



**HAL**  
open science

## Lactate signaling and fuel selection in rainbow trout: mobilization of energy reserves

Giancarlo Talarico, Elisa Thorald, Elie Farhat, Loïc Teulier, Jan Mennigen,  
Jean-Michel Weber

### ► To cite this version:

Giancarlo Talarico, Elisa Thorald, Elie Farhat, Loïc Teulier, Jan Mennigen, et al.. Lactate signaling and fuel selection in rainbow trout: mobilization of energy reserves. *AJP - Regulatory, Integrative and Comparative Physiology*, 2023, 325 (5), pp.R556-R567. 10.1152/ajpregu.00033.2023 . hal-04250094

**HAL Id: hal-04250094**

**<https://hal.science/hal-04250094v1>**

Submitted on 19 Oct 2023

**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.

**Lactate signaling and fuel selection in rainbow trout:**

**Mobilization of energy reserves**

Giancarlo G.M. Talarico <sup>1</sup>, Elisa Thorat <sup>1,2</sup>, Elie Farhat <sup>1</sup>, Loïc Teulier <sup>2</sup>, Jan A. Mennigen <sup>1</sup>  
and Jean-Michel Weber <sup>1\*</sup>

<sup>1</sup> Biology Department, University of Ottawa, Ottawa, Ontario, Canada

<sup>2</sup> Univ Lyon, Université Claude Bernard Lyon 1, CNRS, ENTPE, UMR 5023 LEHNA,  
F69622, Villeurbanne, France

**Running head:** Lactate signaling and fuel selection in fish

**Supplemental material available at:** <https://doi.org/10.6084/m9.figshare.22006769>

**\* Address correspondence to:**

Jean-Michel Weber  
Biology, University of Ottawa  
30 Marie Curie, Ottawa, Ontario  
Canada K1N 6N5  
E-mail: [jmweber@uOttawa.ca](mailto:jmweber@uOttawa.ca)  
ORCID 0000-0003-2218-2952  
Phone: (613) 562-5800 ext. 6008  
Fax: (613) 562-5486

## 1 **Abstract**

2 Lactate is now recognized as a regulator of fuel selection in mammals because it  
3 inhibits lipolysis by binding to the hydroxycarboxylic acid receptor 1 (HCAR1). The goals  
4 of this study were to quantify the effects of exogenous lactate on: (i) lipolytic rate or rate  
5 of appearance of glycerol in the circulation ( $R_a$  glycerol) and hepatic glucose production  
6 ( $R_a$  glucose), and (ii) key tissue proteins involved in lactate signaling, glucose transport,  
7 glycolysis, gluconeogenesis, lipolysis and  $\beta$ -oxidation in rainbow trout. Measurements of  
8 fuel mobilization kinetics show that lactate does not affect lipolysis as it does in  
9 mammals ( $R_a$  glycerol remains at  $7.3 \pm 0.5 \mu\text{mol kg}^{-1} \text{min}^{-1}$ ), but strongly reduces  
10 hepatic glucose production ( $16.4 \pm 2.0$  to  $8.9 \pm 1.2 \mu\text{mol kg}^{-1} \text{min}^{-1}$ ). This reduction is  
11 likely induced by decreasing gluconeogenic flux through the inhibition of cytosolic  
12 phosphoenolpyruvate carboxykinase (Pck1, alternatively called Pepck1; 60% and 24%  
13 declines in gene expression and protein level, respectively). It is also caused by lactate  
14 substituting for glucose as a fuel in all tissues except white muscle that increases *glut4a*  
15 expression and has limited capacity for monocarboxylate transporter (Mct)-mediated  
16 lactate import. We conclude that lipolysis is not affected by hyperlactatemia because  
17 trout show no activation of autocrine Hcar1 signaling (gene expression of the receptor is  
18 unchanged or even repressed in red muscle). Lactate regulates fuel mobilization via  
19 Pck1-mediated suppression of gluconeogenesis and by replacing glucose as a fuel.  
20 This study highlights important functional differences in the Hcar1 signaling system  
21 between fish and mammals for the regulation of fuel selection.

22 **Keywords:** fish metabolism, lactate, lipolysis, hepatic glucose production,  
23 carbohydrates, lipids, Hcar1.

## 24 INTRODUCTION

25 In addition to its traditional roles as glycolytic end-product, oxidative fuel and  
26 gluconeogenic precursor, lactate is now recognized as an essential metabolic signal (1-  
27 5). The hydroxycarboxylic acid receptor (HCAR1: a G-protein coupled receptor  
28 previously called GPR81) was originally identified as a key binding target for lactate in  
29 mammalian adipocytes (6), but has since been detected in muscle (7-9) and liver (10),  
30 among others. It has now also been found in fish (11, 12). Upon lactate binding, the  
31 HCAR1 receptor acts via the G<sub>i</sub> protein to inhibit the cAMP/PKA pathway (8). Functional  
32 studies have linked this lactate-induced HCAR1 signaling pathway to lipid metabolism in  
33 several tissues, notably the retention of neutral lipids through the inhibition of lipolysis in  
34 adipose tissue (13), the inhibition of lipolysis in muscle (7-9), and conversely, enhanced  
35 lipid oxidation in the (fasted) liver (10). Studies probing the metabolic roles of HCAR1  
36 lactate signaling in muscle have also reported stimulation of mitochondrial biogenesis,  
37 both via cAMP/PKA dependent and independent pathways (7-9). In muscle, lactate has  
38 been found to mediate these effects via a positive autocrine feedback loop because  
39 acute and chronic lactate administration resulted in dose-dependent increases in  
40 HCAR1 mRNA and protein abundance *in vitro* and *in vivo* (7-9). Importantly, this  
41 feedback loop appears to be dependent on the suppression of cAMP signaling (8),  
42 suggesting that the (auto)stimulation of HCAR1 expression and translation is an  
43 indicator of HCAR1 signaling activity.

44 Multiple factors affecting metabolic fuel selection have been characterized in fish,  
45 particularly rainbow trout (14). Glucose mobilization (the rate of hepatic glucose  
46 production or  $R_a$  glucose) is reduced by exogenous glucose or alanine (15, 16), insulin

47 (17), propranolol (18), prolonged swimming (19) and low temperature (20), but it is  
48 stimulated by epinephrine (18). The mobilization of lipid reserves (lipolysis or rate of  
49 appearance of glycerol in the circulation:  $R_a$  glycerol) is also increased by epinephrine,  
50 but contrary to its effect in mammals, it is inhibited by norepinephrine in fish (21).  
51 Surprisingly, fish lipolytic rate remains unaffected by endurance swimming (22) or  
52 graded exercise up to critical swimming speed ( $U_{crit}$ ) (23). Whether lactate signaling or  
53 Hcar1 are involved in modulating fuel selection in fish is unknown. Therefore, this study  
54 aims to determine how exogenous lactate modulates fuel selection *in vivo* by measuring  
55 its effects on hepatic glucose production and lipolytic rate of rainbow trout. Exogenous  
56 supply rather than exercise-induced hyperlactatemia was selected here to focus on  
57 lactate as a signal and to avoid the confounding impact of the metabolic, hormonal, and  
58 neural changes caused by swimming. Our goals were to quantify the effects of elevated  
59 lactate levels on: (i)  $R_a$  glucose and  $R_a$  glycerol, and (ii) key tissue proteins involved in  
60 lactate signaling or carbohydrate and lipid metabolism that could potentially explain the  
61 observed behavior of glucose and glycerol kinetics. We anticipated that lactate would  
62 cause the Hcar1-mediated inhibition of lipolysis as it does in mammals (24, 25) and a  
63 decrease in hepatic glucose production (24). It was predicted that these trout responses  
64 would be reflected by corresponding changes in key regulatory proteins of lipid and  
65 carbohydrate metabolism.

66

## 67 **METHODS**

### 68 **Animals**

69           Hormonally feminized rainbow trout (*Oncorhynchus mykiss*) with a Fulton's  
70 condition factor K of  $1.12 \pm 0.05$  (N=26) [ $K=(10^5 \times M_b) \div L^3$ ]; where  $M_b$  is body mass in  
71 grams and L is total length in millimeters (26)] were purchased from Linwood Acres  
72 Trout Farm (Campbellcroft, Ontario, Canada). They were divided into 3 treatment  
73 groups: for *in vivo* glucose kinetics (series 1 experiments), *in vivo* glycerol kinetics  
74 (series 2 experiments), and tissue measurements of gene expression (qPCR), protein  
75 expression (Western blots) and enzyme activities (series 3 experiments). The physical  
76 characteristics of the 3 groups are in Table 1. All fish were held in a 1,200 L flow-  
77 through tank supplied with dechloraminated Ottawa tap water at 13°C, on a 12 h: 12 h  
78 light: dark photoperiod and they were fed Profishnet floating fish pellets (Martin Mills,  
79 Elmira, ON, Canada) 5 days a week. They were acclimated to these conditions for at  
80 least 3 weeks before experiments. All the procedures were approved by the Animal  
81 Care Committee of the University of Ottawa (protocol BL-1625) and adhered to the  
82 guidelines established by the Canadian Council on Animal Care (CCAC).

83

## 84 **Catheterizations**

85           Fish were anesthetized with ethyl 3-aminobenzoate methanesulfonate (MS-222;  
86  $60 \text{ mg l}^{-1}$  buffered with  $0.2 \text{ g l}^{-1}$  sodium bicarbonate) and surgically fitted with 2  
87 catheters (for the glucose and glycerol kinetics experiments) or a single catheter (for  
88 gene expression, protein expression and enzyme activity experiments) (BTPE-50  
89 catheters, Instech Laboratories, Plymouth Meeting, PA, USA) in the dorsal aorta (27).  
90 The catheters were kept patent by flushing with Cortland's saline containing  $50 \text{ U ml}^{-1}$   
91 heparin (H3393, Sigma-Aldrich, St. Louis, MO, USA). After surgery, the fish were left to

92 recover overnight in a 90 L swim-tunnel (Loligo Systems, Tjele, Denmark) where they  
93 were kept in the resting state at a water velocity of 0.5 body length per second ( $\text{BL s}^{-1}$ ).  
94 This weak current reduces stress and helps the flow of water over the gills, but it does  
95 not require swimming to maintain body position because the animals are sitting at the  
96 bottom of the chamber (15). The swim tunnel was supplied with the same quality water  
97 as the holding tank and kept at  $13^{\circ}\text{C}$ .

98

### 99 **Glucose and glycerol kinetics (series 1 and 2)**

100 The rates of hepatic glucose production (or rate of appearance of glucose:  $R_a$   
101 glucose) and glycerol production (or lipolytic rate:  $R_a$  glycerol) were measured by  
102 continuous infusion of  $[6\text{-}^3\text{H}]$  glucose (American Radiolabeled Chemicals, St. Louis,  
103 MO, USA; specific activity  $2220 \text{ GBq mmol}^{-1}$ ) and  $[2\text{-}^3\text{H}]$  glycerol (American  
104 Radiolabeled Chemicals;  $925 \text{ GBq mmol}^{-1}$ ). These tracer methods have been  
105 thoroughly validated in fish (28) and specifically tested in rainbow trout to assess the  
106 effects of a variety of physiological stresses on  $R_a$  glucose (14, 19, 20, 29). The method  
107 to quantify  $R_a$  glycerol is also well-established for rainbow trout (21-23). All infusates  
108 were freshly prepared immediately before each experiment by drying an aliquot of the  
109 tracer obtained from the supplier under  $\text{N}_2$  and resuspending in Cortland's saline. For  
110 glucose kinetics, a priming dose of tracer equivalent to 3 h of infusion was injected as a  
111 bolus at the start of each infusion to reach isotopic steady state in  $<45 \text{ min}$  (28, 30). A  
112 priming dose was not required to measure glycerol kinetics because the total glycerol  
113 pool is small and isotopic steady state is reached in  $<45 \text{ min}$  without it (21, 23, 30). For  
114 each flux measurement, the infusate was administered continuously at  $\sim 1 \text{ ml h}^{-1}$  (the

115 exact infusion rate was determined for each fish to adjust for differences in body mass)  
116 using a calibrated syringe pump (Harvard Apparatus, South Natick, MA). Infusion rates  
117 averaged  $1523 \pm 36 \text{ Bq kg}^{-1} \text{ min}^{-1}$  (N=8) for labeled glucose and  $9227 \pm 297 \text{ Bq kg}^{-1}$   
118  $\text{min}^{-1}$  (N=10) for labeled glycerol. These trace amounts (labeled + unlabeled  
119 metabolites) had no effect on glucose or glycerol metabolism because they accounted  
120 for  $<0.0000001\%$  of baseline endogenous hepatic glucose production (glucose kinetics)  
121 and  $<0.00001\%$  of baseline endogenous rate of appearance of glycerol in the circulation  
122 (glycerol kinetics). Blood samples ( $\sim 100 \mu\text{l}$  each) were drawn 50, 55 and 60 min after  
123 starting the tracer infusion to quantify baseline glucose or glycerol kinetics, and every 20  
124 min thereafter during a 3 h administration of exogenous lactate at a rate of  $30 \mu\text{mol kg}^{-1}$   
125  $\text{min}^{-1}$ . Lactate was infused at  $\sim 1 \text{ ml h}^{-1}$ , but the exact rate was adjusted individually for  
126 each fish to correct for differences in body mass. This rate is equivalent to twice the  
127 baseline endogenous rate of lactate release in the circulation (31) and caused a gradual  
128 increase in blood lactate concentration that reached  $\sim 13 \text{ mM}$  after 3 h in previous  
129 experiments (32). The total amount of blood sampled from each fish accounted for  
130  $<10\%$  of the total blood volume. Blood samples were immediately centrifuged to  
131 separate plasma (5 min; 13,000 RPM) and stored at  $-20^\circ\text{C}$  until analyses.

132

### 133 **Blood sample analyses for metabolite kinetics (series 1 and 2)**

134 Plasma lactate, glucose and glycerol concentrations were measured  
135 spectrophotometrically (Spectra Max Plus 384 Microplate reader, Molecular Devices,  
136 Sunnyvale, CA, USA) using standard  $\text{NAD}^+/\text{NADH}$ -coupled enzymatic assays at 340  
137 nm (16, 33). Radioactivity was measured by scintillation counting (Perkin-Elmer Tricarb



138 2910TR, Waltham, MA, USA) in Bio-Safe II™ scintillation cocktail (Research Products  
139 International, Mt Prospect, IL, USA). [6-<sup>3</sup>H] glucose activity was measured after drying  
140 each plasma sample under N<sub>2</sub> to eliminate tritiated H<sub>2</sub>O. [2-<sup>3</sup>H] glycerol activity was  
141 measured by incubating samples with ATP and hexokinase to phosphorylate the  
142 labeled free glucose that was then removed by ion-exchange column chromatography  
143 [DOWEX-1 (formate form) and DOWEX-50 (HCl form)] before drying under N<sub>2</sub> (33). A  
144 previous study had shown that 10.6 ± 0.9% of labelled glycerol is lost during this  
145 separation procedure (23) and glycerol activities were corrected accordingly.

146

### 147 **Tissue measurements (series 3)**

148 To avoid working with radioactive tissues, these experiments were carried out on  
149 a different group of fish than series 1 and 2. Fish saline (control group) or lactate  
150 (treatment group; 30 μmol lactate kg<sup>-1</sup> min<sup>-1</sup>) was administered at ~1 ml h<sup>-1</sup> for 3 h. Blood  
151 samples were taken before starting saline or lactate administration (0 h) and after 3 h of  
152 saline or lactate infusion. The animals were then euthanized by a sharp blow on the  
153 head and tissues were collected. The whole liver, red muscle (along the lateral line) and  
154 white muscle (perpendicular to the dorsal fin) were collected and stored at -80°C until  
155 analyses.

156

### 157 *RNA extraction and gene expression*

158 Total RNA from liver, red and white muscle was extracted and quantified as  
159 previously (16, 34). QuantiTect reverse transcriptase kit (Qiagen, Toronto, ON, Canada)  
160 was used to generate cDNA using total RNA and following the manufacturer's protocol.

161 Two-step real-time RT-PCR assays were performed to quantify fold-changes in relative  
162 hepatic mRNA abundances of the lactate-sensitive hydroxycarboxylic acid receptor 1  
163 (*hcar1*), key gluconeogenic transcripts (phosphoenolpyruvate carboxykinase, *pck1*,  
164 *pck2a*, *pck2b* and glucose-6-phosphatase, *g6pca*, *g6pcb1a*, *g6pcb1b*) and glucose  
165 transporters (*glut4a* and *glut4b*, alternatively called *slc2a4*). Additionally, multiple  
166 transcripts involved in lipid metabolism were measured: fatty acid oxidation [carnitine  
167 palmitoyltransferase 1; *cpt1* (NM\_001124735.1 which is equivalent to Trout\_B1b as  
168 described in Morash et al., 2010) , hydroxyacyl CoA dehydrogenase; *hoad*), transport  
169 (fatty acid translocase; *cd36*) and synthesis (fatty acid synthase; *fasn*). Standard curves  
170 from pooled cDNA serial dilution were generated to optimize reaction conditions and  
171 diluted samples were run in duplicates. Negative controls (no-reverse transcriptase and  
172 no-template) were included in each assay to control for DNA contamination. All primer  
173 sequences and amplification efficiencies are presented in Tables S2 (carbohydrate  
174 metabolism targets) and S3 (lipid metabolism targets). Amplification efficiencies were  
175 calculated from serially diluted 7-point standard curves and ranged between 92.8-  
176 108.7%, with  $R^2$  values  $>0.93$ . Relative transcript abundance derived from standard  
177 curves was normalized using the NORMA-Gene procedure (35). Finally, mRNA fold  
178 changes were calculated relative to the control group.

179

### 180 *Western blotting*

181 Total protein from liver, red and white muscle was extracted, quantified and  
182 prepared as previously (34) using a protease inhibitor, (88665, Thermo Fisher Scientific,  
183 Waltham, MA, USA), kinase inhibitor (S1504, Sigma-Aldrich) and phosphatase inhibitor

184 (S6508, Sigma-Aldrich). Proteins were migrated for 2 h at 100 V and blotted at 100 V for  
185 2 h on nitrocellulose membrane (pore size 0.2  $\mu\text{m}$ , Bio-Rad Laboratories, Hercules, CA,  
186 USA) in 20% Western transfer buffer. The membranes were incubated in Odyssey  
187 blocking buffer (LI-COR Biosciences, Lincoln, NE, USA) for 1 h at room temperature.  
188 Membranes were incubated overnight at 4°C in rabbit-raised Pck1 (A2036) and Glut4  
189 (A7637) primary antibodies (ABclonal Technology, Woburn, MA, USA). Membranes  
190 were washed and incubated with IRDye 800 CW goat-anti-rabbit secondary antibody  
191 (925-32211, LI-COR) for 1.5 h at room temperature, protected from light. The primary  
192 and secondary antibodies were diluted 1:500 and 1:20,000, respectively, as advised by  
193 the manufacturers. Following incubation, the membranes were washed and visualized  
194 by infrared fluorescence using the Odyssey Imaging System (LI-COR Biosciences)(16,  
195 34). Band intensity was quantified by Odyssey Infrared Imaging System software (v.3.0;  
196 LI-COR Biosciences), normalized to total protein stain intensity and expressed as a  
197 relative-fold change compared with control groups for all tissue.

198

### 199 *Enzyme activities*

200 Tissue homogenates were prepared as previously (36). Enzyme activity was  
201 determined kinetically at 21.0°C by measuring the oxidation of NADH or reduction of  
202  $\text{NADP}^+$  at 340 nm and expressed in  $\mu\text{mol min}^{-1} \text{g}^{-1}$  protein. The activity was assayed in  
203 triplicate. Control reactions were run for 10 min for each enzyme assay after adding  
204 reagents. Background activity was subtracted from enzyme activity. The conditions  
205 of the individual enzyme assay were as detailed below (values given are final  
206 concentrations in the well). Hexokinase (Hk; EC 2.7.1.1) and glucokinase (Gck; EC

207 2.7.1.2) assay mixture contained 300 mM imidazole, 100 mM KCl, 10 mM MgCl<sub>2</sub>, 1 mM  
208 NADP<sup>+</sup>, 5 U ml<sup>-1</sup> G6PDH, 5 mM ATP and glucose (omitted for control), 5 mM for Hk and  
209 50 mM for Gck, reflecting different affinities for the substrate. Phosphoenolpyruvate  
210 carboxykinase (Pck; EC 4.1.1.32) reaction mixture contained 50 mM imidazole, 20 mM  
211 NaHCO<sub>3</sub>, 1 mM MnCl<sub>2</sub>, 0.5 mM PEP (Na<sub>3</sub>), 0.12 mM NADH, 6 U ml<sup>-1</sup> malate  
212 dehydrogenase and 0.2 mM deoxyguanosine diphosphate (dGDP; omitted for control).  
213 Hydroxyacyl CoA dehydrogenase (Hoad; EC 1.1.1.35) reaction mixture contained 50  
214 mM imidazole, 5 mM EDTA, 1 mM KCN, 0.05 mM NADH and 0.1 mM acetoacetyl CoA  
215 (omitted for control).

216

### 217 **Calculations and statistics**

218  $R_a$  glucose and  $R_a$  glycerol were calculated using the steady-state equation of  
219 Steele (37), where  $R_a$  (in  $\mu\text{mol kg}^{-1} \text{min}^{-1}$ ) is the infusion rate of labeled glucose or  
220 glycerol (in  $\text{Bq kg}^{-1} \text{min}^{-1}$ ) divided by the measured specific activity of glucose or glycerol  
221 (in  $\text{Bq } \mu\text{mol}^{-1}$ ). Statistical comparisons for metabolite kinetics (series 1 and 2) were  
222 performed using one-way repeated-measures analysis of variance (RM-ANOVA) with  
223 the Dunnett's post hoc test to determine which time points were statistically different  
224 from baseline. Glucose, glycerol and lactate concentrations were analyzed by two-way  
225 RM ANOVA (series 3; table 3), where the treatment and (sampling) time were the  
226 effects. Based on rearing conditions, body mass between experimental series were  
227 different. Gene expression, protein expression and enzyme activity results were  
228 analyzed using a two-tailed unpaired t-test to assess the effects of lactate. Before all  
229 tests, normality and homoscedasticity were assessed using the Shapiro-Wilk and

230 Levene's test, respectively. When the assumptions of normality or equality of variances  
231 were not met, the data were normalized by natural logarithm or square root  
232 transformation. When transformation failed to normalize the distribution, Kruskal-Wallis  
233 non-parametric one-way ANOVA on ranks (series 1 and 2) or non-parametric Mann-  
234 Whitney U test (series 3) were performed. Values presented are means  $\pm$  s.e.m. and a  
235 level of significance of  $P < 0.05$  was used in all tests.

236

## 237 **RESULTS**

### 238 **Series 1: Glucose kinetics**

239 During the measurement of glucose kinetics, exogenous lactate infusion had no  
240 effect on plasma glucose concentration ( $p > 0.05$ ; Fig. 1A), but progressively increased  
241 plasma lactate concentration to  $10.9 \pm 0.4$  mM over 3 hours ( $p < 0.001$ ; Fig. 1B and  
242 Table 2). Elevating plasma lactate caused an increase in glucose specific activity  
243 ( $p < 0.001$  at 1 h and  $p < 0.05$  at 2.33 h; Fig. 2A) and a decrease in hepatic glucose  
244 production from a baseline rate of  $16.4 \pm 2.0$   $\mu\text{mol kg}^{-1} \text{min}^{-1}$  to a final value of  $8.9 \pm$   
245  $1.2$   $\mu\text{mol kg}^{-1} \text{min}^{-1}$ . ( $p < 0.001$ ; Fig. 2B and Table 2).

246

### 247 **Series 2: Glycerol kinetics**

248 During the measurement of glycerol kinetics, the infusion of exogenous lactate  
249 caused large increases in plasma glycerol concentration ( $p < 0.001$ ; Fig. 3A) and plasma  
250 lactate concentration ( $p < 0.001$ ; Fig. 3B). Glycerol concentration doubled and lactate  
251 concentration reached  $10.5 \pm 1.4$  mM, a level similar to the glucose kinetics  
252 experiments (Table 2). Increasing the availability of plasma lactate caused minor

253 fluctuations in glycerol specific activity (Fig. 4A;  $p<0.05$ ) and glycerol production or rate  
254 of lipolysis ( $p<0.05$ ; Fig. 4B). For these 2 parameters, however, post-hoc tests could not  
255 identify any particular means that were significantly different from baseline (Fig. 4 and  
256 Table 2).

257

### 258 **Series 3: Gene expression, protein signaling and enzyme activities**

#### 259 *Metabolite concentrations*

260 Plasma metabolite concentrations of the fish used for tissue measurements  
261 (series 3) and their statistical analyses are in Table 3. Control animals that received a  
262 saline infusion showed no changes in glucose, glycerol or lactate levels. Those given an  
263 infusion of exogenous lactate also maintained steady glucose concentration, but more  
264 than doubled glycerol concentration. In addition, they showed a large increase in  
265 plasma lactate concentration like the animals used to measure *in vivo* metabolite fluxes  
266 (series 1 and 2). Interactions between time and treatment effects were significant for  
267 glycerol and lactate concentrations.

268

#### 269 *Gene expression*

270 Exogenous lactate reduced the relative mRNA expression of the  
271 hydroxycarboxylic acid 1 (lactate) receptor *hcar1* in red muscle ( $p<0.01$ ), showed a non-  
272 significant trend to decrease it in white muscle ( $p=0.057$ ), and had no effect in liver  
273 ( $p>0.05$ ; Fig. 5). The impacts of lactate on target genes that play key roles in the  
274 regulation of carbohydrate and lipid metabolism are shown in Fig. 6. For carbohydrate  
275 metabolism (left panels of Fig. 6), exogenous lactate decreased the relative mRNA

276 abundances of the glucose transporters *glut4a* and *glut4b* in red muscle ( $p < 0.01$  and  
277  $p < 0.001$  respectively), but increased them in white muscle ( $p < 0.05$ ; Fig. 6). In liver,  
278 lactate reduced the relative expression of the *pck1* paralogue of phosphoenolpyruvate  
279 carboxykinase ( $p < 0.05$ ), but had no effect on other paralogues of this gluconeogenic  
280 enzyme (*pck2a* and *pck2b*;  $p > 0.05$ ; Fig. 6). None of the glucose-6-phosphatase  
281 paralogues (*g6pca*, *g6pcb1a* and *g6pcb1b*) were affected by lactate ( $p > 0.05$ ; Fig. 6).  
282 For proteins involved in lipid metabolism (right panels of Fig. 6), the relative transcript  
283 abundance of two  $\beta$ -oxidation enzymes were quantified. Lactate did not affect *cpt1* in  
284 liver, red muscle or white muscle ( $p > 0.05$ ). The relative expression of *hoad* was  
285 stimulated in white muscle ( $p < 0.01$ ), but remained constant in liver and red muscle  
286 ( $p > 0.05$ ; Fig. 6). The relative mRNA expression of *cd36* was decreased in liver ( $p < 0.05$ ),  
287 but remained unaffected by lactate in red and white muscle ( $p > 0.05$ ; Fig. 6). Similarly,  
288 exogenous lactate caused no measurable change in the transcript abundance of *fasn* in  
289 liver ( $p > 0.05$ ; Fig. 6).

290

### 291 *Protein expression*

292 The relative protein abundance of Pck1 and Glut4 was quantified by Western  
293 blotting (Fig. 7). Exogenous lactate decreased the protein expression of Pck1 in liver  
294 ( $p < 0.05$ ), echoing what had been observed for the mRNA abundance of this  
295 gluconeogenic enzyme (Fig. 6). The expression of Glut4 in white or red muscle was not  
296 affected by lactate ( $p > 0.05$ ).

297

### 298 *Enzyme activities*

299           The effects of exogenous lactate on the activities of target enzymes playing key  
300 roles in the regulation of carbohydrate and lipid metabolism are presented in Fig. 8. For  
301 carbohydrate metabolism, lactate caused the activation of Hk in white muscle ( $p < 0.05$ ),  
302 but had no effect on liver Pck, Hk, or Gck ( $p > 0.05$ ). For lipid metabolism, Hoad activity  
303 was reduced by lactate in liver ( $p < 0.01$ ), but remained constant in white and red muscle  
304 ( $p > 0.05$ ; left panels of Fig. 8).

305

## 306 **DISCUSSION**

307           This study shows that high lactate does not inhibit lipolysis in fish as it does in  
308 mammals, but strongly decreases hepatic glucose production. This lack of effect on  
309 lipolytic rate is due to weak putative Hcar1-mediated signaling because the expression  
310 of the trout receptor is not modified by elevated lactate except in red muscle where it  
311 actually declines. Therefore, the known HCAR1 autocrine feedback mechanism that  
312 slows lipolysis in mammals does not seem to operate in fish. Trout  $R_a$  glucose is greatly  
313 reduced by high lactate, likely through a decrease in gluconeogenesis caused by the  
314 inhibition of Pck1. The overall need for glucose may be reduced because it is replaced  
315 by lactate as an oxidative fuel in tissues that readily use carbohydrates, such as brain,  
316 heart, and liver. Indeed, previous work suggests that the majority of lactate produced is  
317 oxidized at rest and during recovery from exercise in rainbow trout (38). The liver (38),  
318 heart (39) and brain (40) can all readily oxidize lactate in the resting state. Opposite  
319 responses in *glut4* expression of red vs white muscle suggest that glucose import is  
320 reduced in red muscle where it is replaced by lactate, but increased in white muscle: a  
321 tissue with a very limited capacity for Mct-mediated transmembrane lactate transport



322 (41). Results emphasize the importance of measuring metabolite fluxes directly rather  
323 than to rely on changes in concentration when investigating metabolic responses.  
324 Without directly quantifying glycerol and glucose kinetics, it would have been impossible  
325 to demonstrate that lactate does not affect lipolysis (because glycerol concentration  
326 increases dramatically) and strongly inhibits hepatic glucose production (because  
327 glycemia remains steady).

328

### 329 **Lactate infusion protocol mimics strenuous exercise**

330 We have administered exogenous lactate in the circulation rather than exercise  
331 the animals. Before starting exogenous supply, the fish showed no signs of stress and  
332 had circulating lactate (~1 mM), glucose (~7 mM) and glycerol levels (~0.2 mM) (Figs. 1  
333 and 3) well within normal resting values (23, 42, 43). Lactate was then infused at twice  
334 the baseline endogenous rate of release in the circulation (31) to reach plasma  
335 concentrations of  $10.9 \pm 0.4$  mM and  $10.5 \pm 1.4$  mM after 3 h in series 1 and 2  
336 experiments, respectively (Figs. 1 and 3, Table 2). The rate of exogenous supply was  
337 equal to the natural endogenous release of trout when swimming at ~3 body lengths/s  
338 (42). Final plasma lactate concentrations were similar to those measured in previous  
339 exogenous supply experiments (32) and closely mimicked a normal increase in blood  
340 lactate induced by strenuous exercise (38, 41).

341

### 342 **High lactate does not inhibit fish lipolysis**

343 The rate of appearance of glycerol in the circulation is the best index of whole-  
344 organism lipolytic rate (30) and it has been widely used to assess lipid mobilization in

345 mammals (33, 44-47) as well as fish (21-23). This study is the first to investigate the  
346 effects of exogenously increased circulating lactate on lipolytic rate *in vivo* for any  
347 species. How lactate modulates glycerol and fatty acid fluxes has never been  
348 measured, and this type of manipulation provides a novel research avenue to improve  
349 the understanding of lactate signaling.

350

351 Elevated lactate levels do not affect trout  $R_a$  glycerol that remains at an average  
352 baseline value of  $7.3 \pm 0.5 \mu\text{mol kg}^{-1} \text{min}^{-1}$  (Fig. 4). This contrasts greatly with the well-  
353 known anti-lipolytic effect of hyperlactatemia reported in mammals (5, 48) and suggests  
354 that other reported responses of mammalian lipid metabolism to lactate, like tissue  
355 triacylglycerol accumulation and lowering of plasma fatty acid levels (7-9) are also  
356 absent in trout. This idea is supported by the observation that lactate has no effect on  
357 the gene expression of *fasn* (Fig. 6), that encodes for a protein essential for lipogenesis  
358 (49, 50). Similarly, the expression of *lpl* does not respond to lactate and *hs1* mRNA  
359 shows opposite responses in red muscle (activation that would oppose lipid storage)  
360 and white muscle (inhibition that would promote storage) (Fig. S1). What could then be  
361 the underlying physiological reasons why lipid metabolism of fish remains mostly  
362 insensitive to lactate? In mammals, lipolytic suppression is mediated by lactate binding  
363 to HCAR1 in adipose tissue and muscle (25). Even though fish possess this lactate  
364 receptor (11, 12), the signaling pathway does not seem to operate in trout because  
365 Hcar1 is not activated by lactate and may therefore have a different function than in  
366 mammals. Mammalian HCAR1 is regulated via an autocrine feedback loop (3) whereby  
367 lactate increases the expression of the receptor (7, 51). In trout, lactate has no

368 stimulating effect on *hcar1* expression in any tissue, and even suppresses it by 78% in  
369 red muscle (Fig. 5). Rainbow trout always maintain very high rates of lipolysis and  
370 triacylglycerol/fatty acid substrate cycling under a wide range of physiological conditions  
371 that include rising plasma lactate concentration up to ~10 mM in the resting state (Fig.  
372 4), endurance exercise lasting several days (22), and graded exercise up to critical  
373 swimming speed (23). In mammals, lactate inhibits lipolysis (5) and similar stresses of  
374 endurance and strenuous exercise cause major changes in fat mobilization (45, 52).  
375 The lack of Hcar1 signaling observed here may be responsible for the high lipolytic  
376 activity and the “lipolytic inertia” commonly observed in fish. Therefore, this study  
377 highlights major functional differences between fish and mammals for the role of lactate  
378 and Hcar1 signaling in metabolic fuel selection.

379

### 380 **High lactate reduces hepatic glucose production**

381 Elevated lactate causes a decline in  $R_a$  glucose from  $16.4 \pm 2.0$  to  $8.9 \pm 1.2$   $\mu\text{mol}$   
382  $\text{kg}^{-1} \text{min}^{-1}$  (Fig. 2B), and this 46% reduction occurs within one hour of exogenous  
383 supply. A similar decrease in resting glucose production was reported in endurance-  
384 trained humans (24), but not in sedentary subjects (53) when circulating lactate was  
385 clamped at 4 mM.  $R_a$  glucose represents the combined contributions of  
386 gluconeogenesis and glycogenolysis, but does not provide information on the relative  
387 importance of each pathway. However, tissue measurements show that a reduction in  
388 gluconeogenic flux is most likely responsible for the observed decrease in total glucose  
389 production because lactate infusion reduces both *pck1* transcript abundance (-60%; Fig.  
390 6) and Pck1 protein levels (-24%; Fig. 7). In mammals, PCK1 is the most significant

391 regulating step of gluconeogenesis. It catalyzes the conversion of oxaloacetate to  
392 phosphoenolpyruvate that serves as a substrate for downstream gluconeogenic  
393 enzymes, among them fructose 1,6-bisphosphatase and glucose-6-phosphatase which  
394 ultimately cause the release of free glucose in the circulation. The Pck1 transcript has a  
395 very short half-life (~30 min) and there is no evidence that Pck is subject to covalent  
396 modifications or allosteric regulation. Its activity depends on transcription and/or *pck1*  
397 degradation (54), and, therefore, the observed inhibition of trout  $R_a$  glucose is caused,  
398 at least in part, by a decrease in gluconeogenesis mediated by the downregulation of  
399 Pck1.

400

401 The role of Pck2, the mitochondrial isozyme, has recently been the subject of  
402 renewed interest, especially in the context of substrate preference for gluconeogenesis  
403 (54-56). Because Pck2 silencing reduces the ability of mammals to use lactate as a  
404 gluconeogenic substrate (56) and hypoxia induces the expression of *pck2b* in rainbow  
405 trout alevins (55), we have quantified the hepatic expression of *pck2* transcripts, but  
406 found no effect of lactate (Fig. 6). The relative expression of cytosolic and mitochondrial  
407 Pck appears to be species, tissue, and physiological state-dependent (54, 57). Overall,  
408 hepatic Pck activity does not change following lactate infusion (Fig. 8) and previous  
409 reports show strong compartmentalization of Pck activity to mitochondria in rainbow  
410 trout (57, 58). This suggests that other factors than changes in *pck1* transcript and  
411 Pck1 protein abundance are involved in reducing  $R_a$  glucose in trout. Therefore, further  
412 work is needed to establish the exact localization of Pck isozymes and to characterize  
413 the relative influence of each on the regulation of trout gluconeogenesis.

414

415

416

417

418

419

420

421

422

423

424

425

426

427

428

429

We have also measured the hepatic expression of several paralogues of glucose-6-phosphatase: the enzyme that liberates glucose from both hepatic *de novo* gluconeogenesis as well as glycogenolysis (58). Lactate has no effect on the expression of *g6pc* paralogues (Fig. 6) and this supports the idea that the decrease in  $R_a$  glucose is mainly caused by upstream gluconeogenic suppression of Pck1. It would be useful to know the phosphorylation status and the activities of glycogen synthase and glycogen phosphorylase, as well as the size of liver glycogen stores to assess potential contributions of glycogen metabolism to the reduction in  $R_a$  glucose. We cannot discard the possibility that changes in  $R_a$  glucose arise from changes in glycogenolysis, but a previous study using labeled lactate shows that, under similar conditions, tracer incorporation into the glucose or glycogen pools is extremely limited (38). Overall, therefore, rainbow trout reduce hepatic glucose production mainly through the inhibition of gluconeogenesis and probably not by modulating glycogen breakdown.

### 429 **Effects of high lactate on fuel selection**

430

431

432

433

434

435

436

Like other animals, trout maintain high rates of lactate production and utilization, even at rest (31, 32, 42). The most important pathway for lactate disposal is oxidation (38) and the end product is a preferred oxidative fuel over other substrates like glucose and fatty acids (14). In trout, lactate oxidation increases strongly with exogenous supply (32) and the contribution of other fuels to energy metabolism decreases accordingly in the liver (38), heart (39) and brain (40) under resting conditions. Here in trout, the high availability of lactate causes the same decrease in circulating glucose utilization as for

437  $R_a$  glucose (Fig. 2B) because glycemia remains constant (Fig. 1A). This decrease in  
438 glucose disposal is driven by a reduction in glucose oxidation potentially supported by  
439 the lowered expression of *gckb* (Fig. 6), although no change in Gck activity could be  
440 detected (Fig. 8). Fatty acid oxidation is another pathway that may be reduced,  
441 particularly in the liver where both transport (*cd36* expression; Fig. 6) and  $\beta$ -oxidation  
442 (Hoad activity; Fig. 8) are inhibited. Overall, therefore, exogenous supply causes the  
443 partial replacement of glucose and fatty acids by lactate as an oxidative fuel for energy  
444 metabolism.

445

#### 446 **Red and white muscles metabolize carbohydrates differently**

447         Hyperlactatemia causes opposite responses in *glut4* paralogue expression of red  
448 (-42% and -43% for *glut4a* and *glut4b*, respectively) versus white muscle (+166% and  
449 +178% for *glut4a* and *glut4b*, respectively) (Fig. 6), suggesting that glucose utilization is  
450 reduced in red muscle and increased in white muscle. Tissue glucose and lactate  
451 metabolism are constrained by transmembrane transport through Glut (59) and Mct  
452 isoforms (41). Substitution of glucose by lactate appears to take place in red muscle,  
453 but may not be possible in white muscle that has an extremely low capacity for lactate  
454 transport. White muscle expresses Mct isoforms very poorly, especially the Mct1  
455 paralogues that specialize in lactate import for oxidation (41). The overall switch from  
456 glucose to lactate seen at the whole organism level means that relatively more glucose  
457 becomes available for white muscle that, unlike other tissues, may take advantage of  
458 this opportunity and increase glucose utilization. This idea is supported by the fact that  
459 white muscle is the only tissue showing a rise in Hk activity (Fig. 8) and further

460 emphasizes that important differences in carbohydrate metabolism exist between the  
461 two muscle types. Conversely, the expression of both *glut4* paralogues decreased  
462 significantly in the red muscle of lactate infused fish. This finding is in line with an  
463 observed, but non-significant, decrease in Hk activity in red muscle, suggesting that  
464 increasingly available glucose is not used as a fuel by this tissue. Similarly, the  
465 observed (non-significant) tendency of hepatic Gck activity to decrease suggests that  
466 the liver does not increase its use of glucose either.

467

### 468 **Perspectives and significance**

469 Higher lactate availability does not reduce lipolytic rate because rainbow trout  
470 only show weak Hcar1 signaling that may have a different metabolic function than in  
471 mammals. The trout receptor responds differently because its expression remains  
472 unaffected by lactate in all tissues except red muscle where it is even strongly  
473 suppressed. This lack of Hcar1 activation may contribute to the high lipolytic rate and  
474 the “lipolytic inertia” observed quasi permanently in fish. Rainbow trout maintain high  $R_a$   
475 glycerol during hyperlactatemia, and elevated rates of triacylglycerol/fatty acid cycling  
476 during all types of exercise even when strenuous. Results show that trout  $R_a$  glucose is  
477 greatly diminished because high lactate decreases gluconeogenic flux by inhibiting  
478 Pck1 via reductions in *pck1* transcript abundance and Pck1 protein levels.  
479 Hyperlactatemia also reduces overall tissue need for glucose by substituting it for  
480 lactate as an oxidative fuel. However, this substitution does not occur in white muscle  
481 that activates *glut4* expression and can probably not stimulate lactate import because of  
482 its limited capacity for Mct-mediated transmembrane lactate transport. This study

483 highlights clear functional differences of the Hcar1-mediated lactate signaling system  
484 between fish and mammals in the regulation of fuel selection for energy metabolism.

485



## 486 **Acknowledgements**

487 We thank the animal care service of the University of Ottawa for assistance in fish  
488 handling and husbandry.

489 Current addresses:

490 Elisa Thorat, Lund University, Department of Biology, Section for Evolutionary Ecology,  
491 Sölvegatan 37, SE-223 62 Lund, Sweden.

492 Elie Farhat, Institutt for biovitenskap (IBV), Universitetet i Oslo, Postboks 1066 Blindern,  
493 0316 Oslo, Norway.

494

## 495 **Author Contributions**

496 GGMT, JAM, LT and JMW: conception and design of research; GGMT, ET, and  
497 EF performed experiments; all authors analyzed data; all authors interpreted results of  
498 experiments; GGMT and JMW prepared figures; GGMT drafted manuscript; all authors  
499 edited and revised manuscript, and all authors approved the final version of the  
500 manuscript.

501

## 502 **Funding**

503 This work was supported by grants from the Natural Sciences and Engineering  
504 Research Council of Canada to J.-M. Weber (discovery grant 105639-2012) and J.  
505 Mennigen (discovery grant 2114456-2017), as well as from the Canadian Foundation  
506 for Innovation John Evans Leader's fund (CFI grant 148035 to J. Mennigen). E. Thorat's  
507 travel and stay in Canada were financed by the France Canada Research Fund (FCRF  
508 grant 149716-2018 to J.-M. Weber) while she was completing her PhD at Université  
509 Claude Bernard Lyon 1, France.

**Table 1:** Physical characteristics of the animals

	<i>In vivo</i> Glucose kinetics (series 1)	<i>In vivo</i> Glycerol kinetics (series 2)	Tissue measurements (series 3)
Sample size	8	10	8
Body mass (g)	478 ± 25	661 ± 39	217 ± 7
Body length (cm)	34.8 ± 0.6	38.0 ± 0.8	27.6 ± 0.3
Fulton's condition factor (K)	1.13 ± 0.03	1.20 ± 0.03	1.04 ± 0.02
Hematocrit (%)	19.2 ± 1.6	19.6 ± 1.2	24.4 ± 0.8

Three types of experiments were carried out on adult rainbow trout to measure rates of glucose mobilization (series 1), rates of fatty acid mobilization (series 2) or gene expression, protein expression, and enzyme activities (series 3). Values are means ± s.e.m.

**Table 2:** Initial (baseline) and final values after 3 h of exogenous lactate infusion for plasma metabolite concentrations and fluxes measured in the glucose kinetics experiments (series 1) and glycerol kinetics experiments (series 2).

	Baseline (0 h)	Final (3 h)
<i>Glucose kinetics (series 1)</i>		
Plasma glucose (mM)	7.1 ± 0.5	7.9 ± 0.7
$R_a$ glucose ( $\mu\text{mol kg}^{-1} \text{min}^{-1}$ )	16.4 ± 2.0	<b>8.9 ± 1.2 ***</b>
Plasma lactate (mM)	0.8 ± 0.2	<b>10.9 ± 0.4 ***</b>
<i>Glycerol kinetics (series 2)</i>		
Plasma glycerol (mM)	0.21 ± 0.03	<b>0.48 ± 0.04 ***</b>
$R_a$ glycerol ( $\mu\text{mol kg}^{-1} \text{min}^{-1}$ )	8.2 ± 1.4	5.7 ± 0.7
Plasma lactate (mM)	1.1 ± 0.4	<b>10.5 ± 1.4 ***</b>

$R_a$  glucose: rate of glucose mobilization or hepatic glucose production.

$R_a$  glycerol: rate of mobilization of fatty acids (glycerol production or lipolytic rate).

Values are means ± s.e.m (N=8-10). Significant effects of exogenous lactate infusion are indicated by \*\*\* (P<0.001).

**Table 3:** Initial and final values with statistical analyses for plasma glucose, glycerol and lactate concentrations measured in fish used for tissue measurements of gene expression, protein expression and enzyme activities (series 3). The animals were divided into 2 groups that received either an infusion of Cortland's saline (controls) or an infusion of lactate (treatment), both for 3 h.

	Group	Baseline (0 h)	Final (3 h)	Time effect	Treatment effect	Time×treatment interaction
Glucose (mM)	Control	4.52 ± 0.37	4.57 ± 0.64	ns	ns	ns
	Lactate	4.57 ± 0.43	4.12 ± 0.48			
Glycerol (mM)	Control	0.21 ± 0.02	0.24 ± 0.03	**	*	**
	Lactate	0.20 ± 0.02	0.51 ± 0.09			
Lactate (mM)	Control	0.67 ± 0.05	0.67 ± 0.06	****	****	****
	Lactate	0.64 ± 0.04	14.9 ± 1.16			

Values are means ± s.e.m.

ns (not significant)  $P > 0.05$ , \*  $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*\*  $P < 0.0001$ .

510 **Figure captions**

511 **Fig. 1.** Circulating glucose (A) and lactate concentrations (B) of rainbow trout while  
512 hepatic glucose production was quantified during exogenous lactate infusion that  
513 started at time 0 (series 1). Values are means  $\pm$  s.e.m. (N=8). \*\*\* Indicates significant  
514 differences from mean resting values (P<0.001).

515  
516 **Fig. 2.** Effects of exogenous lactate on glucose specific activity (A) and hepatic glucose  
517 production (B) in rainbow trout (series 1). Values are means  $\pm$  s.e.m. (N=7-8).  
518 Significant differences from mean baseline values are indicated by \* (P<0.05), \*\*  
519 (P<0.01) and \*\*\* (P<0.001).

520  
521 **Fig. 3.** Circulating glycerol (A) and lactate concentrations (B) of rainbow trout while  
522 lipolytic rate (= rate of appearance of glycerol) was quantified during exogenous lactate  
523 infusion that starts at time 0 (series 2). Values are means  $\pm$  s.e.m. (N=10). Significant  
524 differences from mean baseline values are indicated by \*\* (P<0.01) and \*\*\* (P<0.001).

525  
526 **Fig. 4.** Effects of exogenous lactate on glycerol specific activity (A) and rate of  
527 production of glycerol or lipolytic rate (B) in rainbow trout (series 2). Values are means  $\pm$   
528 s.e.m. (N=10).

529  
530 **Fig. 5.** Effects of exogenous lactate on the relative mRNA expression of the  
531 hydroxycarboxylic acid receptor 1 (*hcar1*) in rainbow trout tissues. Values are means  $\pm$   
532 s.e.m. (N=6-8). Significant effect of lactate is indicated by \*\* (P<0.01). Relative mRNA  
533 abundance was normalized using the NORMA-Gene procedure (35) and fold changes  
534 were calculated relative to the control group.

535

536

537

538

539 **Fig. 6.** Effects of exogenous lactate on the relative mRNA expression of genes  
540 associated with carbohydrate (left panels) and lipid metabolism (right panels) in rainbow  
541 trout tissues. Glucose transporters 4a and 4b (*glut4a* and *glut4b*), phosphoenolpyruvate  
542 carboxykinase (*pck1*, *pck2a* and *pck2b*), glucose 6 phosphatase (*g6pca*, *g6pcb1a* and  
543 *g6pcb1b*), carnitine palmitoyltransferase 1 (*cpt1*), hydroxyacyl CoA dehydrogenase  
544 (*hoad*), fatty acid translocase (*cd36*), and fatty acid synthase (*fasn*). Values are means  
545  $\pm$  s.e.m. (N=5-8). Significant effects of lactate are indicated by \* (P<0.05), \*\* (P<0.01)  
546 and \*\*\* (P<0.001). Relative mRNA abundance was normalized using the NORMA-Gene  
547 procedure (35) and fold changes were calculated relative to the control group.

548

549 **Fig. 7.** Effects of exogenous lactate on the protein expression of liver  
550 phosphoenolpyruvate carboxykinase (Pck1) and muscle glucose transporter 4 (Glut4) in  
551 rainbow trout. Values are means  $\pm$  s.e.m. (N=6). Significant effect of lactate is indicated  
552 by \* (P<0.05).

553

554 **Fig. 8.** Effects of exogenous lactate on the activity of enzymes involved in carbohydrate  
555 (left panels) and lipid metabolism (right panels) in rainbow trout tissues.  
556 Phosphoenolpyruvate carboxykinase (Pck) hexokinase (Hk), glucokinase (Gck)  
557 hydroxyacyl CoA dehydrogenase (Hoad). Values are means  $\pm$  s.e.m. (N=7-8).  
558 Significant effects of lactate are indicated by \* (P<0.05), and \*\* (P<0.01).

559 **References**

- 560 1. **Brooks GA.** Lactate as a fulcrum of metabolism. *Redox Biology* 35: 101454, 2020.
- 561 2. **Sun S, Li H, Chen J, and Qian Q.** Lactic Acid: No Longer an Inert and End-Product of Glycolysis.  
562 *Physiology* 32: 453-463, 2017.
- 563 3. **Rooney K, and Trayhurn P.** Lactate and the GPR81 receptor in metabolic regulation: implications  
564 for adipose tissue function and fatty acid utilisation by muscle during exercise. *Br J Nutr* 106: 1310-1316,  
565 2011.
- 566 4. **Philp A, MacDonald AL, and Watt PW.** Lactate - a signal coordinating cell and systemic function.  
567 *J Exp Biol* 208: 4561-4575, 2005.
- 568 5. **Brooks GA, Arevalo JA, Osmond AD, Leija RG, Curl CC, and Tovar AP.** Lactate in contemporary  
569 biology: a phoenix risen. *The Journal of Physiology* 600: 1229-1251, 2022.
- 570 6. **Liu C, Wu J, Zhu J, Kuei C, Yu J, Shelton J, Sutton SW, Li X, Yun SJ, Mirzadegan T, Mazur C,  
571 Kamme F, and Lovenberg TW.** Lactate Inhibits Lipolysis in Fat Cells through Activation of an Orphan G-  
572 protein-coupled Receptor, GPR81. *Journal of Biological Chemistry* 284: 2811-2822, 2009.
- 573 7. **Sun J, Ye X, Xie M, and Ye J.** Induction of triglyceride accumulation and mitochondrial  
574 maintenance in muscle cells by lactate. *Scientific reports* 6: 33732-33732, 2016.
- 575 8. **Chen S, Zhou L, Sun J, Qu Y, and Chen M.** The Role of cAMP-PKA Pathway in Lactate-Induced  
576 Intramuscular Triglyceride Accumulation and Mitochondria Content Increase in Mice. *Frontiers in  
577 Physiology* 12: 2021.
- 578 9. **Zhou L, Chen SY, Han HJ, and Sun JQ.** Lactate augments intramuscular triglyceride accumulation  
579 and mitochondrial biogenesis in rats. *Journal of biological regulators and homeostatic agents* 35: 105-  
580 115, 2021.
- 581 10. **Wu G, Dai Y, Yan Y, Zheng X, Zhang H, Li H, and Chen W.** The lactate receptor GPR81 mediates  
582 hepatic lipid metabolism and the therapeutic effect of metformin on experimental NAFLDs. *European  
583 Journal of Pharmacology* 924: 174959, 2022.
- 584 11. **Kuei C, Yu J, Zhu J, Wu J, Zhang L, Shih A, Mirzadegan T, Lovenberg T, and Liu C.** Study of  
585 GPR81, the Lactate Receptor, from Distant Species Identifies Residues and Motifs Critical for GPR81  
586 Functions. *Molecular Pharmacology* 80: 848-858, 2011.
- 587 12. **Thomsen MT, Lefevre S, Nilsson GE, Wang T, and Bayley M.** Effects of lactate ions on the  
588 cardiorespiratory system in rainbow trout (*Oncorhynchus mykiss*). *American Journal of Physiology-  
589 Regulatory, Integrative and Comparative Physiology* 316: R607-R620, 2019.
- 590 13. **Sakurai T, Davenport R, Stafford S, Grosse J, Ogawa K, Cameron J, Parton L, Sykes A, Mack S,  
591 Bousba S, Parmar A, Harrison D, Dickson L, Leveridge M, Matsui J, and Barnes M.** Identification of a  
592 novel GPR81-selective agonist that suppresses lipolysis in mice without cutaneous flushing. *European  
593 Journal of Pharmacology* 727: 1-7, 2014.

- 594 14. **Weber J-M, Choi K, Gonzalez A, and Omlin T.** Metabolic fuel kinetics in fish: swimming, hypoxia  
595 and muscle membranes. *J Exp Biol* 219: 250-258, 2016.
- 596 15. **Choi K, and Weber J-M.** Pushing the limits of glucose kinetics: how rainbow trout cope with a  
597 carbohydrate overload. *J Exp Biol* 218: 2873-2880, 2015.
- 598 16. **Jubouri M, Talarico GGM, Weber J-M, and Mennigen JA.** Alanine alters carbohydrate  
599 metabolism of rainbow trout: Glucose flux and cell signaling. *J Exp Biol* 224: jeb232918, 2021.
- 600 17. **Forbes JLI, Kostyniuk DJ, Mennigen JA, and Weber J-M.** Unexpected effects of insulin on  
601 glucose disposal explains glucose intolerance of rainbow trout. *Am J Physiol - Regulatory, Integrative and*  
602 *Comparative Physiology* 316: R387-R394, 2019.
- 603 18. **Weber J-M, and Shanghavi DS.** Regulation of glucose production in rainbow trout: Role of  
604 epinephrine *in vivo* and in isolated hepatocytes. *Am J Physiol* 278: R956-R963, 2000.
- 605 19. **Shanghavi DS, and Weber J-M.** Effects of sustained swimming on hepatic glucose production of  
606 rainbow trout. *J Exp Biol* 202: 2161-2166, 1999.
- 607 20. **Haman F, Zwingelstein G, and Weber J-M.** Effects of hypoxia and low temperature on substrate  
608 fluxes in fish: plasma metabolite concentrations are misleading. *Am J Physiol* 273: R2046-R2054, 1997.
- 609 21. **Magnoni L, Vaillancourt E, and Weber J-M.** In vivo regulation of rainbow trout lipolysis by  
610 catecholamines. *J Exp Biol* 211: 2460-2466, 2008.
- 611 22. **Bernard SF, Reidy SP, Zwingelstein G, and Weber J-M.** Glycerol and fatty acid kinetics in  
612 rainbow trout: effects of endurance swimming. *J Exp Biol* 202: 279-288, 1999.
- 613 23. **Turenne ED, and Weber J-M.** Lean, mean, lipolytic machines: lipid mobilization in rainbow trout  
614 during graded swimming. *J Exp Biol* 221: jeb171553, 2018.
- 615 24. **Miller BF, Fattor JA, Jacobs KA, Horning MA, Navazio F, Lindinger MI, and Brooks GA.** Lactate  
616 and glucose interactions during rest and exercise in men: effect of exogenous lactate infusion. *The*  
617 *Journal of Physiology* 544: 963-975, 2002.
- 618 25. **Ahmed K, Tunaru S, Tang C, Müller M, Gille A, Sassmann A, Hanson J, and Offermanns S.** An  
619 Autocrine Lactate Loop Mediates Insulin-Dependent Inhibition of Lipolysis through GPR81. *Cell*  
620 *Metabolism* 11: 311-319, 2010.
- 621 26. **Blackwell BG, Brown ML, and Willis DW.** Relative weight ( $W_r$ ) status and current use in fisheries  
622 assessment and management. *Reviews in fisheries Science* 8: 1-44, 2000.
- 623 27. **Haman F, and Weber J-M.** Continuous tracer infusion to measure in vivo metabolite turnover  
624 rates in trout. *J Exp Biol* 199: 1157-1162, 1996.
- 625 28. **Haman F, Powell M, and Weber J-M.** Reliability of continuous tracer infusion for measuring  
626 glucose turnover rate in rainbow trout. *J Exp Biol* 200: 2557-2563, 1997.

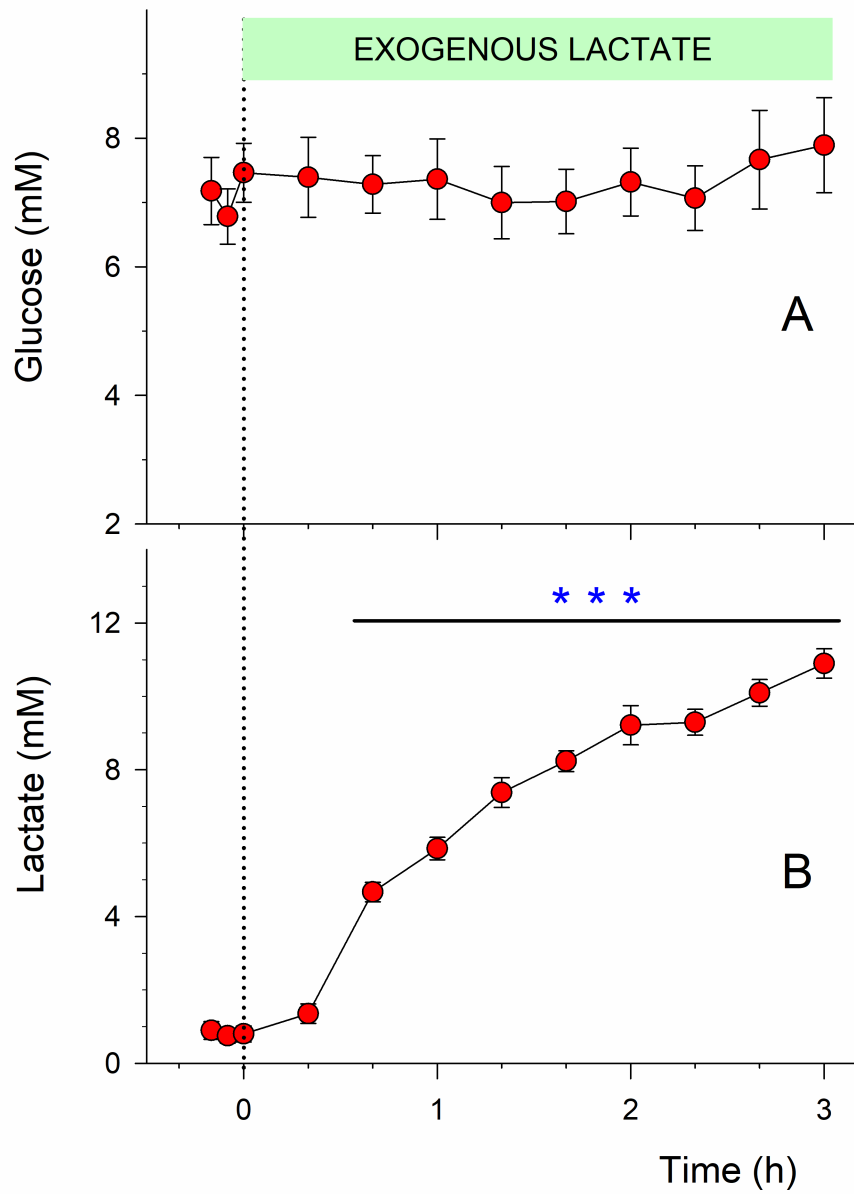


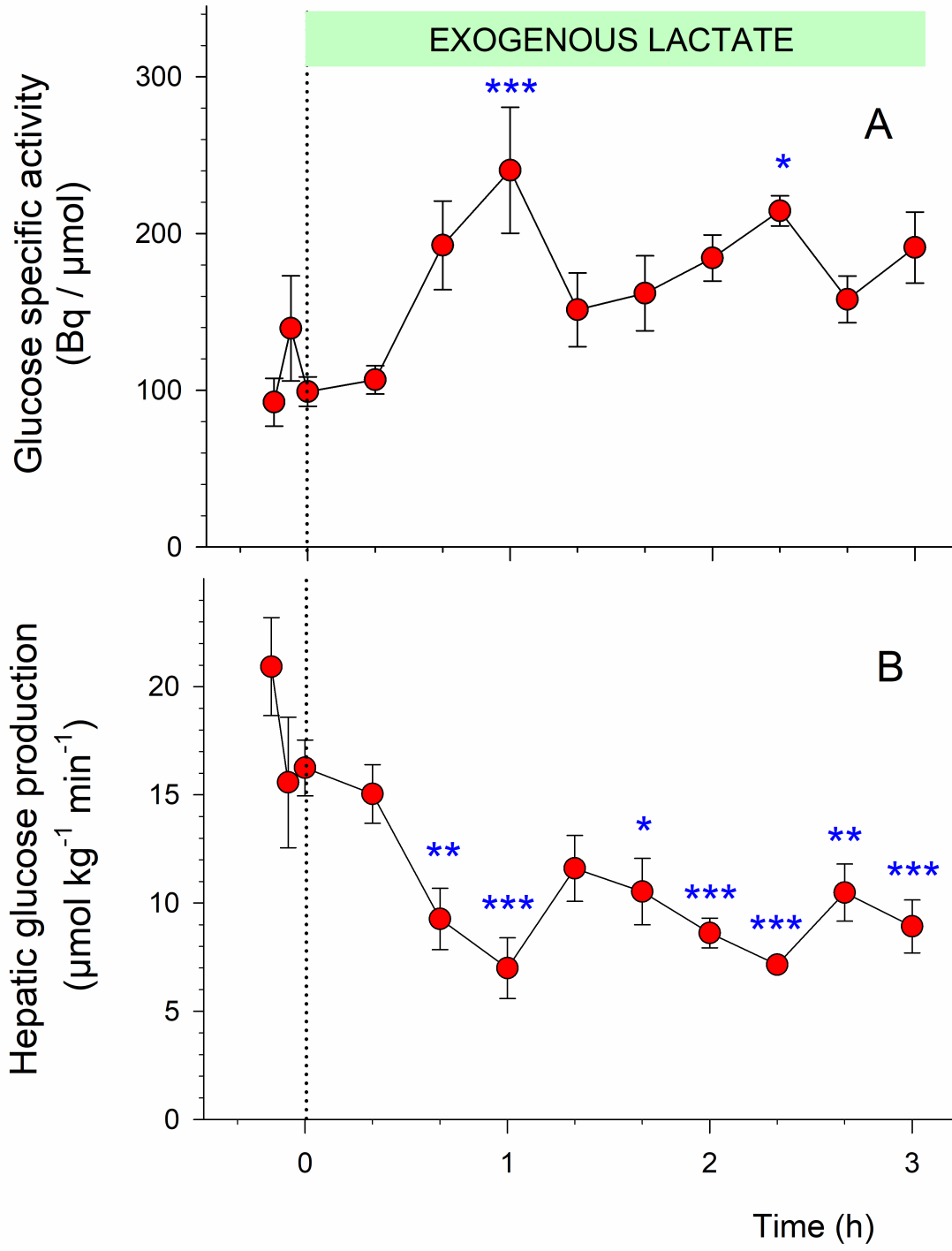
- 627 29. **Choi K, and Weber J-M.** Coping with an exogenous glucose overload: Glucose kinetics of  
628 rainbow trout during graded swimming. *Am J Physiol* 310: R493-R501, 2016.
- 629 30. **Wolfe RR.** *Radioactive and stable isotope tracers in biomedicine: Principles and practice of*  
630 *kinetic analysis.* New York: Wiley-Liss, 1992, p. 471.
- 631 31. **Omlin T, and Weber J-M.** Hypoxia stimulates lactate disposal in rainbow trout. *J Exp Biol* 213:  
632 3802-3809, 2010.
- 633 32. **Omlin T, Langevin K, and Weber J-M.** Exogenous lactate supply affects lactate kinetics of  
634 rainbow trout, not swimming performance. *Am J Physiol* 307: R1018-R1024, 2014.
- 635 33. **Weber J-M, Roberts TJ, and Taylor CR.** Mismatch between lipid mobilization and oxidation:  
636 Glycerol kinetics in running African goats. *Am J Physiol* 264: R797-R803, 1993.
- 637 34. **Farhat E, Talarico GGM, Grégoire M, Weber J-M, and Mennigen JA.** Epigenetic and post-  
638 transcriptional repression support metabolic suppression in chronically hypoxic goldfish. *Scientific*  
639 *Reports* 12: 5576, 2022.
- 640 35. **Heckmann L-H, Sørensen PB, Krogh PH, and Sørensen JG.** NORMA-Gene: a simple and robust  
641 method for qPCR normalization based on target gene data. *BMC Bioinformatics* 12:250: 2011.
- 642 36. **Farhat E, Cheng H, Romestaing C, Pamerter M, and Weber J-M.** Goldfish Response to Chronic  
643 Hypoxia: Mitochondrial Respiration, Fuel Preference and Energy Metabolism. *Metabolites* 11: 187, 2021.
- 644 37. **Steele R.** Influences of glucose loading and of injected insulin on hepatic glucose output. *Ann NY*  
645 *Acad Med Sci* 82: 420-430, 1959.
- 646 38. **Milligan CL, and Girard SS.** Lactate metabolism in rainbow trout. *J Exp Biol* 180: 175-193, 1993.
- 647 39. **Milligan CL, and Farrell AP.** Lactate utilization by an *in situ* perfused trout heart: effects of  
648 workload and blockers of lactate transport. *J Exp Biol* 155: 357-373, 1991.
- 649 40. **Soengas JL, Strong EF, and Andres MD.** Glucose, lactate, and beta-hydroxybutyrate utilization  
650 by rainbow trout brain: changes during food deprivation. *Physiol Zool* 71: 285-293, 1998.
- 651 41. **Omlin T, and Weber J-M.** Exhausting exercise and tissue-specific expression of monocarboxylate  
652 transporters in rainbow trout. *Am J Physiol* 304: R1036-R1043, 2013.
- 653 42. **Teulier L, Omlin T, and Weber J-M.** Lactate kinetics of rainbow trout during graded exercise: do  
654 catheters affect the cost of transport? *J Exp Biol* 216: 4549-4556, 2013.
- 655 43. **Forbes JLI, Kostyniuk DJ, Mennigen JA, and Weber J-M.** Glucagon regulation of carbohydrate  
656 metabolism in rainbow trout: *in vivo* glucose fluxes and gene expression. *J Exp Biol* 222: jeb211730,  
657 2019.
- 658 44. **Issekutz BJ, Shaw WAS, and Issekutz TB.** Effect of lactate on FFA and glycerol turnover in resting  
659 and exercising dogs. *J Appl Physiol* 39: 349-353, 1975.

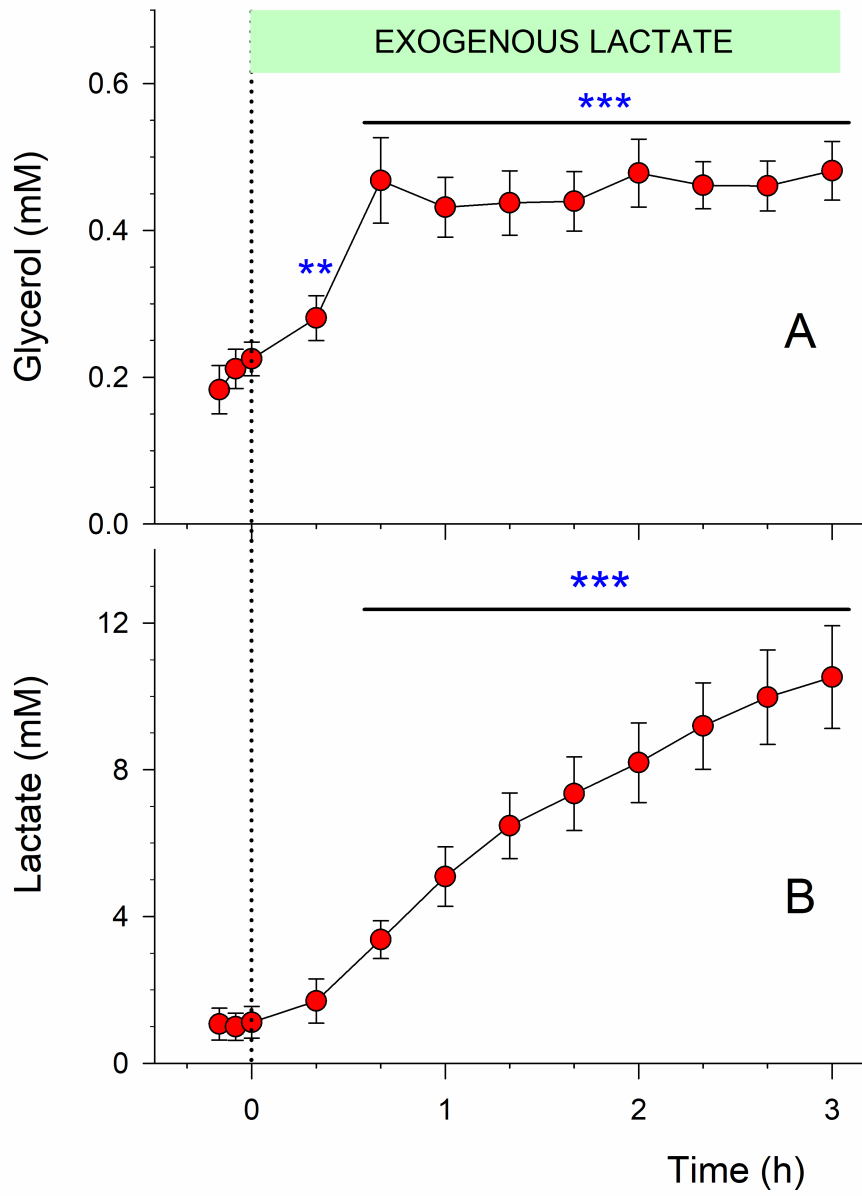
- 660 45. **Wolfe RR, Klein S, Carraro F, and Weber J-M.** Role of triglyceride-fatty acid cycle in controlling  
661 fat metabolism in humans during and after exercise. *Am J Physiol* 258: E382-E389, 1990.
- 662 46. **Weber J-M, and Reidy SP.** Extending food deprivation reverses the short-term lipolytic response  
663 to fasting: role of the triacylglycerol/fatty acid cycle. *J Exp Biol* 215: 1484-1490, 2012.
- 664 47. **McClelland GB, Hochachka PW, Reidy S, and Weber J-M.** High-altitude acclimation increases  
665 the triacylglycerol/fatty acid cycle at rest and during exercise. *Am J Physiol* 281: E537-E544, 2001.
- 666 48. **Brooks GA.** The Science and Translation of Lactate Shuttle Theory. *Cell Metabolism* 27: 757-785,  
667 2018.
- 668 49. **Thompson BR, Lobo S, and Bernlohr DA.** Fatty acid flux in adipocytes: The in's and out's of fat  
669 cell lipid trafficking. *Mol Cell Endocrinol* 318: 24-33, 2010.
- 670 50. **Girard J, Ferre P, and Foufelle F.** Mechanisms by which carbohydrates regulate expression of  
671 genes for glycolytic and lipogenic enzymes. *Annual Review of Nutrition* 17: 325-352, 1997.
- 672 51. **Longhitano L, Forte S, Orlando L, Grasso S, Barbato A, Vicario N, Parenti R, Fontana P, Amorini  
673 AM, Lazzarino G, Li Volti G, Di Rosa M, Liso A, Tavazzi B, Lazzarino G, and Tibullo D.** The Crosstalk  
674 between GPR81/IGFBP6 Promotes Breast Cancer Progression by Modulating Lactate Metabolism and  
675 Oxidative Stress. *Antioxidants* 11: 275, 2022.
- 676 52. **Klein S, Weber J-M, Coyle EF, and Wolfe RR.** Effect of endurance training on glycerol kinetics  
677 during strenuous exercise in humans. *Metabolism: clinical and experimental* 45: 357-361, 1996.
- 678 53. **Miller BF, Fattor JA, Jacobs KA, Horning MA, Suh S-H, Navazio F, and Brooks GA.** Metabolic and  
679 cardiorespiratory responses to “the lactate clamp”. *American Journal of Physiology-Endocrinology and  
680 Metabolism* 283: E889-E898, 2002.
- 681 54. **Yu S, Meng S, Xiang M, and Ma H.** Phosphoenolpyruvate carboxykinase in cell metabolism:  
682 Roles and mechanisms beyond gluconeogenesis. *Molecular Metabolism* 53: 101257, 2021.
- 683 55. **Marandel L, Kostyniuk DJ, Best C, Forbes JLI, Liu J, Panserat S, and Mennigen JA.** Pck-ing up  
684 steam: Widening the salmonid gluconeogenic gene duplication trail. *Gene* 698: 129-140, 2019.
- 685 56. **Stark R, Guebre-Egziabher F, Zhao X, Feriod C, Dong J, Alves TC, Ioja S, Pongratz RL, Bhanot S,  
686 Roden M, Cline GW, Shulman GI, and Kibbey RG.** A Role for Mitochondrial Phosphoenolpyruvate  
687 Carboxykinase (PEPCK-M) in the Regulation of Hepatic Gluconeogenesis \*. *Journal of Biological  
688 Chemistry* 289: 7257-7263, 2014.
- 689 57. **Mommsen TP, Walsh PJ, and Moon TW.** Gluconeogenesis in hepatocytes and kidneys of  
690 Atlantic salmon. *Molecular Physiology* 8: 89-100, 1985.
- 691 58. **Marandel L, Seilliez I, Veron V, Skiba-Cassy S, and Panserat S.** New insights into the nutritional  
692 regulation of gluconeogenesis in carnivorous rainbow trout (*Oncorhynchus mykiss*): a gene duplication  
693 trail. *Physiol Genomics* 47: 253-263, 2015.

694 59. **Navale AM, and Paranjape AN.** Glucose transporters: physiological and pathological roles.  
695 *Biophysical Reviews* 8: 5-9, 2016.

696







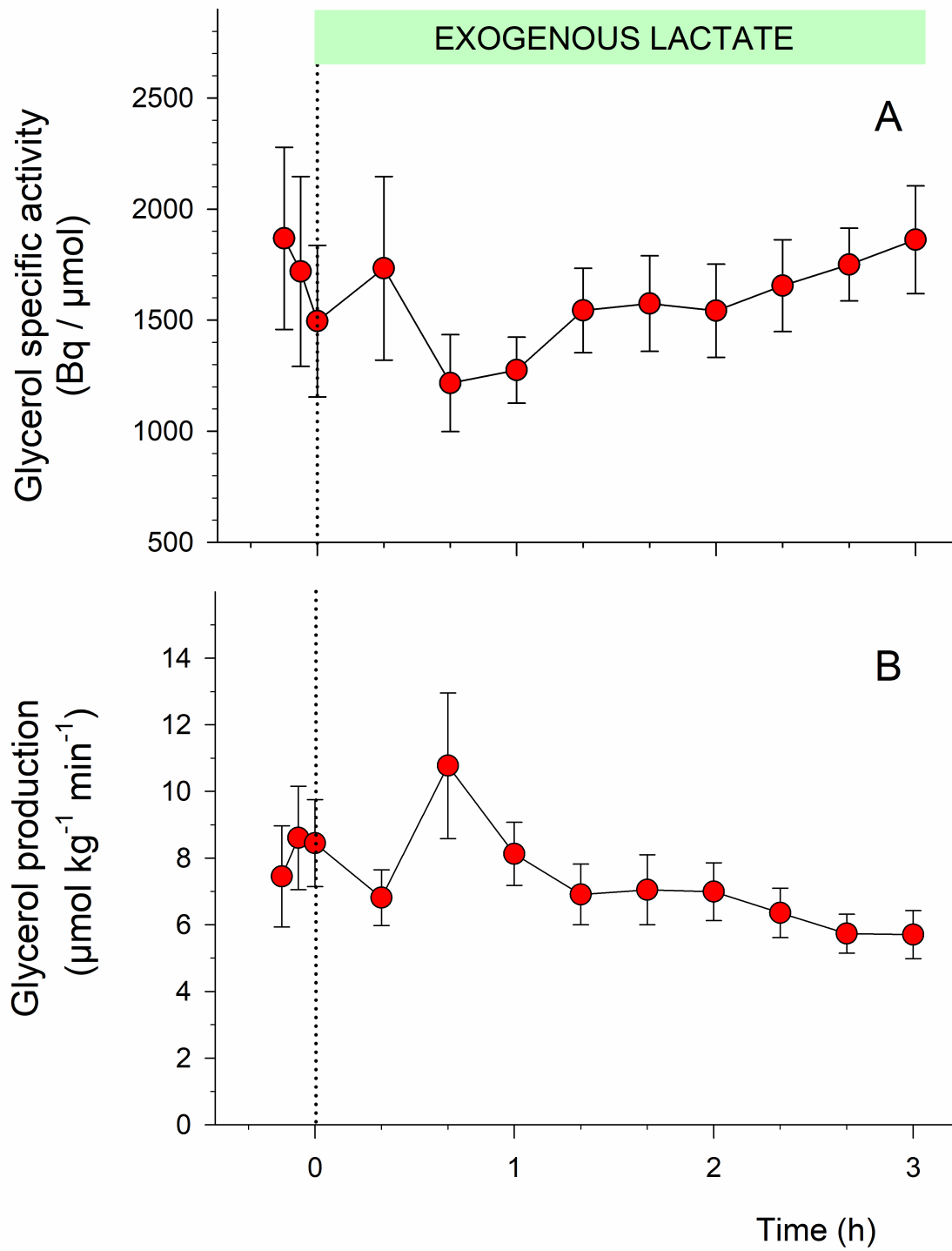
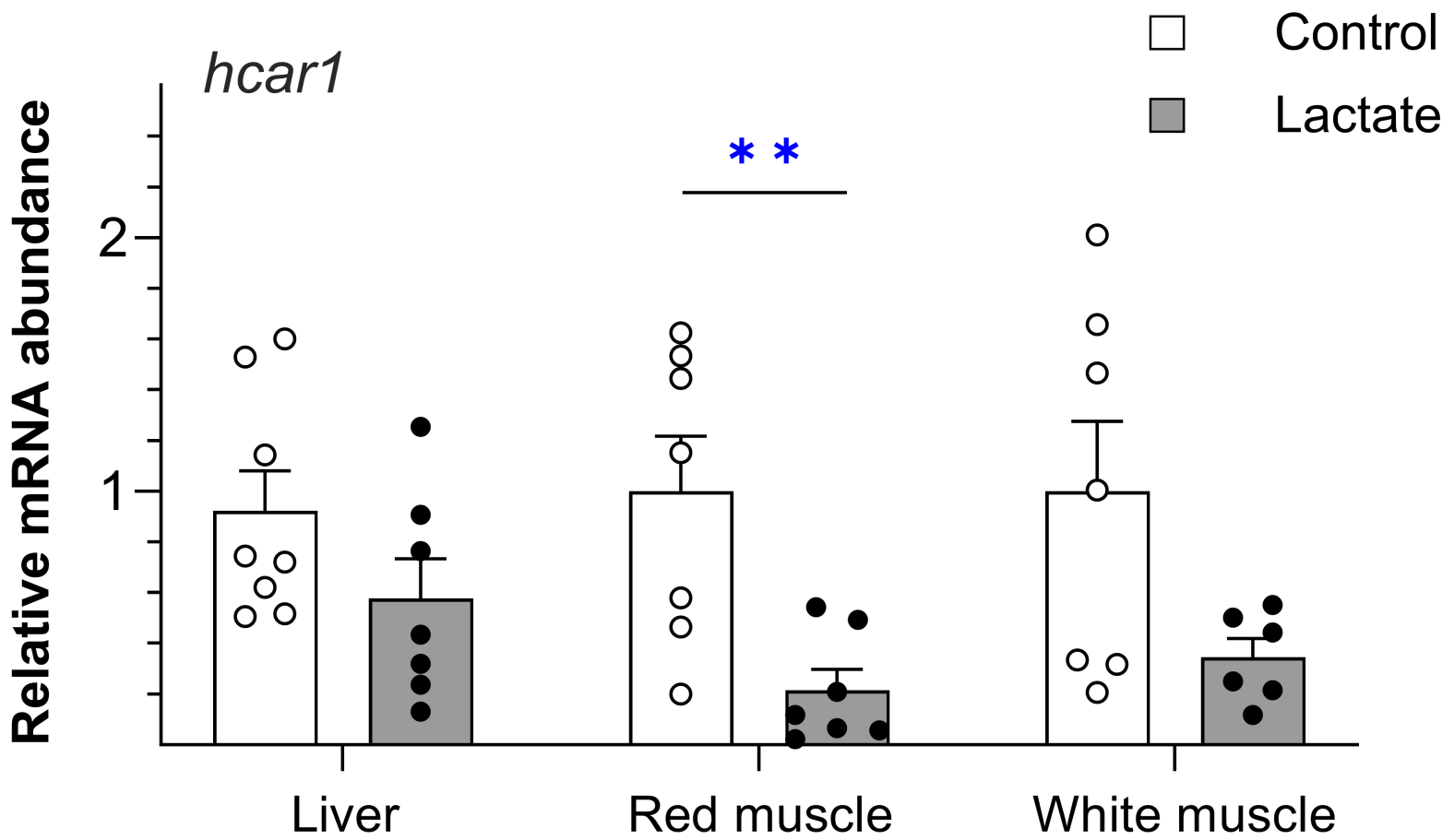


Fig 4

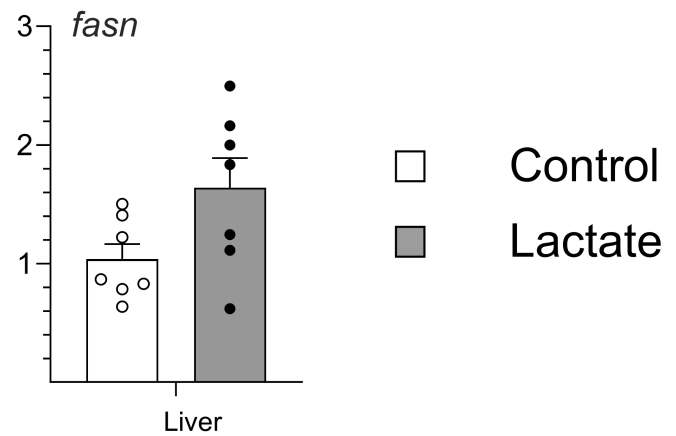
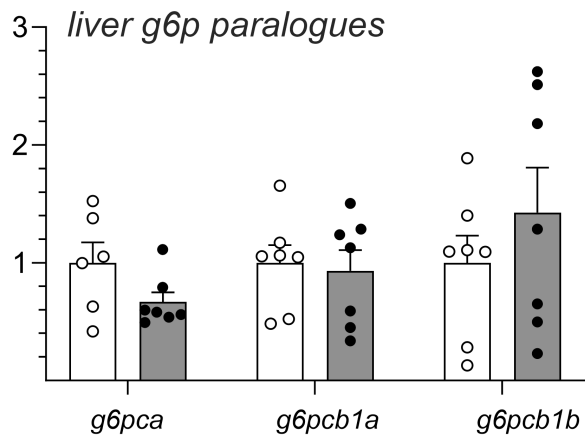
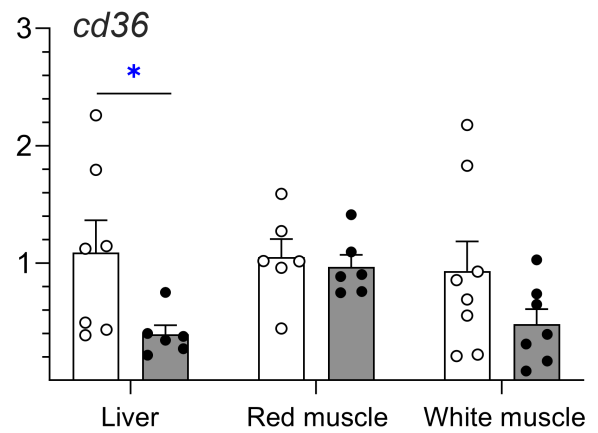
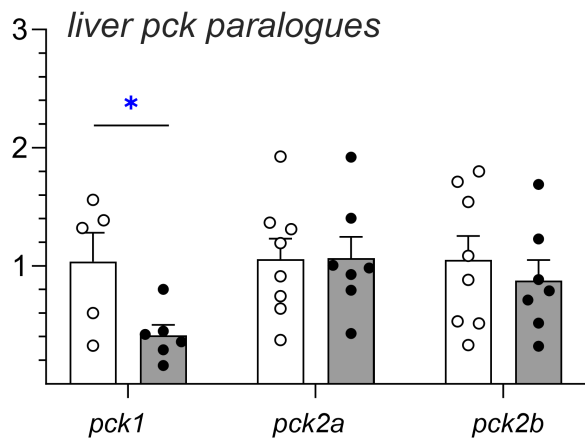
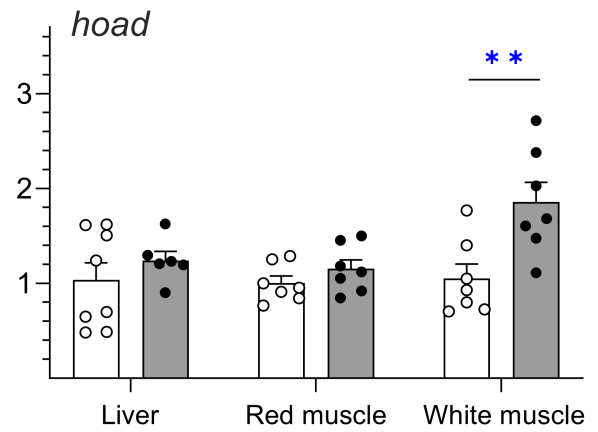
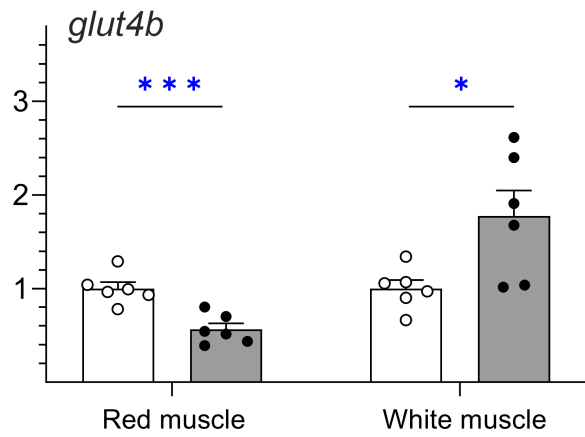
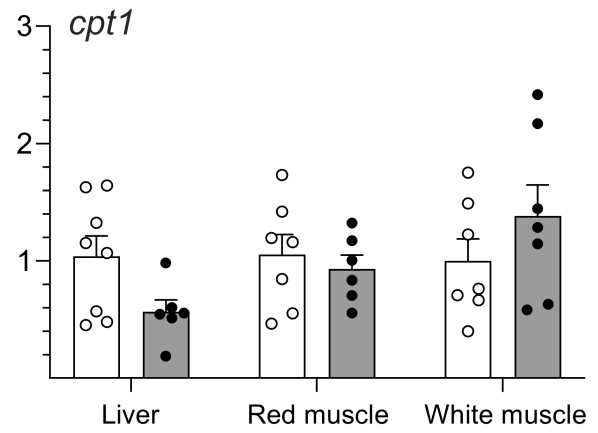
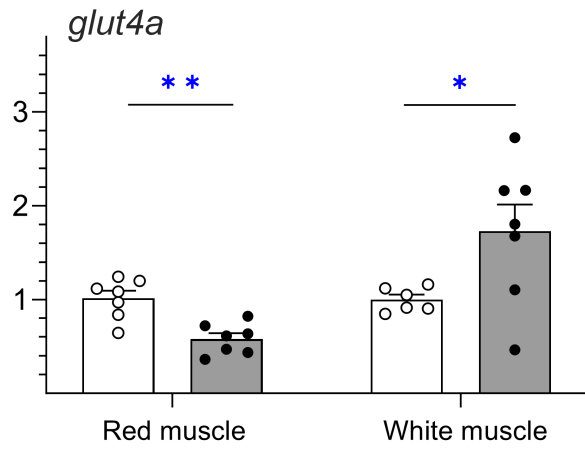




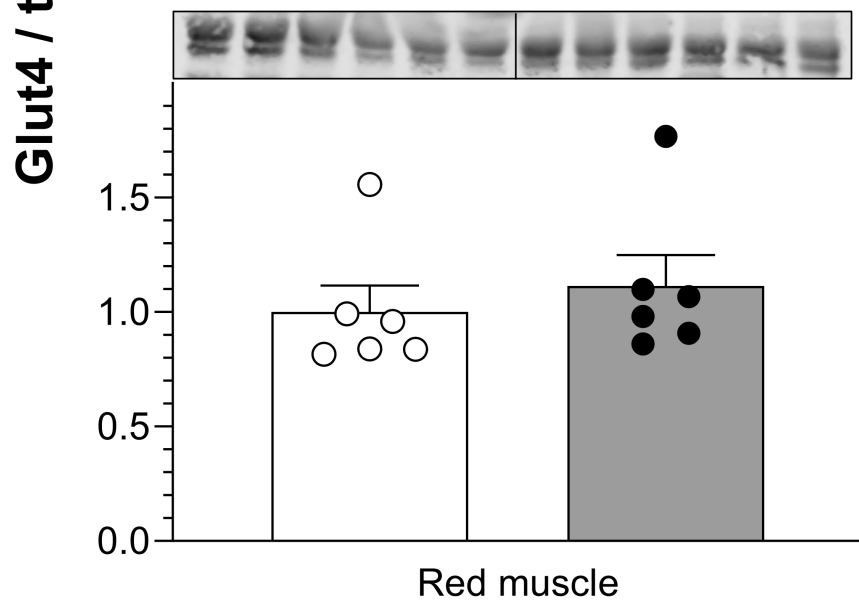
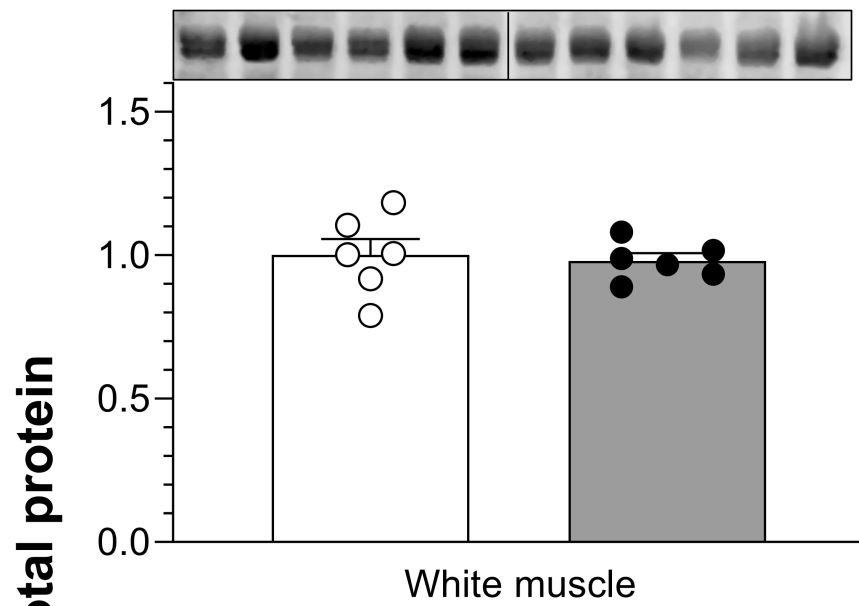
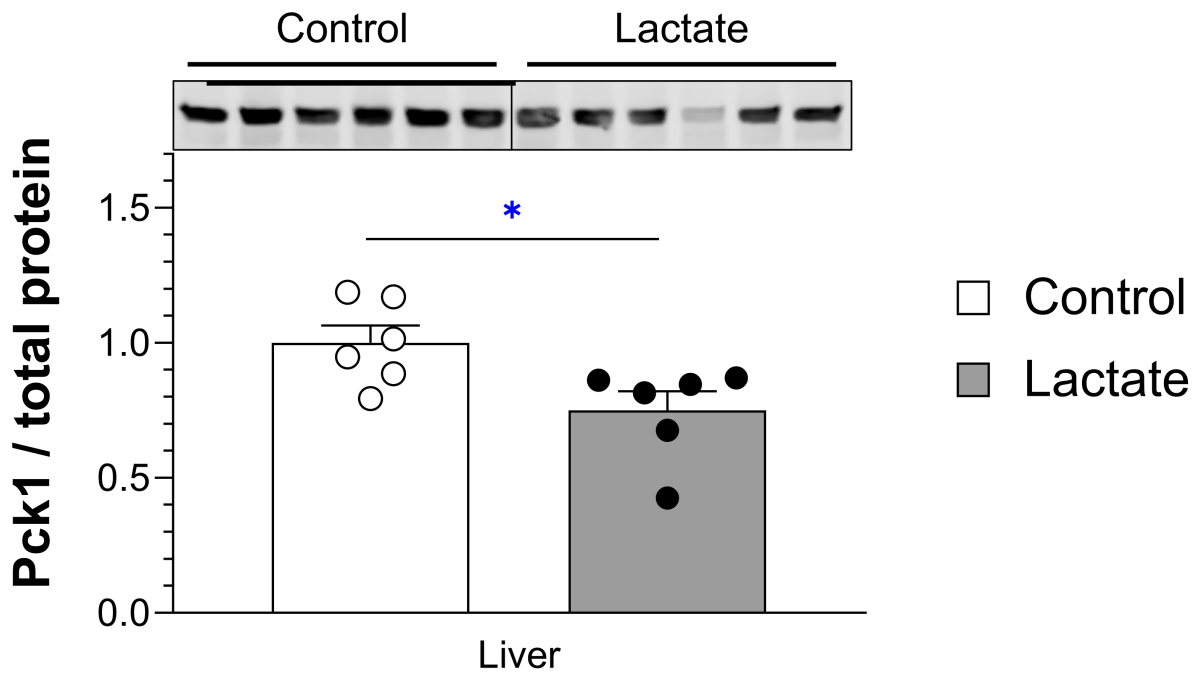
# Carbohydrates

# Lipids

Relative mRNA abundance

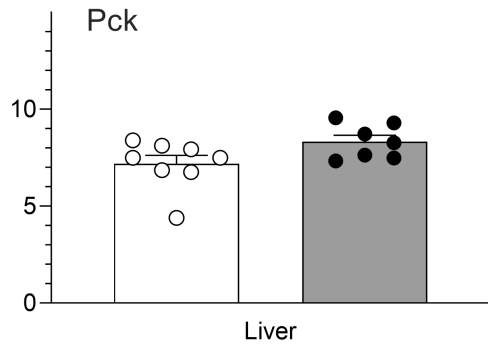


Control  
Lactate



# Carbohydrates

# Lipids



□ Control  
■ Lactate

Enzyme activity ( $\mu\text{mol min}^{-1} \text{g protein}^{-1}$ )

