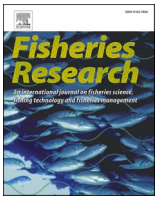
Fisheries Research 237 (2021) 105882

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres



Physiological responses to live air transport of red king crab (*Paralithodes camtschaticus*)

Vasco C. Mota *, Sten I. Siikavuopio, Philip James

Nofima AS, P.O. Box 6122, NO-9291, Tromsø, Norway

ARTICLE INFO

Handled by Niels Madsen

Keywords:
Red king crab
Paralithodes camtschaticus
Haemolymph
Live transport
Ions
Free amino acids

ABSTRACT

Live transport of red king crab from the fishing grounds to the market is an activity that is increasing and the future sustainability of this practice depends on maintaining optimal animal welfare during transport. The current study evaluated the physiological response of red king crab (*Paralithodes camtschaticus*) to live air transport, mimicking current commercial practices. Specifically, this study assessed stress and osmoregulatory haemolymph metabolite variation, together with free amino acids (FAAs) pool variation in the haemolymph of red king crab. Forty male crabs (2136 ± 800 g) were caught in the North Cape area in the Barents Sea during April 2019. They were transported by the fishing boat directly to a land-based live holding facility in Honningsvåg, Norway where they were held for < 10 days. They were then divided in two groups: i) the first group of 20 crabs underwent immediate haemolymph sampling, and ii) the second group of 20 crabs was divided in subgroups of 5 crabs, placed in a standard air freight Styrofoam boxes with freezer packs and transported by road and air to the Nofima facility, in Tromsø, Norway. The time from the packing until when the haemolymph sampling occurred was 20 h. All samples of haemolymph were taken from the coxa membrane of the third right side walking leg and were analysed for sodium (Na^+), chloride (Cl^-), carbon dioxide (CO_2), lactate, total protein, and FAAs. The survival of the transported crabs was 100 %, and after transport the measured indicators showed a significantly positive (lactate and total protein) or a negative (Na^+, Cl^-) variation in relation to the air transport. From the measured FAAs, five, Alanine (Ala), Arginine (Arg), Threonine (Thr), Valine (Val) and Taurine (Tau), were significantly higher for the group after transport when compared to the group before transport. No FAAs were significantly lower as a result of transport. In conclusion, it was apparent that red king crabs exposed to air during a 20 -h transport period exhibited the typical physiological responses associated to hypoxia stress. Moreover, in this study we report for the first time a change in the FAA pool results due to transport where five out of the twenty-one measured FAA where significantly elevated. Specifically, Ala, an important osmolyte during salinity stress. These results bring new insights into how red king crabs cope with live air transport and offer new evidence for the need to assess the crabs' health and welfare during live holding and transport. Moreover, the results obtained from this study can also contribute to the development of an industry friendly methodology to assess the stress and health status of crabs during and after live transport.

1. Introduction

Red king crab (*Paralithodes camtschaticus)* fisheries occur in its native Northern Pacific Ocean, Sea of Japan and Bering Sea regions, and in the area that the species has been introduced into in the Barents Sea. These fisheries are an important resource for the countries bordering these regions, such as the USA, Russia, and Norway, with a combined economic value of 300–350 million US dollars (Dvoretsky and Dvoretsky, 2018; Garber-Yonts and Lee, 2016; Lorentzen et al., 2018).

Typically in Norway, red king crab are captured with vessels operating pots near coastal waters, which is followed by immediate processing, i.e., cooking and freezing, or by live holding for limited periods followed by transport by air to international wholesale markets. Live overseas transport accounts for over seventy percent of harvested Norwegian king crab and these aremainly exported to markets such as South Korea (Voldnes et al., 2020). This strategy is highly lucrative due to the increased value of live red king crab in seafood markets, supermarkets and restaurants. However, the future sustainability of live transport lies

* Corresponding author.
E-mail address: vasco.mota@nofima.no (V.C. Mota).

https://doi.org/10.1016/j.fishres.2021.105882
Received 27 May 2020; Received in revised form 22 December 2020; Accepted 15 January 2021
Available online 29 January 2021

in optimising animal welfare during live holding and transport to the destination market (Lorentzen et al., 2018).

Live transport is preceded by live holding, the latter normally consists of keeping the crabs in land-based flow-through tanks supplied with natural seawater until transport. Studies on the capture-based aquaculture of red king crab have aimed to improve crab welfare during this period. For example, it was shown that mortality and occurrence of injuries were related to high stocking density (James et al., 2013; Siikavuopio et al., 2016), and feed intake was negatively related with increasing water temperature (Siikavuopio and James, 2015). However, the impact of live transport on red king crab is largely unknown, with the exception of an abstract by Zagorsky et al. (2014), where two transport methods were compared. Commercially, there are essentially two live transport methods: i) in water, using transport tanks, i.e., vivier-truck tanks, equipped with aeration or oxygenation and, ii) in air, using boxes with chiller packs (packs with frozen filler). The latter is the most common practice for the red king crab, particularly when the markets are beyond the range of road transport. Several studies on the transport of crustaceans have shown that several physiological parameters, health and welfare during live transport can be severely impacted (see review by (Fotedar and Evans, 2011).

Physiological responses to air transport stressors can be related to air exposure, temperature variations and handling factors. It has been previously described that exposure to air disrupted the oxygen consumption of crustacean and led to an accumulation of metabolites in haemolymph associated with anaerobic metabolism (Fotedar and Evans, 2011). For example, spiny lobster (*Jasus edwardsii*) emersed during simulated live transport showed elevated haemolymph glucose, lactate, and ammonia (Speed et al., 2001). Likewise, snow crabs (*Chionoecetes opilio*) exposed to increasing periods of air, mimicking a live transport, showed a spike of lactate in the haemolymph (James et al., 2019). Temperature variation, another stressor of transport, was shown to cause haemolymph acid-base imbalances in European lobster (*Homarus gammarus*) during live transport (Whiteley and Taylor, 1992) and oxidative stress in southern king crab (*Lithodes santolla*) during emersion (Schvezov et al., 2019). Stressors in general, seem to lead to alterations of haemolymph metabolites, and some of these can be used as biomarkers for determining crustaceans' physical condition or vitality.

Haemolymph composition of free amino acids (FAAs) can also be a useful indicator of crustacean's welfare and health. In many crustacean species, amino acids have been found to play an important role in the osmoregulation of intracellular fluid via the increase or decrease of amino acid pool in response to hypo/hyper-osmotic environments. For example, FAAs in the haemolymph of the giant freshwater prawn, (*Macrobrachium rosenbergii*) exposed to high salinities led to an overall increase of amino acids (Huong et al., 2001). Also, FAAs in the muscle and haemolymph concentrations vary during moulting, i.e., the periodic shedding of the exoskeleton. Dooley et al. (2002) found that the concentration of proline (Pro) in haemolymph was lower in the Australian freshwater crayfish (*Cherax destructor*) in premoult and postmoult compared to intermoult. This FAA plasticity in crustaceans' haemolymph may indicate that some amino acids have an important adaptative role in stress conditions. Whether the transport of red king crab would lead to an alteration of haemolymph FAA pool is unknown.

The objective of the present study was to evaluate the physiological response of red king crab (*Paralithodes camtschaticus*) to live air transport, mimicking current commercial practices. Specifically, to evaluate stress and osmoregulatory haemolymph metabolite variation, as well as FAAs pool variation, in the haemolymph of red king crab.

2. Material and methods

2.1. Experimental design

The current study consisted of evaluating the effect of live air transport of red king crab on several haemolymph parameters. For this purpose, two groups of 20 crabs were randomly sampled from a wild captured stock of crabs maintained at a live holding facility. The first group (from now on "before transport") underwent immediate haemolymph sampling at the beginning of the trial. The second group (from now on "after transport") of 20 crabs were divided in subgroups of 5 crabs, placed in standard air freight Styrofoam boxes (dimensions 78 cm × 39 cm × 23 cm) with freeze packs (0.5 L) and transported by road (approx. 4 h) and air (approx. 3 h) to Nofima AS experimental facility (Tromsø, Norway). After arrival at Nofima AS crabs were stored overnight (13 h) in a cooling room (2 °C) in their boxes. The time from the packing in the holding facility until the haemolymph sampling occurred was 20 h.

2.2. Animals

Red king crabs were captured in crab pots by commercial fishery vessels in the North Cape area in the Barents Sea during April 2019. Immediately after, the crabs were transported to a live-holding facility (Capefish AS), in Honningsvåg, Norway, where they were kept in indoor flow-through tanks (0.7 m^3) for < 10 days using ambient seawater (salinity 33 ppt, temperature 3–5 °C). During this period crabs were starved as is standard industry practice. Forty male (2136 ± 800 g) crabs that were post-moult and did not have damaged legs were selected and used in the present study. The individuals that met the above criteria were randomly picked from a larger population kept at the live-holding facility that were captured on different days within a period of 10-days.

2.3. Sampling and sample analysis

Samples of haemolymph (2 ml) were taken from the coxa membrane of the third right side walking leg (4th pereiopod) using a Vacuette® needle (20 G x 1.5') and a clot activator vacuum tube (Greiner Bio-One, Kremsmunster, Austria). After 15 min. resting in ice, samples were centrifuged for 10 min. at 2500 G at room temperature (approx. 22 °C) and immediately after, the supernatant was transferred to an Eppendorf tube freeze and stored at - 80 °C for further analysis.

Haemolymph sodium (Na^+), chloride (Cl^-), carbon dioxide (CO_2), lactate and total protein were determined from the crab serum using an automated clinical chemistry system (Pentra C400, Horiba, CA, USA). The diagnostic reagents were supplied by Horiba ABX (Montpellier, France) and its determination used the following methods: Na^+ and Cl^-, ion selective electrode; CO_2, enzymatic test using phosphoenolpyruvate carboxylase and a stable NADH analog; lactate, Trinder method and; total protein, Biuret reaction/colorimetric method.

Extraction of FAA from haemolymph samples protocol was adapted from Dooley et al. (2000). Briefly, 0.5 ml of the samples was added in glass vials together with 0.05 ml (20 mM) of DL-Norleucine (Sigma-Aldrich; internal standard) and 2 ml of 80 % ethanol. Then, the glass vials were placed in a shaking water bath at 70 °C for 20 min. Later, the samples were centrifugated at 4000 G for 10 min at room temperature (approx. 22 °C), the supernatant removed, and the pellet resuspended in 2 ml of 80 % ethanol. The process was repeated three times and the samples were stored at 4 °C until further analysis.

Amino acid analysis consisted of a chromatographic separation on an ion exchange column, as previously described by Mæhre et al. (2013). Prior to the load of samples into the analyser, the samples were evaporated, and the pellet resuspended in 1 ml of the lithium citrate loading buffer. The analysis was performed using a Biochrom 30 amino acid analyser (Biochrom Co, Cambridge, UK) and the UV signals were analysed by Chromeleon software (Dionex, Sunnyvale, CA, USA) and compared with A9906 physiological amino acids (Sigma Chemicals Co, St. Louis, MO, USA).

2.4. Statistics

Statistical analyses were performed with IBM SPSS Statistics V26

(IBM, Corp., USA). Free amino acid results that were below the amino acid analyser detection limit were given the minimal value, i.e. 0.5 nmol. Individual crabs are considered replicates. Individuals with insufficient serum for analysis were removed; N = 17 (before transport) and N = 14 (after transport) for automated clinical chemistry system analysis; N = 13 (before and after transport) for FAA analysis. Homogeneity of variance was assessed using Levene's test and normality using the Shapiro-Wilk test. Independent samples *t*-test was used to compare differences between the two groups. A significant level (α) of 0.05 was used for all analyses. All data are presented as mean ± standard deviation (S.D.).

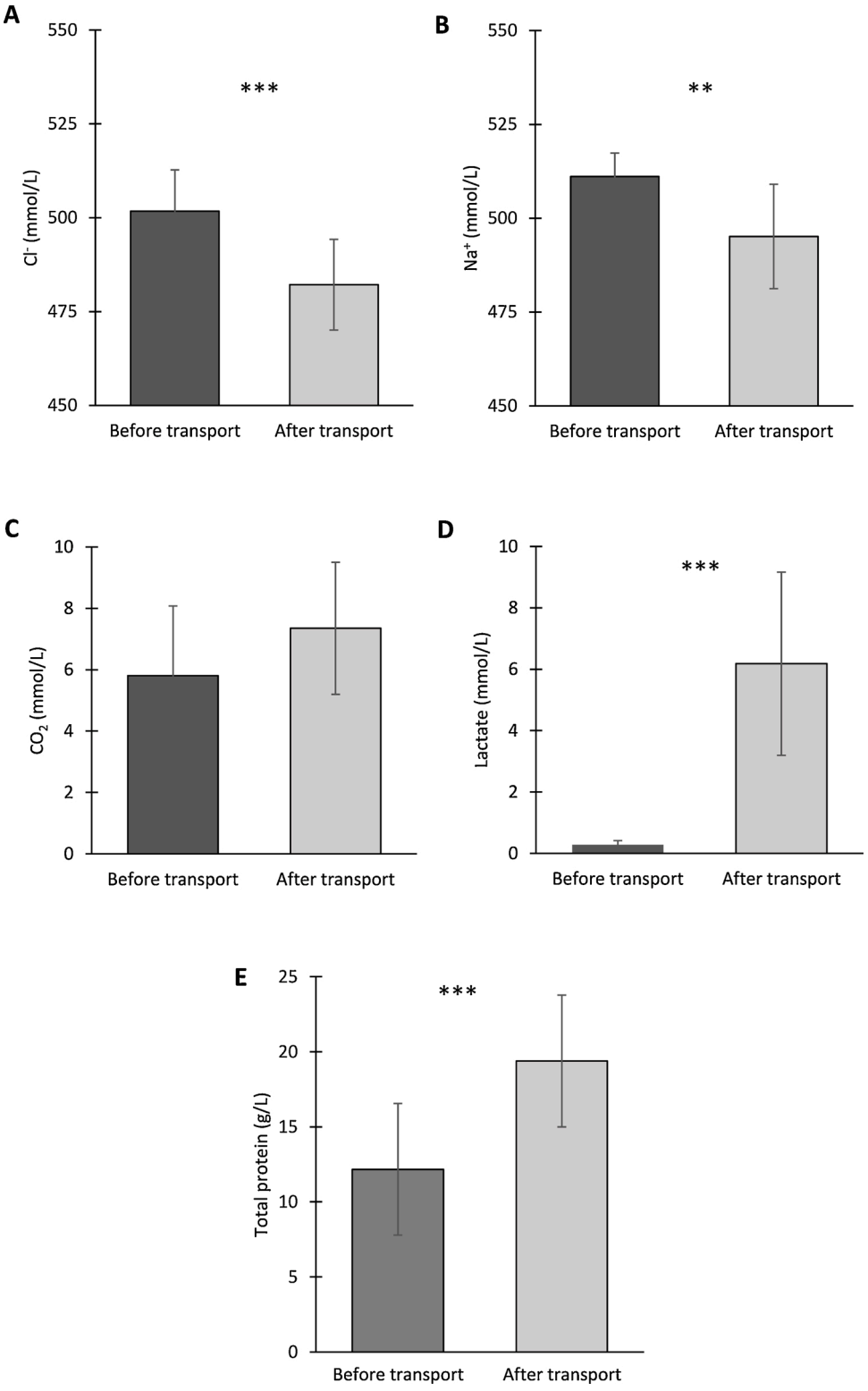


Fig. 1. Concentration of Cl^{-}, Na^{+}, CO_2, lactate and total protein in haemolymph (mean ± S.D.). N = 17 (before transport) and N = 14 (after transport). *P*-value < 0.010 (**) and < 0.001 (***).

3. Results

The survival of the transported crabs was 100 %.

The haemolymph of crabs transported had significantly lower Na^+ (↓ 3.1 %) and Cl^- (↓ 3.9 %) ions when compared to levels before transport (Fig. 1A, B).

The haemolymph CO_2 did not differ between the two treatments (Fig. 1C), whereas the haemolymph lactate was significantly higher (↑ 2134 %) in the transported crabs (Fig. 1D).

The haemolymph total protein concentration of the transported group presented a significantly higher (↑ 59.3 %) value when compared to levels before transport (Fig. 1E).

The average concentrations of haemolymph FAA from the two groups are shown in Table 1. Among all measured FAAs, Alanine (Ala), Arginine (Arg), Glutamine (Gln), Glycine (Gly), Leucine (Leu), Proline (Pro) and Taurine (Tau) were the most abundant, all with concentrations above 20 μg/mL. From these measured FAA, five - Ala, Arg, Threonine (Thr), Valine (Val) and Tau - were significantly higher for the group after transport when compared to the group before the transport. No FAAs were significantly lower as a result of transport.

4. Discussion

In the current study an array of haemolymph biomarkers was measured to assess red king crabs' condition after air transport. The survival rate of the transport was 100 %. Osmoregulatory and stress haemolymph indicators showed a positive (lactate and total protein), a negative (Na^+, Cl^-) or a neutral (CO_2) variation in relation to the 20 -h air transport. The current study also showed that the haemolymph FAA pool changes in response to transport, namely by the increase in concentration of Ala, Arg, Thr, Val and Tau.

Haemolymph metabolites have been investigated as a tool for monitoring the physiological condition in wild and cultured crustaceans exposed to different environmental conditions, including the impact of live transport in commercially important marine crustaceans, such as shrimp, lobster and crab. Apart from some species-specific and transport-specific variations, some common responses are usually described. For instance, air exposure during transport usually results in anoxic stress to the animals. A physiological compensation mechanism to anoxic condition consists of an increase in haemocyanins, which are a class of proteins responsible for transporting oxygen between the tissues in crustaceans. Total protein measurement in the haemolymph is a proxy parameter to capture this response. For example, Lorenzon et al. (2008) found an increase of total protein in the brown crab (*Cancer pagurus*) transported in boxes with high air humidity. However, this compensation mechanism also seems to be condition-specific dependent, as no changes were found in total protein in emersed snow crab (James et al., 2019). In the current study, total protein had a 59.3 % increase in the transported crab, which contrasts with the previous work from (Zagorsky et al., 2014), where total protein remained unchanged in crabs transported in boxes with wet material. However, the research by Zagorsky et al. (2014) is only available as a conference abstract so it is difficult to compare the results to assess the possible cause for this difference. The results from the current study indicate that this total protein haemolymph increase could be due to the increment of circulating hemocyanin induced by hypoxia as part of an ongoing physiological compensation process (Cheng et al., 2003).

The anoxic stress usually leads to haemolymph acid-base imbalances, namely acidosis and ion variations. Crustacean haemolymph lactate is a major end-product of anaerobic metabolism and several studies have shown its accumulation due to anoxic stress or emersion. For instance, this response was observed in emersed or air transported brown crab (Lorenzon et al., 2008), snow crab (James et al., 2019), spiny lobster (Speed et al., 2001) and Norwegian lobster (*Nephrops norvegicus*) (Spicer et al., 1990). In the current study, the animals transported showed a significant increase of lactate from close to 0 to over 6 mmol/L. Previously, Zagorsky et al. (2014) described an increase of red king crab haemolymph lactate from 0.5 to 1.0 mmol/L to 2.4–3.4 mmol/L during air transport. The elevation of lactate levels may suggest an increase in the anaerobic metabolism and presumably result from an inability to maintain an adequate supply of oxygen to tissues. Pre-cooling to ~2 °C before air exposure and thus reducing the metabolic stress was shown to lower lactate levels in southern king crab (*Lithodes santolla*) (Lorenzo et al., 2020). Nevertheless, the effect of air exposure seems to surpass the effect of lowering the temperature on lactate levels as shown by several studies (Lorenzon et al., 2008, 2007; Zagorsky et al., 2014). Moreover, lactate may have an adaptative role during air exposure by increasing hemocyanin oxygen affinity (Bridges, 2001). This may suggest that anoxic stress is likely the main factor during transport for the elevated lactate.

Haemolymph acid-base imbalances are common in crab transport and are usually represented by an increase in pH resulting from lactate and CO_2 accumulation due to the reduction in respiratory capacity. A sharp rise in haemolymph CO_2 could have been expected, nevertheless, in the current study this was not observed. This effect may have been masked by the variation on serum CO_2 levels after transport. An increase in CO_2 levels is accompanied by an elevation of haemolymph bicarbonate levels (Mota et al., 2020). An elevation of haemolymph bicarbonate was observed in several crustaceans as a response to hypoxia caused acidosis which was moderated by a Cl^-/HCO_3^- exchange system (Cheng et al., 2003). The freshwater giant prawn (Cheng et al., 2003) and American lobster (*Homarus americanus*) (Lorenzon et al., 2007) exposed to reduced dissolved oxygen, i.e. hypoxia, showed a reduction of haemolymph Cl^- concentration. In the present study, the haemolymph Cl- ions (and Na^+) had a significant but minor reduction (between 3–4 %), which may indicate an ongoing acid-base compensation which would be worth testing in the future by measuring more indicators, including serum bicarbonate. Moreover, this observation adds to the evidence that red king crab is an osmoregulator, as previously suggested in other studies (Ilyushchenko and Zenzerov, 2012; Stesko and Manushin, 2017). Moreover, Ilyushchenko and Zenzerov (2012) showed that crabs can survive in a salinity as low as 8 ppt, therefore showing the capability to actively exchange ions between the internal and external environment.

Haemolymph FAA changes during the transport of a red king crab or other crustacean species is reported for the first time in this study. Apart from a fundamental role in muscle and other tissue composition, amino

Table 1
Mean (± S.D.) concentrations of free amino acids (μg/mL) before and after the transport (N = 13).

Amino acid	Before transport	After transport	*P*-value[a]
Ala	12.3 ± 4.4	32.3 ± 12.3	**< 0.001**
Arg	33.1 ± 18.6	61.1 ± 21.6	**0.002**
Asn	13.0 ± 6.2	12.9 ± 10.3	0.990
Asp	13.1 ± 6.3	11.4 ± 10.2	0.629
Cys	11.9 ± 5.7	10.4 ± 9.3	0.630
Glu	14.4 ± 6.9	12.6 ± 11.2	0.630
Gln	28.0 ± 11.1	20.8 ± 14.9	0.176
Gly	31.5 ± 16.4	45.5 ± 27.2	0.124
His	15.2 ± 7.3	13.4 ± 11.8	0.646
Ile	12.9 ± 6.2	16.5 ± 12.1	0.344
Leu	15.1 ± 10.6	29.3 ± 24.8	0.075
Lys	14.3 ± 6.9	21.7 ± 16.6	0.157
Met	14.6 ± 7.0	16.6 ± 12.2	0.625
Phe	16.2 ± 7.8	15.5 ± 12.7	0.865
Pro	50.3 ± 24.6	41.0 ± 17.0	0.276
Ser	11.8 ± 5.0	13.6 ± 8.2	0.512
Thr	11.7 ± 5.6	21.6 ± 12.1	**0.016**
Trp	16.6 ± 8.0	14.5 ± 12.9	0.629
Tyr	17.8 ± 8.5	16.0 ± 13.8	0.693
Val	12.4 ± 5.7	21.3 ± 12.2	**0.028**
Tau	20.8 ± 10.9	40.8 ± 30.2	**0.040**

[a] Values in bold indicate significant differences, $P < 0.05$.

acids have important physiological roles in crustaceans, especially in their free form, i.e. FAA. Maintaining haemolymph osmolality is one of these roles (Romano and Zeng, 2012). Hyperosmotic stress was shown to cause changes in haemolymph FAA pool in giant freshwater prawn, particularly by elevating the concentration of the non-essential amino acids Ala, Pro, Gly and the essential amino acids, Arg and lysine (Lys), after a 6 -h transfer to seawater (Cheng et al., 2003). Similarly, results suggest that FAA, mainly Gly, Pro, and Ala, are involved in intracellular isosmotic regulation in the muscle of European lobster acclimatised to fresh water (Haond et al., 1999). In contrast, Australian freshwater crayfish acclimated to different salinities did not show differences in the FAA from muscle or haemolymph (Dooley et al., 2000). The latter authors suggested that the role of FAA on osmoregulation varies if the animal is an osmoconformer (weak or no regulatory capacity) or osmoregulator (active regulation of the internal fluids).In the current study, five FAA increased Ala, Arg, Thr, Val and Tau in response to the air transport. From these, FAA, Ala and Tau have been previously reported with an important osmoregulation role. Namely, Ala had the most significant difference (p-value < 0.001) and relative increase (+ 162 %). Free Ala has been previously proposed to be one of the most abundant and potent osmolytes for intracellular isosmotic regulation in crustaceans (Emiko and Hiroki, 1994; Okuma et al., 1995). Abe et al. (1999) also observed an increase of Ala in Japanese mitten crabs (*Eriocheir japonicus*) exposed to salinity stress. Whether the increase of Ala and the other amino acids in this study reveals a coping mechanism to transport stress is unknown and should be the focus of future studies. Alternatively, one may also consider that the increase of amino acid could be a result from haemoconcentration, i.e. the increase of haemolymph metabolites resulting from the loss of fluid in the tissues during an air exposure transport.

In conclusion, it was apparent that red king crab exposed to air during a 20 -h transport period exhibited the typical physiological responses associated to hypoxia stress by increasing haemolymph lactate, total protein and decreasing Cl^{-}. Moreover, the current study reports for the first time a change in FAA pool due to transport. Five out of the twentyone measured FAA were significantly elevated. Specifically, Ala, an important osmolyte during salinity stress. These results offer new insights into how red king crabs cope with live air transport mimicking commercial conditions. They also support the need to assess the crabs' welfare and health during live holding and transport. Moreover, the results obtained from this study can also contribute to the development of an industry friendly methodology to assess the stress and health status of crabs during and after live transport.

CRediT authorship contribution statement

Vasco C. Mota: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft. **Sten I. Siikavuopio:** Conceptualization, Writing - review & editing. **Philip James:** Conceptualization, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

Funding for this work was provided by The National Centre of Excellence for Capture-based Aquaculture (nr. 20933) and Farmed Animals WeLfare TooLbox project (nr. 12278). The authors would like to thank the Nofima colleagues Federico Lian and Anette Hustad for the crab sampling, Elin Sandaker and Tonje Vikan for the laboratorial analysis, Guro Edvinsen at University of Tromsø for the free amino acid analysis and Cassandra Roberts for proofreading the manuscript.

References

Abe, H., Okuma, E., Amano, H., Noda, H., Watanabe, K., 1999. Effects of seawater acclimation on the levels of free D-and L-alanine and other osmolytes in the Japanese mitten crab *Eriocheir japonicus*. Fish. Sci. 65, 949–954.
Bridges, C., 2001. Modulation of haemocyanin oxygen affinity: properties and physiological implications in a changing world. J. Exp. Biol. 204, 1021–1032.
Cheng, W., Liu, C.-H., Kuo, C.-M., 2003. Effects of dissolved oxygen on hemolymph parameters of freshwater giant prawn, *Macrobrachium rosenbergii* (de Man). Aquaculture 220, 843–856.
Dooley, P., Long, B., West, J., 2000. Amino acids in haemolymph, single fibres and whole muscle from the claw of freshwater crayfish acclimated to different osmotic environments. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 127, 155–165.
Dooley, P., Crouch, P., West, J.M., 2002. Free amino acids in claw muscle and haemolymph from Australian freshwater crayfish at different stages of the moult cycle. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 131, 625–637.
Dvoretsky, A.G., Dvoretsky, V.G., 2018. Red king crab (*Paralithodes camtschaticus*) fisheries in Russian waters: historical review and present status. Rev. Fish Biol. Fish. 28, 331–353.
Emiko, O., Hiroki, A., 1994. Total D-amino and other free amino acids increase in the muscle of crayfish during seawater acclimation. Comp. Biochem. Physiol. Part A Mol. Integr. Physiol. 109, 191–197.
Fotedar, S., Evans, L., 2011. Health management during handling and live transport of crustaceans: a review. J. Invertebr. Pathol. 106, 143–152.
Garber-Yonts, B.E., Lee, J.T., 2016. Economic Status Report Summary. BSAI Crab Fisheries, 2016.
Haond, C., Bonnal, L., Sandeaux, R., Charmantier, G., Trilles, J.-P., 1999. Ontogeny of intracellular isosmotic regulation in the European lobster *Homarus gammarus* (L.). Physiol. Biochem. Zool. 72, 534–544.
Huong, D.T.T., Yang, W.-J., Okuno, A., Wilder, M.N., 2001. Changes in free amino acids in the hemolymph of giant freshwater prawn *Macrobrachium rosenbergii* exposed to varying salinities: relationship to osmoregulatory ability. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 128, 317–326.
Ilyushchenko, A., Zenzerov, V., 2012. New data on the tolerance of Barents Sea red king crabs to low salinity. Russ. J. Ecol. 43, 177.
James, P., Vasilyev, R., Siikavuopio, S., Kovatcheva, N., Samuelsen, T., Mundheim, H., Carlehög, M., 2013. The effects of varying the percentage of herring versus salmon protein in manufactured diets on the survival, meat content, hepatosomatic index and meat sensory quality of adult red king crab *Paralithodes camtschaticus* held in captivity. Aquaculture 416, 390–395.
James, P., Izquierdo-Gómez, D., Siikavuopio, S.I., 2019. Use of reflex indicators for measuring vitality and mortality of the snow crab (*Chionoecetes opilio*) in captivity. Aquac. Res. 50, 1321–1328.
Lorentzen, G., Voldnes, G., Whitaker, R.D., Kvalvik, I., Vang, B., Gjerp Solstad, R., Thomassen, M.R., Siikavuopio, S.I., 2018. Current status of the red king crab (*Paralithodes camtchaticus*) and snow crab (*Chionoecetes opilio*) industries in Norway. Rev. Fish Sci. Aquac. 26, 42–54.
Lorenzo, R.A., Tapella, F., Romero, M.C., 2020. Pre-cooling effect on live transport of the Southern king crab, *Lithodes santolla*. Fish. Res. 227, 105552.
Lorenzon, S., Giulianini, P.G., Martinis, M., Ferrero, E., 2007. Stress effect of different temperatures and air exposure during transport on physiological profiles in the American lobster *Homarus americanus*. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 147, 94–102.
Lorenzon, S., Giulianini, P.G., Libralato, S., Martinis, M., Ferrero, E., 2008. Stress effect of two different transport systems on the physiological profiles of the crab *Cancer pagurus*. Aquaculture 278, 156–163.
Mæhre, H., Hamre, K., Elvevoll, E., 2013. Nutrient evaluation of rotifers and zooplankton: feed for marine fish larvae. Aquac. Nutr. 19, 301–311.
Mota, V.C., Nilsen, T.O., Gerwins, J., Gallo, M., Kolarevic, J., Krasnov, A., Terjesen, B.F., 2020. Molecular and physiological responses to long-term carbon dioxide exposure in Atlantic salmon (Salmo salar). Aquaculture 734715.
Okuma, E., Fujita, E., Amano, H., Noda, H., Abe, H., 1995. Distribution of free D-amino acids in the tissues of crustaceans. Fish. Sci. 61, 157–160.
Romano, N., Zeng, C., 2012. Osmoregulation in decapod crustaceans: implications to aquaculture productivity, methods for potential improvement and interactions with elevated ammonia exposure. Aquaculture 334, 12–23.
Schvezov, N., Lovrich, G.A., Tapella, F., Gowland-Sainz, M., Romero, M.C., 2019. Effect of the temperature of air exposure on the oxidative stress status of commercial male southern king crab *Lithodes santolla*. Fish. Res. 212, 188–195.
Siikavuopio, S.I., James, P., 2015. Effects of temperature on feed intake, growth and oxygen consumption in adult male king crab *Paralithodes camtschaticus* held in captivity and fed manufactured diets. Aquac. Res. 46, 602–608.
Siikavuopio, S.I., James, P., Olsen, B.R., Evensen, T., Mortensen, A., 2016. Holding wild caught red king crab, Paralithodes camtschaticus: effects of stocking density and feeding on survival and meat content. Aquac. Res. 47, 870–874.
Speed, S.R., Baldwin, J., Wong, R.J., Wells, R.M., 2001. Metabolic characteristics of muscles in the spiny lobster, *Jasus edwardsii*, and responses to emersion during simulated live transport. Comp. Biochem. Physiol. B Biochem. Mol. Biol. 128, 435–444.
Spicer, J., Hill, A., Taylor, A., Strang, R., 1990. Effect of aerial exposure on concentrations of selected metabolites in blood of the Norwegian lobster *Nephrops norvegicus* (Crustacea: Nephropidae). Mar. Biol. 105, 129–135.
Stesko, A., Manushin, I., 2017. On the distribution of the red king crab in the White Sea Throat. Russ. J. Biol. Invasions 8, 178–183.

Voldnes, G., Kvalvik, I., Nøstvold, B., 2020. Taking care of a highly valuable resource throughout the value chain-Lack of market orientation in red king crab export? Mar. Policy 117, 103965.

Whiteley, N., Taylor, E., 1992. Oxygen and acid-base disturbances in the hemolymph of the lobster *Homarus gammarus* during commercial transport and storage. J. Crust. Biol. 12, 19–30.

Zagorsky, I., Zagorskaya, D., Kovacheva, N., 2014. Comprehensive welfare assessment of red king crab (*Paralithodes camtschaticus*) during transport and storage. Aquaculture Europe 2014. European Aquaculture Society, Donostia–San Sebastián, Spain.