Effect of CO$_2$-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.)

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Abstract. Oceanic uptake of anthropogenic CO$_2$ results in a reduction in pH termed “Ocean Acidification” (OA). Comparatively little attention has been given to the effect of OA on the early life history stages of marine animals. Consequently, we investigated the effect of culture in CO$_2$-acidified sea water (approx. 1200 ppm, i.e. average values predicted using IPCC 2007 A1F1 emissions scenarios for year 2100) on early larval stages of an economically important crustacean, the European lobster *Homarus gammarus*. Culture in CO$_2$-acidified sea water did not significantly affect carapace length of *H. gammarus*. However, there was a reduction in carapace mass during the final stage of larval development in CO$_2$-acidified sea water. This co-occurred with a reduction in exoskeletal mineral (calcium and magnesium) content of the carapace. As the control and high CO$_2$ treatments were not undersaturated with respect to any of the calcium carbonate polymorphs measured, the physiological alterations we record are most likely the result of acidosis or hypercapnia interfering with normal homeostatic function, and not a direct impact on the carbonate supply-side of calcification per se. Thus despite there being no observed effect on survival, carapace length, or zoeal progression, OA related (indirect) disruption of calcification and carapace mass might still adversely affect the competitive fitness and recruitment success of larval lobsters with serious consequences for population dynamics and marine ecosystem function.

1 Introduction

The ocean is a substantial reservoir of CO$_2$ (Feely et al., 2004; Sabine et al., 2004; Morse et al., 2006). Addition of CO$_2$ to sea water alters the carbonate chemistry and reduces pH, in an effect recently termed “Ocean Acidification” (OA). Over the past 200 years increasing $p$CO$_2$ has resulted in a decrease in surface sea water pH of 0.1 units (Caldeira and Wickett, 2003; Orr et al., 2005). It is predicted that atmospheric CO$_2$ concentrations could reach 1200 ppm by the year 2100 resulting in a decrease in average surface ocean pH of 0.3 to 0.4 units (Caldeira and Wickett, 2003; Raven et al., 2005). Our understanding of the biological and ecological consequences of OA is, however, still in its infancy (Raven et al., 2005). Reductions in seawater pH have been demonstrated to affect the physiological and developmental processes of a number of marine organisms (e.g. Pörtner et al., 2004, 2005; Raven et al., 2005) through reduced internal pH (acidosis) and increased CO$_2$ (hypercapnia), raising the possibility that not only species, but also ecosystems, will be affected (Widdicombe and Spicer, 2008).

As CO$_2$ increases and pH decreases there is a concomitant reduction in carbonate ion (CO$_3^{2-}$) availability, which can lead to increased dissolution of calcium carbonate (CaCO$_3$) structures. This may have a significant impact on species, which have CaCO$_3$ skeletons, such as reef building organisms, some phytoplankton, molluscs, crustaceans and echinoderms. Research into the effects of OA has thus far primarily investigated impacts on these calcareous marine organisms, particularly focusing on corals (e.g. Reynaud et al., 2003; Langdon and Atkinson, 2005), molluscs (e.g. Michaelidis et al., 2005; Gazeau et al., 2007) and coccolithophores.
commercial catch and hence is an ideal model to use to understand the impacts that OA might have on the early development stages of a commercially important crustacean. Consequently, this study investigated the effect of CO$_2$-induced acidification on the early life stages of *H. gammarus*. The patterns of growth and shell mineralogy of the carapace during larval development were determined by measuring the length, area, dry mass and Ca and Mg contents of the carapace. As Mg-CaCO$_3$ is more soluble than other polymorphs of calcium carbonate, aragonite and calcite, (Feely et al., 2004) it may be less advantageous to form Mg-CaCO$_3$ under decreasing pH as it will be the first to dissolve (Kleyпас et al., 2006), hence these lobsters may be at greater risk from dissolution. Exposure to long-term hypercapnia may be energetically costly to marine organisms and therefore may be detrimental to developmental processes, such as growth, reproduction, natural recruitment and survival (Barry et al., 2005; Wood et al., 2008).

2 Materials and methods

2.1 Animal material

Ovigerous females were supplied by local fishermen and held in aquaria (160×100×35 cm) at the National Lobster Hatchery (NLH) in Padstow, Cornwall, UK. Each aquarium was constantly supplied with aerated, filtered re-circulating sea water (T=17±1°C, S=35) pumped directly from waters adjacent to the NLH. Water was pre-treated in a pressurized sand filter, passed through activated carbon, and finally UV-irradiated. Adult lobsters were fed *ad libitum* with blue mussels, *Mytilus edulis*. Experiments were carried out between June and July 2007, to coincide with the natural hatching season (between April and September).

Sea water was placed in ten open conical flasks (vol.=1 l) and the CO$_2$ concentration was modified by equilibrating the water with air containing different CO$_2$ concentrations exactly as described by Findlay et al. (2008). Air/CO$_2$ mixtures were produced using a bulk flow technique where known amounts of scrubbed air (CO$_2$ removed using KOH) and CO$_2$ gas were supplied, *via* flow meters (Jencons, UK, Roxspur, France), and mixed before equilibrating with sea water. Control flasks were aspirated (101 min$^{-1}$) with an air mixture containing 380 ppm of CO$_2$, however the pressure was not high enough to completely equilibrate these flasks, which had high alkalinity, and hence the measured sea water CO$_2$ value was slightly lower (mean 315 ppm). To produce the reduced pH treatment, sea water was aspirated (1 ml min$^{-1}$ CO$_2$ mixed with 101 min$^{-1}$ scrubbed air) with the high-CO$_2$ air containing 1200 ppm of CO$_2$. The pCO$_2$ was monitored regularly using a pCO$_2$ micro-electrode (LazarLabs) and pH using a pH probe (Denver). Any fluctuations in pH were noted, and adjusted, *via* the flow meters, accordingly.
Newly-hatched Zoea I larvae, from 3 different mothers, were (carefully) distributed haphazardly between a number of aquaria (flasks vol.=1 l; N=50 zoea per flask; T=17±1°C), with all flasks containing larvae from all females. Flasks contained one of the following aerated media: sea water (“untreated control”) or sea water with elevated CO₂ (1200 ppm) (N=5 for each treatment). Both treatments commenced simultaneously and were incubated for 28 days. Media changes were performed every 24 h. The elevated CO₂ treatment flasks were left to equilibrate for 2 h to the required CO₂ levels before larvae were transferred to them. Both moulted exoskeletons and mortalities were removed before changing media. Larvae were fed (Artemia nauplii, density=5 indiv ml⁻¹ sea water) after media changes (Carlberg and Van Olst, 1976).

2.2 Larval growth and development

Larvae were removed haphazardly from each flask (N=9), at day 7, 14, 21 and 28. Larval development can vary depending on temperature; therefore in order to ascertain larval development times under the control conditions, preliminary studies were first carried out. The sampling days represent the mid-point of development through each of the four larval stages (i.e. Zoea I, II, III, and IV). Individuals were washed briefly in distilled water, carefully blotted dry with paper tissue, and stored frozen (T=−20°C). They were subsequently freeze-dried (LYOVAC GT2, Leybold-Heraeus, Germany) to a constant mass, before the carapace was carefully removed and weighed using a microbalance (AT200, Mettler-Toledo, Switzerland). Carapace length (CL) and carapace area (CA) were measured using digital photographs under lower power magnification (x 10) and ImageJ software. CL was calculated as shown in Fig. 1. CA was calculated by taking measurements of the removed and flattened carapace again using digital photography under lower power magnification (x 10) and ImageJ software. Larval survival was observed daily, along with moult stage, which was recorded as a measure of development, and determined using the schemes of Aiken (1973) and Chang et al. (2001); this involves detailed examination of the exoskeleton and pleopods.

2.3 Carapace mineral content

Measurements of the calcium and magnesium content of the carapace from the same individuals measured above, for each of the four developmental stages (Zoea I, II, III, and IV), were made using Inductively Coupled Plasma Spectrometry (ICP). After the morphological measurements were made the carapace was dissolved in concentrated nitric acid (75% pro analysis) to extract the mineral portion. The resultant solution was diluted with Milli-Q water before ICP analysis. To compare between treatments and stages (these are relative measures and not absolute measures) the calcium and magnesium concentrations are expressed both as a percent-age of total mass of animal carapace and also per unit of total carapace area, exactly as presented by Spicer and Eriks-son (2003). This gives an indication of the content of each mineral as the animal grows relative to the previous development stage and the percentage of total mass takes into account any differences in the thickness of the carapace.

2.4 Statistical analysis

Data are expressed as mean±1 S.E.; the data were tested for normality using the Kolmogorov-Smirnov test and homogeneity of variances and applying Levene’s test prior to analysis. Two-way repeated-measures ANOVA was used to investigate significant differences in physiological parameters as a result of CO₂ and of exposure time, and least significant difference post hoc tests were carried out to assess the significance of differences between treatment groups.

3 Results

3.1 Larval growth and development

There were no significant effects of hypercapnia on carapace length in larval H. gammarus (p>0.05) when expressed against time and developmental stage (Fig. 2a and b). There was however, an observed effect of hypercapnia on carapace mass throughout larval development, causing a significant reduction in mass at Zoea IV (p<0.05, Fig. 2c). As larvae were removed for sampling throughout the experiment, survival could only be observed during experimental exposures.

![Fig. 1. Larval carapace length measured using digital photography under lower power magnification (x 10) and ImageJ software.](image-url)
Fig. 2. Relationships between growth and development for larval *H. gammarus* during exposure to CO$_2$-acidification (1200 ppm). (a) Carapace length (mm) and development time (days); (b) Carapace length (mm) and developmental stage; (c) Carapace mass (mg) and developmental stage. Values represent mean±1 standard error; white, control; grey, 1200 ppm of CO$_2$.

From these observations, incubation with CO$_2$ did not appear to have an affect on the survival of larval lobsters.

### 3.2 Carapace mineral content

Changes in calcium concentration of the carapace during larval development are presented in Fig. 3. The calcium content in the carapace was significantly effected over time, with respect to treatment, this was detectable both when expressed as concentration per surface area ($p<0.05$; Fig. 3a) and when presented as a percentage of the total carapace content ($p<0.05$; Fig. 3b). In the high CO$_2$ treatment, the calcium concentration was almost half of the control at Zoea IV (0.13 µg mm$^{-2}$ S.E. 0.01 vs. 0.23 µg mm$^{-2}$ S.E. 0.01). This indicates that after metamorphosis into Zoea IV the increased CO$_2$ significantly impacted the carapace calcium content.

The effect of increased CO$_2$ on magnesium in the carapace, when expressed as a concentration per surface area (Fig. 4a), produced a reduction in concentration over time when compared to the control, with significant differences occurring at Zoea IV ($p<0.05$). Reduction in magnesium concentration, due to culture in CO$_2$-acidified sea water, were also apparent when expressed as a percentage of total carapace content ($p<0.05$), with significant differences evident at Zoea III (Fig. 4b); 0.81% (S.E. 0.07) compared to 1.16% (S.E. 0.13) in the control larvae.

### 4 Discussion

#### 4.1 Growth and carapace mineralogy

This is the first study, to the authors’ knowledge, to document net changes in the calcium and magnesium content of the carapace of any lobster species during larval development. We found that larval length, area and mass of the carapace are coupled with development stage of the zoea larvae; and that there are progressive changes in the content of calcium and magnesium. Calcium and magnesium form the principal mineral portion of the crustacean exoskeleton (Neufeld and Cameron, 1992); the concentrations of which are most likely to be determined by environmental conditions (Wickins, 1984). The pattern of calcification displayed by *H. gammarus* generally follows a net increase in calcium as the larvae moult through each progressive zoea, with metamorphosis into the Zoea IV containing the largest concentration of calcium. However, when expressed as a percentage of mass, the proportion of calcium in relation to other exoskeletal components stays fairly constant throughout larval development. The only other study to investigate calcification in larval lobsters was completed by Spicer and Eriksson (2003), on the Norway lobster *Nephrops norvegicus*. However, only Zoea III was examined and while *N. norvegicus* Zoea III had 1.7 Ca µg mm$^{-2}$ (4.3% of mass), *H. gammarus* had 0.2 Ca µg mm$^{-2}$ (9.7% of mass). *H. gammarus* Zoea III values, in term of calcium concentration per surface area, were much lower than those found in *N. norvegicus*. 
Fig. 3. Changes in the calcium concentration of the carapace during development and exposure to CO$_2$-acidification (1200 ppm), expressed as (a) concentration per surface area and (b) % carapace dry mass. Values are means±1 standard error; white bar, control; grey bar, 1200 ppm of CO$_2$. Asterisk denotes significant differences from control ($p<0.05$).

Fig. 4. Changes in the magnesium concentration of the carapace during development and exposure to CO$_2$-acidification (1200 ppm), expressed as (a) concentration per surface area and (b) % carapace dry mass. Values are means±1 standard error; white bar, control; grey bar, 1200 ppm of CO$_2$. Asterisk denotes significant differences from control ($p<0.05$).

However, the percentage of calcium in relation to mass was double the value in *H. gammarus* compared to *N. norvegicus*, indicating that the processes involved in calcification may be reasonably different between the two species. Magnesium concentrations were also measured and similarly displayed an increase with development; although the ratios of calcium to magnesium can be variable in many marine calcifying species (Boßelmann et al., 2007). It is hypothesised that in crustaceans, magnesium is often used as a substitute for calcium in the mineral matrix of the exoskeleton (Richards, 1951). However, when the percentage of calcium increased at Zoea IV the percentage of magnesium decreased, possibly showing that calcium plays a more important role during the final stages of development in *H. gammarus*.

4.2 Impacts of elevated CO$_2$ on growth and carapace mineralogy

This is also the first study to examine the effects of CO$_2$-induced acidification on growth and net carapace divalent ion concentration (as a measure of calcification; Findlay et al., 2009) of any lobster species. In the field increased moulting frequency and high rates of mortality are associated with larval development; therefore these early stages may be particularly vulnerable to ocean acidification due to an increased energy requirement for calcification of the exoskeleton (Haug et al., 2006). Carapace length in *H. gammarus* was not significantly affected by culture in CO$_2$-acidified sea water (1200 ppm CO$_2$), with all remaining coupled throughout. However, both carapace mass and calcification were considerably reduced during metamorphosis into Zoea IV due to increased CO$_2$. The fact that carapace length was not affected by culture in CO$_2$-acidified sea water even though both mass and mineral content did appear to decrease, is feasible because Spicer and Eriksson (2003) indicates that the majority of growth occurs through laying down organic material and chitin and not CaCO$_3$. The reduced carapace mass observed was therefore most likely due to CO$_2$-induced acidification resulting in a decline in the net production of CaCO$_3$, which would potentially result in a lighter carapace.

It is thought that lobsters utilize HCO$_3^-$ or CO$_2$ for the precipitation of CaCO$_3$ (Cameron, 1989) not CO$_3^{2-}$ therefore if the experimental conditions had resulted in undersaturation with respect to carbonate minerals, we still might not expect a direct impact on calcification in larval lobsters. However, the sea water in both the control and the elevated CO$_2$ treatment had relatively high levels of CO$_3^{2-}$, and neither became low enough to result in undersaturation with respect to any of the calcium carbonate polymorphs relevant here ($\Omega_{\text{aragonite}}>2.5$; Table 1). This seems to occur as a result of naturally high alkalinity levels in the sea water (>2450 $\mu$Eq kg$^{-1}$), and indicates that neither CO$_3^{2-}$ or
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Table 1. System data (mean±standard error) for the control and the high CO₂ treatment. Salinity, temperature, pH and pCO₂ were measured; all other data (DIC=dissolved inorganic carbon, A₇=total alkalinity; CO₃²⁻=carbonate ion concentration; Ωcalcite=calcite saturation state; Ωaragonite=aragonite saturation state) were calculated from pH and pCO₂ using CO₂sys (Pierrot et al., 2006), with dissociation constants from Mehrbach et al. (1973) refit by Dickson and Millero (1987) and KSO₄ using Dickson (1990).

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>High CO₂ Treatment</th>
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<tbody>
<tr>
<td>CO₂ (ppm)</td>
<td>315±18.83</td>
<td>1202±29.83</td>
</tr>
<tr>
<td>pH</td>
<td>8.39±0.006</td>
<td>8.10±0.009</td>
</tr>
<tr>
<td>Temp (°C)</td>
<td>17.0±1.0</td>
<td>17.0±1.0</td>
</tr>
<tr>
<td>Sal (psu)</td>
<td>35.0±1.0</td>
<td>35.0±1.0</td>
</tr>
<tr>
<td>A₇ (µEq kg⁻¹)</td>
<td>2544±148.9</td>
<td>4290±145.9</td>
</tr>
<tr>
<td>DIC (µmol kg⁻¹)</td>
<td>2152±131.1</td>
<td>3967±132.8</td>
</tr>
<tr>
<td>Ωcalcite</td>
<td>6.71±0.43</td>
<td>6.79±0.32</td>
</tr>
<tr>
<td>Ωaragonite</td>
<td>4.33±0.28</td>
<td>4.38±0.20</td>
</tr>
<tr>
<td>HCO₃⁻ (µmol kg⁻¹)</td>
<td>1863±112.9</td>
<td>3651±119.5</td>
</tr>
<tr>
<td>CO₃²⁻ (µmol kg⁻¹)</td>
<td>281±18.1</td>
<td>285±13.3</td>
</tr>
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HCO₃⁻ were limiting calcification, nor was there any indication of enhanced dissolution. One caution to these results is that pH and pCO₂ were measured during the experiment but total alkalinity and DIC were calculated using CO₂sys (Pierrot et al., 2006), with dissociation constants from Mehrbach et al. (1973) refit by Dickson and Millero (1987) and KSO₄ using Dickson (1990), and therefore these may not represent exact values, particularly as the sea water comes from a coastal environment. The increased CO₂, added through gas bubbling, increased the total dissolved inorganic carbon, and hence lowered the pH, although not below levels perceived to be “normal”. Therefore the observed impacts on mass and reduced calcium concentration in these larval H. gammarus may primarily be the result of hypercapnia interfering with normal homeostatic function (perhaps via a trade-off), and not a direct impact on calcification per se, e.g. general physiological stress can result in a reduction in the energy allocated to shell thickening (Henry et al., 1981). A similar study by Gazeau et al. (2007), using comparable CO₂ values, also displayed a net decline in the calcium carbonate structure in the mussel, Mytilus edulis, and the Pacific oyster, Crassostrea gigas. As in this study, they too found that calcium carbonate polymorphs did not become undersaturated, but did suggest that saturation states were correlated with net calcification rates. Here we suggest that saturation states may not always be the main limiting factor for calcification under increasing CO₂, as the processes and mechanisms for calcification in multi-cellular organisms are complex and are closely linked with many other physiological processes (Pörtner, 2008). As the solubility of a calcite structure increases with the incorporation of magnesium, under increasing CO₂ concentrations (Raven et al., 2005), several species have the ability to secrete a lower concentration of magnesium in response to environmental changes (Stanley et al., 2002). However, as the decrease in magnesium ions was fairly consistent with the decrease in calcium ions it seems unlikely that this mechanism for dealing with an altered environment was occurring in the present study.

CO₂-induced acidification displayed a progressive long-term CO₂ effect on the calcified exoskeleton in Zoea IV, which is arguably the most critical period for production of viable post-larvae. There has been no examination of the effects of OA on post-larval lobsters completed to date. As OA is predicted to occur over ocean surface waters, with a great degree of certainty, and corrosive waters are already seasonally observed in shelf sea upwelling areas (Feely et al., 2008) and around major rivers (Salisbury et al., 2008), marine organisms inhabiting the pelagic zone will be unable to avoid these unfavourable changes in ocean chemistry (Haugan, 1997).

From most studies on marine organisms to date there appears to be a substantial cost involved with increased CO₂ on developmental processes, whether it be decreased calcification or shell dissolution in order to maintain internal chemistry (Gazeau et al., 2007; Michaelidis et al., 2005), or increase muscle wastage in order to maintain skeletal integrity (Wood et al., 2008). A net decline in calcification, along with a reduced shell mass of developing larval lobsters may affect their competitive fitness and recruitment success; this could trigger cascading trophic effects on population dynamics and potentially on the functioning of marine ecosystems. It is not certain whether the adverse effects associated with OA may be countered by physiological acclimatization and/or genetic adaptation of marine organisms (Riebesell, 2004). However initial findings do not appear promising and assessments of potential impacts are hampered by the scarcity of relevant research (Orr et al., 2005).

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