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Research Article

Thermal preference, critical thermal limits, oxygen routine consumption and active metabolic scope of *Macrobrachium tenellum* (Smith, 1871) maintained at different acclimation temperatures

Pedro Hernández-Sandoval[1], Fernando Díaz[2], Ana Denisse Re-Araujo[2], J. Armando López-Sánchez[3]
María del Carmen Martínez-Valenzuela[4], Marcelo García-Guerrero[5] & Carlos Rosas[6]
[1]Programa de Doctorado en Ciencias Biológico Agropecuarias, Universidad Autónoma de Nayarit Unidad
Académica de Ingeniería Pesquera, Instituto de Investigación en Ambiente Los Mochis Sinaloa, México
[2]Laboratorio de Ecofisiología de Organismos Acuáticos, Departamento de Biotecnología Marina
Centro de Investigación Científica y de Educación Superior de Ensenada
Ensenada, Baja California, México
[3]Programa de Doctorado en Ciencias Biológico Agropecuarias
Unidad Académica de Ingeniería Pesquera, Universidad Autónoma de Nayarit, Nayarit, México
[4]Instituto de Investigación en Ambiente Los Mochis, Sinaloa, México
[5]Instituto Politécnico Nacional, Centro Interdisciplinario de Investigación para el Desarrollo Integral Regional
Unidad Oaxaca, Laboratorio de Acuacultura, Oaxaca, México
[6]Unidad Multidisciplinaria de Docencia e Investigación, Facultad de Ciencias
Universidad Nacional Autónoma de México, Mérida, México
Corresponding author: Fernando Díaz (fdiaz@cicese.mx)

ABSTRACT. Temperature is one of the most dominant environmental factor influencing the biology and performance of aquatic ectotherms in the wild and in culture conditions. Thus, the aims of the present study were to investigate thermoregulatory behavior, thermal tolerance and active metabolic scope in *Macrobrachium tenellum*. To fulfill our goal, we measure, the preferred temperature, critical threshold limits, thermal window width, oxygen consumption routine rate and active metabolic scope in the prawn *M. tenellum* acclimated to 20, 23, 26, 29 and 32°C. The preferred temperature obtained by the graphic acute method was 28.5°C. Acclimation temperature significantly affected the thermal tolerance which increased with the acclimation temperature. The scope for thermal tolerance had an interval of 25.3 to 27.7°C. The thermal window calculated for *M. tenellum* was 325°C^2. The acclimation response ratios had an interval of 0.42-0.50. These values allow us to characterize these species as inhabitants of subtropical and tropical regions. The oxygen consumption routine rates increased as the acclimation temperature increased from 20 to 32°C. The range of temperature coefficient (Q_{10}) between 29-32°C was the lowest, at 1.98. The active metabolic scope for prawns was the lowest for organisms acclimated to 20 and 32°C and the highest value was obtained at 29°C. The results obtained in the present study are important to determine the optimum conditions in which *M. tenellum* needs to live in the natural environment and may partially explain their wide distribution pattern along the Mexican Pacific Ocean littoral.

Keywords: *Macrobrachium tenellum*, preferred temperature, thermal tolerance, metabolic rate, aquaculture.

INTRODUCTION

The freshwater prawn *Macrobrachium tenellum* (Smith, 1871) is distributed in fresh and brackish waters, along the coastal tropical and subtropical Pacific from northern Mexico to Peru (Holthuis, 1980; Espinoza-Chaurand *et al*., 2011). Previous studies focused on oxygen concentrations, temperature, salinity, nutrition, density effect, larval or juvenile production and feeding regime of this species (Cuevas, 1980; Hernández-Rodríguez *et al*., 1995, 1996; Hernández-Rodríguez & Bückle, 1997; Signoret *et al*., 1997; Aguilar *et al*., 1998; Arana *et al*., 2001; García-Ulloa *et al*., 2008; Rodríguez-Flores *et al*., 2012).

Thermoregulatory behavior of ectothermic organisms is an important physiological response used to determine the temperature range under which the physiological and metabolic processes are optimum

(Bellgraph *et al*., 2010; Ward *et al*., 2010; Xu *et al*., 2015). Recently, behavioral thermoregulation has received renewed attention, in relation to the mechanisms that ectotherms use to cope with climate change effects (Dülger *et al*., 2012; Piasečknà *et al*., 2015; Lattuca *et al*., 2017).

The measurement of the metabolic rate has been used as a tool to determine the impact that several environmental factors can have, such as the temperature, salinity or exposure to pollutants, allowing us to determine the energetic costs that these combinations have on the organism (Lemos *et al*., 2001; Altinok & Grizzle, 2003; Brougher *et al*., 2005). The oxygen consumption is intimately associated with the metabolic work and the energy flow that the organism can use for the homeostatic control mechanisms (Salvato *et al*., 2001; Das *et al*., 2005).

According to Pörtner & Farrel (2008) variations in water temperatures that may occur in its natural habitat due to changes of the season and global climate change and thermal tolerance capacity might be the key on physiological traits for their survival in the field. It is very important to know the critical thermal maxima (CT_{max}) and the critical thermal minimum (CT_{min}), because those limits are considered a measure of thermal tolerance. Critical thermal limits are determined by increasing or decreasing the temperature progressively from the acclimation temperature until physical disorganization occurs in response to the thermal stressor. Both responses frequently used to quantify ectotherms tolerance to extremely high or low temperatures and so determine organism's resistance to different thermal phenomena and permit identify the temperature at which the first symptoms of stress appear without being damaging (Becker & Genoway, 1979; Paladino *et al*., 1980; Beitinger & Bennett, 2000).

According to Pörtner (2010) and Sokolova *et al*. (2012), at the critical temperature, aerobic scope disappears and transition to an anaerobic mechanism in the *pessimum* range, followed by a progressive decline of cellular energy levels occurred. These processes explain why animals can only live for a very limited time beyond this threshold.

Fry (1947) proposed a polygon, also called area of the thermal window, calculated from preferred temperature and the CT_{max} and CT_{min} limits of animals previously acclimated at different temperatures. The polygon is considered ecologically relevant because it provides an indicator how organisms tolerate temperature changes. This area reported as $°C^2$ can use as a comparative index of thermal tolerance among species (Eme & Bennet, 2009). This thermal window is a useful criterion to understand not only thermal behavior but also how different species are adapted to live in specific environments successfully (Pörtner, 2002, 2006, 2010, Pörtner *et al*., 2005; Pörtner & Farrell, 2008; Noyola *et al*., 2015).

The absolute aerobic scope (AS), calculated as the difference in O_2 consumption between the standard metabolic rate (SMR) and the maximum metabolic rate (MMR) (Chabot *et al*., 2016; Farrell, 2016), represents the excess oxygen available for biological fitness; besides growth, reproduction and activity. When metabolic rates measured in animals acclimated at different temperatures two curves obtained (Fry, 1947). While the aerobic metabolism and temperature normally show that, in extreme temperatures, the difference between SMR and MMR is close to zero (Ferreira *et al*., 2014). Aerobic scope, as with other physiological functions has an optimum temperature range (Topt). Beyond this optimum point, temperature causes energy to channel for protection (*pejus* interval of temperature) or to repair the cellular integrity of individuals (*pessimum* range) (Pörtner & Knust, 2007; Pörtner, 2010).

The preferred temperature T_{pref} and physiological AS measures could predict the temperature at which organism's productivity is optimal. Because of this, this study aimed to determine the preferred temperatures, thermal tolerance, thermal window width, oxygen routine rate and aerobic scope through novel methodology in *M. tenellum* kept under laboratory conditions.

MATERIALS AND METHODS

Prawn collection, handling, and acclimation procedures

Juveniles of *M. tenellum* (n = 1000) collected from Chacahua coastal lagoon, Oaxaca (15°57'N, 97°31'W). Prawns transported to CIIDIR-IPN Oaxaca facilities; after that maintained in two 1000 L tanks filled with tap water, at room temperature, and with permanent aeration. From the second day, they fed daily *ad libitum* at 9 and 16 h with Camaronina® (35% crude protein). Daily cleaning performed by siphoning all uneaten food and feces. After 30 days of acclimation, all specimens were transported in two 200 L tanks with permanent aeration and plastic mesh to provide shelter, to the Marine Biotechnology Laboratory of Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE). There, specimens placed in a 2 m^3 reservoirs and then gradually acclimated to local fresh tap water by exchange of 10% per day. During this time, water temperature always maintained at 26°C. After seven days, the temperature increased to 28°C with titanium 1000 W heaters.

Organisms were placed in five tanks (50 in each) 1000 L (n = 1000). Once they reached the 1.23 g ± 0.041 wet weight (ww), they were acclimated for 30 days to five temperatures (20, 23, 26, 29 and 32°C ± 1°C). Acclimation temperatures obtained with a rate of increase or decrease in temperature of 2°C per day; these conditions were kept using 1000 W heaters connected to individual temperature controllers.

All reservoirs maintained with constant aeration and fed up to 8% of their wet weight twice a day (Camaronina®; 35% crude protein). Uneaten food and feces removed daily by siphoning. Photoperiod was not controlled and a replacement of 50% of the total water volume every other day was performed (Díaz *et al.*, 2002). PVC Pipes placed as shelter (10×10×10 cm).

Thermal preference and critical thermal limits (CT_{max} and CT_{min})

Preferred temperature determined by the acute method described by Reynolds & Casterlin (1979). A PVC channel (400 cm long; 20 cm diameter) used to produce a horizontal gradient with 20 chambers (20 cm long each) filled with fresh water up to 12 cm. The gradient temperature maintained by placing a 1000 W titanium heater at one end of the chamber and a chiller temperature controller (Neslab HX-150) at the other. The temperature gradient had an interval from 9 to 41°C. Aeration was provided in every chamber to maintain dissolved oxygen between 5 and 9 mg O_2 L^{-1}.

The temperature within the chambers measured with one digital thermometer placed in each segment (Díaz *et al.*, 2007). Then, three specimens selected from each temperature labeled with plastic tags. Next day placed in the chamber correspondent to its acclimation temperature. Movements and localization of the prawns along the different chambers recorded every 10 min for 120 min. Organisms not fed during the 24 h period before the experiments, to avoid interference of digestives processes (Nelson *et al.*, 1985). Five replicates were performed for each experimental thermal condition. Then, thermal *preferendum* graphically determined by the intersection of preferred temperatures of organisms from each temperature acclimation with the iso-theoretical temperature equality line. This line created considering that; the theoretical temperature selection is the same as the acclimation temperature.

To determine the CT_{max}, five specimens for each acclimation temperature selected and placed in a 60 L glass aquarium, equipped with a 1000 W heater and constant aeration. The specimens placed 30 min before the initiation of the experiment, to reduce stress (Pérez *et al.*, 2003). Water temperature increased at a rate of 1°C min^{-1} (Lutterschmidt & Hutchison, 1997) to observe the response of the specimen (increased activity, initial disorientation, and total disorientation); the end of CT_{max} for prawns was a loss of righting response (LRR). This was performed three times (n = 15).

For every CT_{min} determination, 15 specimens were used (n = 75) from each acclimation temperature (20, 23, 26, 29 and 32°C). Determinations consisted of placing each prawn in a cylindrical acrylic chamber into the same horizontal thermal gradient as its acclimation temperature. The temperature in each cylinder chamber decreased gradually at a rate of 1°C min^{-1}, until the organism reached the LRR response, with organisms lying on one side and unable to recover normal position (Nelson & Hooper, 1982). When prawns reached this point, they returned to their acclimation temperature while monitoring survival during 96 h. Every prawn used only once, and results of animals that did not recover after returning them to their acclimation temperature were discarded 1/10 in 32°C in all acclimation temperatures (10%) for CT_{max} and zero for CT_{min}. The area of the thermal window obtained with the CT_{max} and CT_{min} data following Bennett & Beitinger (1997) and expressed in °C^2.

The acclimation response ratio (ARR) calculated as an index to assess the magnitude of thermal acclimation of organisms. To do that we used the following equation (Claussen, 1977):

$$ARR = \frac{\Delta\, CT_{max\ or\ min}}{\Delta T} = \frac{CTm_2 - CTm_1}{AT_2 - AT_1} \qquad (1)$$

where CTm_2-CTm_1 represents the difference between values of critical temperatures (max or min) within the whole acclimation temperature range examined (AT_2-AT_1).

Oxygen consumption routine rate

An intermittent respirometric system used, as described by Díaz *et al.* (2007). Nine specimens were selected from each acclimation temperature (n = 45). Prawns placed at 16 h before starting the experiment and not fed during the previous 24 h. After that, they individually placed in 9 chambers of 3 L and a control. Chambers kept closed for 30 min, to avoid dissolved oxygen depletion beyond 25%, a condition that may cause stress (Stern *et al.*, 1984). Before closing the chambers, initial dissolved oxygen measured, and measures are taken every 1 min for 30 min. After this time, final dissolved oxygen measured. Two repetitions performed with a two h interval between each one. The initial and final oxygen dissolved measured using an OXY-10 mini (Presens) oximeter equipped with oxygen probe and mini sensors. One chamber used as a control to measure oxygen consumption of the microorganisms present in the water, and the necessary corrections made. All observations made between 9:00 and 14:00 h. The oxygen routine consumption rate (ORCR) calculated by the following equation from Cerezo *et al.* (2006) and Zheng *et al.* (2008).

$$ORCR = (C_t - C_0)\, V / (W \times T) \qquad (2)$$

where, C_t: the oxygen content change in the chamber before and after the test; C_0: the difference in oxygen in control; V: the volume of the chamber; W: the prawn weight in kg, and T: the time in hours.

Calculation of the thermal coefficient for the metabolic rate of the prawn (Q_{10}), which represents the organism's sensitivity to temperature variation, was derived by the equation (3), proposed by Schmidt-Nielsen (1997):

$$Q_{10} = (Rate_2 / Rate_1)^{(10/Temp2-Temp1)} \qquad (3)$$

Active metabolic scope determined with novel methodology

100 individuals were weighed 1.7 ± 0.04 g, placed in a closed system of recirculation and divided into five groups. Every group was acclimated to 20, 23 26, 29 and 32°C for 21 days. For determination the active metabolic scope, we used the Temperature Induced Metabolic Rate (TIMR) methodology, which uses the determination of CT_{max}, where there is a range of temperatures where locomotive activity enhanced as the extreme temperature provokes an escape response in organisms. Base in this, we propose measuring weight specific oxygen consumption upon stimulation of organism activity provoked high metabolic rates during the escape reactions defined as escape metabolic rate (ESMR) when exposed to 95% of the CT_{max} (TIMRMax). Similarly, a minimum metabolic rate can be obtained of the CT_{min} when activity is depressed by exposure to 105% of the CT_{min} (TIMRMin) reaching a metabolic condition where resting metabolic rate (REMR) is forced. Considering that escape activity could be a good indicator of the metabolic performance of ectotherms, it is possible to assume that an active metabolic scope (AMS) induced by temperature can be obtained as ESMR-REMR, where AMS reflects the escape activity in extreme thermal conditions.

For each acclimation temperature, ten individuals used to calculate TIMRMax and ten for TIMRMin according to the novel methodology proposed. To determine TIMRMax, organisms placed individually in a 60 L aquarium equipped with a 1000 W heater and constant aeration in their respective acclimation temperature. For organisms that remained in these conditions for 30 min, the temperature was increased 1°C min^{-1} until reaching 95% of its CT_{max} and immediately transferred to an intermittent respirometric system (Díaz *et al.*, 2007) with a temperature similar to that of CT_{max} (95%). Oxygen consumption measured every 30 sec for 5 min with an oximeter (Oxy-10 mini, Presens) equipped with an optical fiber sensor. This corresponded to the temperature that induces escape metabolic rate (ESMR).

For determination of TIMRMin, prawns exposed to a temperature reduction at a rate of 1°C min^{-1}, similar to that described to obtain CT_{min}. When organisms reached CT_{min} of 105%, they immediately transferred to an intermittent respirometric system (Díaz *et al.*, 2007) with a temperature similar to that of CT_{min} (105%). Oxygen consumption measured every 30 sec for 5 min with an oximeter (Oxy-10 mini, PreSens) equipped with an optical fiber sensor. This corresponds to the resting metabolic rate (REMR).

The active metabolic scope AMS was calculated according to novel methodology as the difference between the ESMR-REMR where ESMR = escape metabolic rate and REMR = resting metabolic rate (both as mg O_2 h^{-1} kg^{-1} ww). The factorial metabolic scope also calculated as ESMR/REMR for comparative purposes. All determinations performed on organisms in the intermolt period according to the criterion described by Peebles (1997).

Statistical analysis

Normality (Shapiro-Wilk $P > 0.05$) tests and homoscedasticity (Levene $P > 0.05$) applied to each data group failed. The data of the thermoregulatory behavior, CT_{min}, CT_{max}, Oxygen Routine Consumption and TIMR were analyzed by the Kruskal-Wallis nonparametric test followed by a Dunn's multiple comparisons *post-hoc* test. Sigma Plot (v 12.5) software was used for all tests and graphics.

RESULTS

The thermal preference determined by the acute method in *M. tenellum* was 28.5ºC. The temperatures of the acclimations had not a significant effect on the final preferred temperature ($P > 0.05$) (Fig. 1). The preferred temperature of prawns was independent on acclimation temperature, and we found to be 27.0, 24.4, 28.2, 28.5 and 28.2ºC for acclimation temperatures of 20, 23, 26, 29 and 32ºC respectively.

A linear regression was modeled ($PT = 23.524 + (0.153 \times AT)$); ($r^2 = 0.82$), with the slope of the line ($b = 0.153$) indicating a independent temperature preference relationship.

CT_{max} median values were 37.3, 38.6, 39.7, 41.1 and 42.7°C; and were significantly different ($P \leq 0.05$). CT_{min} median values were 10.5, 12.6, 13.3, 14.0 and 14.9°C (at respective acclimation temperature of 20,

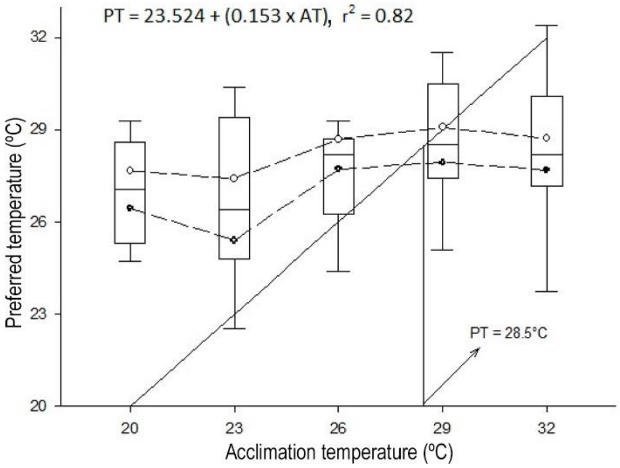

Figure 1. Preferred temperature of *Macrobrachium tenellum*, acclimated to different temperatures. The zone, bordered by circles open and closed, represents the 95% confidence interval of the median M ± IC, n =150. The bars represent 50% of the organism's distribution. The 45°construction continuous line represents the point where preferred and acclimation temperature are equal.

23, 26, 29 and 32°C). These values increased directly with acclimation temperature and all were significantly different ($P \leq 0.05$). The linear regression models describing the responses of CT_{max} and CT_{min} about acclimation temperature were $\mathrm{CT}_{max} = 28.285 + (0.446 \times \mathrm{AT})$; $r^2 = 0.995$; $P \leq 0.001$ and $\mathrm{CT}_{min} = 4.234 + (0.339 \times \mathrm{AT})$; $r^2 = 0.932$; $P \leq 0.001$. In accordance with this, the scope for thermal tolerance had an interval of 25.3 to 27.7°C. The thermal window width delimited by the values of CT_{max} and CT_{mi}n for the different acclimation temperatures was 325°C^2 (Fig. 2). The ARR values were between 0.28 and 0.52, for CT_{max} and between 0.42 and 0.50 for CT_{min}, with an average of 0.40 and 0.46 respectively.

The oxygen consumption routine rate increased significantly ($P \leq 0.05$); $y = -419.79 + 26.13 \times \mathrm{AT}$; $r^2 = 0.95$) and was directly proportionate to acclimation from 20 to 32°C. A maximum rate of 430 mg O_2 kg^{-1} h^{-1} ww eached 32°C (Fig. 3). The range of temperature coefficient (Q_{10}) in the prawns was highest between 26-29°C, with a value of 3.86 and lowest between 29-32°C with a value of 1.98.

The REMR was between 922.92 and 999.34 mg O_2 h^{-1} kg^{-1} ww, ESRM increased significantly ($P < 0.05$) from 2661.08 to 4511.47 26 mg O_2 h^{-1} kg^{-1} ww, followed by a significant decrease ($P < 0.05$) to 1950.15 mg O_2 h^{-1} kg^{-1} ww at 32°C (Fig. 4). The AMS increased significantly from 2900 to 3720 mg O_2 h^{-1} kg^{-1} ww in 26 to 29°C ($P < 0.05$) respectively, followed by a significant decrease at 32°C (Fig. 5).

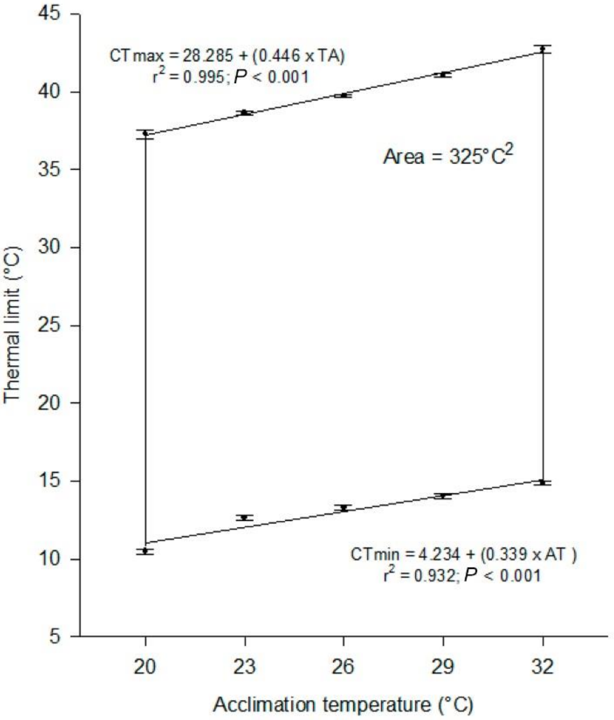

Figure 2. Thermotolerance represented by critical thermal maxima and critical thermal minimum and the thermal window of *Macrobrachium tenellum* acclimated to different temperatures M ± IC, n = 150.

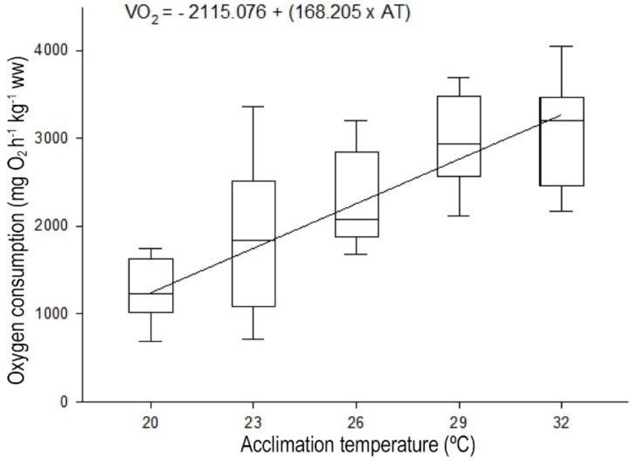

Figure 3. Effect of acclimation temperature on routine metabolic rate in *Macrobrachium tenellum*. The bars represent 50% of the distribution and the vertical lines represent the quartiles M ± IC, n = 45.

Factorial aerobic scope increased gradually from 2.9 in organisms maintained at 20°C to 6.1, in organisms acclimated to 29°C, decreasing to 4.0 in those exposed to 32°C. Furthermore, *M. tenellum* became slower at a higher temperature and showed a reduced number of escape responses before exhaustion.

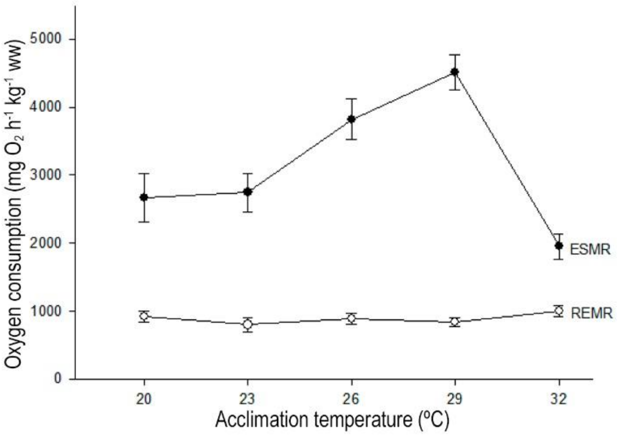

Figure 4. Temperature induced metabolic rate maxima, represents escape metabolic rate (ESMR closed circles) M ± IC, n = 50 and temperature induced metabolic rate minima represents Resting metabolic rate (REMR open circles) of *Macrobrachium tenellum.* M ± IC, n = 50.

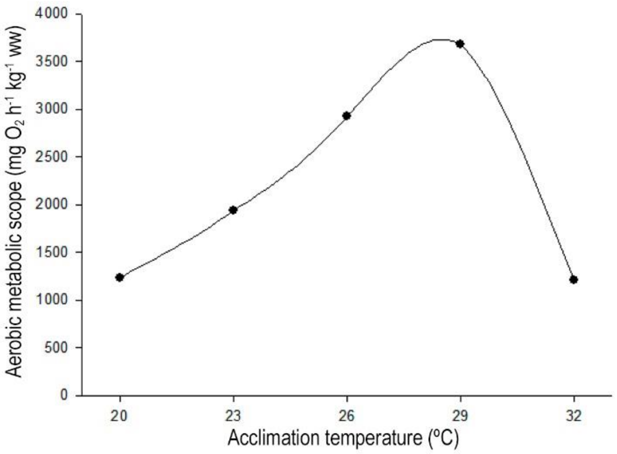

Figure 5. Temperature induced metabolic rate, represents the active metabolic scope (AMS) of *Macrobrachium tenellum* exposed to different temperatures.

DISCUSSION

Aquatic organisms have developed a variety of temperature preference responses that grouped into three categories: positive, independent and negative (Johnson & Kelsch, 1998). An independent response occurs when the preferred temperature it does not change with acclimation temperature. Indicating that *M. tenellum* is adapted to respond to great thermal extremes over the short term as tropical species must have a broad range of tolerance to survive relatively rapid temperature change without time for acclimation to adjust thermal preferences sudden, this response explains the wide distribution that this prawn has in the coasts of the Pacific.

Preferred temperature determined for *M. tenellum* using the acute method was similar to that of previous studies for other prawns from subtropical and tropical regions. For *M. tenellum* from Baja California, and *M. tenellum* of the tropical Mexican Pacific coast, Hernández-Rodríguez *et al.* (1995) and Rodríguez-Flores *et al.* (2012) reported a thermal preference of 28°C to 32.2°C. Díaz *et al.* (1993) reported for postlarvae and juvenile *M. rosenbergii* (De Man, 1879), a final *preferendum* between 29-31°C, whereas in *M. acanthurus* (Wiegmann, 1839), Díaz *et al.* (2002) reported a preferred temperature of 29.5°C. In *M. acanthochirus* (Villalobos, 1967), the preferred temperature obtained by Hernández-Díaz *et al*. (2003) was 27.5°C; Hernández (2008) reported a preferred temperature for *M. occidentale* (Holthuis, 1950) of 27.2°C. Sebastian (1996) suggested that the optimum temperature for most freshwater prawns is within the range of 28-32°C, which is explained by its biological history of tropical origin (Espinoza-Chaurand *et al.*, 2011).

The final preferred temperature obtained for *M. tenellum* was 28.5°C; this was a good indicator of the thermal requirements for the species, given the organisms are physiologically capable of reaching a steady state when they have a sufficient time to acclimate at this temperature. It mentioned by Reynolds & Casterlin (1979), Nichelmann (1983) and Díaz *et al*. (2015) that within this temperature, organisms do not experience thermal stress and their physiological functions optimized. It suggested that in this condition this species can maintain their body temperature by using behavioral thermoregulation, which may partially explain its distribution along the Mexican Pacific littoral, *i.e.*, Baja California Sur, Sinaloa, Jalisco, Oaxaca, and Chiapas, Mexico.

The endpoint of critical thermal maxima in prawns was Loss of Righting Response (LRR). This point represents the pre-death thermal point at which locomotory movements become disorganized due to neuromuscular blockade and presynaptic failure, and prawns lose the ability to escape the conditions which may ultimately lead to death (White, 1983; Beitinger *et al*., 2000; Ern *et al*., 2015).

The same response has been documented in another crustacean species (Nelson & Hooper, 1982; Hernández-Rodríguez *et al*., 1996; Díaz *et al*., 2002, 2004; Re *et al*., 2005; Kumlu *et al*., 2010; González *et al*., 2010; Re *et al*., 2012) all with similar results. It proposed that CT_{max} for *M. tenellum* corresponds to the critical threshold temperature where the scope of metabolic activity is close to zero. Ern *et al*. (2014, 2015) reported a collapse of heart rate and gill ventilation rate in three crustacean species which occurs when organisms experience the Critical Thermal Limits, indicating a failure in oxygen transport to the mitochondria. Therefore organisms can live for a short period in critical temperatures (Pörtner, 2010; Ern *et al*., 2015). CT_{max} is an ecologically relevant index of the upper thermal tolerance for decapod crustaceans, since this is a thermal tolerance indicator of *M. tenellum*, allowing the identification of the temperature at which the first sign of stress occurs: like increment of activity, initial disorientation, total disorientation that is considering a CT_{max} endpoint.

When CT_{min} limits analyzed, a similar thermal frontier appears between tropical-temperate and temperate-cold crustacean species. Tropical crustaceans acclimated at low temperatures showed CT_{min} values between 6.1-16.8°C and 7.2-11.4°C (Díaz-Herrera *et al*., 1998; Díaz *et al*., 2002; Kir & Kumlu, 2008; Kumlu *et al*., 2010). Whereas temperate species acclimated at high temperatures, had CT_{min} values between 1.0 and 6.28°C (McGaw, 2003; Reiser *et al*., 2014; Cumillaf *et al*., 2016), suggesting that the low limit for tropical animals may be the high limit for temperate animals.

In *M. tenellum*, the acclimation response ratio was determined as an index of the thermal acclimation magnitude, which for *M. tenellum* was between 0.28 and 0.52. The ARR data for different species of crustaceans suggests that those species inhabiting subtropical and tropical regions have the higher values than those species inhabiting cold and temperate regions. (Spoor 1955; McLesse, 1956; Bowler, 1963; Claussen, 1977, 1980, Layne *et al*., 1987; Firkins & Holdich, 1993; Hernández-Rodríguez *et al*., 1996; Díaz-Herrera *et al*., 1998; Díaz *et al*., 2002, 2004; Re *et al*., 2005, 2006; Lagerspetz & Vainio, 2006; Kir & Kumlu, 2008; Noyola *et al*., 2015).

It has been argued by Díaz-Herrera *et al*. (1998), Díaz *et al*. (2002, 2004), Re *et al*. (2005, 2006), Kir & Kumlu (2008) that species with low ARR values experience gradual long-term temperature fluctuations can make metabolic adjustments, without alterations in their tolerance ranges. On the other hand, subtropical and tropical species such as prawns experience the greatest fluctuations of temperature over short periods and have wider tolerance ranges to survive the relatively rapid changes in water temperature.

The thermal window obtained for *M. tenellum* juveniles was 325°C^2, in other tropical and subtropical crustacean species have been reported values of thermal window area of 286 to 336°C^2 (Díaz-Herrera *et al*., 1998; Díaz *et al*., 2002; Manush *et al*., 2004; Kumlu *et al*., 2010; Noyola *et al*., 2015). The thermal tolerance polygon is considered ecologically relevant because it provides indicator prawns tolerate temperature changes (Pörtner, 2010). Individuals from unchanging environments may have narrow thermal windows, while those from thermally heterogeneous habitats, such as prawns, may have the ability to shift to thermal limits (Fangue *et al*., 2006, Hopkin *et al*., 2006; Tepolt & Somero, 2014).

The scope for thermal tolerance obtained for *M. tenellum* was between 25.3 and 27.7°C in other prawn's species have been reported values between 22.9 to 27.3 (Díaz-Herrera *et al*., 1998; Díaz *et al*., 2002), indicating that these species may cope with wide thermal seasonal fluctuations. This may determine the degree of thermal adaptation and correlate with the regular temperature fluctuations of the habitat to which a species belongs (Brett, 1971). Feldmeth *et al*. (1974) mentioned that these species have an intermediate degree of eurythermicity and are, therefore, able to maintain effective metabolism over a wider temperature interval.

It found that if the acclimation temperature increases, oxygen consumption of *M. tenellum* would also increase. Similar results were observed in the shrimp *P. vannamei* at different sizes (Martínez-Palacios *et al*., 1996) as well as prawns like *M. americanum* (Bate, 1868), *M. rosenbergii* and *M. acanthurus* (Gasca-Leyva *et al*., 1991; Chen & Kou, 1996; Manush *et al*., 2004; García-Guerrero *et al*., 2011). Also, the temperature coefficient (Q_{10}) of *M. tenellum*, from 29 to 32°C was lower (1.98) in comparison to 20 to 26°C (3.42) indicating that in this interval they better performance (Dent & Lutterschmidt, 2003; Chatterjee *et al*., 2004). On the other hand, Kita *et al*. (1996), Chatterjee *et al*. (2004), Das *et al*. (2004, 2005), and Debnath *et al*. (2006) mentioned that if compared to acclimation temperatures the Q_{10} matches the optimum temperature for growth, and its decrease indicates that metabolism had lowered and there is more energy available for metabolic tasks. This interval matches the thermal *preferendum* of prawns (28.5°C) from the present work, so the optimum temperature for growth can also be estimated with the Q_{10}; it is suggested that within this optimal temperature interval crustaceans enzymatic and physiological responses may function better (Vernberg, 1983).

TIMRMin obtained for *M. tenellum* denote the minimum energy requirements for life excluding all non-essential activity and can be indicative of several life history traits. Similar results reported by Ern *et al*. (2015) in *Penaeus monodon* and *Astacus astacus*. Brown *et al*. (2003) found that resting metabolic rate SMR is a key outcome determinant of aggressive interactions between prawns.

TIMRMax obtained in *M. tenellum* diminished at 35°C probably a failure in oxygen transport to the mitochondria, a situation that can only sustain temporarily through anaerobic lactate production and soon leads to acute energy deficiency. This situation could affect the ability of these prawns to forage, grow and reproduce, and would, therefore, have implications for long-term population sustainability (Pörtner, 2001; Ern *et al*., 2015)

TIMR method in *M. tenellum* produces temperature metabolic rate relationship that causes a direct increase of oxygen consumption through the effect that temperature (CT_{max} 90%) produces in enzymatic kinetics and consequently in the entire energetic metabolism. Active metabolic scope for *M. tenellum* reached a maximum at a temperature of 29°C corresponding to its preferred temperature and suggesting that in these conditions, it is possible to perform all non-vital processes such growth and reproduction. Khan *et al*. (2014) working with *Polyprion oxygeneios* (Schneider & Forster, 1801) obtained a similar rate for the maximum aerobic scope corresponding to the preferred temperature interval. In lower or higher temperatures, the active metabolic scope of prawn diminished from 45 to 57%, indicating that under these conditions they may lose most energy and suffer muscle malfunction due to unfulfilled oxygen demand in tissues as observed by Ern *et al*. (2015) with *Astacus astacus*.

The factorial scope of *M. tenellum* in this study had an interval of 3-6 and corresponded to the range 3 to 5 reported to many crustaceans (Adamczewaska & Morris, 1994; Rosewarne *et al*., 2014), showing a moderate degree of aerobic potential in five acclimations temperatures, except at 29°C in where a higher value was obtained. In another prawn, shrimp and crayfish such as *M. rosenbergii*, *P. monodon* and *A. astacus*. Ern *et al*. (2014, 2015) observed similar behavior. The factorial scope values obtained for *M. tenellum* are around half of those reported for active species and are comparable to those obtained for intermittent swimmers (Schurmann & Steffensen 1997; McKenzie *et al*., 2001).

Knowledge of the preferences and thermal tolerance of a species is important as it allows defining adequate conditions based on the thermal requirements of the organisms. Information regarding lethal temperature and the species' physiological optimum is important to reduce the probability of survival in a climate space. Therefore, the results obtained in the present study are important to determine the optimum conditions in which *M. tenellum* needs to live in the natural environment.

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