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1 **Acid–base balance in the hæmolymph of European abalone (*Haliotis***
2 ***tuberculata*) exposed to CO₂-induced ocean acidification**

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17
18 **Abstract**

19 Ocean acidification (OA) and the associated changes in seawater carbonate chemistry
20 pose a threat to calcifying organisms. This is particularly serious for shelled molluscs, in
21 which shell growth and microstructure has been shown to be highly sensitive to OA. To
22 improve our understanding of the responses of abalone to OA, this study investigated the
23 effects of CO₂-induced ocean acidification on extra-cellular acid–base parameters in the
24 European abalone *Haliotis tuberculata*. Three-year-old adult abalone were exposed for 15
25 days to three different pH levels (7.9, 7.7, 7.4) representing current and predicted near-future
26 conditions. Hæmolymph pH and total alkalinity were measured at different time points during
27 exposure and used to calculate the carbonate parameters of the extracellular fluid. Total
28 protein content was also measured to determine whether seawater acidification influences
29 the composition and buffer capacity of hæmolymph. Extracellular pH was maintained at
30 seawater pH 7.7 indicating that abalones are able to buffer moderate acidification (-0.2 pH
31 units). This was not due to an accumulation of HCO₃⁻ ions but rather to a high hæmolymph
32 protein concentration. By contrast, hæmolymph pH was significantly decreased after 5 days
33 of exposure to pH 7.4, indicating that abalone do not compensate for higher decreases in
34 seawater pH. Total alkalinity and dissolved inorganic carbon were also significantly
35 decreased after 15 days of low pH exposure. It is concluded that changes in the acid–base
36 balance of the hæmolymph might be involved in deleterious effects recorded in adult *H.*

37 *tuberculata* facing severe OA stress. This would impact both the ecology and aquaculture of
38 this commercially important species.

39

40 **Keywords:** ocean acidification; abalone; acid–base balance; hæmolymph pH and alkalinity;
41 buffer capacity

42 **Abbreviations:** A_T: Total alkalinity; DIC: Dissolved Inorganic Carbon; pH_{NBS}: pH of the
43 National Bureau of Standard; pH_T: pH on the Total scale; pH_{SW}: seawater pH (total scale);
44 pH_{HL}: hæmolymph pH (total scale); RCP 8.5: Representative Concentration Pathway 8.5
45

46 1. Introduction

47 The increase of anthropogenic CO₂ emissions over the past 200 years and its subsequent
48 absorption (about ¼) by the ocean is responsible for seawater pH decrease and substantial
49 changes in carbonate chemistry, a process known as ocean acidification (OA) (Caldeira and
50 Wickett, 2003; Fabry et al., 2008; Gattuso et al., 2015). According to the most pessimistic
51 scenario for future greenhouse gas emissions (Representative Concentration Pathway 8.5:
52 RCP 8.5), surface ocean pH should decrease by 0.33 pH units by the year 2100 (IPCC,
53 2014), resulting in deleterious effects on the biology and ecology of numerous marine organisms
54 (Widdicombe and Spicer, 2008; Kroeker et al., 2010; Wittmann and Pörtner, 2013). Changes in
55 ocean chemistry may be more pronounced in coastal areas where numerous species of
56 economic importance (such as molluscs) can be found and such changes may be exacerbated
57 by diurnal and seasonal variations in shallow and intertidal zones (Truchot, 1988; Byrne et al.,
58 2011; Legrand et al., 2018). OA is also predicted to affect aquaculture activities around the globe
59 through its effects on species physiology and behaviour in relation to farming practices (Cochrane
60 et al., 2009; Clements and Chopin, 2016; Weatherdon et al., 2016).

61 Among its reported biological effects, increased seawater pCO₂ has been shown to induce
62 hypercapnia and acidosis in organisms, both of which are energetically costly processes that can
63 affect vital functions such as growth and calcification (Pörtner et al., 2004; Fabry et al., 2008;
64 Melzner et al., 2009; Orr et al., 2005; Hofmann et al., 2010). Due to a low capacity to regulate
65 their acid–base balance and the highly calcified shells they build, marine molluscs are

66 considered to be among the most vulnerable species with regard to OA (Fabry et al., 2008;
67 Gazeau et al., 2013; Parker et al., 2013). Abalones (Mollusca, Vetigastropoda) are
68 ecologically important herbivore species, providing key ecosystem services through their role
69 in nutrient and mineral cycling, and are economically important as a food source (Cook,
70 2016; Huchette and Clavier, 2004). Many abalone species have experienced severe
71 population declines worldwide due to both overfishing (Rogers-Bennett et al., 2002) and
72 environmental disruptions, such as global warming and wasting disease (Cook, 2016; Moore
73 et al., 2002; Morales-Bojórquez et al., 2008; Nicolas et al., 2002; Travers et al., 2009). In the
74 context of a worldwide expansion in their aquaculture, understanding the effects of
75 environmental stresses on abalone physiology is an important issue for the management of
76 wild populations as well as for the optimization of fisheries and aquaculture practices
77 (Morash and Alter, 2015).

78 *Haliotis tuberculata* is the only abalone species present in Europe, living in low intertidal
79 and subtidal rocky coastal areas where it offers a high potential for fishery and aquaculture
80 (Huchette and Clavier, 2004; Courtois de Viçose et al., 2007). Several studies focusing on
81 early life-history stages of abalone, especially larvae, have demonstrated adverse effects of
82 elevated pCO₂, such as reduced survival, developmental delay, body and shell abnormalities
83 and reduced mineralization (Byrne et al., 2011; Crim et al., 2011; Guo et al., 2015; Kimura et
84 al., 2011; Onitsuka et al., 2018; Wessel et al., 2018; Zippay and Hofmann, 2010). Impacts of
85 OA on shell calcification and integrity have been well studied on various stages of *H.*
86 *tuberculata*, from larvae to juveniles and adults (Wessel et al., 2018; Auzoux-Bordenave et
87 al., 2020; Avignon et al., 2020). Reduced growth in shell length and alterations of the shell
88 microstructure were observed in juvenile abalone exposed to pH_T 7.6, which correspond to
89 projected pH values expected for 2100 (IPCC, 2014; Gattuso et al., 2015). Since these pH
90 conditions corresponded to an aragonite saturation state below 1, it was concluded that the
91 effects on shell growth and integrity were principally caused by direct aragonite dissolution
92 within the abalone shell (Auzoux-Bordenave et al., 2020). Additional effects on the organic
93 periostracum and nacre structure suggested that other processes involved in shell
94 biomineralization, such as matrix protein production and enzymatic activities, would also be

95 influenced by changes in seawater pH. Avignon et al. (2020) demonstrated significant effects
96 on growth in shell length, microstructure and resistance in adult *H. tuberculata* exposed to
97 pH_T 7.7. Although the aragonite saturation was above 1 (1.24) here, the effects on shell
98 integrity were partly attributed to direct effects on aragonite dissolution. The study also found
99 that the expression of genes involved in either stress responses or biomineralization
100 processes was not significantly modified in response to decreased pH. These observations
101 suggested that other indirect effects, due to extracellular acid–base balance modification,
102 could lead to metabolic disturbances affecting growth, calcification and, ultimately, fitness
103 (Pörtner et al., 2004; Fabry et al., 2008; Melzner et al., 2009; Michaelidis et al., 2005).
104 According to Cyronak et al. (2016), elevated H^+ concentration and subsequent problems of
105 homeostasis would be more likely than carbonate ion concentration to induce the reduction
106 of calcification in marine organisms facing OA.

107 Metazoans use two buffer systems in response to potential fluctuations of their extracellular
108 pH (Heisler, 1989). The most commonly used is a bicarbonate-based buffer system which is a
109 relatively low-cost system energetically depending on the number of protons (H^+) to be
110 eliminated and the capacity of the species to accumulate bicarbonate ions in their extracellular
111 fluids (Heisler, 1989; Melzner et al., 2009). The second buffer system is non-bicarbonate based
112 and relies on organic molecules (protein and peptides) present in the hæmolymph that are able
113 to capture H^+ with their polypeptide side chains.

114 The ability to prevent CO_2 -induced changes of the hæmolymph pH (pH_{HL}) is believed to
115 be a key determinant of an organisms' ability to tolerate near future OA (Collard et al., 2013;
116 Wittmann and Pörtner, 2013; Melzner et al., 2009). Marine molluscs are usually considered to
117 be poor acid–base regulators compared with other taxa and their ability to buffer their
118 extracellular fluid when experiencing OA stress is thus very limited (Melzner et al., 2009;
119 Gazeau et al., 2013, Parker et al., 2013). However, some intertidal molluscs are able to
120 compensate the decrease of their extracellular pH to some extent (Widdicombe and Spicer,
121 2008; Marchant et al., 2010; Scanes et al., 2017). In adult bivalves, long-term hypercapnia was
122 seen to cause a reduction in extra-cellular pH_{HL} , which was partly prevented by an increase of
123 bicarbonate hæmolymph concentration, supposedly coming from shell dissolution (Michaelidis et

124 al., 2005; Thomsen et al., 2010; Heinemann et al., 2012). Cao-Pham et al. (2019) reported an
125 Na^+/H^+ exchanger-like in the apical membrane of the epithelium facing the sea water in the inner
126 mantle giant clam *Tridacna squamosa* which hosts zooxanthellae. Based on the localization of
127 the exchanger and the upregulation of the expression level of this transporter by light, these
128 authors suggested that the exchanger could be involved in the elimination of protons produced
129 during light-enhanced calcification. This indicates a possible pH compensation mechanism. In
130 cephalopods, the cuttlefish *Sepia officinalis* was shown to partially compensate its pH_{HL} by
131 accumulating bicarbonate ions in its extracellular fluid (Gutowska et al., 2010). To our
132 knowledge, the acid–base physiology has been studied in only two genera of gastropods: in
133 abalone and in patellid limpets. The limpet *Patella vulgata* showed an ability to fully
134 compensate its pH_{HL} after 5 days of exposure to low pH (pH_{NBS} 7.5) by increasing its
135 hæmolymph bicarbonate concentration, supposedly from shell dissolution (Marchant et al.,
136 2010). Apart from patellid limpets *Patella* sp. which are distantly related to other gastropods,
137 there are only two studies on the acid–base regulation abilities of abalone exposed to
138 environmental stress. Cheng et al. (2004) reported that a decrease in dissolved O_2 disrupted
139 the acid–base balance as well as anaerobic metabolism of *H. diversicolor supertexta*. On the
140 other hand, when exposed to elevated pCO_2 , juvenile *Haliotis fulgens* showed no significant
141 changes in the concentration of products from the anaerobic metabolism, compared with
142 control conditions (Tripp-Valdez et al., 2017).

143 As an herbivorous gastropod, abalone is considered as a low trophic species exhibiting a
144 low metabolism (compared with more active carnivorous molluscs). Low rates of metabolism
145 typically correlate with lower concentrations of ion transport proteins (such as Na^+/K^+ and H^+ -
146 ATPases, Gibbs and Somero, 1990), suggesting reduced capacities of acid–base balance
147 and a poor ability to compensate for changes in acid–base status (Fabry et al., 2008; Pörtner et
148 al., 2004; Melzner et al., 2009; Parker et al., 2013). In adult *H. tuberculata* under OA stress, the
149 hæmolymph extracellular pH was reported to be 0.1 pH unit lower in individuals subjected to pH_{T}
150 7.7, compared with those maintained in pH_{T} 8.0, suggesting that abalone only poorly
151 compensate for the pH decrease of their extracellular fluid if at all (Avignon et al., 2020).
152 Interestingly, compared with abalones, patellid limpets were only moderately affected by OA

153 (Marchant et al., 2010; Duquette et al., 2017). In other taxa, such as crustaceans, sipunculids
154 or echinoderms, the capacity to tolerate a moderate sea water pH decrease has been linked
155 with the ability to regulate the extracellular acid–base balance (Pörtner et al., 2004; Di Giglio
156 et al., 2020). Consequently, we hypothesize that abalone have a limited ability to
157 compensate pH_{HL} .

158 To better understand how abalone respond to CO_2 -induced OA, the present study
159 investigated, for the first time, the extra-cellular acid–base parameters in the hæmolymph of
160 adult *Haliotis tuberculata* exposed to acute OA stress. Three pH_T levels (7.9, 7.7, 7.4) were
161 compared, to which the animals were exposed for 15 days. Extracellular pH and total
162 alkalinity of the hæmolymph were measured at different time points through the experiment
163 and were used to calculate the carbonate parameters of the extracellular fluid (e.g. pCO_2 ,
164 carbonate and bicarbonate ions, dissolved inorganic carbon: DIC, aragonite and calcite
165 saturation state). Total protein content was also measured in hæmolymph samples to
166 determine whether lowering the seawater pH influenced the composition or buffer capacity of
167 extracellular fluid in adult abalone.

168

169 **2. Material and Methods**

170 **2.1 Abalone collection and acclimation**

171 Three-year-old adult abalone *Haliotis tuberculata* were picked up without any selection from
172 an offshore sea-cage structure containing 600 individuals per cage, at the France Haliotis
173 abalone farm (48°36'50N, 4°36'3W; Plouguerneau, Brittany, France). Abalone were
174 transported to the laboratory ensuring minimum stress and minimum handling during
175 transport. They were conditioned before experiments under ambient seawater pCO_2/pH and
176 temperature conditions and fed *ad libitum* with the macroalga *Palmaria palmata*.

177

178

179 **2.2 Experimental set-up**

180 Two experiments were carried out in two different laboratories. A first experiment (Exp.1),
181 carried out in February 2015 at the Marine Biology Laboratory (ULB, Brussels), was done to
182 assess acid–base parameters and how to measure them in adult abalones conditioned in
183 ambient conditions of $p\text{CO}_2$. A second experiment (Exp.2), carried out in November 2015 at
184 the MNHN Concarneau marine station (Brittany, France), was then done to assess whether
185 the decrease of seawater pH had an impact on acid–base parameters of abalone.

186

187 **2.2.1. Experiment 1: ambient conditions**

188 Adult abalones (63 ± 5 mm in shell length, $n = 48$) were distributed without any selection
189 among three 45-L open-circuit experimental aquaria ($n = 16$ abalone per aquarium) supplied
190 with filtered seawater renewed at a rate of $60\text{--}65 \text{ L}\cdot\text{h}^{-1}$ and continuously aerated with ambient
191 air. Animals were conditioned for 10 days in the laboratory in ambient conditions of
192 temperature and $p\text{CO}_2$ and were fed *ad libitum* with *P. palmata*.

193

194 **2.2.2. Experiment 2: OA experiment**

195 Adult abalone (61 ± 3 mm in shell length, $n = 180$) were distributed without any selection
196 among nine 45-L open-circuit experimental aquaria ($n = 20$ abalone per aquarium) supplied
197 with through-flowing $3\text{-}\mu\text{m}$ filtered natural field seawater renewed at a rate of $60\text{--}65 \text{ L}\cdot\text{h}^{-1}$ and
198 continuously aerated with ambient air. The aquaria were cleaned twice a week using a
199 siphoning hose and the water filters were changed daily. Following the three weeks of
200 conditioning, aquaria housing abalone were assigned to three pH treatments for 15 days.
201 The pH treatments were as follows: present-day field conditions $\text{pH}_T 7.9$ ($p\text{CO}_2 \approx 600 \mu\text{atm}$);
202 $\text{pH}_T 7.7$ ($p\text{CO}_2 \approx 1000 \mu\text{atm}$), predicted to occur in 2100 according to the RCP 8.5 scenario
203 (IPCC, 2014; Gattuso et al., 2015); and an extreme level of $\text{pH}_T 7.4$ ($p\text{CO}_2 \approx 2000 \mu\text{atm}$).
204 Three replicate 45-L aquaria were set up for each pH treatment, in which seawater $p\text{CO}_2$
205 concentrations were adjusted by bubbling CO_2 (Air Liquide, France). $p\text{CO}_2$ in each tank was

206 controlled through electro-valves regulated by a pH-stat system (IKS Aquastar, Germany).
207 pH values of the IKS system were adjusted from daily measurements of the electromotive
208 force in the aquaria using a pH meter (Metrohm 826 pH mobile, Metrohm, Switzerland) with a
209 glass electrode (Metrohm electrode plus) converted into pH units on the total scale (pH_T)
210 using Tris/HCl and 2-aminopyridine/HCl buffers (Dickson, 2010). Before the start of the
211 experiment, pH was gradually decreased by 0.1 pH unit per day until the different target pH
212 levels were reached.

213

214 **2.3. pH and carbonate parameters monitoring**

215 Seawater parameters were monitored throughout the 10 days of control conditions in Exp.1
216 and the 15 days of exposures in Exp.2. Temperature and pH_T were recorded daily in each
217 experimental aquarium using a pH meter as described above, and salinity was measured
218 twice a week using a conductivity meter (3110, WTW, Germany). Total alkalinity (A_T) of the
219 seawater was measured weekly on 100 mL samples taken from each experimental
220 aquarium. Seawater samples were filtered through 0.7 µm Whatman GF/F membranes,
221 immediately poisoned with mercury chloride and stored at 4°C until analyses. A_T was
222 determined potentiometrically using an automatic titrator (Titroline alpha, Schott SI Analytics,
223 Germany) calibrated with the National Bureau of Standards scale. A_T was calculated using a
224 Gran function applied to pH values ranging from 3.5 to 3.0, as described by Dickson et al.
225 (2007), and corrected by comparison with standard reference material provided by Andrew
226 G. Dickson (CRM Batch 111). Seawater carbonate chemistry, i.e. bicarbonate (HCO₃⁻),
227 carbonate (CO₃⁻) and dissolved inorganic carbon (DIC) concentrations, pCO₂ and the
228 saturation states of aragonite (Ω_{aragonite}) and calcite (Ω_{calcite}) were calculated from pH_T, A_T,
229 temperature and salinity using the CO2SYS program (Pierrot et al., 2006) set with the
230 constants of Mehrbach et al. (1973) refitted by Dickson and Millero (1987).

231 **2.4. Abalone survival and sampling**

232 Abalone survival was assessed every day throughout the experiments and any dead
233 individuals were removed from the aquaria immediately. Survival (%) was calculated as the
234 proportion of living individuals at the end of the experiment relative to the total number of
235 abalones per aquarium at the beginning of the experiment. Abalones were randomly
236 sampled for hæmolymph analysis. In Exp. 1, 3 to 5 individuals were removed at each
237 sampling time. The hæmolymph was pooled from these individuals and the data were
238 averaged over the 3 sampling times ($n = 3$). In Exp.2, abalones were sampled after 5, 10 and
239 15 days of pH exposure (D5, D10 and D15, respectively). Hæmolymph was pooled from 3 to
240 5 individuals collected from the same aquarium and the data were averaged over the 3
241 aquaria per pH treatment ($n = 3$ per sampling time and pH treatment). Hæmolymph was
242 sampled immediately from these animals and shell length and width were measured to the
243 nearest 0.5 mm using Vernier callipers. Animals were replaced into their initial aquaria, with a
244 tag to avoid re-sampling of the same individual.

245

246 **2.5. Hæmolymph sampling and analysis**

247 Hæmolymph was withdrawn carefully from the pedal sinus using a refrigerated 2-mL syringe
248 and 25 G x $\frac{1}{2}$ needles. Hæmolymph from the 3 to 5 individuals was pooled in a 15-mL vial on
249 ice and the electromotive force was measured using a glass micro-electrode (Biotrode,
250 Metrohm, Germany). This value was converted into pH units of the total scale (pH_T) as
251 described above for seawater pH_T determination.

252 Pooled samples were pelleted in a centrifuge (250 g, 10 min, 6°C) and the supernatant was
253 distributed immediately into 96-well microplates for protein analysis. Protein concentration
254 was determined spectrophotometrically by BCA assay (Pierce, SIGMA) using bovine serum
255 albumin (BSA) as a standard (Smith et al., 1985). A calibration curve was obtained by
256 measuring a dilution series of standard BSA solution, 25 to 500 $\mu\text{g}\cdot\text{mL}^{-1}$ ($n = 6$ replicate wells
257 in a 96-well microplate). Absorption of each sample was determined using a microplate
258 reader (BioTek plate reader, Winooski, VT, USA) operating at 570 nm, and protein content

259 was calculated from the average absorbance of the six replicate wells according to the
260 calibration curve.

261 A_T of the hæmolymph was determined by a potentiometric titration method adapted to small
262 volumes (Gran, 1952; Collard et al., 2013, 2014), using a 3-mm diameter glass
263 microelectrode (Biotrode, Metrohm, Germany). A_T was tentatively measured on several
264 samples of whole hæmolymph and the supernatant of the 250-g centrifugation (also used for
265 protein determination). Because these measurements turned out to be unfeasible (see
266 Results section), the supernatant of the 250-g centrifugation (7 mL) was ultra-filtrated using a
267 centrifugal filter unit with a molecular cut-off of 3 kDa (Amicon Ultra 2 mL, Millipore, USA
268 4000g, 45min, 6°C). The ultra-filtrated fraction was then transferred into a 1.5-mL tube for A_T
269 measurement. Hæmolymph pCO_2 , bicarbonate, carbonate and DIC concentrations were
270 calculated from pH_T , A_T , temperature and salinity using the CO2SYS program as described
271 in section 2.2 for the determination of seawater carbonate parameters. The methods of
272 hæmolymph sampling and analysis apply to both experiment 1 and 2.

273

274 **2.6. Statistical analyses**

275 All statistical analyses were performed with Rstudio software (R Core Team, 2015).
276 Differences in abalone survival, shell length and hæmolymph parameters (i.e. pH_{HL} , total
277 alkalinity, pCO_2 , bicarbonate ion concentration, saturation states and protein content) across
278 pH_{SW} treatments were analysed with general linear model ANOVAs (pH_{SW} : fixed factor) using
279 the mean value per aquarium ($n=3$ replicates per pH condition, Exp.2). The normality of the
280 residuals and homogeneity of variances were verified using respectively Shapiro-Wilk and
281 Bartlett tests. Statistical analyses were performed separately for each time point on these
282 data. Post-hoc HSD Tukey tests were used to test the differences between the group means.
283 Data given in the text and figures are presented as mean \pm standard deviation (SD), unless
284 otherwise indicated. Differences were considered significant at $P < 0.05$.

285

286 3. Results

287

288 3.1. Experiment 1: ambient conditions

289 Mean values of seawater parameters over the whole period ($n = 6$) are given in Table 1A.
290 Seawater temperature was $14.5 \pm 0.3^\circ\text{C}$, salinity was 34.1 ± 0.1 , pH_T 8.03 ± 0.01 and pCO_2
291 $576 \pm 30 \mu\text{atm}$. Extra-cellular acid–base parameters measured in adult abalones kept in
292 ambient conditions are reported in Table 1B. Mean hæmolymph pH_T (pH_{HL}) was 7.32, *ca.* 0.7
293 units lower than seawater pH_T (Table 1B). The titration carried out on freshly collected
294 hæmolymph and on the supernatant of hæmolymph centrifuged at 250 g did not allow total
295 alkalinity to be determined because the titration curve obtained did not fit a Gran function
296 (Suppl. material S1). After ultrafiltration of the hæmolymph through a membrane with a
297 molecular cut-off of 3kDa, the typical titration curve was obtained and used to calculate the
298 total alkalinity according to the Gran method (Suppl. material S1). Average value of the latter
299 for abalones kept in ambient conditions was $3796 \pm 72 \mu\text{E.kg}^{-1}$. pH and A_T of the
300 hæmolymph were used to calculate other parameters of the carbonate system (Table 1B).
301 pCO_2 reached $4331 \mu\text{atm}$, bicarbonate $3664 \mu\text{mol.kg}^{-1}$, $\Omega_{\text{aragonite}}$ and Ω_{calcite} were respectively
302 lower and higher than 1.

303

304 3.2. Experiment 2: acidified conditions

305 Mean values of seawater parameters are presented in Table 2A. Temperature followed the
306 natural variations found in the Bay of Concarneau, from $15.1^\circ \pm 0.1^\circ\text{C}$ at the start of the
307 experiment (T0, early November) to $13.4^\circ\text{C} \pm 0.3^\circ\text{C}$ at the end of the experiment (D15). The
308 pH_T levels of the experimental aquaria were maintained close to the nominal values
309 throughout the experiment, at means of $\text{pH}_T = 7.91$ ($\text{pCO}_2 = 567 \pm 61 \mu\text{atm}$), $\text{pH}_T = 7.69$
310 ($\text{pCO}_2 = 997 \pm 126 \mu\text{atm}$), and $\text{pH}_T = 7.40$ (pCO_2 of $2035 \pm 114 \mu\text{atm}$) (Table 2A). Total
311 alkalinity (A_T) measured in the nine experimental aquaria averaged $2295 \pm 11 \mu\text{Eq.kg}^{-1}$
312 during the experiment. Mean salinity was 34.6 ± 0.2 in all experimental aquaria and remained

313 stable over the experiment (n = 30). $\Omega_{\text{aragonite}}$ was higher than 1 in pH treatments 7.9 and 7.7
314 and below 1 in the lowest pH treatment (7.4).

315

316 3.2.1. Survival and growth

317

318 The mortality of adult abalones during the experiment was very low, with a survival
319 percentage higher than 90% at the end of the experiment (Day 15). There were no significant
320 differences in survival between the three pH treatments (ANOVA, $F(2,6) = 0.6$, $p = 0.58$).
321 Mean shell length of adult abalone at the start of the experiment (T0, Exp. 2) was 61 ± 3 mm
322 and did not differ significantly across the four time points (ANOVA, $F(3,120) = 0.75$, $p = 0.52$).
323 There were no significant differences in total length between the three pH treatments
324 (ANOVA, $F(2,121) = 0.90$, $p = 0.41$).

325

326 3.2.2. Hæmolymph acid–base status

327

328 *Hæmolymph pH_T*

329 Mean hæmolymph pH (pH_{HL}) measured in control abalones ranged between 7.29 and 7.36
330 *i.e.* 0.54 to 0.61 lower than seawater pH_T (Table 2B). A significant effect of decreased
331 seawater pH was observed on pH_{HL} of abalone at any time point (Fig.1A, Table 3A). At D5
332 and D10, pH_{HL} of abalone exposed to pH_{SW} 7.4 was significantly lower than that of control
333 individuals exposed to pH_{SW} 7.9 (Table 3B). At D15, pH_{HL} of abalone exposed to pH_{SW} 7.4
334 was significantly lower than that of individuals exposed to 7.7 and 7.9 (Table 3B). There were
335 no significant differences in pH_{HL} between abalone exposed to pH_{SW} 7.7 and 7.9 at any time
336 point (Table 3B).

337

338 *Total alkalinity (A_T)*

339 Total alkalinity (A_T) measured in the hæmolymph of control abalones was $3177 \pm 103 \mu\text{E}\cdot\text{kg}^{-1}$
340 (Table 2B). A_T of the hæmolymph was significantly different in abalones exposed to lower
341 seawater pH (Fig. 1B, Table 3A). After 15 days of exposure, hæmolymph A_T of abalones

342 exposed to pH_{SW} 7.4 was significantly lower than that of control individuals exposed to 7.7
343 and 7.9 (Table 3B). There were no significant differences in hæmolymph A_T between
344 abalones exposed to pH_{SW} 7.7 and 7.9 at any time point (Table 3B).

345

346 *pCO₂*:

347 Mean pCO₂ in control abalones ranged between 3141 and 3675 µmol.kg⁻¹ (Table 2B).
348 Significant differences in hæmolymph pCO₂ were observed in abalones exposed to lower
349 seawater pH (Table 3A). At D10, extracellular pCO₂ in abalones exposed to pH_{SW} 7.4 was
350 significantly lower than that of control individuals exposed to 7.7 and 7.9 (Table 3B). There
351 were no significant differences in hæmolymph pCO₂ between abalones exposed to pH_{SW} 7.7
352 and 7.9 at any time point (Table 3B).

353

354 *HCO₃⁻*

355 Mean hæmolymph [HCO₃⁻] in control abalones ranged between 3059 and 3077 µmol.kg⁻¹
356 (Table 2B). In abalones exposed to decreased pH, hæmolymph [HCO₃⁻] was significantly
357 different after 15 days of exposure (Table 3A). At this time point, [HCO₃⁻] in abalones
358 exposed to pH_{SW} 7.4 was significantly lower than that of individuals exposed to pH_{SW} 7.7 and
359 7.9 (Table 3B). There were no significant differences in hæmolymph [HCO₃⁻] between
360 abalones exposed to pH_{SW} 7.7 and 7.9 at any time point (Table 3B).

361

362 *Saturation state (Ω)*

363 Ω_{aragonite} and Ω_{calcite} in control abalones were respectively 0.71 ± 0.08 and 1.11 ± 0.12 (Table
364 2B). A significant effect of decreased seawater pH was observed on Ω_{aragonite} and Ω_{calcite} at
365 any time point (Table 3A). At D5, Ω_{aragonite} in abalone exposed to pH_{SW} 7.4 and 7.7 was
366 significantly lower than that of control individuals exposed to pH_{SW} 7.9 (Table 3B). At D10
367 Ω_{aragonite} in abalone exposed to pH_{SW} 7.4 was significantly lower than that of control

368 individuals exposed to pH_{SW} 7.9 (Table 3B). At D15, $\Omega_{\text{aragonite}}$ in abalone exposed to pH_{SW} 7.4
369 was significantly lower than that of individuals exposed to pH_{SW} 7.9 and 7.7 (Table 3B).

370

371 3.2.3. Protein content

372 The average protein content in the hæmolymph of control abalones was $16.7 \pm 5 \text{ g.L}^{-1}$ (Table
373 2B) and did not differ significantly between pH treatments at any time point (Table 3A).

374

375 4. Discussion

376

377 This paper reports the first investigation of extra-cellular acid–base parameters and buffer
378 capacity in the adult abalone *H. tuberculata* exposed to CO₂-induced ocean acidification. In
379 control *H. tuberculata*, pH_{HL} was 7.4, which is close to the range for extracellular pH
380 measured in the Taiwan abalone *H. diversicolor supertexta* (between 7.23 and 7.28, Cheng
381 et al., 2004). In adult *H. tuberculata* facing OA stress, all the extra-cellular acid–base
382 parameters measured or calculated (except pCO₂) were significantly reduced in the pH_{SW} 7.4
383 treatment (0.5 units below control pH), while pH_{SW} 7.7 did not affect the variables
384 significantly.

385 A pH-bicarbonate diagram (Davenport diagram, Fig. 2) further indicates that adult *H.*
386 *tuberculata* are able to maintain their hæmolymph pH with moderate acidification (-0.2 pH_{SW}
387 units) but not at a more severe level (-0.5 pH_{SW} units). This is consistent with our previous
388 results showing that adult abalones exposed to a -0.3 pH decrease for two months were
389 unable to maintain their pH_{HL} (Avignon et al., 2020). It is noteworthy that the pH_{HL}
390 homeostasis at pH_{SW} 7.7 is not due to an accumulation of bicarbonate ions, contrary to the
391 limpet *Patella vulgata*, which was reported to increase its hæmolymph bicarbonate
392 concentration to compensate its pH_{HL} (Marchant et al., 2010). Furthermore, it appears that
393 abalone subjected to pH_{SW} 7.4 suffered metabolic acidosis (reduced hæmolymph pH and
394 bicarbonate concentration). This suggests the induction of anaerobic metabolism by OA at

395 pH_{SW} 7.4. This finding does not agree with the results obtained by Tripp-Valdez et al. (2017)
396 in *Haliotis fulgens*. When subjected to pH_T 7.3–7.4 (recalculated from their pCO₂ and A_T data
397 using CO₂SYS; -0.4 to -0.5 pH_T units compared with the control), *H. fulgens* juveniles,
398 maintained at control temperature in normoxic conditions, showed no significant changes in
399 the concentration of products from the anaerobic metabolism, compared with control
400 conditions. However, the abalone in the present study are large adults, which probably
401 develop anaerobic conditions more easily, particularly in the foot (see Venter et al., 2018).

402
403 In addition to pH_{HL}, total alkalinity (A_T) of the hæmolymp was also measured in *H.*
404 *tuberculata* using a potentiometric titration method adapted to small volumes (Gran, 1952;
405 Collard et al., 2013, 2014). The titrations carried out on either freshly collected hæmolymp
406 or on the 250-g centrifugation supernatant differed from the classical titration of a
407 bicarbonate/carbonate buffered marine solution and did not allow the determination of A_T. A
408 classical titration curve allowing A_T calculation was, however, obtained on the ultra-filtrated
409 fraction after removing organic molecules of MW > 3kDa. As the large hemocyanin protein
410 molecule in abalone is carried in the hæmolymp, this may have interfered with the titration
411 of A_T. These results suggested that abalone hæmolymp contained a significant
412 concentration of proteins and/or peptides (MW > 3kDa). Indeed, the protein concentration
413 measured in the hæmolymp of *H. tuberculata* (mean 15–22 g.L⁻¹) is much higher than that
414 found in other gastropods (e.g. 0.5 to 1.5 mg.L⁻¹ in the limpet *Patella sp*, Brown et al., 2004)
415 or in the range of concentrations measured in the Australian abalone *H. rubra* (around 10
416 g.L⁻¹, Hooper et al., 2014). We suggest that these proteins/peptides scavenge protons of
417 respiratory origin when an abalone is subjected to moderate acidification (pH_{SW} 7.7).
418 However, they appeared incapable of buffering the extra protons when the pH_{SW} was
419 lowered to 7.4. The protein content of the hæmolymp appeared to be not much influenced
420 by hypercapnia, but this conclusion should be carefully considered in view of the high
421 variability in protein concentration between individuals.

422
423 In summary, adult abalone *H. tuberculata* appeared able to buffer moderate (-0.2 pH_{SW}
424 units) acidification, probably due to its high hæmolymp protein concentration but was not

425 able to compensate for greater decreases in pH_{SW} . These results are consistent with
426 previous studies on the mussel *Mytilus edulis* (Thomsen et al., 2010, 2013). In this bivalve
427 species, these authors clearly demonstrated the absence of HCO_3^- accumulation and
428 suggested that buffering by extracellular proteins is the sole mechanism acting to stabilize
429 hæmolymph pH (Thomsen et al., 2010). However, this strategy contrasts with that of the
430 more active cephalopod *Sepia officinalis*, which greatly increases extracellular $[\text{HCO}_3^-]$ in
431 order to stabilize its extracellular pH_{HL} upon exposure to OA (Gutowska et al., 2010).
432 Generally, active invertebrates tend to show a stronger HCO_3^- buffering capacity, while less
433 active invertebrates may experience metabolic suppression associated with a decline in pH
434 (Melzner et al. 2009; Pörtner, 2008).

435 Mean pCO_2 values in abalone hæmolymph were higher for the pH_{SW} 7.4 treatment, but
436 the differences were significant only at day 10 of the experiment. As previously shown in
437 marine molluscs an increase in extra-cellular pCO_2 may cause hypercapnia and acidosis, two
438 energetically processes that can negatively affect vital processes, such as somatic growth
439 and calcification (Pörtner et al., 2004; Fabry et al., 2008; Melzner et al., 2009). The saturation
440 state of abalone hæmolymph (Ω) towards aragonite was below 1 in all conditions including
441 the control treatment. Nevertheless, *H. tuberculata* calcifies efficiently aragonite in control
442 conditions, indicating that conditions in the calcifying site strongly differ from those in the
443 hæmolymph and that acidosis of the hæmolymph is not directly responsible for the effects on
444 shell calcification reported in previous OA experiments (Wessel et al., 2018; Auzoux-
445 Bordenave et al., 2020; Avignon et al., 2020).

446

447 The results of the present study support the hypothesis that changes in extracellular acid–
448 base balance might be involved in deleterious effects recorded in adult *H. tuberculata* facing
449 severe OA stress, as previously reported in marine bivalves (Michaelidis et al., 2005; Melzner et
450 al., 2009; Waldbusser et al., 2011). As previously emphasized, very little information is available
451 on the acid–base homeostasis abilities of marine gastropods. *P. vulgata* lives in the higher
452 intertidal zone where important local variations in physico-chemical conditions might occur
453 inducing hypoxic, hypercapnic and desiccation stresses (Marchant et al. 2010). When facing

454 severe acidification (-0.7 pH_{SW} units) of its environment, the limpet was able to compensate its
455 pH_{HL} by increasing its HCO₃⁻ buffering capacity (Marchant et al., 2010). *H. tuberculata*, in
456 contrast, inhabits the subtidal and low intertidal zone where physico-chemical stresses are
457 much lower. For instance, pH_T in the Bay of Brest, one of this specie natural habitat, ranges
458 between 8.2 and 7.9 (Qui-Minet et al., 2018). This suggests that *H. tuberculata* has not
459 developed the biochemical machinery to ensure a strong acid–base homeostasis. This
460 weakness, together with the effects reported on growth and shell calcification (Wessel et al.,
461 2018; Auzoux-Bordenave et al., 2020; Avignon et al., 2020), would impact both the ecology
462 and aquaculture of this commercially important species. Understanding how different
463 abalone life stages respond to OA will make it possible to reveal the capacity of abalone to
464 adapt genetically to pCO₂ increases of their environment and to identify bottlenecks for
465 population persistence under near-future pH conditions.

466

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478

479 **Compliance with ethical standards**

480 The authors declare that they have no conflicts of interest or competing financial interests.
481 The experiments complied with the current French laws. All applicable international, national,
482 and institutional guidelines for the care and use of animals were followed.

483

484 **Figures and tables**

485

486 **Figure 1.** Hæmolymph pH_T (A) and Total alkalinity (B) in adult abalone exposed to three pH
487 levels (7.9, 7.7 and 7.4) after 15 days of exposure ($n = 3$ per pH treatment). Means of bars
488 with different letters are significantly different ($P < 0.05$).

489

490 **Figure 2.** pH_{HL} bicarbonate concentration (Davenport) diagram showing the time course of
491 acid–base compensation (mean \pm SD) in the hæmolymph of abalone *H. tuberculata* over 15
492 days of exposure to elevated pCO_2 . The solid curved lines represent pCO_2 isopleths.
493 Symbols represent the exposure time (respectively 5, 10 and 15 days), while the grey levels
494 correspond to the seawater pH value.

495

496 **Table 1. A.** Seawater temperature and carbonate chemistry parameters of control
497 Experiment 1 (mean \pm SD). pH on the total scale (pH_T), temperature ($^\circ\text{C}$) and total alkalinity
498 (A_T ; $\mu\text{Eq.kg}^{-1}$) were used to calculate CO_2 partial pressure (pCO_2 ; μatm), dissolved inorganic
499 carbon (DIC; $\mu\text{mol.kg}^{-1}$), HCO_3^- and CO_3^{2-} concentrations ($\mu\text{mol.kg}^{-1}$), aragonite saturation
500 state ($\Omega_{\text{aragonite}}$) and calcite saturation state (Ω_{calcite}) using the CO2SYS program. pH_T and
501 temperature are the average values of those logged daily in the aquaria throughout the
502 experiment ($n = 3$).

503 **B.** Acid–base parameters in the hæmolymph of control abalone in Exp.1 (mean \pm SD).
504 Hæmolymph pH (pH_{HL}), temperature ($^\circ\text{C}$) and total alkalinity (A_T ; $\mu\text{Eq.kg}^{-1}$) were used to
505 calculate carbonate chemistry parameters using the CO2SYS program ($n = 3$).

506

507 **Table 2. A.** Seawater temperature and carbonate chemistry parameters at each time point of
508 Experiment 2 after 5 (D5), 10 (D10) and 15 (D15) days of exposure to the experimental pH
509 (mean \pm SD). pH on the total scale (pH_T), temperature ($^\circ\text{C}$) and total alkalinity (A_T ; $\mu\text{Eq.kg}^{-1}$)
510 were used to calculate CO_2 partial pressure (pCO_2 ; μatm), dissolved inorganic carbon (DIC;
511 $\mu\text{mol.kg}^{-1}$), HCO_3^- and CO_3^{2-} concentrations ($\mu\text{mol.kg}^{-1}$), aragonite saturation state ($\Omega_{\text{aragonite}}$)
512 and calcite saturation state (Ω_{calcite}) using the CO2SYS program. pH_T and temperature are the

513 average values of those logged daily in the aquaria throughout the experiment (n = 3 per pH
514 treatment and sampling time).

515 **B.** Acid–base parameters and total protein content (mean ± SD) in the hæmolymph of
516 abalone *H. tuberculata* exposed to three pH treatments after 5 (D5), 10 (D10) and 15 (D15)
517 days of exposure (Exp.2). Hæmolymph pH (pH_{HL}), temperature (°C) and total alkalinity (A_T;
518 µEq.kg⁻¹) were used to calculate carbonate chemistry parameters using the CO2SYS
519 program. Total protein content (g.L⁻¹) was determined spectrophotometrically by BCA assay
520 using BSA as standard (n = 3 per pH treatment and sampling time).

521

522 **Table 3.** Summary of statistics. **A.** Anova results of the effects of seawater pH (pH_{SW}) on
523 hæmolymph pH (pH_{HL}), total alkalinity (A_T), pCO₂, bicarbonate (HCO₃⁻) concentrations,
524 saturation state (Ω_{aragonite} and Ω_{calcite}) and total proteins in the adult abalone *Haliotis*
525 *tuberculata* after 5 (D5), 10 (D10) and 15 (D15) days of exposure (pH_{SW}: fixed factor).
526 Significant P-values are shown in bold (P < 0.05); **B.** Multiple comparison Tukey HSD test
527 testing the influence of seawater pH (pH_{SW}) on hæmolymph pH (pH_{HL}), total alkalinity,
528 bicarbonate (HCO₃⁻) concentration and Ω_{aragonite} at different time points. Significant P-values
529 in bold (P < 0.05).

530

531 **Suppl. material S1:** Titration of abalone hæmolymph by 0.1 M HCl **a:** whole hæmolymph,
532 **b:** supernatant after 250-g centrifugation **c:** 3 kDa ultrafiltered fraction of the hæmolymph.

533

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Figure 1

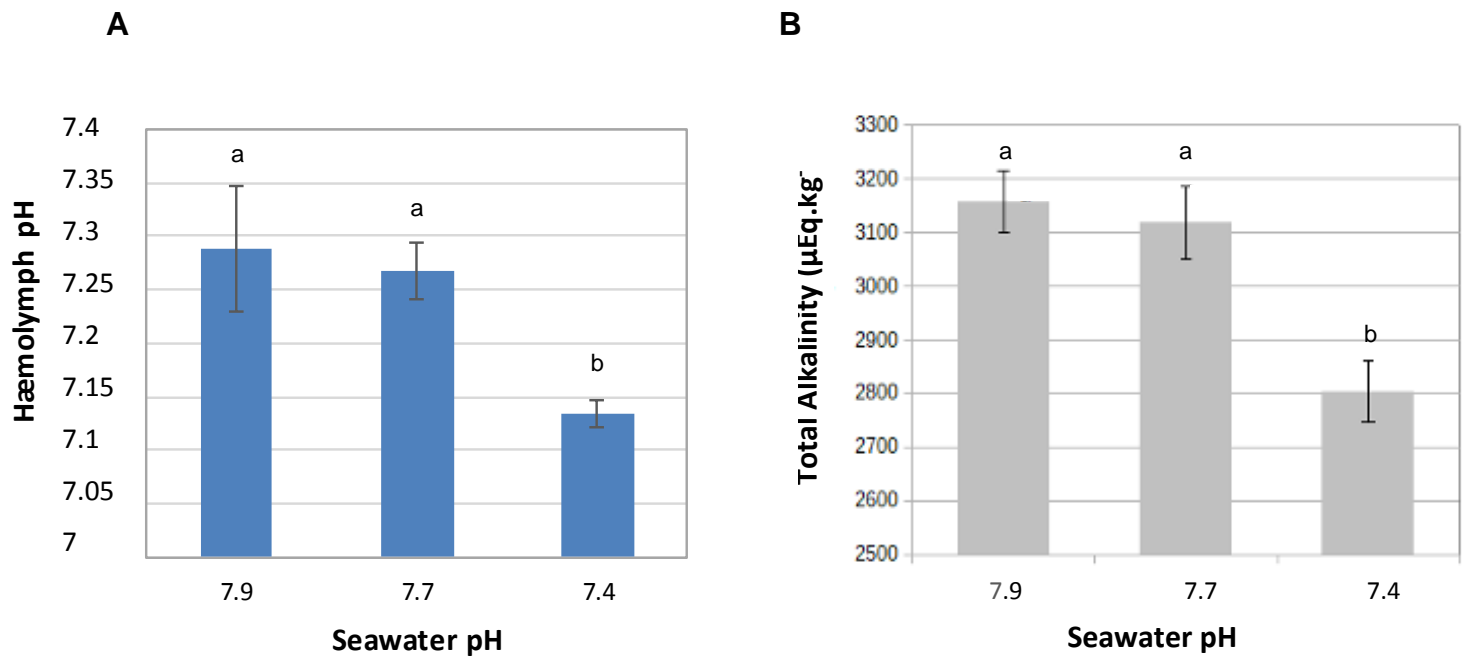


Figure 2

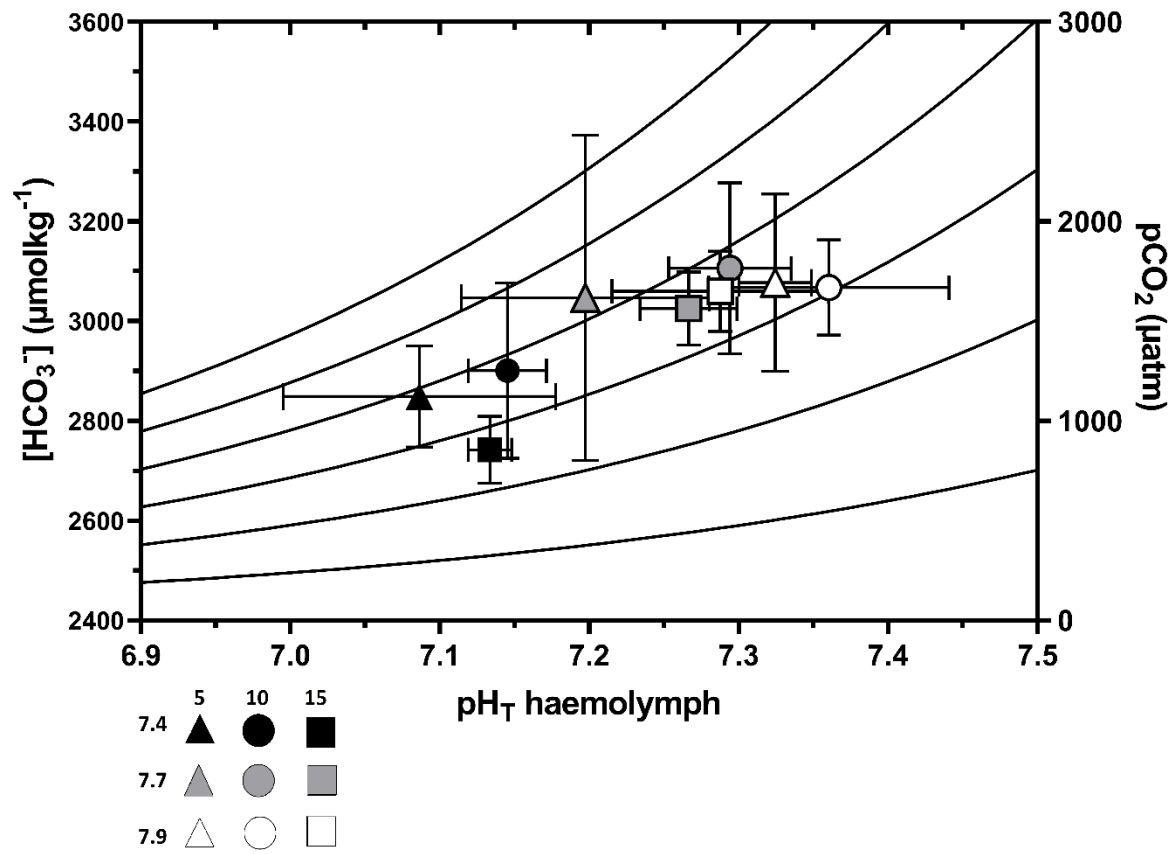


Table 1

	Nominal pH	pH _T	Temperature	A _T	p CO ₂	DIC	HCO ₃ ⁻	CO ₃ ²⁻	Ω _{aragonite}	Ω _{calcite}
			(°C)	(μEq.kg ⁻¹)	(μatm)	(μmol.kg ⁻¹)	(μmol.kg ⁻¹)	(μmol.kg ⁻¹)		
A. Seawater	8.0	8.03 ± 0.01	14.5 ± 0.3	3105 ± 21	576 ± 30	2861 ± 18	2639 ± 16	199 ± 15	3.05 ± 0.23	4.75 ± 0.19
B. Hæmolymph	8.0	7.32 ± 0.16	14.5 ± 0.3	3796 ± 72	4331 ± 1679	3887 ± 155	3664 ± 109	58 ± 16	0.89 ± 0.25	1.39 ± 0.39

Table 2**A. Seawater**

Time point (days)	Nominal pH	pH _T	Temperature (°C)	A _T (μEq.kg ⁻¹)	p CO ₂ (μatm)	DIC (μmol.kg ⁻¹)	HCO ₃ ⁻ (μmol.kg ⁻¹)	CO ₃ ²⁻ (μmol.kg ⁻¹)	Ω _{aragonite}	Ω _{calcite}
D5	7.9	7.87 ± 0.01	15.0 ± 0.1	2287 ± 3	633 ± 14	2148 ± 5	2014 ± 6	110 ± 2	1.69 ± 0.03	2.63 ± 0.04
	7.7	7.67 ± 0.01	15.1 ± 0.0	2281 ± 6	1056 ± 22	2213 ± 2	2102 ± 2	72 ± 2	1.11 ± 0.02	1.73 ± 0.04
	7.4	7.43 ± 0.03	15.1 ± 0.1	2291 ± 1	1913 ± 160	2298 ± 9	2183 ± 7	43 ± 3	0.66 ± 0.05	1.03 ± 0.07
D10	7.9	7.92 ± 0.01	13.9 ± 0.1	2297 ± 4	555 ± 18	2143 ± 8	2003 ± 10	119 ± 3	1.81 ± 0.04	2.83 ± 0.07
	7.7	7.66 ± 0.05	13.9 ± 0.1	2294 ± 5	1083 ± 129	2234 ± 16	2123 ± 18	69 ± 7	1.06 ± 0.11	1.65 ± 0.17
	7.4	7.40 ± 0.02	13.9 ± 0.1	2306 ± 2	2056 ± 119	2328 ± 9	2209 ± 6	39 ± 2	0.60 ± 0.03	0.93 ± 0.04
D15	7.9	7.95 ± 0.05	13.4 ± 0.3	2305 ± 4	514 ± 6	2141 ± 3	1996 ± 3	124 ± 1	1.90 ± 0.01	2.96 ± 0.02
	7.7	7.75 ± 0.04	13.4 ± 0.2	2303 ± 5	852 ± 76	2212 ± 10	2095 ± 14	84 ± 7	1.27 ± 0.11	1.99 ± 0.17
	7.4	7.38 ± 0.07	13.4 ± 0.2	2305 ± 5	2138 ± 390	2333 ± 26	2211 ± 17	38 ± 6	0.58 ± 0.09	0.90 ± 0.14

B. Hæmolymph

Time point (days)	Nominal pH	pH _{HL}	Temperature (°C)	A _T (μEq.kg ⁻¹)	Total protein (g.L ⁻¹)	p CO ₂ (μatm)	DIC (μmol.kg ⁻¹)	HCO ₃ ⁻ (μmol.kg ⁻¹)	CO ₃ ²⁻ (μmol.kg ⁻¹)	Ω _{aragonite}	Ω _{calcite}
D5	7.9	7.32 ± 0.02	15.0 ± 0.1	3189 ± 155	10.3 ± 3.3	3393 ± 5	3252 ± 150	3077 ± 145	48 ± 4	0.74 ± 0.07	1.15 ± 0.11
	7.7	7.20 ± 0.09	15.1 ± 0.0	3130 ± 260	8.3 ± 3.1	4617 ± 1036	3254 ± 302	3047 ± 266	36 ± 3	0.54 ± 0.04	0.85 ± 0.07
	7.4	7.09 ± 0.07	15.1 ± 0.1	2910 ± 80	17.1 ± 4.1	5543 ± 1106	3082 ± 113	2849 ± 83	26 ± 3	0.40 ± 0.05	0.62 ± 0.09
D10	7.9	7.36 ± 0.07	13.9 ± 0.1	3185 ± 65	18.2 ± 4.6	3141 ± 569	3239 ± 94	3067 ± 78	50 ± 6	0.76 ± 0.10	1.19 ± 0.15
	7.7	7.29 ± 0.03	13.9 ± 0.1	3208 ± 151	15.7 ± 3.1	3646 ± 129	3290 ± 141	3106 ± 140	44 ± 5	0.67 ± 0.08	1.04 ± 0.12
	7.4	7.15 ± 0.02	13.9 ± 0.1	2969 ± 148	20.4 ± 7.5	4801 ± 242	3115 ± 151	2901 ± 143	29 ± 2	0.44 ± 0.04	0.69 ± 0.06
D15	7.9	7.29 ± 0.06	13.4 ± 0.3	3157 ± 58	21.7 ± 5.1	3675 ± 560	3246 ± 81	3059 ± 66	41 ± 5	0.63 ± 0.08	0.99 ± 0.12
	7.7	7.27 ± 0.03	13.4 ± 0.2	3117 ± 68	20.3 ± 3.4	3776 ± 149	3212 ± 56	3025 ± 60	39 ± 3	0.59 ± 0.05	0.93 ± 0.08
	7.4	7.13 ± 0.01	13.4 ± 0.2	2804 ± 57	18.4 ± 4.6	4644 ± 124	2950 ± 57	2742 ± 55	26 ± 1	0.40 ± 0.01	0.62 ± 0.02

Table 3**A.**

Parameters	D5	D10	D15
pH _{HL}	F _{2,6} = 8.472, p= 0.018	F _{2,6} = 12.23, p= 0.007	F _{2,6} = 9.36, p= 0.014
Total alkalinity	F _{2,6} = 1.324, p= 0.334	F _{2,6} = 2.137, p= 0.199	F _{2,6} = 20.18, p= 0.002
pCO ₂	F _{2,6} = 3.036, p= 0.123	F _{2,6} = 10.89, p= 0.01	F _{2,6} = 4.859, p= 0.056
HCO ₃ ⁻	F _{2,6} = 0.933, p = 0.444	F _{2,6} = 1.547, p= 0.287	F _{2,6} = 16.83, p= 0.003
Ω _{aragonite}	F _{2,6} = 17.11, p = 0.003	F _{2,6} = 9.73, p= 0.013	F _{2,6} = 10.29, p= 0.011
Ω _{calcite}	F _{2,6} = 17.24, p = 0.003	F _{2,6} = 9.67, p= 0.013	F _{2,6} = 10.67, p= 0.011
Total Proteins	na	F _{2,6} = 0.372, p= 0.704	F _{2,6} = 0.372, p= 0.704

B.

pH groups	7.9/7.7	7.9/7.4	7.7/7.4
pH _{HL} D5	0.149	0.015	0.215
pH _{HL} D10	0.351	0.007	0.037
pH _{HL} D15	0.827	0.016	0.033
Total alkalinity D15	0.795	0.003	0.005
pCO ₂ D10	0.405	0.009	0.044
HCO ₃ ⁻ D15	0.840	0.004	0.008
Ω _{aragonite} D5	0.037	0.003	0.100
Ω _{aragonite} D10	0.453	0.012	0.053
Ω _{aragonite} D15	0.792	0.013	0.028

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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