated with a slightly positive
191 TROC estimate (see Table 1). While being not obviously hypometabolic (38), the olm can
192 dramatically reduce movements and metabolic rate during food scarcity (39), and could
193 survive years without eating (40). The free radical generation is probably at low enough levels
194 (17), enabling this species to accumulate very little oxidative damage over its life span. A
195 longitudinal study of individuals is needed to confirm our interpretation of cross-sectional
196 data, and would allow for an exploration of how the complex telomere maintenance process
197 (41, 42) explain the presently described positive telomere dynamics in this species.

198 Interestingly, *P. anguinus* seem to belong to those long-lived organisms that live much longer
199 than expected based on body mass (18) and exhibit telomere lengthening or no change with
200 age (43, 44). The extreme longevity of those types of organisms is partly explained by their
201 ecological niche or by their physical aptitude which reduces the predation risk and avoid
202 adverse conditions (45, 46, 47). In parallel, increased or unchanged RTL with age could be a
203 signature of small and long-lived species. In fact, if long telomeres protect from cell
204 senescence and a stable somatic telomerase activity help to sustain high metabolic costs, the
205 overuse of telomere maintenance processes may be paid as increased cell immortalization
206 risks. Consequently, small and long-lived rodents have evolved specific anti-cancer
207 mechanisms (48). Whether this is the case of the olm remains an open question.

208 With a significant increase of TL length with age in a stable thermal environment, the present
209 data confirm more complex telomere dynamics than a simple decline with age throughout life
210 in vertebrates. Studying the biology of long-lived animals staying healthy and capable of

211 reproduction until death will contribute to our better understanding of how ageing processes
212 evolved in response to environmental factors (49). It may also lead to novel interventions that
213 extend human health span. Further studies focused on others small and long-lived ectotherms
214 like some rockfishes' species or the red sea urchin are of prime importance to fully decipher
215 interaction between body size, longevity and telomere dynamic.

216 **Data accessibility**

217 The data for this study have been deposited on Dryad under the following DOI:
218 doi:10.5061/dryad.1jwstqk0c (50) and are directly accessible via the following weblink:
219 <https://datadryad.org/stash/share/EcPEv3jwqMg0sHyo726uASDIZhlpSptjoBWESdkqgHs>.

220 **Author contribution**

221 YV established the study design, AD conducted DNA extraction, SZ established and
222 conducted the qPCR measurements on Proteus samples, FC analyzed the data. YV, GO & FC
223 co-wrote the manuscript, with input from AD and SZ.

224 **Competing interest statement**

225 The authors declare having no competing interests

226 **References**

- 227 1. Lombard DB, Chua KF, Mostoslavsky R, Franco S, Gostissa M, Alt FW. 2005 DNA
228 Repair, Genome Stability, and Aging. *Cell*, **120**, 497-512,
229 doi.org/10.1016/j.cell.2005.01.028.
- 230 2. Sfeir A, de Lange T. 2012 Removal of shelterin reveals the telomere end-protection
231 problem. *Science*. **336**, 593-597. doi: 10.1126/science.1218498.
- 232 3. Blackburn EH. 2005 Telomeres and telomerase: their mechanisms of action and the
233 effects of altering their functions. *FEBS Letters*. **579**, 859-62.
234 doi:10.1016/j.febslet.2004.11.036.
- 235 4. Harley CB, Futcher AB, Greider CW. 1990 Telomeres shorten during ageing of
236 human fibroblasts. *Nature*. **345**, 458-60. doi: 10.1038/345458a0.
- 237 5. Chatelain M, Drobniak SM, Szulkin M. 2020 The association between stressors and
238 telomeres in non-human vertebrates: a meta-analysis. *Ecology Letters*. **23**, 381-398.
239 doi: 10.1111/ele.13426.
- 240 6. Blackburn EH. (2000). Telomere states and cell fates. *Nature*, **408**, 53-56.
241 doi.org/10.1038/35040500.
- 242 7. Boonekamp JJ, Mulder GA, Salomons HM, Dijkstra C Verhulst S. 2014 Nestling
243 telomere shortening, but not telomere length, reflects developmental stress and
244 predicts survival in wild birds. *Proceedings of the Royal Society B*, **281**, 20133287.
245 doi: 10.1098/rspb.2013.3287.
- 246 8. Heidinger BJ, Blount JD, Boner W, Griffiths K, Metcalfe NB, Monaghan P. 2012
247 Telomere length in early life predicts lifespan. *Proceedings of National Academy of*
248 *Sciences USA*. **109**, 1743-1748. doi: 10.1073/pnas.1113306109.
- 249 9. Tricola GM, Simons MJP, Atema E, Boughton RK, Brown JL, Dearborn DC, Divoky
250 G, Eimes JA, Huntington CE, Kitaysky AS, Juola FA, Lank DB, Litwa HP, Mulder

- 251 EGA, Nisbet ICT, Okanoya K, Safran RJ, Schoech SJ, Schreiber EA, Thompson PM,
252 Verhulst S, Wheelwright NT, Winkler DW, Young R, Vleck CM, Haussmann MF.
253 2018 The rate of telomere loss is related to maximum lifespan in birds. *Philosophical*
254 *Transactions of the Royal Society B*. **373**, 20160445. doi: 10.1098/rstb.2016.0445.
- 255 10. Klapper W, Heidorn K, Kühne K, Parwaresch R, Krupp G. 1998 Telomerase activity
256 in 'immortal' fish. *FEBS Letters*. **434**, 409-412. doi: 10.1016/s0014-5793(98)01020-5.
- 257 11. Rollings N, Friesen CR, Sudyka J, Whittington CM, Giraudeau M, Wilson M, Olsson
258 M. 2017 Telomere dynamics in a lizard with morph-specific reproductive investment
259 and self-maintenance. *Ecology and Evolution*. **7**, 5163-5169. doi: 10.1002/ece3.2712.
- 260 12. Olsson M, Wapstra E, Friesen C. 2018 Ectothermic telomeres: it's time they came in
261 from the cold. *Philosophical Transactions of the Royal Society B*, **373**, 20160449.
262 <http://dx.doi.org/10.1098/rstb.2016.044>
- 263 13. Olsson M, Pauliny A, Wapstra E, Uller T, Schwartz T, Miller E, Blomqvist D. 2011
264 Sexual differences in telomere selection in the wild. *Molecular Ecology*, **20**, 2085-
265 2099. doi:10.1111/j.1365-294X.2011.05085.x.
- 266 14. Lee WS, Monaghan P, Metcalfe NB. 2012 Experimental demonstration of the growth
267 rate--lifespan trade-off. *Proc Biol Sci*. **12**, 28020122370. doi: 10.1098/rspb.2012.2370.
- 268 15. Reinke BA, Cayuela H, Janzen FJ, Lemaître JF, Gaillard JM, Lawing AM, Iverson JB,
269 Christiansen DG, Martínez-Solano I, Sánchez-Montes G, Gutiérrez-Rodríguez J. Rose
270 FL,Miller DAW. 2022. Diverse aging rates in ectothermic tetrapods provide
271 insights for the evolution of aging and longevity. *Science*, **24**, 376, 1459-1466. doi:
272 10.1126/science.abm0151.
- 273 16. Friesen CR, Wapstra E, Olsson M. 2021 Of telomeres and temperature: Measuring
274 thermal effects on telomeres in ectothermic animals. *Molecular Ecology*,
275 doi:10.1111/mec.16154

- 276 17. Issartel J, Hervant F, DeFraipont M, Clobert J, Voituron Y. 2009 High anoxia
277 tolerance in the subterranean salamander *Proteus anguinus* without oxidative stress nor
278 activation of antioxidant defenses during reoxygenation. *Journal of Comparative*
279 *Physiology B*, **179**, 543-551. doi: 10.1007/s00360-008-0338-9.
- 280 18. Voituron Y, DeFraipont M, Issartel J, Guillaume O, Clobert J. 2011 Extreme lifespan
281 of the human fish (*Proteus anguinus*): a challenge for ageing mechanisms. *Biology*
282 *Letters*, **7**, 105-107. doi: 10.1098/rsbl.2010.0539.
- 283 19. Bulog, B. 1994. Two decades of functional-morphological studies of *Proteus*
284 *anguinus* (Amphibia, Caudata). *Acta Carsologica* **19**, 247–263.
- 285 20. Vandel A, Bouillon M. 1954 Le protéé et son intérêt biologique. *Annales de*
286 *Spéléologie*, **14**:111–127.
- 287 21. Juberthie C. 1991 Service d'élevage des Protées Laboratoire souterrain du C.N.R.S.
288 *Mémoires de Biospéologie*. **18**, 315–318.
- 289 22. Cawthon RM. 2009 Telomere length measurement by a novel monochrome multiplex
290 quantitative PCR method. *Nucleic Acids Research*. **37**: e21. doi: 10.1093/nar/gkn1027.
- 291 23. Eastwood JR, Mulder E, Verhulst S, Peters A. 2018 Increasing the accuracy and
292 precision of relative telomere length estimates by RT qPCR. *Mol Ecol Resour.* 18, 68-
293 78. doi: 10.1111/1755-0998.12711.
- 294 24. Ujvari B, Biro PA, Charters JE, Brown G, Heasman K, Beckmann C, Madsen, T.
295 2016. Curvilinear telomere length dynamics in a squamate reptile. *Functional*
296 *Ecology*, **31**, 753-759, doi:10.1111/1365-2435.12764
- 297 25. Schielzeth H. 2010 Simple means to improve the interpretability of regression
298 coefficients. *Methods in Ecology and Evolution*, **1**, 103-113. doi.org/10.1111/j.2041-
299 210X.2010.00012.x

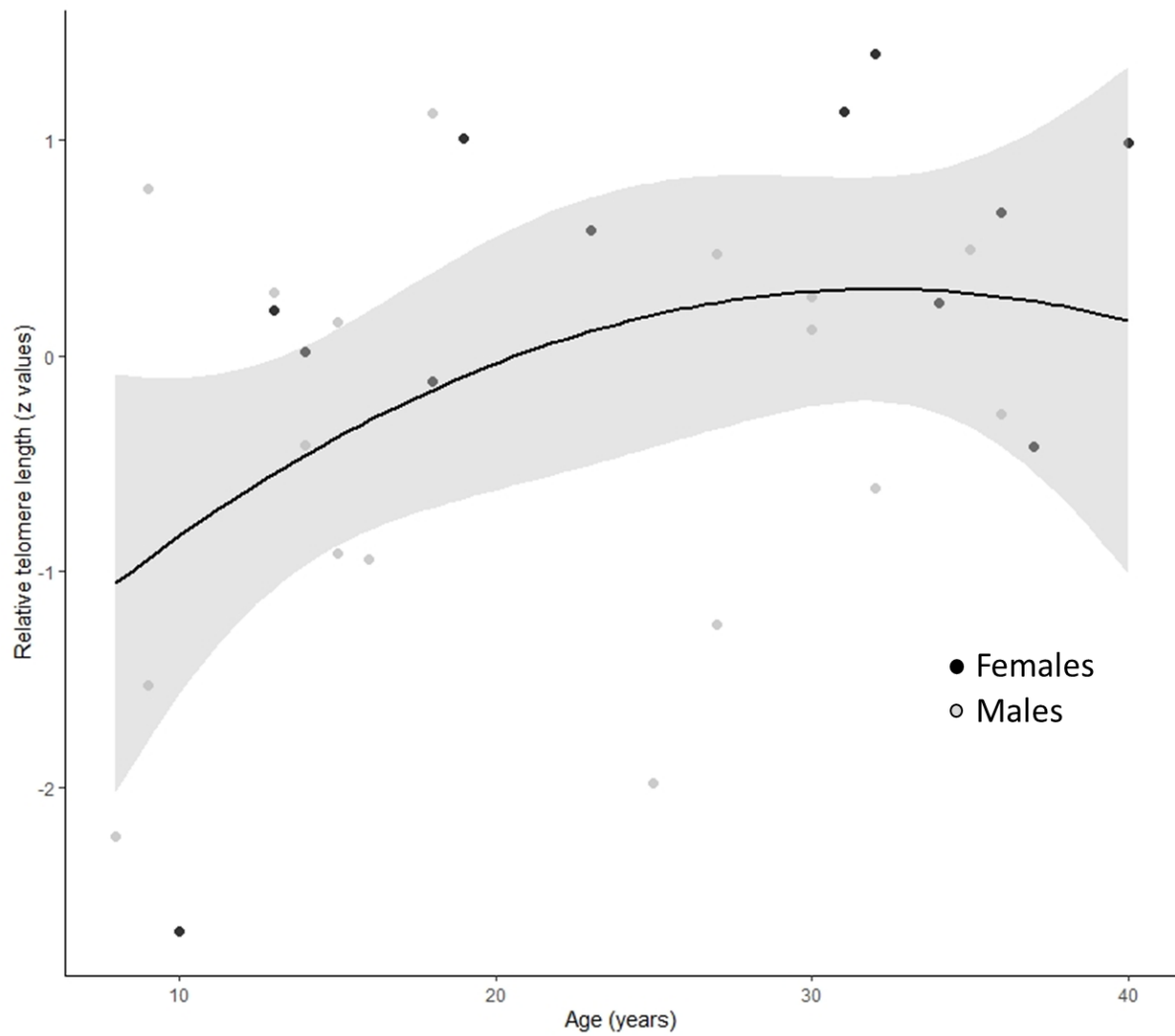
- 300 26. Monaghan P, Ozanne SE. 2018 Somatic growth and telomere dynamics in vertebrates:
301 relationships, mechanisms and consequences. *Philosophical Transactions of the Royal*
302 *Society B: Biological Sciences*. **373**, 20160446. doi:10.1098/rstb.2016.0446
- 303 27. Muggeo VMR. 2017 Interval estimation for the breakpoint in segmented regression: a
304 smoothed score-based approach. *Australian & New Zealand Journal of Statistics*. **59**,
305 311-322. doi.org/10.1111/anzs.12200
- 306 28. Cohen J. 1992 Quantitative methods in psychology: A power primer. *Psychological*
307 *bulletin*, **112**,155-159.
- 308 29. Remot F, Ronget V, Froy H Rey B, Gaillard JM, Nussey DH, Lemaitre JF. 2021
309 Decline in telomere length with increasing age across nonhuman vertebrates: A
310 meta- analysis. *Molecular Ecology*, doi: 10.1111/mec.16145.
- 311 30. Hoelzl F, Smith S, Cornils JS, Aydinonat D, Bieber C, Ruf T. 2016 Telomeres are
312 elongated in older individuals in a hibernating rodent, the edible dormouse (*Glis glis*).
313 *Scientific Reports*, **6**, 36856. doi:10.1038/srep36856.
- 314 31. Olsson M, Wapstra E, Friesen C. 2018. Ectothermic telomeres: it's time they came in
315 from the cold. *Phil. Trans. R. Soc. B*. **373**: 20160449.
316 <http://dx.doi.org/10.1098/rstb.2016.044>
- 317 32. Steenstrup T, Hjelmberg JVB, Kark JD, Christensen K, Aviv A. 2013 The telomere
318 lengthening conundrum – Artifact or biology? *Nucleic Acids Research*. **41**, 1– 7. doi:
319 10.1093/nar/gkt370.
- 320 33. Bateson M, Nettle D. 2017 The telomere lengthening conundrum - it could be biology.
321 *Aging Cell*, **16**, 312-319. doi: 10.1111/accel.12555.
- 322 34. Hoelzl F, Cornils JS, Smith S, Moodley Y, Ruf T. 2016 Telomere dynamics in free-
323 living edible dormice (*Glis glis*): the impact of hibernation and food supply. *The*
324 *Journal of Experimental Biology*, **219**, 2469-2474. doi:10.1242/jeb.140871.

- 325 35. Criscuolo F, Dobson FS, Schull Q. 2021 The influence of phylogeny and life history
326 on telomere lengths and telomere rate of change among bird species: A
327 meta- analysis. *Ecology and Evolution*, **11**, 12908-12922. doi:10.1002/ece3.7931.
- 328 36. Dantzer B, Fletcher QE. 2015 Telomeres shorten more slowly in slow-aging wild
329 animals than in fast-aging ones. *Experimental Gerontology*, **71**, 38-47. doi:
330 10.1016/j.exger.2015.08.012.
- 331 37. Haussmann MF, Winkler DW, O'Reilly KM, Huntington C., Nisbet ICT, Vleck CM.
332 2003 Telomeres shorten more slowly in long-lived birds and mammals than in short-
333 lived ones. *Proceedings of the Royal Society B*, **270**, 1387-1392.
334 doi:10.1098/rspb.2003.2385.
- 335 38. Guillaume O, Deluen M, Raffard A, Calvez O, Trochet A. 2020 Reduction in the
336 metabolic levels due to phenotypic plasticity in the Pyrenean newt, *Calotriton asper*,
337 during cave colonization. *Ecology and Evolution*, **10**, 12983-12989. doi:
338 10.1002/ece3.6882.
- 339 39. Hervant F, Mathieu J, Durand J. 2001 Adaptation to long-term starvation and
340 refeeding in the cave Amphibian *Proteus anguinus*. Comparison with an epigean
341 species, *Euproctus asper*. *Mémoires de Biospéologie (International Journal of*
342 *Subterranean Biology)*, **28**, 93-105.
- 343 40. Gadeau de Kerville, H. 1926 Note sur le Protée anguillard (*Proteus anguinus* Laur.)
344 ayant vécu huit ans sans aucune nourriture. *Bulletin de la Société Zoologique*, **51**, 81-
345 84.
- 346 41. Bettin N, Oss Pegorar C, Cusanelli E. 2019 The Emerging Roles of TERRA in
347 Telomere Maintenance and Genome Stability. *Cells*, **8**, 246. doi:10.3390/cells8030246
- 348 42. Palm W, de Lange T. 2008 How Shelterin Protects Mammalian Telomeres. *Annual*
349 *Review of Genetics*, **42**, 301-334. doi:10.1146/annurev.genet.41.110306.130350.

- 350 43. Foley NM, Hughes GM, Huang Z, Clarke M, Jebb D, Whelan CV, . . . Teeling E.C.
351 2018 Growing old, yet staying young: The role of telomeres in bats' exceptional
352 longevity. *Science Advances*, **4**, eaao0926.
- 353 44. Criscuolo F, Pillay N, Zahn S, Schradin C. 2020 Seasonal variation in telomere
354 dynamics in African striped mice. *Oecologia*, **194**, 609-620. doi:10.1007/s00442-020-
355 04801-x.
- 356 45. Szekely P, Korem Y, Moran U, Mayo A, Alon U. 2015 The Mass-Longevity
357 Triangle: Pareto Optimality and the Geometry of Life-History Trait Space. *PLoS*
358 *Computational Biology*, **11**, e1004524. doi: 10.1371/journal.pcbi.1004524.
- 359 46. Stark G, Tamar K, Itescu Y, Feldman A, Meiri S. 2018 Cold and isolated ectotherms:
360 drivers of reptilian longevity. *Biological Journal of the Linnean Society*, **125**, 730-740.
361 doi.org/10.1093/biolinnean/bly153.
- 362 47. Constant T, Giroud S, Viblanc VA, Tissier ML, Bergeron P, Dobson FS, Hald C.
363 2020 Integrating Mortality Risk and the Adaptiveness of Hibernation. *Frontiers in*
364 *Physiology*, **11**. doi:10.3389/fphys.2020.00706
- 365 48. Tian X, Doerig K, Park R, Can Ran Qin A, Hwang C, Neary A, Gorbunova V. 2018
366 Evolution of telomere maintenance and tumour suppressor mechanisms across
367 mammals. *Philosophical Transactions of the Royal Society B: Biological Sciences*,
368 **373**, 20160443. doi:10.1098/rstb.2016.0443 10.6084/m9
- 369 49. Stenvinkel P, Shiels, PG. 2019 Long-lived animals with negligible senescence: clues
370 for ageing research. *Biochemical Society Transactions*, **47**, 1157-1164. doi:
371 10.1042/BST20190105
- 372 50. Voituron Y 2023 Temperature-independent telomere lengthening with age in the long-
373 lived human fish (*Proteus anguinus*). Dryad, doi:10.5061/dryad.1jwstqk0c
374

375 Figure 1

376 Relative telomere length (z-transformed T/S ratio) of blind cave salamander in relation to age
377 in 41 individuals. Confidence interval (95%) is indicated in grey. Values plotted are the
378 predicted values obtained from the Linear Mixed Model using sample storage duration as a
379 random factor, and sex and body size as cofactors.



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383 Table 1

384 Relationship between relative telomere length (RTL) of individual olms and age (scaled
385 square terms for a quadratic relationship), sex and body size (as the snout-vent length) tested
386 using a Linear Mixed, with Relative telomere length (RTL) as response variable, and Age²,
387 Age and storage duration as fixed factors. RTL is expressed as z-transformed log(T/S ratio).
388 See Methods for the description of the model selection process. Vif values were of 1.05
389 (Age²), 1.02 (Age), 1.06 (storage duration), suggesting no particular collinearity issues (all <
390 5). Observations, 29; R² = 0,347.

Predictors	Estimates	Std Error	CI	F value	P
Intercept	2.32	0.92	0.42 – 4.23	2.51	0.019
Age²	-0.42	0.27	-0.97 – 0.14	1.439	0.242
Age	0.38	0.18	0.02 – 0.76	5.684	0.025
Storage duration	-0.16	0.07	-0.30 – -0.03	6.136	0.020
<i>Observations</i>	29				
<i>R²</i>	0.347				
<i>Adjusted R²</i>	0.268				

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