Oxygen limitation of thermal tolerance defined by cardiac and ventilatory performance in spider crab, Maja squinado

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Frederich, Markus, and Hans O. Pörtner. Oxygen limitation of thermal tolerance defined by cardiac and ventilatory performance in spider crab, Maja squinado. Am J Physiol Regulatory Integrative Comp Physiol 279: R1531–R1538, 2000.—Geographic distribution limits of ectothermal animals appear to be correlated with thermal tolerance thresholds previously identified from the onset of anaerobic metabolism. Transition to these critical temperatures was investigated in the spider crab (Maja squinado) with the goal of identifying the physiological processes limiting thermal tolerance. Heart and ventilation rates as well as PO2 in the hemolymph were recorded on-line during progressive temperature change between 12 and 0°C (1°C/h) and between 12 and 40°C (2°C/h). Lactate and succinate were measured in tissues and hemolymph after intermediate or final temperatures were reached. High levels of hemolymph oxygenation suggest that an optimum range of aerobic performance exists between 8 and 17°C. Thermal limitation may already set in at the transition from optimum to pejus (pejus = turning worse, progressively deleterious) range, characterized by the onset of a decrease in arterial PO2 due to reduced ventilatory and cardiac performance. Hemolymph PO2 values fell progressively toward both low and high temperature extremes until critical temperatures were reached at ~1 and 30°C, as indicated by low PO2 and the onset of anaerobic energy production by mitochondria. In conclusion, the limited capacity of ventilation and circulation at extreme temperatures causes insufficient O2 supply, thereby limiting aerobic scope and, finally, thermal tolerance.

aerobic capacity; anaerobic metabolism; optodes; partial pressure of oxygen

Critical temperatures (Tc) have been defined for different marine invertebrate and fish species as being characterized by the onset of anaerobic metabolism, which is caused by a mismatch of O2 demand and O2 supply (for review, see Refs. 35 and 36). Extended exposure to temperatures above high Tc or below low Tc finally leads to death of the animal unless thermal acclimation, i.e., a shift of Tc values, occurs (40, 51). One hypothesis is that the adjustment of mitochondrial density and capacity is involved in setting thermal tolerance limits and is therefore related to geographic distribution (35, 36). As a consequence, the relationship between O2 availability to tissues and O2 demand appears to be crucial for survival of exposure to temperature extremes. Study of the processes of O2 uptake by ventilation and O2 distribution by circulation therefore appear important to further our understanding of the O2 limitation of thermal tolerance. Therefore, we chose to study these systemic aspects of thermal tolerance, selecting a crustacean, Maja squinado (Herbst), as a model organism. As yet, physiological studies of crustaceans have addressed temperature effects on O2 consumption, heart and ventilatory performance, or growth (12–16, 23, 34, 44). In most of these studies, temperatures were chosen within the physiological range. Hence, there is little information on parameters that become limiting on both sides of the window of thermal tolerance in this group.

The present study was designed to investigate the effect of acute temperature change on PO2 in the hemolymph of Maja squinado combined with an analysis of ventilation and heart rates as the processes responsible for O2 uptake and distribution. Maja squinado was chosen under the assumption that the identification of a low Tc would be easier in this warm-adapted species than in cold-adapted species. Maja squinado is found between the warm waters of the north African coast and the west and south coasts of England and only occasionally occurs in the German Bight (9, 22).

Materials and Methods

Animals. Adult male and female Maja squinado were obtained from local fishermen in Roscoff, France, in November 1998. Animals were kept in large tanks with aerated natural seawater at 10°C, and most of them were transported within 15 h from Roscoff to the Alfred Wegener Institute in Bremerhaven, Germany. They were held in tanks with aerated, recirculating natural seawater at 10 ± 0.5°C and 32% salinity. The animals were fed twice a week with pieces of cod (Gadus morhua) and mussels (Mytilus edulis). Experiments were carried out at the Station Biologique de Roscoff and at the Alfred Wegener Institute.

Surgical procedure and on-line data recording. Animals were prepared for experimentation by drilling a small hole through the carapace directly behind the heart, avoiding injury to the hypodermis. The hole was covered with a latex dam to prevent hemolymph loss during the following surgery. A glass capillary was inserted through the latex dam 1 mm deep into the carapace and fixed with dental periphery wax.

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To identify the optimum position of the O$_2$ sensor in the pericardial sinus, a cannula was fed through the capillary into the pericardial sinus until pulsation of the hemolymph level could be seen in the capillary. The cannula was removed, and a calibrated optode (a fiber-optic oxygen sensor; see description below and Refs. 25 and 26) was inserted through the glass capillary, brought to exactly the same position, and fixed with dental periphery wax.

Animals were kept in a temperature-controlled 25-liter aquarium with air-saturated seawater. P$_{O2}$ of the seawater changed slightly with temperature between 157.9 ± 1.1 mmHg at 0°C and 147.0 ± 1.2 mmHg at 40°C, depending on the temperature dependence of water vapor pressure. Articular membrane of the coxa of the last pericardial sinus, a cannula was fed through the capillary. Hemolymph samples were withdrawn via a cannula inserted and heart rate. After the final temperatures were reached, they were increased or decreased to 36°C at maximum speed and simultaneous cooling on ice. Precipitates were removed by centrifugation at 14,000 rpm. Supernatants were neutralized with 5 mol/l KOH, followed by centrifugation for the removal of precipitated KClO$_4$. l-Lactate and succinate were measured enzymatically using photometric standard tests (3).

RESULTS

Animals exhibited great variability in hemolymph P$_{O2}$ and heart and ventilation rates at control temperature and during temperature decrease or increase. No differences could be found between male and female specimens (mean wt 595 ± 151 g). After 12 h at 12 ± 0.2°C, mean P$_{O2}$ was 92.6 ± 27.8 mmHg (n = 13; for minimum and maximum values, see Table 1.). Mean heart rate was 52.9 ± 14.8 beats/min, and ventilation rate differed between left and right scaphognathites, as reported previously for different crustacean species (6, 31–33). Mean ventilation rate of both scaphognathites in 13 different animals was 60.0 ± 28.3 beats/min at 12°C. As an example, Fig. 1 shows the typical variability in P$_{O2}$ and heart and ventilation rates for one specimen at 12°C over a period of 13 h. This animal exhibited large fluctuations in P$_{O2}$ with a low mean of 27.2 ± 12.5 mmHg and no period of constant P$_{O2}$ throughout. P$_{O2}$ varied between 3.1 and 55.7 mmHg. Although this animal exhibited a low P$_{O2}$ value compared with others, the pattern of P$_{O2}$ fluctuations

Table 1. P$_{O2}$, heart rate, and ventilation rate after 12 h of incubation at 12.1 ± 0.2°C in Maja squinado

<table>
<thead>
<tr>
<th>P$_{O2}$, mmHg</th>
<th>Heart Rate, beats/min</th>
<th>Ventilation Rate, beats/min</th>
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<tbody>
<tr>
<td>Mean ± SD</td>
<td>92.0 ± 27.8</td>
<td>52.9 ± 14.8</td>
</tr>
<tr>
<td>Maximum</td>
<td>134.8</td>
<td>138.4</td>
</tr>
<tr>
<td>Minimum</td>
<td>33.3</td>
<td>5.0</td>
</tr>
</tbody>
</table>

n = 13 animals. Ventilation rate values are means of both scaphognathites. Large interindividual differences coincided with extreme fluctuations in all investigated parameters, including severe bradycardia and apnea.
was similar in all investigated specimens. Periods of apnea corresponded to very low hemolymph O$_2$ levels. Bradycardia occurred together with apnea and large drops in PO$_2$, whereas smaller fluctuations in PO$_2$ and ventilation rate were not correlated with bradycardia events. Short bursts of tachycardia seemed to compensate for periods of bradycardia.

When temperature decreased or increased, major changes occurred in cardiac and ventilatory performance and PO$_2$. Initial trials confirmed that after temperature changed from 12 to 5 or 20°C, PO$_2$ changed initially but remained at a constant mean level for 6 h after the new temperature was reached. This implies that no acute over- or undershoot reaction was involved. It also demonstrates that the rate of cooling or heating was sufficient to bring PO$_2$ close to steady state for each temperature analyzed.

The drop in PO$_2$ with rising or falling temperature was curvilinear toward both ends of the temperature window, with a range of maximum PO$_2$ between 8 and 17°C (92.6 ± 6.4 mmHg). PO$_2$ decreases at low and high temperatures were not symmetrical; a tailing was visible toward higher temperatures (Fig. 2). Ventilation rate increased linearly between 6 and 17°C at an average rate of 8.2 ± 2.6 beats·min$^{-1}$·°C$^{-1}$. Below 8°C, the ventilation rate dropped sharply ($P < 0.05$, ANCOVA) and rose again to 18.8 ± 10.9 beats/min at 3.7°C without a visible effect on PO$_2$. During warming above 17°C, no further increase in ventilation rate occurred but ventilation leveled off significantly ($P < 0.05$, ANCOVA) and even decreased slightly, -2.1 ± 0.2 beats·min$^{-1}$·°C$^{-1}$. Beyond 30°C, a significant ($P < 0.05$, ANCOVA) steep reduction (-10.6 ± 0.3 beats·min$^{-1}$·°C$^{-1}$) occurred after a transitional rise at 30°C. Apnea occurred at 39.7°C.

Heart rate also showed this triphasic behavior between 6 and 40°C, with a slight but nonsignificant ($P > 0.05$, ANCOVA) reduction in slope from 3.3 ± 0.1 to 1.8 ± 0.2 beats·min$^{-1}$·°C$^{-1}$ at 14.4°C. A sudden, temporary increase at 30°C was followed by a significant ($P < 0.05$, ANCOVA) decrease (-9.3 ± 0.3 beats·min$^{-1}$·°C$^{-1}$) until acardia was reached at 40.5°C, which led to death when temperature was not reduced to control values immediately. At low temperatures, a depression in heart rate below 8°C coincided with the observed sharp decrease in ventilation rate and a slight reduction in PO$_2$. Below 4°C, heart rate decreased again, followed by an increase to 12.9 ± 4.9 beats/min. This small increase in heart rate around 1°C represents a final “tachycardia” before acardia sets in, with no cardiac output being detectable, as shown by Frederich et al. (17) using the Doppler technique. Animals survived when temperature was increased above 0°C again within 30 min.

Heart rate proved to be more resistant to temperature change than ventilation rate and PO$_2$. Therefore, ventilatory performance seemed to be more crucial for surviving extreme temperatures. As a consequence, $T_e$ and preference and tolerance ranges were identified especially from ventilation rate and PO$_2$ data. Calculated intersections of fitted regressions (Table 2) confirmed visible break points at 8 and 17°C. Because temperatures of 8 and 17°C indicate the transition from optimum to an increasingly deleterious range (called the pejus range; see DISCUSSION), they are called pejus temperatures ($T_{pI}$ and $T_{pII}$). The lower pejus temperature ($T_{pI}$) was characterized by a sudden decrease in ventilation and heart rates accompanied by a slight reduction in PO$_2$ at 8°C. Apnea set in at minimum PO$_2$, and the temperature at this point was defined as the low $T_e$ ($T_{eII}$; 1°C) because anaerobic metabolism was observed slightly below this value (see Fig. 4). Similarly, the upper break point at 30°C was identified as the upper $T_e$ ($T_{eII}$) because significant anaer-
obic energy production occurred slightly above this value (see Fig. 4 and DISCUSSION).

Arterial PO2 is clearly dependent on ventilation rate because ventilation sets the amount of O2 available to the animal. Figure 3 shows two different patterns of correlation depending on the temperature range. Below 17°C, which was determined as the upper TpI (TpI I) for ventilation, PO2 increased strongly with ventilation rate. Maximum oxygenation was reached at 40 beats/min. Further acceleration of scaphognathite beat frequency did not result in elevated hemolymph PO2. This situation changed in the temperature range above 17°C. High levels of PO2 were reached only at ventilation rates of 80–100 beats/min. A lower scaphognathite beat frequency was not sufficient to maintain high O2 levels in the hemolymph.

Lactate was found to accumulate significantly in hemolymph, musculature, hepatopancreas, and heart tissue at 33.3°C (Fig. 4). Lactate levels rose significantly in the musculature already at 21.6°C but only to a small, nonsignificant extent during cooling. A minor increase in the hepatopancreas and in the hemolymph at −0.3°C was also nonsignificant. Succinate accumulated significantly in all investigated tissues at 33.3°C.

Table 2. Threshold temperatures in Maja squinado for changes in PO2, heart rate, and ventilation rate

<table>
<thead>
<tr>
<th></th>
<th>TcI</th>
<th>TpI</th>
<th>TpII</th>
<th>TcII</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO2</td>
<td>0.7</td>
<td>8.9</td>
<td>17.8</td>
<td>30.9</td>
</tr>
<tr>
<td>Ventilation rate</td>
<td>0.7</td>
<td>9.3</td>
<td>17.3</td>
<td>31.1</td>
</tr>
<tr>
<td>Heart rate</td>
<td>−0.1</td>
<td>n.v.</td>
<td>n.v.</td>
<td>31.5</td>
</tr>
</tbody>
</table>

Values (in °C) were identified by intersections of best fitted regressions for each parameter. Tc, critical temperature; Tp, pejus temperature; TcI and TcII, lower and upper Tc characterized by onset of anaerobic metabolism; TpI and TpII, lower and upper Tp characterized by transition from optimum to pejus range; n.v., not visible. The pattern of changes in heart rate did not reveal TpI and TpII as significant discontinuities.
and in the hepatopancreas only at $-0.3^\circ$C. As with lactate, the trend for succinate levels to rise remained nonsignificant in the other tissues at $-0.3^\circ$C.

**DISCUSSION**

The on-line recordings of arterial $P_{O_2}$ by fiber-optic oxygen sensors proved to be a suitable and reliable method for the quantification of dynamic temperature effects on hemolymph $O_2$ levels in *Maja squinado*. This technique allows investigation of changes in $P_{O_2}$ with temperature over time and avoids disturbance by repeated sampling, as required by other experimental protocols (see, for example, Refs. 15, 30, 45). It also avoids immobilization of the animal, as required for the use of fragile microelectrodes (2). $P_{O_2}$ was investigated because it reflects both the efficiency of arterial $O_2$ uptake and the pressure head for $O_2$ diffusion from the hemolymph to tissue mitochondria.

Hemolymph $P_{O_2}$ is buffered by hemocyanin-bound $O_2$. We refrained from studying temperature effects on $O_2$ binding by hemocyanin, although different studies have shown that parameters such as half-saturation pressure ($P_{50}$) and Bohr shift change with temperature in crustaceans (for review, see Refs. 7, 8, 27–29). Hemocyanin characteristics suggest that $O_2$ binding at the gills may become insufficient at high temperature and $O_2$ unloading in the tissues may be incomplete at low temperature (29). In our study, release of $O_2$ from hemocyanin is likely to explain the tailing in the $P_{O_2}$ decrease between 23 and $32^\circ$C visible at a hemolymph $P_{O_2}$ of 24.5 ± 6.5 mmHg (Fig. 2). As expected, $P_{O_2}$ buffering occurred close to the $P_{50}$ of *Maja squinado* hemocyanin, which amounts to 21.0 mmHg at 15°C and is expected to rise with temperature (28). In any case, hemocyanin oxygenation is a secondary parameter to quantify $O_2$ availability to tissues, whereas arterial hemolymph $P_{O_2}$ is a direct indicator because it correlates with the level of physically dissolved $O_2$ and represents the pressure head driving diffusion.

Fluctuations in $P_{O_2}$ and corresponding heart and ventilation rates under resting conditions were similar to those described for the crayfish *Astacus leptodactylus* (2). Mean $P_{O_2}$ values of 92.6 ± 6.4 mmHg between 8 and 17°C are in the upper range of $P_{O_2}$ data compiled by McMahon and Wilkens (33) and Mangum (28) for 28 decapod species and much higher than reported for *Carcinus maenas* and *Necora puber* (30). Forgue et al. (15) reported a mean $P_{O_2}$ of 45.8 mmHg at 15°C for *Maja squinado*. This value is still within the range of interindividual variability in $P_{O_2}$ seen in the present study.

To investigate the response to fluctuating temperature, we changed temperature quite rapidly over a wide range. The fast, progressive temperature change minimized acclimation phenomena that may involve shifts in thermal thresholds (e.g., associated with changes in mitochondrial density; Ref. 36). Reactions to such a progressive temperature change will take longer at low than at high temperatures because of the $Q_{10}$ effect. Stable $P_{O_2}$ readings during extended incubations at selected temperatures confirmed that this was accounted for by the slower rate of temperature change in the range between 12 and $0^\circ$C.

Measurements of $P_{O_2}$ as well as heart and ventilation rates allowed determination of threshold temper-
atures at the organismic level in the context of changes in lactate and succinate concentrations. Previously, critical temperatures ($T_{cI}$ and $T_{cII}$) have been identified by the onset of succinate (and/or acetate) formation, indicating tissue hypoxia, the transition to an anaerobic mitochondrial metabolism, and an elimination of aerobic scope for activity at both critical temperatures (for review, see Refs. 35, 36). The present data confirm that critical temperatures exist in *Maja squinado*, because the accumulation of lactate and succinate coincided with very low arterial PO$_2$ values and indicates the onset of anaerobiosis at extreme temperatures (Fig. 4). However, major changes in circulatory performance and hemolymph PO$_2$ occurred before critical temperatures were reached (Fig. 2). Threshold temperatures ($T_{pI}$ and $T_{pII}$) became visible, which indicated the transition from a temperature range with maximum arterial PO$_2$ to low or high ranges of temperature characterized by falling PO$_2$ values. The progressive drop in arterial PO$_2$ reflects a reduction of O$_2$ availability to mitochondria. This is equivalent to an apparent reduction of mitochondrial aerobic capacity and thereby a reduced scope for aerobic activity of the whole animal despite maintenance of standard metabolism. The concept of “aerobic scope for activity” as defined on the basis of measurements of O$_2$ consumption in fish (4) reflects the range between minimum and maximum O$_2$ consumption by mitochondria and depends on sufficient O$_2$ delivery by ventilation and circulation. Therefore, this concept extends from the whole animal to mitochondrial levels.

The high PO$_2$ between $T_{pI}$ and $T_{pII}$ was maintained by a progressive increase in ventilation rate with temperature as required to compensate for the rise in O$_2$ demand (Fig. 3). $T_{pII}$ was characterized by a change to more or less constant ventilation rates and onset of a decrease in PO$_2$, reflecting a rising O$_2$ demand in metabolism that was no longer compensated for by ventilation. $T_{pI}$ was characterized by a sudden decrease in ventilation and heart rates, followed by a decrease in PO$_2$. This threshold is furthermore characterized by a disproportionate reduction in cardiac output and a redistribution of hemolymph from lateral into sternal and hepatic arteries, as shown elsewhere (17). Critical temperatures characterized by the onset of anaerobic metabolism were reached close to 1 or 30°C, respectively (see Figs. 2 and 4). Lactate accumulated as the main anaerobic end product in crustaceans (1, 19, 20, 43). In addition, an increase in succinate concentrations indicated mitochondrial anaerobiosis (35). Because of the large interval between sampling temperatures and the fast rate of temperature change, a more precise quantification of $T_{cI}$ and $T_{cII}$ is not possible. For survival in the natural environment, however, the thresholds $T_{pI}$ and $T_{pII}$ may have greater importance (see below).

The processes causing tissue hypoxia appeared to be similar at low and high temperatures. Between 8 and 0°C, a reduction in heart rate, ventilation rate, and PO$_2$ occurred with similar slopes (10 ± 1.7%/°C). Cooling caused whole animal metabolism and all O$_2$-consum-

![Perspective](http://ajpregu.physiology.org/)

**Fig. 5.** Model of temperature tolerance adapted from Shelford's law of tolerance. The critical temperatures $T_{cI}$ and $T_{cII}$ are characterized by the transition to anaerobic metabolism and indicate the physiological tolerance range. The pejus temperatures $T_{pI}$ and $T_{pII}$ characterize the transition from optimum to pejus range and indicate the optimum performance range. Possibly, the latter is identical with the ecological tolerance range, because actual water temperatures in the environment of the investigated population vary between $T_{pI}$ and $T_{pII}$ (see Perspectives).
restricted. Our data suggest that it is possible to use physiological break points within this concept. In *Maja squinado*, an optimum range was found between 8 and 17°C (Fig. 5). This range is characterized by maximum PO₂ and represents the temperature window of maximum scope for aerobic activity. It therefore indicates the range of optimum performance supporting successful survival in the natural environment. We suggest that those thresholds limiting the optimum range be called “pejus temperatures,” Tₚ₋₁ (8°C) and Tₚ₋₂ (17°C). Beyond Tₚ₋₁ and Tₚ₋₂, falling PO₂ values indicate a reduced scope of aerobic energy production until critical temperatures Tₑ—I and Tₑ—I are reached, characterized by low PO₂ values and the transition to anaerobic metabolism (Fig. 5). Finally, pessimum ranges (pessimum = worst, lethal range) extend beyond critical temperatures and the limits of tolerance. Animals are still able to survive within the physiological tolerance range between Tₑ—I and Tₑ—I, however, with largely reduced scope for activity toward both extremes (pejus ranges).

As a corollary, limited ventilation and circulation performance leads to an O₂ limitation of thermal tolerance at both low and high temperature extremes. The development of hemolymph PO₂ with changing temperature characterizes the range of optimum O₂ availability as well as these O₂ limitations. Pejus temperatures define the transition to low and high ranges of progressively decreased O₂ availability (pejus ranges) until critical temperatures finally indicate tissue hypoxia and onset of anaerobic metabolism. Future study must investigate these ranges and thresholds in a wide range of animal species to test the general applicability of concepts and terms used in the present paper.

**Perspectives**

Two key questions characterize the perspectives originating from this study.

**What is the ecological relevance of an oxygen-limited thermal tolerance and associated threshold (i.e., pejus and critical) temperatures?** As a preliminary answer, the pejus temperatures at 8 and 17°C agree well with the temperature fluctuations of the English Channel, which is the natural environment of the investigated population. Bottom (60 m) mean temperatures vary between 9.1°C in winter and 16.0°C in summer (10, 42). It thus appears possible that pejus temperatures, i.e., those temperatures limiting the range of maximum performance and scope for activity, are equivalent to those defining the limits of geographic distribution. However, the animals used in the present study were acclimated to only one (mean) temperature, and the experimental protocol led to the determination of the acute tolerance window. This window may shift between seasons depending on thermal acclimation. This immediately leads to the second question.

**Which mechanisms may be responsible for setting pejus and critical temperatures depending on acclimation, season, and latitude?** In the lugworm *Arenicola marina*, it has been demonstrated that both critical temperatures shift in parallel, as shown for two different populations in a latitudinal cline (40, 41). Higher mitochondrial densities were found in cold-adapted populations of *Arenicola marina* (41) and in cold-adapted perciform fishes (24). Our current hypothesis is that a downward shift in critical (and possibly pejus) temperatures involves a rise in mitochondrial density and tissue aerobic capacity, whereas an upward shift is limited to a decrease in these parameters (35, 36). Mitochondrial proliferation in the cold supports maintenance of sufficient aerobic capacity and function in all tissues, including those responsible for ventilation and circulation. In the warm, however, O₂ demand by mitochondria may become limiting, especially at high densities. Proton leakage at the inner mitochondrial membrane is suggested to represent the cost of mitochondrial maintenance, leading to a higher O₂ demand with a higher number of mitochondria present and, accordingly, a downward shift of upper critical (and possibly pejus) temperatures in cold-adapted animals (35, 36). Data on O₂ consumption in fiddler crabs, *Uca* sp., from different latitudes (46, 47) suggest that the process of cold adaptation and an associated rise in metabolic rate take place in decapod crustaceans as well. Accordingly, thermal limits of in vivo heart rates varied between species of porcelain crabs depending on the temperatures experienced at different vertical levels in the intertidal zone (44). However, it remains to be investigated to what extent *Maja squinado* would be able to shift its range of thermal tolerance in accordance with its wide range of geographic distribution.

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