



HAL
open science

How to measure mitochondrial function in birds using red blood cells: a case study in the king penguin and perspectives in ecology and evolution

Antoine Stier, Caroline Romestaing, Quentin Schull, Emilie Lefol,
Jean-Patrice Robin, Damien Roussel, Pierre Bize

► To cite this version:

Antoine Stier, Caroline Romestaing, Quentin Schull, Emilie Lefol, Jean-Patrice Robin, et al.. How to measure mitochondrial function in birds using red blood cells: a case study in the king penguin and perspectives in ecology and evolution. *Methods in Ecology and Evolution*, 2017, 8 (10), 10.1111/2041-210X.12724 . hal-01487867

HAL Id: hal-01487867

<https://hal.science/hal-01487867v1>

Submitted on 29 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

How to measure mitochondrial function in birds using red blood cells: a case study in the king penguin and perspectives in ecology and evolution

Journal:	<i>Methods in Ecology and Evolution</i>
Manuscript ID	MEE-16-11-875.R1
Manuscript Type:	Research Article
Date Submitted by the Author:	n/a
Complete List of Authors:	<p>Stier, Antoine; University of Glasgow, Institute of Biodiversity, Animal Health and Comparative Medicine; IPHC - CNRS, DEPE Romestaing, Caroline; Laboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés (U.M.R. CNRS 5023), Université Claude Bernard Lyon1, Université de Lyon; Bd du 11 novembre 1918, Bât. Darwin C; 69622 VILLEURBANNE Cedex, France</p> <p>Schull, Quentin; IPHC - CNRS, DEPE</p> <p>Lefol, Emilie; Université de Sherbrooke, Département de biologie; IPHC - CNRS, DEPE</p> <p>Robin, Jean-Patrice; IPHC - CNRS, DEPE</p> <p>Roussel, Damien; Laboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés (U.M.R. CNRS 5023), Université Claude Bernard Lyon1, Université de Lyon; Bd du 11 novembre 1918, Bât. Darwin C; 69622 VILLEURBANNE Cedex, France</p> <p>Bize, Pierre; University of Aberdeen, Institute of Biological and Environmental Sciences</p>
Keywords:	Laboratory methods < Molecular Biology
Abstract:	<p>1. Mitochondria are the powerhouse of animal cells. They produce through oxidative phosphorylation more than 90% of the cellular energy (ATP) required for organism's growth, reproduction and maintenance. Hence, information on mitochondrial function is expected to bring important insights in animal ecology and evolution. Unfortunately, the invasiveness of the procedures required to measure mitochondrial function (e.g. sampling of liver or muscles) has limited its study in wild vertebrate populations so far. Here, we capitalize on the fact that bird red blood cells (RBCs) possess functional mitochondria to describe a minimally-invasive approach to study mitochondrial function using blood samples.</p> <p>2. In the king penguin, we present a protocol using a high-resolution respirometry system and specific agonists and antagonists enabling the assessment of mitochondrial function in RBCs. We evaluated the inter-assay repeatability of our measures of mitochondrial function, and tested the influence of sample storage and bird handling time on these measures. We also compared measures of mitochondrial function in RBCs and in the pectoral muscle obtained from the same individuals.</p>

3. Mitochondria from RBCs showed the expected responses to mitochondrial agonists and antagonists, and therefore the protocol presented allows computing effective measures of mitochondrial function. The different measures of RBC mitochondrial function were significantly repeatable, were not affected by the handling time of the bird prior to blood sampling (i.e. stress response), and only minimally affected by the storage time of the sample at 4°C up to 24h. Most notably, we showed that mitochondrial parameters measured in RBCs moderately correlated to those measured in the pectoral muscle.

4. The present study sheds light on the use of RBCs in birds as a valuable and minimally-invasive source of information on mitochondrial function. This approach opens new opportunities to study mitochondrial function in free-living animals and could bring knowledge gains in ecology and evolution. Fish, amphibians and reptiles also possess mitochondria in their RBCs, and the approach presented here could also be applicable to these taxa.

SCHOLARONE™
Manuscripts

Review Only

1 **How to measure mitochondrial function in birds using red blood cells: a case**
2 **study in the king penguin and perspectives in ecology and evolution**

3

4 Antoine Stier^{a*}, Caroline Romestaing^b, Quentin Schull^c, Emilie Lefol^{c,d}, Jean-Patrice
5 Robin^c, Damien Roussel^{b#} & Pierre Bize^{e#}

6

7 ^a Institute of Biodiversity, Animal Health and Comparative Medicine, University of
8 Glasgow, Glasgow, UK

9 ^b Laboratoire d'Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS UMR
10 5023, Université de Lyon.

11 ^c Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

12 ^d Département de biologie, Université de Sherbrooke, 2500 boul. de l'Université,
13 Sherbrooke, QC, Canada J1K 2R1.

14 ^e Institute of Biological and Environmental Sciences, University of Aberdeen,
15 Aberdeen, UK

16

17 *Corresponding author: antoine.stier@gmail.com

18 #These authors share seniorship.

19

20 Running title: Measurement of mitochondrial function in birds

21

22 Summary

23 1. Mitochondria are the powerhouse of animal cells. They produce through oxidative
24 phosphorylation more than 90% of the cellular energy (ATP) required for organism's
25 growth, reproduction and maintenance. Hence, information on mitochondrial
26 function is expected to bring important insights in animal ecology and evolution.
27 Unfortunately, the invasiveness of the procedures required to measure
28 mitochondrial function (e.g. sampling of liver or muscles) has limited its study in wild
29 vertebrate populations so far. Here, we capitalize on the fact that bird red blood cells
30 (RBCs) possess functional mitochondria to describe a minimally-invasive approach to
31 study mitochondrial function using blood samples.

32 2. In the king penguin, we present a protocol using a high-resolution respirometry
33 system and specific agonists and antagonists enabling the assessment of
34 mitochondrial function in RBCs. We evaluated the inter-assay repeatability of our
35 measures of mitochondrial function, and tested the influence of sample storage and
36 bird handling time on these measures. We also compared measures of mitochondrial
37 function in RBCs and in the pectoral muscle obtained from the same individuals.

38 3. Mitochondria from RBCs showed the expected responses to mitochondrial
39 agonists and antagonists, and therefore the protocol presented allows computing
40 effective measures of mitochondrial function. The different measures of RBC
41 mitochondrial function were significantly repeatable, were not affected by the
42 handling time of the bird prior to blood sampling (*i.e.* stress response), and only
43 minimally affected by the storage time of the sample at 4°C up to 24h. Most notably,
44 we showed that mitochondrial parameters measured in RBCs moderately correlated
45 to those measured in the pectoral muscle.

46 4. The present study sheds light on the use of RBCs in birds as a valuable and
47 minimally-invasive source of information on mitochondrial function. This approach
48 opens new opportunities to study mitochondrial function in free-living animals and
49 could bring knowledge gains in ecology and evolution. Fish, amphibians and reptiles
50 also possess mitochondria in their RBCs, and the approach [presented here](#) could also
51 be applicable to these taxa.

52

53 **Keywords:** mitochondria, erythrocyte, non-invasive methodology, high-resolution
54 respirometry, metabolism

55

For Review Only

56 Introduction

57 Life history theory (Roff 1992) and metabolic theory of ecology (Brown *et al.*
58 2004) suggest that metabolic rate – the rate at which organisms take up, transform
59 and allocate energy to growth, reproduction and maintenance – is at the heart of
60 adaptation and success of organisms to particular environments. In animals more
61 than 90% of the cellular energy is produced as adenosine triphosphate (ATP) during
62 mitochondrial respiration (Nicholls & Ferguson 2002). Hence, our understanding of
63 the evolutionary success of particular individuals requires insights about the factors
64 that shape mitochondrial function (defined here as the ability to use O₂ to oxidize
65 substrate and produce ATP and heat) and the downstream effects that
66 mitochondrial function can exert on life histories (Salin *et al.* 2012; Toews *et al.*
67 2013; Hill 2014; Stier *et al.* 2014a; Stier *et al.* 2014b; Stier *et al.* 2014c; Salin *et al.*
68 2015; Schwartz *et al.* 2015; Bar-Yaacov *et al.* 2015; Koch *et al.* 2016; Delhayé *et al.*
69 2016).

70 The mitochondrion consists of outer- and inner- phospholipid membranes
71 separated by an intermembrane space, and contain mtDNA and ribosome in the
72 mitochondrial matrix (Fig. 1). ATP is produced by the mitochondria through a process
73 called oxidative phosphorylation (hereafter referred as OXPHOS; Nicholls & Ferguson
74 2002). The inner-membrane has a controlled permeability to protons and contains
75 the five OXPHOS complexes responsible for the coupling of substrate oxidation to
76 ATP production (Fig. 1). Complexes I to IV transport electrons from the substrates
77 (NADH, succinate and FAD-linked substrates) toward molecular oxygen while
78 pumping protons from the mitochondrial matrix into the inter-membrane space at
79 the same time. This process builds up an electrochemical gradient across the

80 mitochondrial inner-membrane, and the energy released by the backflow of protons
81 to the matrix through complex V (i.e. the ATP synthase) is used for the
82 phosphorylation of ADP into ATP. Protons can also backflow to some extent to the
83 matrix without passing by the complex V, leading to an energy released mostly as
84 heat. This phenomenon is referred as the mitochondrial proton leak (Divakaruni &
85 Brand 2011). The level of mitochondrial coupling between substrate oxidation and
86 ATP production could vary both between and within species, but also within
87 individual in response to factors such as fasting (Salin *et al.* 2015, Salin *et al.* 2016a).
88 This is one parameter of biological interest since it determines the amount of ATP
89 and heat generated for a given amount of O₂/substrate consumed (Brand 2005). This
90 mitochondrial coupling between respiration and ATP production is usually estimated
91 by the ratio between the overall mitochondrial O₂ consumption and the residual O₂
92 consumption linked to proton leak, a parameter also known as the respiratory
93 control ratio (RCR). Finally, some electrons can also escape during their transport
94 among the different complexes (especially in complex I and III), which leads to the
95 production of reactive oxygen species (ROS) that are implicated, at least to some
96 extent, in the ageing process (Speakman *et al.* 2015).

97 Given that studying mitochondrial function could provide important insights
98 in ecology and evolution it might be surprising that very few ecologists and
99 evolutionary biologists have embarked on this path (e.g. Salin *et al.* 2012; Toews *et*
100 *al.* 2013; Monternier *et al.* 2014). A lack of communication and transfer of
101 knowledge between mitochondrial biologists and ecologists/evolutionary biologists
102 can probably explain in part this phenomenon. However, we strongly believe that
103 methodological considerations have been a main limiting factor for the study of

104 mitochondrial function in natural populations. Indeed, the classical approach to
105 investigate mitochondrial biology is to obtain a tissue sample (typically from the liver
106 or muscles) and then work with isolated mitochondria, permeabilized cells or
107 homogenate samples (Brand & Nicholls 2011). Consequently, studying mitochondrial
108 function usually involves terminal sampling in small animals (e.g. Toews *et al.* 2013)
109 or laborious surgical procedures in larger animals (e.g. Monternier *et al.* 2014).
110 Those invasive procedures are nevertheless rarely compatible with the research aims
111 of most ecologists and evolutionary biologists, eager to collect information in natural
112 populations while keeping the disturbance to their study system as low as possible
113 and/or to perform repeated measurements of the same individual over time (*i.e.*
114 longitudinal design; Stier *et al.* 2015). In this context, our aim was to develop a
115 minimally-invasive method to study mitochondrial function in non-mammalian
116 vertebrates, and in particular bird species. Blood sampling is frequently performed in
117 natural populations of birds and well accepted as a minimally invasive procedure
118 (Sheldon *et al.* 2008). RBCs are by far the most abundant cell type in the blood, and
119 interestingly RBCs of birds (as well as other non-mammalian vertebrate species)
120 possess not only a nucleus but also functional mitochondria (Stier *et al.* 2013; Stier *et*
121 *al.* 2015). In the present study, our aim is to validate the use of RBCs to study
122 mitochondrial function in birds.

123 We describe a standard protocol that allows measuring mitochondrial
124 function in bird RBCs using a high-resolution respirometry system. We investigated
125 the response of intact RBCs to well-known mitochondrial agonists and antagonists
126 that allow the dissection of mitochondrial function in different parameters of
127 interest (Gnaiger 2009; Brand & Nicholls 2011). We conducted our study in a natural

128 population of king penguins (*Aptenodytes patagonica*), which is a large bird species
129 frequently used to assess mitochondrial function in the wild using pectoral muscle
130 biopsies (e.g. Rey *et al.* 2008; Monternier *et al.* 2014). We used this opportunity to
131 measure mitochondrial function in RBCs and to compare our results with findings
132 from the skeletal muscle, which is a tissue commonly used to assess mitochondrial
133 function. To evaluate the robustness of measures of mitochondrial function in RBCs,
134 we tested the sensitivity of our mitochondrial parameters to the effect of handling
135 stress (*i.e.* the time elapsed between capture and blood sampling) and of storage
136 time (*i.e.* the time elapsed between blood sampling in the field and mitochondrial
137 analysis in the laboratory; 4h to 24h). We also report on the repeatability of our
138 measures and on two different ways of normalizing mitochondrial respiration.

139

140 **Material and Methods**

141 STUDY SITE AND ANIMALS

142 This study took place in the king penguin colony of “La Grande Manchotière”
143 (*ca.* 24,000 breeding pairs) on Possession Island in the Crozet Archipelago (46° 25’S;
144 51° 52’E). Adult king penguins were caught either during courtship on the beach near
145 the research facility (N = 9 females and 9 males) or during incubation 3 days after the
146 start of their incubation shift (N = 46 females in incubation shift 2 and 29 males in
147 incubation shift 3).

148

149 SAMPLING PROCEDURES

150 Birds caught during courtship were immediately transferred to the nearby
151 research facility (< 2min walking distance). A blood sample (c.a. 2mL) was then
152 collected from the marginal flipper vein using a heparinised syringe and stored on
153 crushed ice until further processing. A 200 mg muscle biopsy was taken under
154 isoflurane-induced anesthesia from the superficial pectoralis muscle as described
155 previously (Rey *et al.* 2008). Fifty mg of muscle were immediately immersed in ice-
156 cold BIOPS solution (10 mM Ca-EGTA buffer, 0.1 μ M free calcium, 20 mM imidazole,
157 20 mM taurine, 50 mM K-MES, 0.5 mM DTT, 6.56 mM MgCl₂, 5.77 mM ATP, 15 mM
158 phosphocreatine, pH 7.1) until further processing.

159 Birds caught during incubation were blood sampled in the colony within 4
160 min after capture. For 23 of these birds, a second blood sample was taken after 30
161 min of standardized handling (see Viblanc *et al.* 2015 for details on capture and
162 handling protocol) to test the effect of handling time (i.e. stress response) on
163 mitochondrial measurements.

164 All blood samples were kept on crushed ice (< 2 hours) prior to centrifugation
165 at 3000g for 10 min to separate plasma from RBCs. The plasma fraction was then
166 removed and 100 μ L of RBCs was transferred into a new tube containing 1 mL of ice-
167 cold phosphate buffer saline (PBS). White blood cells and thrombocytes are located
168 on top of the blood cell pellet after centrifugation (Samour 2006). Therefore, RBCs
169 were pipetted from the bottom part of the cell pellet in our experiments to limit
170 contamination by other cell types. After gentle homogenisation, RBCs were washed
171 a first time by centrifuging the samples at 600 g for 5 min to pellet the cells and
172 discarding the supernatant. RBCs were then re-suspended in 1 mL of ice-cold PBS
173 and stored at 4°C until being used for mitochondria measurements.

174

175 MITOCHONDRIAL MEASUREMENTS IN INTACT RBCs

176 We choose to work with intact RBCs, since our preliminary observations
177 revealed difficulties to properly permeabilize avian RBCs. Immediately before the
178 start of the mitochondrial measurements, samples were washed a second time as
179 described above and re-suspended in 1mL of respiratory buffer MiR05 (0.5 mM
180 EGTA, 3 mM MgCl₂, 60 mM K-lactobionate, 20 mM taurine, 10 mM KH₂PO₄, 20 mM
181 Hepes, 110 mM sucrose, free fatty acid bovine serum albumin (1 g/L), pH 7.1). We
182 then added 1 mL of RBC suspension to 1mL of MiR05 buffer already equilibrated at
183 38°C in the respirometry chamber of one Oxygraph-2k high-resolution respirometer
184 (Oroboros Instruments, Innsbruck, Austria). This system allows measuring small
185 changes in O₂ concentration in a closed chamber, and thereby provides a good
186 opportunity to measure mitochondrial respiration using minimum amount of
187 biological samples.

188 We applied a protocol involving serial additions of various mitochondrial
189 agonists/antagonists to our RBC suspension in order to get a comprehensive
190 assessment of mitochondrial function, as illustrated in Fig. 2A, and in the
191 corresponding stepwise description below:

- 192 1. Baseline O₂ consumption is recorded after approximately 5 min of
193 stabilization following the addition of the sample to the chamber (R_{baseline}).
- 194 2. ATP-dependent O₂ consumption is inhibited by adding oligomycin (1 µg.mL⁻¹),
195 an inhibitor of ATP synthase ($R_{\text{oligomycin}}$). The residual oxygen consumption at
196 this stage is mostly linked to mitochondrial proton leak.

197 3. Maximal uncoupled O_2 consumption is then obtained by the addition of the
198 mitochondrial uncoupler FCCP (carbonyl cyanide-p-trifluoro-methoxyphenyl-
199 hydrazone) at a final concentration of $1 \mu\text{M}$ (R_{FCCP}). At this concentration,
200 FCCP abolishes the proton gradient, thereby forcing the OXPHOS system to
201 work at its maximum capacity to compensate for proton leakage. The
202 maximal uncoupled respiration is limited by the capacity of the electron
203 transport system (ETS) to oxidize the available substrate. Because FCCP can
204 inhibit mitochondrial respiration above a certain threshold, we performed a
205 preliminary stepwise titration study to determine the optimal concentration
206 of FCCP that leads to maximum mitochondrial O_2 consumption.

207 4. Mitochondrial O_2 consumption is then abolished by adding antimycin A (5
208 μM), an inhibitor of mitochondrial complex III ($R_{\text{antimycinA}}$). The residual oxygen
209 consumption after antimycin A inhibition reflects non-mitochondrial oxygen
210 consumption.

211
212 We determined mitochondrial O_2 consumption by subtracting residual non-
213 mitochondrial O_2 consumption ($R_{\text{antimycinA}}$) from O_2 consumption measured in
214 response to the other conditions. We computed four measures of mitochondrial
215 respiration and three different flux control ratios (FCR) to evaluate the degree of
216 mitochondrial coupling between O_2 consumption and ATP synthesis, but also the
217 proportion of mitochondrial capacity being used under endogenous conditions
218 (Gnaiger 2009). The seven measures of mitochondrial function derived from our
219 protocol are described in Table 1.

220

221 NORMALIZATION OF MITOCHONDRIAL RESPIRATION

222 Pipetting an exact volume of RBCs (*i.e.* 100 μ L) might be challenging
223 considering the viscosity of the cell pellet after centrifugation. Consequently, the
224 volume of cells might not be as accurate as desired and biased our estimates of
225 mitochondrial parameters. Hence, we tested two methods of *post-measurement*
226 normalization using 18 samples collected in courtship birds. We either weighed the
227 amount of RBCs pipetted before the start of the analyses using a high-precision
228 electronic balance (\pm 0.1mg, Sartorius AC211S[®]), or we quantified the total protein
229 content in the remaining RBCs samples at the end of the analyses using the Pierce
230 BCA protein assay (ThermoScientific). We calculated standardised respiration rates
231 by dividing respiration rates either by the fresh mass of RBCs or by their protein
232 content.

233

234 REPEATABILITY OF RBC MITOCHONDRIAL MEASUREMENTS

235 We evaluated the repeatability of our mitochondrial measurements by
236 assaying 15 samples in duplicate, coming from both courtship and incubating birds.
237 We evaluated the repeatability both on raw data and on data normalized by the
238 fresh mass of RBCs.

239

240 EFFECTS OF STORAGE TIME

241 To evaluate the effect of storage time on mitochondrial measurements, we
242 used two approaches. First, we measured 8 samples twice, a first time after 4h of
243 storage at 4°C and a second time after 24h of storage. Second, we used single
244 measurements collected from the 75 incubating birds, in which the time elapsed

245 between blood sampling and mitochondrial measurements varied between 2 and 10
246 hours. Samples were always stored at 4°C in 1mL of PBS in closed 1.5 mL eppendorf
247 tubes without agitation.

248

249 MITOCHONDRIAL MEASUREMENTS IN SKELETAL MUSCLE

250 Mitochondrial respiratory function of pectoral muscle was determined in
251 permeabilized muscle fibers using a method described previously by Pesta & Gnaiger
252 (2011). Structurally sound fiber bundles were selected from biopsies maintained in
253 ice-cold BIOPS, and mechanically separated, removing any visible adipose and
254 connective tissue. Fiber bundles were transferred in BIOPS solution containing
255 saponin (50µg/ml) for permeabilization and mixed gently at 4°C for 30 min. Then,
256 permeabilized fibers were washed 10 min at 4°C in the Mir05 buffer. Permeabilized
257 fibers were carefully blotted on Whatman filter paper for 2-3s, weighed and placed
258 in the Oxygraph chamber containing 2mL of MiR05 at 38°C. Respiration was fuelled
259 using either pyruvate/malate (5/2.5mM) or succinate (5mM) as respiratory
260 substrates, and *LEAK* respiration was recorded in the presence of substrate but
261 absence of ADP. Phosphorylating state of respiration (*i.e.* classical state III) was
262 determined in the presence of ADP (1 mM), and we define here this state as
263 '*ROUTINE*' to facilitate comparison with intact RBCs since it encompasses respiration
264 linked both to ATP production and mitochondrial proton leak. The respiration linked
265 to ATP synthesis (*OXPHOS*) was calculated as the difference between *LEAK* and
266 '*ROUTINE*' respiration, as done for RBCs. Then, cytochrome-c (10 µM) was added in
267 order to check the integrity of mitochondria within permeabilized fibers by the
268 absence of stimulation of respiration. Mitochondrial preparations exhibiting an

269 increase in O₂ uptake greater than 15% in response to cytochrome-c were excluded
270 from subsequent analysis (Kuznetsov *et al.* 2008). Thereafter, the maximal [capacity](#)
271 [of the electron transport system \(ETS\)](#) was [measured](#) by sequential addition of 1μM
272 of FCCP. Finally, antimycin A (20 μM) was added to allow the measurement of non-
273 mitochondrial oxygen consumption rate. To determine mitochondrial O₂
274 consumption, we subtracted residual O₂ consumption measured after antimycin A
275 inhibition, from O₂ consumption measured in response to the other conditions.
276 Mitochondrial respiration rates of permeabilized fibers were expressed as pmol O₂.s⁻¹
277 .mg⁻¹ wet weight.

278

279 STATISTICS

280 We used Generalized Estimating Equations (GEE) with *bird identity* as
281 individual factor and *state* as the repeated effect to evaluate 1) differences in O₂
282 consumption in response to the different experimental conditions (i.e. baseline,
283 oligomycin, FCCP [and](#) antimycin A) and 2) differences between [RBC](#) mitochondrial
284 parameters (i.e. [ROUTINE](#), [OXPHOS](#), [LEAK](#) [and](#) [ETS](#)). Paired-comparisons involving
285 two groups (i.e. effects of storage [and](#) [sampling times](#)) were performed using non-
286 parametric exact Wilcoxon paired-tests considering the relatively small sample sizes
287 (N ≤ 23). To evaluate the relevance of normalizing RBC mitochondrial respiration, we
288 ran multivariate analyses (MANOVAs) with either fresh RBC mass or total protein
289 content as explanatory factors of mitochondrial O₂ consumption rates. To evaluate
290 the repeatability of mitochondrial parameters, we calculated the intraclass
291 coefficients of correlations (ICC), but also the coefficients of variation (CV) expressed
292 in % for the 14 samples assessed in duplicates. Correlation tests were performed

293 using either non-parametric Spearman correlations (for $N \leq 18$) or parametric
294 Pearson correlations (for $N \geq 40$). Means are always quoted \pm SE and p-values ≤ 0.05
295 were considered as significant.

296

297 ETHICAL STATEMENT

298 The present study used samples collected as part of two on-going scientific
299 programs of the French Polar Institute (IPEV 119 ECONERGY and IPEV 131
300 PHYSIONERGY). All experiments were approved by an independent ethics committee
301 (Comité d'éthique Midi-Pyrénées pour l'expérimentation animale) commissioned by
302 the French Polar Institute, and comply with the current laws of France.
303 Authorizations to enter the breeding colony and handle the birds were provided by
304 the "Terres Australes and Antarctiques Françaises" (permit n°2013-72 issued on 29
305 October 2013).

306

307 Results

308 OXYGEN CONSUMPTION IN RESPONSE TO MITOCHONDRIAL AGONISTS AND ANTAGONISTS

309 Using the 18 birds caught in courtship, we found a significant effect of
310 mitochondrial agonists/antagonists on O_2 consumption (Fig 2A & 2B; GEE model: $\chi^2 =$
311 606.6, $p < 0.001$). Post-hoc comparisons revealed that inhibition of ATP synthase
312 significantly decreased O_2 consumption by $61.8 \pm 1.4 \%$ ($p < 0.001$), while
313 mitochondrial uncoupling with FCCP significantly increased O_2 consumption by 18.5
314 $\pm 5.8 \%$ compared to baseline ($p = 0.001$). Inhibition of mitochondrial respiration
315 with antimycin A decreased O_2 consumption by $85.7 \pm 1.1 \%$ compared to baseline (p
316 < 0.001).

317 This protocol allowed to compute seven measures of mitochondrial function
318 (see Table 1) derived from the changes in mitochondrial respiration rates in response
319 to mitochondrial agonists/antagonists (Fig 2C).

320

321 NORMALIZATION OF RBC MITOCHONDRIAL RESPIRATION RATES

322 Multivariate analyses revealed that mitochondrial respiration rates were
323 significantly influenced by the fresh mass of cells used (MANOVA: $F_{3,14} = 11.06$, $p =$
324 0.001 , effect size (partial η^2) = 0.70), or to a slightly lesser extent by the total protein
325 content of RBC samples (MANOVA: $F_{3,14} = 5.7$, $p = 0.002$, effect size (partial η^2) =
326 0.64).

327

328 REPEATABILITY OF RBC MITOCHONDRIAL MEASUREMENTS

329 Mitochondrial parameters were overall significantly repeatable as shown in
330 Table 2 (all ICC > 0.87). Normalizing mitochondrial parameters by the fresh mass of
331 RBCs increased the repeatability of mitochondrial measurements in all cases (all ICC
332 > 0.91).

333

334 EFFECT OF STORAGE TIME ON RBC MITOCHONDRIAL PARAMETERS

335 The comparison of mitochondrial parameters measured 4h after sampling or
336 24h after sampling did not reveal significant differences (Wilcoxon paired exact tests,
337 all $p > 0.14$, Fig 3), except for a slight increase with time in $FCR_{R/ETS}$ ($p = 0.039$, Fig 3B).
338 In addition, we found overall no significant correlations between storage time and
339 mitochondrial parameters using the 75 samples collected from incubating birds

340 (Pearson correlations, all $p > 0.21$), except for a weak but significant negative
341 correlation with $FCR_{L/ETS}$ ($r = 0.23$, $p = 0.049$).

342

343 EFFECT OF HANDLING TIME ON RBC MITOCHONDRIAL PARAMETERS

344 We found overall no significant impact of handling time on mitochondrial
345 parameters (Wilcoxon paired exact tests, all $p > 0.21$, Fig 4).

346

347 RELATIONSHIPS BETWEEN MITOCHONDRIAL PARAMETERS IN RBCS AND PECTORAL MUSCLE

348 Table 3 reports the coefficients of correlation between RBC mitochondrial
349 respiration values and muscle mitochondrial respiration values measured using two
350 different respiration substrates, pyruvate-malate or succinate. When using pyruvate-
351 malate as substrate for the muscle, we found significant positive relationships
352 between RBC and muscle for *ROUTINE* and *OXPHOS* values (Fig. 5A & B). When using
353 succinate as substrate, we found marginally significant positive relationships for
354 *OXPHOS* and *LEAK* values (Fig. 5C & D) and significant positive relationships between
355 RBC and muscle for *ETS* and $FCR_{L/ETS}$ values (Fig. 5E & F). Other relationships were not
356 significant (Table 3).

357

358 Discussion

359 In this study, we present and validate the use of a novel approach where
360 intact RBCs are used to measure mitochondrial function in a minimally invasive
361 manner. We illustrate this approach in birds, but such methodology could likely be
362 adapted to other non-mammalian vertebrates (i.e. fish, amphibians and reptiles)
363 since they also have functional mitochondria in their RBCs (Stier *et al.* 2015). Despite

364 the fact that mammalian RBCs are lacking mitochondria, blood sampling might
365 nonetheless also be used in this taxon to measure mitochondrial function, though
366 using other blood cell types (e.g. platelets or white blood cells), as recently
367 demonstrated in humans (Sjövall *et al.* 2013; Pecina *et al.* 2014). However, larger
368 blood volume and isolation of specific blood cells will be required in mammals to
369 have access to sufficient amount of mitochondria. The use of blood samples to
370 assess mitochondrial function should open new opportunities to study mitochondrial
371 function in free-living vertebrates and address fundamental roles of mitochondria in
372 ecology and evolution (Dowling *et al.* 2008; Ballard & Pichaud 2013; Hill 2014; 2015;
373 Salin *et al.* 2015; Koch *et al.* 2016). This method should also facilitate future studies
374 looking at the functional importance of mitochondria in the RBCs of non-mammalian
375 vertebrates. It may in turn also bring new and important insight in the evolution of
376 mammalian erythrocytes that lack both nucleus and mitochondria.

377

378 CHARACTERIZING MITOCHONDRIAL FUNCTION IN INTACT RBCs

379 Mitochondria from intact RBCs of king penguins exhibited the expected
380 responses to classical mitochondrial agonists and antagonists. It confirms previous
381 finding in zebra finches about the presence of functional mitochondria in bird RBCs
382 (Stier *et al.* 2013). We show how mitochondrial drugs can be used to extract 7
383 parameters of interests reflecting various aspects of mitochondrial function (Table
384 1). **ROUTINE** respiration reflects the natural activity of mitochondria under the
385 current physiological and cellular state (*i.e.* substrate and ADP availability, ATP
386 turnover, proton leak) and is an intermediary state between the classical state III
387 (unlimited availability of substrate and ADP) and state IV (unlimited availability of

388 substrate but zero ATP synthesis) classically measured in isolated mitochondria or
389 permeabilized tissues/cells (Brand & Nicholls 2011). We decomposed RBCs' *ROUTINE*
390 mitochondrial respiration into two components, the ATP-dependent respiration
391 (*OXPHOS*) and the leak respiration (*LEAK*). The first one reflects the ability of
392 mitochondria to produce ATP via OXPHOS and the second one reflects the proton
393 leakiness of the mitochondria. Both components have different but equally
394 important biological implications. ATP is important to fulfil most cellular activities.
395 Therefore, variation in *OXPHOS* respiration may account for variation in cell
396 replication and growth, and by extension for variation in organismal growth,
397 maturation and reproduction. On the other hand, proton leak is known to be
398 important to produce heat and/or regulate ROS production (Brand 2000). Thus,
399 variation in *LEAK respiration* may account for variation in cell (and organismal)
400 maintenance and lifespan. The values we observe here for RBCs (72.7% of
401 mitochondrial respiration linked to ATP synthesis vs. 27.3% linked to proton leak) are
402 close to those found in various cell types of mammals and birds, since in those cells
403 approximately 60-80% of the mitochondrial respiration is used to synthesize ATP,
404 and 20-40% is linked to the proton leak (Porter & Brand 1995; Else *et al.* 2004;
405 Jimenez *et al.* 2014). *ETS* represents the maximal mitochondrial activity under
406 current physiological conditions; this respiration rate can be constrained by
407 substrate availability and oxidation but is independent of ATP turnover. Importantly,
408 the optimum FCCP concentration is likely to vary across species and conditions, and
409 thus it should be determined on a case-by-case basis. Some caution is also needed
410 when interpreting *ETS* respiration since the use of uncoupling agents in intact cells

411 can have deleterious side effects, such as an intra-cellular acidification (see Brand &
412 Nicholls 2011 for details).

413 Cell flux control ratios (FCRs) are often viewed as the most useful general
414 tests of mitochondrial function in intact cells (Gnaiger 2009; Brand & Nicholls 2011).
415 Notably, since FCRs are ratios, they are internally normalized, which facilitates their
416 interpretation (see below for a discussion on normalization). $FCR_{L/R}$ provides
417 information on the coupling efficiency of the mitochondria between O_2 consumption
418 and ATP production under the current physiological state, while $FCR_{L/ETS}$ provides
419 information on coupling state under stimulated conditions. $FCR_{R/ETS}$ provides
420 information about the proportion of the capacity of the electron transport system
421 being used under current physiological conditions. FCR values are usually
422 characteristic of a specific method in a specific tissue and in a specific group of
423 organisms. Consequently, there are currently no standard FCR values in RBCs that
424 can be used for comparison. Still, $FCR_{L/R}$ in king penguin RBCs are close to those
425 found in cultured myoblasts/fibroblasts of Japanese quails ($FCR_{L/R} \approx 0.25$ to 0.42 ;
426 Jimenez *et al.* 2014).

427 One important consideration when working with RBCs is that they contain a
428 high amount of intra-cellular O_2 bound to haemoglobin. Thus, haemoglobin may act
429 as a reservoir that releases O_2 in the medium in response to a decrease in extra-
430 cellular O_2 caused by mitochondrial respiration, which would lead to an
431 underestimation of the different measures of mitochondrial respiration. If true, this
432 release of O_2 by haemoglobin should become visible (and measurable) when the
433 mitochondrial respiration is blocked; that is after the addition of antimycin A. We
434 never detected a release of O_2 by king penguin RBCs after antimycin A inhibition (see

435 Fig 2A; minimum $R_{\text{antimycinA}} = 2.0 \text{ pmol}\cdot\text{s}^{-1}\cdot\text{mL}^{-1}$, $N = 93$). Comparable findings were
436 found in zebra finch (*Taenopygia guttata*) and Japanese quail (*Coturnix japonica*)
437 (Stier, unpublished results), suggesting that disruption of measures due to
438 haemoglobin is unlikely to be widespread. Still, studies must check for this
439 potentially important source of error when applying the proposed methodology in a
440 new species.

441

442 ROBUSTNESS OF RBC MITOCHONDRIAL MEASURES

443 Our results indicate that our different measures of mitochondrial function
444 were significantly repeatable, that RBCs could be stored at 4°C up to 24h without
445 major effects on measures of mitochondrial function (with the exception of minor
446 but significant effects on $FCR_{L/ETS}$ and $FCR_{R/ETS}$), and that the handling time of birds
447 before blood sampling did not alter measures of mitochondrial function. Those
448 findings are in agreement with a recent study in human platelets pointing out that
449 mitochondrial function in those blood cells is relatively well conserved at 4°C up to
450 48h after blood collection (Sjövall *et al.* 2013). The possibility of conserving samples
451 at 4°C for several hours before measurement would undoubtedly be a real asset for
452 field studies since field sites and laboratory facilities are often not located at the
453 same place. The absence of effect of handling time on mitochondrial parameters is
454 another asset for field studies, since capturing and blood sampling wild animals
455 under controlled time condition can be very laborious. It is nonetheless important
456 that future studies test for repeatability and investigate the importance of storage
457 time and handling time on measures of mitochondrial parameters before
458 generalities on the robustness of RBC measures can be drawn.

459

460 CORRELATIONS BETWEEN MITOCHONDRIAL PARAMETERS IN RBCS AND PECTORAL
461 MUSCLES

462 Although demonstrating the presence of functional mitochondria in RBCs is
463 an important first step, the next logical question is whether measures of
464 mitochondrial function in RBCs do reflect to some extent what is happening in other
465 tissues of the same individual, and as such can provide some general information at
466 the scale of the organism. Although we were unable to compare RBCs and pectoral
467 muscle in the exact same experimental conditions (*i.e.* permeabilized RBCs vs.
468 permeabilized muscle; our attempts to permeabilize RBCs were not successful), we
469 showed that mitochondrial parameters measured in intact RBCs moderately
470 correlated to those measured in permeabilized pectoral muscle fibers (see Table 3
471 for details). Interestingly, similar findings have been found in humans between blood
472 mononuclear cells and organs such as kidney and heart (Karamercan *et al.* 2013).
473 Altogether, it indicates that mitochondrial parameters are to some extent correlated
474 among tissues, including blood. However, this is unlikely to be true for every
475 experimental condition and study species, as exemplified by the lack of significant
476 correlation reported in brown trout between liver and muscle mitochondrial
477 respiration rates (Salin *et al.* 2016b). This opens new opportunities to ecologists and
478 evolutionary biologists eager to investigate links between mitochondrial function
479 and organismal performance using minimally invasive sampling techniques (*i.e.*
480 blood sampling). Having access to such minimally-invasive methodology is a pre-
481 requisite when it comes to make links with fitness traits such as reproductive success
482 and survival, but also when working with protected species.

483

484 FURTHER IMPROVEMENTS IN CHARACTERIZING MITOCHONDRIAL FUNCTION USING

485 RBCS

486 We see at least three methodological improvements to be addressed in

487 future studies. First, while working with intact cells has several advantages (e.g.

488 working in an undisturbed cellular environment and lack of artefacts due to

489 mitochondrial preparation; Brand & Nicholls 2011), it may be beneficial for some

490 studies to better control the environment in which mitochondrial function is

491 measured (i.e. substrate and ADP availability). This could be achieved either by

492 isolating mitochondria or by being able to permeabilize RBCs properly and artificially

493 providing substrates and ADP (Brand & Nicholls 2011). Such methodological

494 development will undoubtedly broaden the scope of questions that could be

495 answered using mitochondria coming from non-mammalian RBCs.

496 Second, normalizing mitochondrial respiration is not an easy task, and has

497 several implications for data interpretation (Brand & Nicholls 2011). We have shown

498 that normalizing measurement by the fresh mass of cells used or by their protein

499 content improve the repeatability of the measurement. However, it would also be

500 possible to normalize mitochondrial respiration by the number of cells or by the

501 mitochondrial content of these cells.

502 Finally, as stated in the introduction, mitochondrial function is not only

503 reflected in terms of O₂ consumed and ATP produced, but also in terms of ROS

504 produced. Assessing ROS production is challenging, but has already being done using

505 fluorescent probes in non-mammalian vertebrate RBCs (e.g. Olsson *et al.* 2008; Stier506 *et al.* 2014a; Delhaye *et al.* 2016). Interestingly, it is now possible to simultaneously

507 record O₂ consumption and fluorescence signal using the O2k-fluorescence module
508 (Oroboros Instruments, Innsbruck, Austria) that could be added to the O2k-Oroboros
509 device that we used in this study. Other fluorescent probes may also help to collect
510 additional information on mitochondrial function, such as mitochondrial membrane
511 potential, ATP synthesis (Salin *et al.* 2016a), or calcium flux, and in turn help to
512 broaden the scope of questions that can be addressed in ecology and evolution.

513

514 PERSPECTIVES IN ECOLOGY & EVOLUTION

515 The applications of our methodology in ecology and evolution are likely to be
516 broad in terms of scientific questions that could be addressed. Indeed, subtle
517 variations at the cellular level in mitochondrial function are likely to have profound
518 consequences at the organismal level (Salin *et al.* 2015), and we believe that the
519 links between mitochondrial function and organismal phenotype deserves now more
520 attention than ever. Hereafter, we highlight four promising avenues where measures
521 of mitochondrial function in RBCs could help to gain knowledge.

522 First of all, whole organism metabolic rate, which is the result of oxygen
523 consumption by mitochondria at the cellular level, has been a trait under great
524 scrutiny in ecology and evolution in the last decades (Brown *et al.* 2004). However,
525 metabolic rate is in the vast majority of cases measured in terms of O₂ consumption,
526 while the true energetic currency is ATP, and the relationships between O₂
527 consumption and ATP production are not constant (Brand 2005; Salin *et al.* 2015).
528 Since the fractions of O₂ consumption used for ATP synthesis and mitochondrial
529 proton leak have very different biological implications, gaining insight about
530 mitochondrial function at the cellular level should further improve our

531 understanding of metabolic rate acting as a factor driving ecological and
532 evolutionary processes.

533 Secondly, mitochondrial function requires a close collaboration between the
534 nuclear and the mitochondrial genomes (*i.e.* named mito-nuclear interactions) since
535 more than 90% of the proteins required for mitochondrial function are encoded in
536 the nucleus and imported into the mitochondria (Wolff *et al.* 2014). While the
537 mitochondrial genome was thought to be an evolutionary bystander for a long time,
538 we have now evidence arguing for the existence of evolutionary adaptations at the
539 mtDNA level (e.g. Pavlova *et al.* 2013; Ballard & Pichaud 2013). Such phenomena
540 might also give rise to mito-nuclear incompatibilities between
541 individuals/populations (*i.e.* decreased fitness of hybrids), and such incompatibilities
542 are believed to be one potential driver of reproductive isolation and speciation (Bar-
543 Yaacov *et al.* 2015). Characterizing mitochondrial function of mtDNA variants
544 appears essential to evaluate their adaptive value, and characterizing mitochondrial
545 function of potential mito-nuclear hybrids appears essential to shed light on the
546 mechanisms underlying mito-nuclear incompatibilities. However, characterizing
547 mitochondrial function in these two contexts has rarely been done to date (but see
548 Toews *et al.* 2013).

549 Thirdly, mitochondria are inherited *only* from the mother, even if inheritance
550 patterns could be slightly more complex in some cases (White *et al.* 2008). This gives
551 rise to evolutionary constraints for males, since mitochondrial mutations benefitting
552 females could spread even if they harm males, a phenomenon known as the
553 “mother’s curse” (Gemmell *et al.* 2004). In vertebrate species, we often lack

554 information about differences in mitochondrial function arising from such
555 constraints, and even more surprisingly, we have little information to date about the
556 inheritance and heritability patterns of mitochondrial function *per se*.

557 Finally, mitochondrial function undoubtedly contributes to animal
558 performance and fitness, probably in an environment-dependent manner (Stier *et al.*
559 2014a; Stier *et al.* 2014b; Salin *et al.* 2015; Conley 2016). Indeed, mitochondrial
560 function will condition the amount of nutrients and O₂ used, as well as the amount
561 of ATP and ROS produced. Decreasing mitochondrial efficiency to produce ATP might
562 seem counter-productive at a first glance. However, such mitochondrial
563 “uncoupling” between O₂ and ATP production could be useful for endotherms to
564 produce heat such as in the brown fat of mammals, but also to slow-down ageing by
565 reducing ROS production (Brand 2000). In contrast, increasing mitochondrial
566 efficiency might be beneficial when resources are limited or to optimize physical
567 performances (Monternier *et al.* 2014; Conley 2016), while it might incur some costs
568 in terms of ROS production.

569

570 **Acknowledgements**

571 We are grateful to the French Polar Institut (IPEV) for providing logistical support for
572 this study through the programs 119 & 131, A. Bourguignon, Y. Handrich and A.
573 Lewden for their contribution to the muscle biopsy sampling, V. Viblanc for his
574 support through the IPEV program 119, [and three anonymous reviewers for their](#)
575 [help in improving the manuscript](#). A. Stier was supported by a Marie Skłodowska-
576 Curie Postdoctoral Fellowship (#658085). [Authors declare no conflict of interest](#).

577

578 **Author's contribution**

579 A.S. designed the study, did the fieldwork, conducted laboratory analyses on RBCs,
580 analyzed the data and wrote the paper. P.B. provided guidance on data analysis, and
581 wrote the paper. D.R. provided guidance on the experiments and helped to draft the
582 manuscript. Q.S., E.L. and JP.R. contributed to the realization of the project, the
583 collection of samples in the field, and commented on the manuscript. C.R. provided
584 invaluable technical advice on mitochondrial measurements, and conducted
585 laboratory analyses on muscle samples.

586

587 **Data accessibility**

588 Data will be loaded on Dryad after the manuscript has been accepted.

589

590 **References**

591 Ballard, J.W.O. & Pichaud, N. (2013). Mitochondrial DNA: more than an evolutionary
592 bystander. *Functional Ecology*, **28**, 218–231.

593 Bar-Yaacov, D., Hadjivasiliou, Z., Levin, L., Barshad, G., Zarivach, R., Bouskila, A. &
594 Mishmar, D. (2015). Mitochondrial Involvement in Vertebrate Speciation? The
595 Case of Mito-nuclear Genetic Divergence in Chameleons. *Genome Biology and
596 Evolution*, **7**, 3322–3336.

597 Brand, M. (2000). Uncoupling to survive? The role of mitochondrial inefficiency in
598 ageing. *Experimental Gerontology*, **35**, 811–820.

599 Brand, M.D. (2005). The efficiency and plasticity of mitochondrial energy
600 transduction. *Biochemical Society Transactions*, **33**, 897–904.

601 Brand, M.D. & Nicholls, D.G. (2011). Assessing mitochondrial dysfunction in cells.
602 *Biochemical Journal*, **435**, 297–312.

603 Brown, J.H., Gillooly, J.F., Allen, A.P., Savage, V.M. & West, G.B. (2004). Toward a
604 metabolic theory of ecology. *Ecology*, **85**, 1771–1789.

605 Conley, K.E. (2016). Mitochondria to motion: optimizing oxidative phosphorylation to

- 606 improve exercise performance. *Journal Of Experimental Biology*, **219**, 243–249.
- 607 Delhaye, J., Salamin, N., Roulin, A., Criscuolo, F., Bize, P. & Christe, P. (2016).
608 Interspecific correlation between RBC mitochondrial ROS production, RBC
609 cardiolipin content and longevity in birds. *AGE*. doi:10.1007/s11357-016-9940-z
- 610 Divakaruni, A.S. & Brand, M.D. (2011). The Regulation and Physiology of
611 Mitochondrial Proton Leak. *Physiology*, **26**, 192–205.
- 612 Dowling, D., Friberg, U. & Lindell, J. (2008). Evolutionary implications of non-neutral
613 mitochondrial genetic variation. *Trends in Ecology & Evolution*, **23**, 546–554.
- 614 Else, P.L., Brand, M.D. & Turner, N. (2004). Respiration rate of hepatocytes varies
615 with body mass in birds. *Journal of Experimental Biology*, **207**, 2307–2311.
- 616 Gemmell, N.J., Metcalf, V.J. & Allendorf, F.W. (2004). Mother's curse: the effect of
617 mtDNA on individual fitness and population viability. *Trends in Ecology &*
618 *Evolution*, **19**, 238–244.
- 619 [Gnaiger E \(2009\) Mitochondrial respiratory control. In: Textbook on Mitochondrial](#)
620 [Physiology \(Gnaiger E, ed\) Mitochondr. Physiol. Soc. electronic ed:](#)
621 www.mitophysiology.org.
622
- 623 Hill, G.E. (2014). Cellular Respiration: The Nexus of Stress, Condition, and
624 Ornamentation. *Integrative and Comparative Biology*, **54**, 645–657.
- 625 Hill, G.E. (2015). Mitonuclear Ecology. *Molecular biology and evolution*, **32**, 1917-
626 1927.
- 627 Jimenez, A.G., Cooper-Mullin, C., Anthony, N.B. & Williams, J.B. (2014). Cellular
628 metabolic rates in cultured primary dermal fibroblasts and myoblast cells from
629 fast-growing and control Coturnix quail. *Comparative Biochemistry and*
630 *Physiology Part A: Molecular & Integrative Physiology*, **171**, 23–30.
- 631 Karamercan, M.A., Weiss, S.L., Villarroel, J.P.P., Guan, Y., Werlin, E., Figueredo, R.,
632 Becker, L.B. & Sims, C. (2013). Can Peripheral Blood Mononuclear Cells Be Used
633 as a Proxy for Mitochondrial Dysfunction in Vital Organs During Hemorrhagic
634 Shock and Resuscitation? *Shock*, **40**, 476–484.
- 635 Koch, R.E., Josefson, C.C. & Hill, G.E. (2016). Mitochondrial function, ornamentation,
636 and immunocompetence. *Biological Reviews*. DOI: 10.1111/brv.12291
- 637 Kuznetsov, A.V., Veksler, V., Gellerich, F.N., Saks, V., Margreiter, R. & Kunz, W.S.
638 (2008). Analysis of mitochondrial function in situ in permeabilized muscle fibers,
639 tissues and cells. *Nature Protocols*, **3**, 965–976.
- 640 Larsen, S., Nielsen, J., Hansen, C.N., Nielsen, L.B., Wibrand, F., Stride, N., Schroder,
641 H.D., Boushel, R., Helge, J.W., Dela, F. & Hey-Mogensen, M. (2012). Biomarkers
642 of mitochondrial content in skeletal muscle of healthy young human subjects.

- 643 *The Journal of Physiology*, **590**, 3349–3360.
- 644 Monternier, P.A., Marmillot, V., Rouanet, J.-L. & Roussel, D. (2014). Mitochondrial
645 phenotypic flexibility enhances energy savings during winter fast in king penguin
646 chicks. *Journal Of Experimental Biology*, **217**, 2691–2697.
- 647 Nicholls, D.G. & Ferguson, S.J. (2002). Bioenergetics. *Academic press*.
- 648 Olsson, M., Wilson, M., Uller, T., Mott, B., Isaksson, C., Healey, M. & Wanger, T.
649 (2008). Free radicals run in lizard families. *Biology Letters*, **4**, 186-188.
- 650 Pavlova, A., Amos, J.N., Joseph, L., Loynes, K., Austin, J.J., Keogh, J.S., Stone, G.N.,
651 Nicholls, J.A. & Sunnucks, P. (2013). PERCHED AT THE MITO-NUCLEAR
652 CROSSROADS: DIVERGENT MITOCHONDRIAL LINEAGES CORRELATE WITH
653 ENVIRONMENT IN THE FACE OF ONGOING NUCLEAR GENE FLOW IN AN
654 AUSTRALIAN BIRD. *Evolution*, **67**, 3412–3428.
- 655 Pecina, P., Houštková, H., Mráček, T., Pecinová, A., Nůsková, H., Tesařová, M.,
656 Hansíková, H., Janota, J., Zeman, J. & Houštěk, J. (2014). Noninvasive diagnostics
657 of mitochondrial disorders in isolated lymphocytes with high resolution
658 respirometry. *BBA Clinical*, **2**, 62–71.
- 659 Pesta, D. & Gnaiger, E. (2011). High-Resolution Respirometry: OXPHOS Protocols for
660 Human Cells and Permeabilized Fibers from Small Biopsies of Human Muscle.
661 *Methods in Molecular Biology*, pp. 25–58. *Methods in Molecular Biology*.
662 Humana Press, Totowa, NJ.
- 663 Porter, R.K. & Brand, M.D. (1995). Causes of differences in respiration rate of
664 hepatocytes from mammals of different body mass. *Am J Physiol*, **269**, R1213–
665 24.
- 666 Rey, B., Halsey, L.G., Dolmazon, V., Rouanet, J.-L., Roussel, D., Handrich, Y., Butler,
667 P.J. & Duchamp, C. (2008). Long-term fasting decreases mitochondrial avian
668 UCP-mediated oxygen consumption in hypometabolic king penguins. *AJP:*
669 *Regulatory, Integrative and Comparative Physiology*, **295**, R92–R100.
- 670 Roff, D.A. (1992). Evolution of life histories: theory and analysis. *Springer New York*.
- 671 Salin, K., Auer, S.K., REY, B., Selman, C. & Metcalfe, N.B. (2015). Variation in the link
672 between oxygen consumption and ATP production, and its relevance for animal
673 performance. *Proceedings of the Royal Society B: Biological Sciences*, **282**,
674 20151028.
- 675 Salin, K., Roussel, D., Rey, B. & Voituron, Y. (2012). David and Goliath: A
676 Mitochondrial Coupling Problem? *Journal of Experimental Zoology Part A:*
677 *Ecological Genetics and Physiology*, **317**, 283–293.
- 678 Salin, K., Villasevil, E.M., Auer, S.K., Anderson, G.J., Selman, C., Metcalfe, N.B. &
679 Chinopoulos, C. (2016a). Simultaneous measurement of mitochondrial

- 680 respiration and ATP production in tissue homogenates and calculation of
681 effective P/O ratios. *Physiological Reports*, **4**, e13007.
- 682 Salin, K., Auer, S.K., Rudolf, A.M., Anderson, G.J., Selman, C. & Metcalfe, N.B.
683 (2016b). Variation in Metabolic Rate among Individuals Is Related to Tissue-
684 Specific Differences in Mitochondrial Leak Respiration. *Physiological And*
685 *Biochemical Zoology*, **89**, 511–523.
- 686 Samour, J. (2006). Diagnostic value of hematology. *Clinical avian medicine*, **2**, 587-
687 609.
- 688
- 689 Schwartz, T.S., Arendsee, Z.W. & Bronikowski, A.M. (2015). Mitochondrial divergence
690 between slow- and fast-aging garter snakes. *Experimental Gerontology*, **71**, 135-146.
- 691 Sheldon, L.D., Chin, E.H., Gill, S.A. & Schmaltz, G. (2008). Effects of blood collection
692 on wild birds: an update. *Journal of Avian Biology*, **39**, 369-378.
- 693 Sjövall, F., Ehinger, J.K.H., Marelsson, S.E., Morota, S., Åsander Frostner, E., Uchino,
694 H., Lundgren, J., Arnbjörnsson, E., Hansson, M.J., Fellman, V. & Elmér, E. (2013).
695 Mitochondrial respiration in human viable platelets—Methodology and
696 influence of gender, age and storage. *Mitochondrion*, **13**, 7–14.
- 697 Speakman, J. et al. (2015). Oxidative stress and life histories: unresolved issues and
698 current needs. *Ecology and Evolution*, **5**, 5745–5757.
- 699 Stier, A., Bize, P., Schull, Q., Zoll, J., Singh, F., Geny, B., Gros, F., Royer, C., Massemin,
700 S. & Criscuolo, F. (2013). Avian erythrocytes have functional mitochondria,
701 opening novel perspectives for birds as animal models in the study of ageing.
702 *Frontiers in zoology*, **10**, 33.
- 703 Stier, A., Bize, P., Roussel, D., Schull, Q., Massemin, S. & Criscuolo, F. (2014a).
704 Mitochondrial uncoupling as a regulator of life-history trajectories in birds: an
705 experimental study in the zebra finch. *Journal Of Experimental Biology*, **217**,
706 3579–3589.
- 707 Stier, A., Bize, P., Hald, C., Bouillaud, F., Massemin, S. & Criscuolo, F. (2014b).
708 Mitochondrial uncoupling prevents cold-induced oxidative stress: a case study
709 using UCP1 knockout mice. *Journal Of Experimental Biology*, **217**, 624–630.
- 710 Stier, A., Massemin, S. & Criscuolo, F. (2014c). Chronic mitochondrial uncoupling
711 treatment prevents acute cold-induced oxidative stress in birds. *Journal Of*
712 *Comparative Physiology B*, **184**, 1021–1029.
- 713 Stier, A., Reichert, S., Criscuolo, F. & Bize, P. (2015). Red blood cells open promising
714 avenues for longitudinal studies of ageing in laboratory, non-model and wild
715 animals. *Experimental Gerontology*, **71**, 118–134.
- 716 Toews, D.P.L., Mandic, M., Richards, J.G. & Irwin, D.E. (2013). MIGRATION,
717 MITOCHONDRIA, AND THE YELLOW-RUMPED WARBLER. *Evolution*, **68**, 241–255.

- 718 Viblanc, V.A., Dobson, F.S., Stier, A. & Schull, Q. (2015). Mutually honest?
719 Physiological 'qualities' signalled by colour ornaments in monomorphic king
720 penguins. *Biological Journal of The Linnean Society*, **118**, 200-214.
- 721 White, D.J., Wolff, J.N., Pierson, M. & Gemmell, N.J. (2008). Revealing the hidden
722 complexities of mtDNA inheritance. *Molecular Ecology*, **17**, 4925–4942.
- 723 Wolff, J.N., Ladoukakis, E.D., Enriquez, J.A. & Dowling, D.K. (2014). Mitonuclear
724 interactions: evolutionary consequences over multiple biological scales.
725 *Philosophical Transactions of the Royal Society B: Biological Sciences*, **369**,
726 20130443.

727

728

729

730

731

732

733

734

735

736

737

738

739

740

741

742

743

744

745

746

747

748

749

750

For Review Only

751 **Table 1.** Calculation and meaning of mitochondrial parameters measured in intact
 752 RBCs. Mitochondrial parameters are derived from changes in O₂ consumption in
 753 response to specific mitochondrial agonists/antagonists (i.e. respiration rates
 754 $R_{agonists/antagonists}$, see also Fig. 2A).

Parameter	Calculation	Information
ROUTINE	$R_{baseline} - R_{antimycinA}$	Mitochondrial O ₂ consumption under endogenous cellular conditions
OXPHOS	$R_{baseline} - R_{oligomycin}$	O ₂ consumption used for ATP synthesis: ability of mitochondria to produce ATP via oxidative phosphorylation (OXPHOS)
LEAK	$R_{oligomycin} - R_{antimycinA}$	O ₂ consumed by mitochondrial proton leak: proton leakiness of the mitochondria
ETS	$R_{FCCP} - R_{antimycinA}$	Maximum capacity of the electron transport system (ETS) under the current cellular state (i.e. availability/oxidation of substrates)
FCR_{L/R}	$LEAK \div ROUTINE$	Fraction of ROUTINE respiration being linked to mitochondrial proton LEAK: coupling efficiency of the mitochondria between O ₂ consumption and ATP production under endogenous cellular conditions
FCR_{L/ETS}	$LEAK \div ETS$	Fraction of ETS maximum capacity being linked to mitochondrial proton LEAK: coupling efficiency of the mitochondria between O ₂ consumption and ATP production under stimulated conditions
FCR_{R/ETS}	$ROUTINE \div ETS$	Fraction of ETS maximum capacity used by the cell under endogenous cellular conditions

Table 2. Repeatability of measures of mitochondrial function based on 14 samples ran in duplicates. Two indicators of repeatability are shown: the intra-class coefficients of correlations (ICC) and the coefficient of variation (CV). *P*-values associated with ICC are given between brackets. Repeatability estimates are reported both for uncorrected parameters and for parameters corrected by the fresh mass of red blood cells, except for FCRs since they are ratios (*NA* = not attributed).

Parameter	Raw value ICC	CV ± SE (%)	Mass corrected ICC	CV ± SE (%)
<i>ROUTINE</i>	0.884 (< 0.001)	6.6 ± 1.1	0.934 (< 0.001)	6.2 ± 1.0
<i>OXPHOS</i>	0.915 (< 0.001)	6.3 ± 1.1	0.947 (< 0.001)	6.3 ± 1.2
<i>LEAK</i>	0.873 (< 0.001)	10.4 ± 1.9	0.912 (< 0.001)	9.3 ± 1.5
<i>ETS</i>	0.876 (< 0.001)	9.2 ± 2.1	0.930 (< 0.001)	7.4 ± 1.3
<i>FCR_{L/R}</i>	0.924 (< 0.001)	5.8 ± 1.2	NA	NA
<i>FCR_{L/ETS}</i>	0.915 (< 0.001)	7.6 ± 1.6	NA	NA
<i>FCR_{R/ETS}</i>	0.943 (< 0.001)	6.2 ± 1.4	NA	NA

755 **Table 3.** Correlations between mitochondrial parameters measured in intact RBCs and in
 756 permeabilized pectoral muscle fibers fuelled either with pyruvate-malate (complex I
 757 substrate) or succinate (complex II substrate). Spearman non-parametric coefficients of
 758 correlation (ρ) are reported along with their associated p-values (N = 13 for pyruvate-malate
 759 and N = 14 for succinate). Significant ($p \leq 0.05$) and marginal effects ($p \leq 0.10$) are shown in
 760 bold and plotted in figure 5.

761
 762

763

Muscle RBCs	Pyruvate-Malate	Succinate
<i>ROUTINE</i>	$\rho = 0.709$ ($p = 0.007$)	$\rho = 0.248$ ($p = 0.392$)
<i>OXPPOS</i>	$\rho = 0.615$ ($p = 0.025$)	$\rho = 0.503$ ($p = 0.067$)
<i>LEAK</i>	$\rho = 0.341$ ($p = 0.255$)	$\rho = 0.512$ ($p = 0.061$)
<i>ETS</i>	$\rho = 0.071$ ($p = 0.817$)	$\rho = 0.727$ ($p = 0.003$)
<i>FCR_{L/R}</i>	$\rho = 0.390$ ($p = 0.188$)	$\rho = 0.231$ ($p = 0.427$)
<i>FCR_{L/ETS}</i>	$\rho = -0.258$ ($p = 0.394$)	$\rho = 0.789$ ($p = 0.001$)
<i>FCR_{R/ETS}</i>	$\rho = 0.148$ ($p = 0.629$)	$\rho = 0.103$ ($p = 0.725$)

764

765

766 **Fig. 1.** The mitochondrion and OXPHOS system.

767

768 **Fig. 2.** Bioenergetics assessment of intact red blood cells: **(A) typical mitochondrial**
769 **measurement run showing** O₂ concentration (blue line) and O₂ consumption (red line) in
770 response to the injection of oligomycin (inhibitor of ATP synthase), FCCP (protonophore
771 stimulating mitochondrial respiration by abolishing proton gradient) and Antimycin A
772 (inhibitor of mitochondrial respiration). Mitochondrial parameters of interest: *ROUTINE*,
773 *LEAK*, *OXPHOS* and *ETS* are also shown (see Table 1 for definitions). **(B) average responses to**
774 **the mitochondrial agonists/antagonists** in terms of O₂ consumption (N = 18). **(C)**
775 **mitochondrial parameters of interest** (N = 18, see Table 1 for definitions). Means are
776 quoted ± SE and different letters indicate significant differences according to GEE models
777 and associated post-hoc tests.

778

779 **Fig 3.** Mitochondrial parameters of the same samples measured 4 or 24h after collection:
780 **(A) mitochondrial respiration rates, and (B) mitochondrial flux control ratios.** Means are
781 quoted ± SE (N = 8) and non-significant effects (*ns*) and significant effects (*) are indicated;
782 see Table 1 for the calculation and definition of the different parameters.

783

784 **Fig. 4:** Mitochondrial parameters of the same individuals sampled once before 4 minutes
785 of handling, and once after 30 minutes of standardized handling: **(A) mitochondrial**
786 **respiration rates and (B) mitochondrial flux control ratios.** Means are quoted ± SE (N = 23)
787 and non-significant effects (*ns*) are indicated; see Table 1 for the calculation and definition of
788 the different parameters.

789

790 **Fig 5. Correlations between mitochondrial parameters measured in intact RBCs and in**
791 **permeabilized pectoral muscle fibres** fuelled either with pyruvate-malate (complex I
792 substrate, N = 13) or succinate (complex II substrate, N = 14). Significant correlations ($p <$
793 0.05) are indicated by a solid line and marginally significant correlations ($p < 0.10$) by a
794 dashed line; see Table 1 for the calculation and definition of the different parameters and
795 Table 3 for statistical values.
796

For Review Only

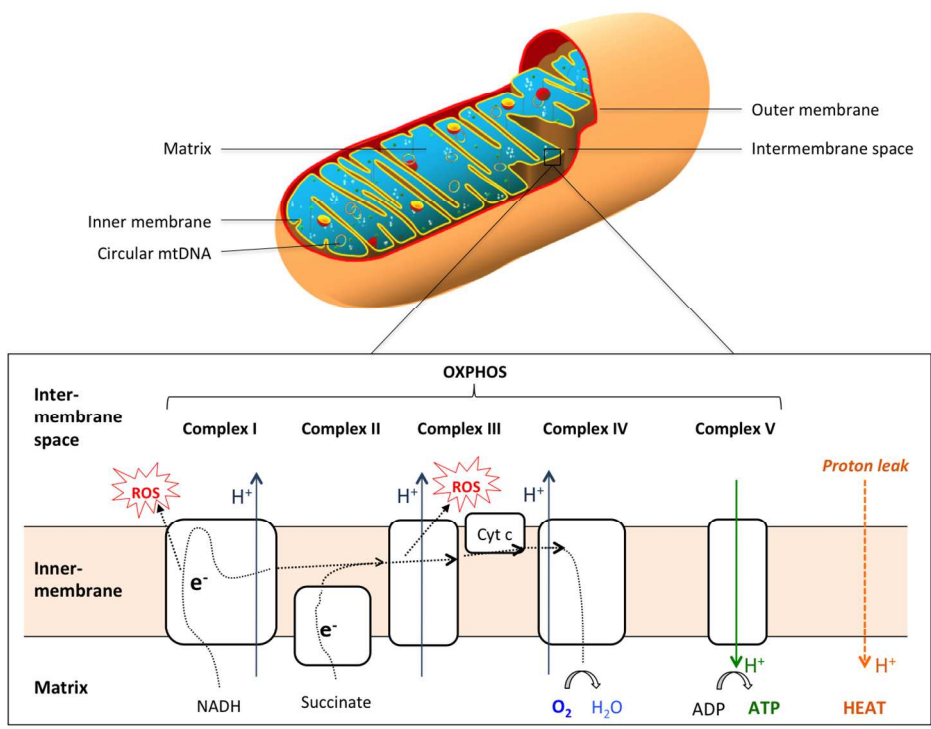


Fig. 1. The mitochondrion and OXPHOS system.
Fig. 1

View Only

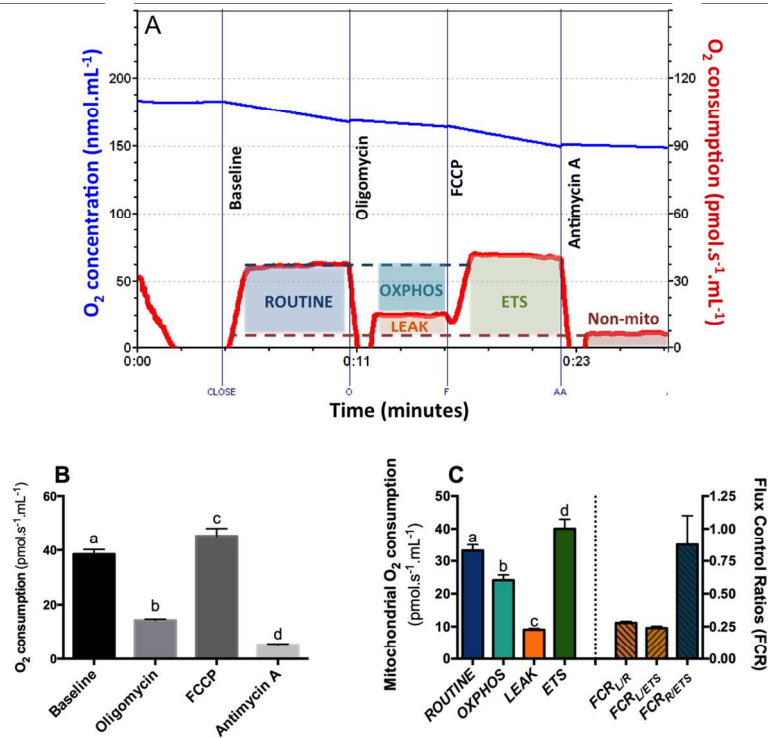


Fig. 2. Bioenergetics assessment of intact red blood cells: (A) typical mitochondrial measurement run showing O₂ concentration (blue line) and O₂ consumption (red line) in response to the injection of oligomycin (inhibitor of ATP synthase), FCCP (protonophore stimulating mitochondrial respiration by abolishing proton gradient) and Antimycin A (inhibitor of mitochondrial respiration). Mitochondrial parameters of interest: ROUTINE, LEAK, OXPHOS and ETS are also shown (see Table 1 for definitions). (B) average responses to the mitochondrial agonists/antagonists in terms of O₂ consumption (N = 18). (C) mitochondrial parameters of interest (N = 18, see Table 1 for definitions). Means are quoted \pm SE and different letters indicate significant differences according to GEE models and associated post-hoc tests.

Fig 2

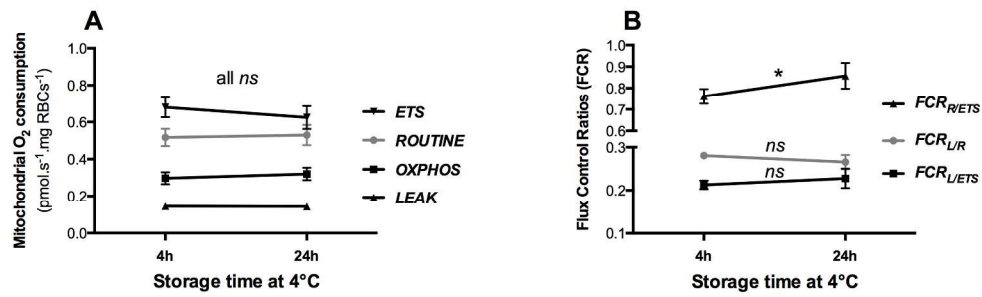


Fig 3. Mitochondrial parameters of the same samples measured 4 or 24h after collection: (A) mitochondrial respiration rates, and (B) mitochondrial flux control ratios. Means are quoted \pm SE (N = 8) and non-significant effects (ns) and significant effects (*) are indicated; see Table 1 for the calculation and definition of the different parameters.

Fig 3

228x71mm (300 x 300 DPI)

Review Only

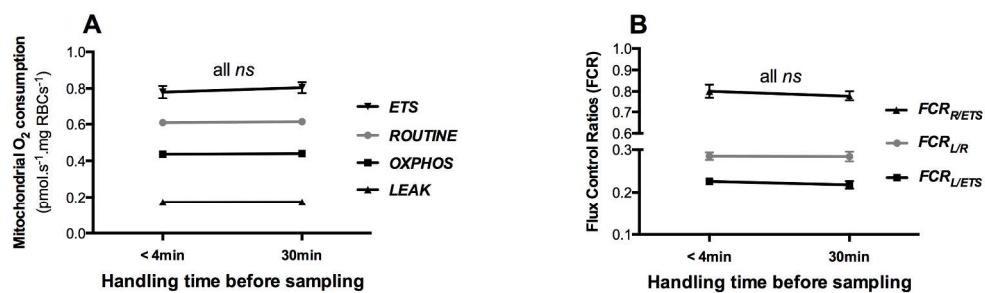


Fig. 4: Mitochondrial parameters of the same individuals sampled once before 4 minutes of handling, and once after 30 minutes of standardized handling: (A) mitochondrial respiration rates and (B) mitochondrial flux control ratios. Means are quoted \pm SE (N = 23) and non-significant effects (ns) are indicated; see Table 1 for the calculation and definition of the different parameters.

Fig 4

232x72mm (300 x 300 DPI)

Review Only

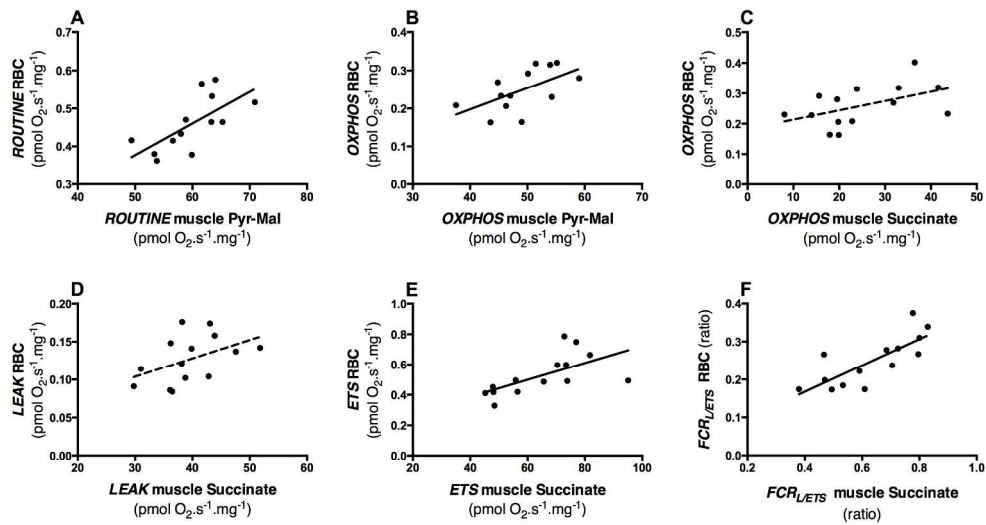


Fig 5. Correlations between mitochondrial parameters measured in intact RBCs and in permeabilized pectoral muscle fibres fuelled either with pyruvate-malate (complex I substrate, $N = 13$) or succinate (complex II substrate, $N = 14$). Significant correlations ($p < 0.05$) are indicated by a solid line and marginally significant correlations ($p < 0.10$) by a dashed line; see Table 1 for the calculation and definition of the different parameters and Table 3 for statistical values.

Fig 5

241x135mm (300 x 300 DPI)