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α-MSH and melanocortin receptors at early ontogeny in European sea bass (Dicentrarchus labrax, L.)

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Temporal patterns of whole-body α-MSH concentrations and of transcripts of melanocortin receptors during early development as well as the endocrine response (α-MSH, cortisol, MCR mRNAs) to stress at the end of the larval period were characterized in Dicentrarchus labrax. Immunohistochemistry showed α-MSH positive cells in the pituitary pars intermedia in all stages examined. As development proceeds, α-MSH content gradually increases; mRNA levels of mc2r and mc4r remain low until first feeding where peak values are observed. Mc1r expression was constant during development, pomc mRNA levels remain low until the stage of flexion after which a significant increase is observed. At the stage of the formation of all fins, whole-body cortisol and α-MSH concentrations responded with peak values at 2 h post stress. Additionally, the stress challenge resulted in elevated transcript levels of pomc, mc2r and mc4r but not in mc1r, with a pattern characterized by peak values at 1 h post stress and a strong correlation with whole body α-MSH concentrations was found. Our data provide for the first time a view on the importance of the α-MSH stress response in early development of European sea bass, an additional and relatively poorly understood signal involved in the stress response in teleosts.

In fish, stress leads to the activation of the hypothalamic-pituitary-interrenal (HPI) axis, and stimulates the pituitary corticotropes in the pars distalis and the melanotropes in the pars intermedia to synthesize and secrete pro-opiomelanocortin (POMC)-derived peptides involved in the mediation and regulation of the stress response1,2. The pituitary gland is the major site of pomc expression. The gene is translated into a precursor protein, from which, among others, in the pars distalis adrenocorticotropic hormone (ACTH) and in the pars intermedia alpha-melanocyte stimulating hormone (α-MSH) are derived3. In European sea bass (Dicentrarchus labrax, L.) a single form of a functional pomc gene has been cloned and characterized4. Melanocortins exert their physiological role by binding to a family of specific G protein-coupled receptors (GPCRs) that positively couple to adenylyl cyclase. Tetrapod species have five melanocortin receptors (MC1R-MC5R), although in teleost fish the number of receptors differs5,6. The MC2R is specifically activated by ACTH, while the other MCRs can be activated by α-MSH as well as ACTH7.

During HPI axis activation, ACTH secreted by the corticotropes is a key regulator of the acute stress response as it stimulates the interrenal cells via MC2R and results in the synthesis and secretion of cortisol which targets a plethora of tissues, if not all cells in an organism1,7,8. Relatively few studies have focused on the function and characterization of MC2R in fish9–13 and a recent study conducted in European sea bass demonstrated a negative feedback by cortisol on MC2R expression in a chronic stress paradigm14.

There are 4 MCRs which convey MSH signals: MC1R, MC3R, MC4R and MC5R. Interaction of α-MSH and the MC1R plays a key role in the control of the pigmentation. For instance, mutations in the MC1R are responsible for reduced melanization. MC3R and MC4R are considered ‘brain receptors’, the expression of the MC4R is thought to play a role in the regulation of the energy balance in fish through the modulation of feeding behavior15–17. MC5Rs are found mainly in exocrine tissues; we do not further address this receptor in this study. Alpha-MSH is (at least in the few species studied so far) also involved in the stress response of fish1. In gilt-head sea bream (Sparus aurata) and in rainbow trout (Oncorhynchus mykiss) air exposure, a severe stress for fish, induces an increased α-MSH levels18,19. Moreover, other studies on salmonids have shown that ACTH and

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α-MSH cells are differentially activated during stress: HPI axis activation by handling and confinement led to elevated plasma concentrations of ACTH only, but when these stressors were combined with a thermal shock α-MSH was also increased\(^\text{29}\). Similarly, the latter is supported by studies on tilapia (Oreochromis mossambicus): prolonged netting stress had no effect on ACTH concentrations, but plasma cortisol levels did increase suggesting activity of another corticotrope; when netting was combined with confinement both cortisol and ACTH increased\(^\text{31}\), and this suggests that the confinement was a second acute stressor activating the ACTH pathway. More studies have shown that MSH is a corticotrope in Mozambique tilapia\(^\text{22}\), in barfin flounder\(^\text{23}\) and in rainbow trout\(^\text{24}\), but not in carp (Cyprinus carpio)\(^\text{10}\). Taken together, these results do suggest a functional role for α-MSH during stress, but whether α-MSH is a corticotrope remains unclear. The search for MCRs other than the MC2R in interrenal tissue is indicated.

In teleosts, cortisol acts as glucocorticoid and mineralocorticoid (fish lack aldosterone synthase) and is the most commonly used hormonal indicator of stress\(^\text{1,25}\). The hormone binding domain in fish glucocorticoid and mineralocorticoid receptors is very similar and binds cortisol, whereas the DNA binding domains define the eventual functionality of the receptors.

Recently, the cortisol response and its molecular regulation during early ontogeny have been studied in European sea bass\(^\text{26,27}\). So far to the best of our knowledge no data in fish physiology exists about the ontogenetic pattern of α-MSH levels, the effects of a stressor on its levels during early ontogeny or the molecular mechanisms involved. To this end, we examined α-MSH temporal patterns and the expression profiles of pomc, mc1r, mc2r and mc4r genes in European sea bass during defined stages of early development; also we analyzed the response to an acute stressor prior to and after earlier exposure to stress at the end of the larval period.

**Results**

**Temporal patterns of α-MSH content and gene expression at early ontogeny.** European sea bass embryos had low basal α-MSH content (44.5 ± 13.5 pg g\(^{-1}\)) that subsequently increased at first feeding (172 ± 93.5 pg g\(^{-1}\)), but these differences were not statistically significant. A significant increase was observed at flexion (307 ± 101 pg g\(^{-1}\)) and remained at statistically significant high values onwards to the formation of all fins (408.8 ± 41.1 pg g\(^{-1}\)), [Fig. 1a; (F3,12 = 17.22; P < 0.001)]. All genes of interest are expressed in all developmental stages examined (Fig. 1). Transcripts of pomc (Fig. 1b) showed a decrease in mRNA abundance from embryos till first feeding and a statistically significant 2.6-fold increase at the stage of flexion and remained high during 'all fins' (F5,30 = 41.13; P < 0.001). Expression levels of mc1r (Fig. 1c) showed no statistically significant differences between the developmental stages examined. Expression of mc2r (Fig. 1d) showed low levels from embryos till mouth opening and at the stage of first feeding there was a 4.1-fold upregulation that gradually dropped at flexion and 'all fins' (F5,30 = 47.88; P < 0.001). Expression levels of mc4r (Fig. 1e) remained low from the embryo stage until mouth opening; a statistically significant 1.8-fold increase was seen at the stage of first feeding and it remained at the same levels till the formation of all the fins (F5,30 = 18.28; P < 0.001).

**α-MSH localization.** Alpha-MSH positive cells in the pituitary pars intermedia (indicated by arrows in Fig. 2) were observed in all stages examined (mouth open, first feeding, flexion and all fins: Fig. 2A–D respectively). Omission of the primary antibody resulted in loss of all staining, which illustrates that our results show specific α-MSH staining. Besides α-MSH positive cells in the pituitary gland, a low intensity (background) staining was observed in chondrocytes. No other positive α-MSH cells were observed (data not shown).

**α-MSH and cortisol concentrations and mRNA expression levels of pomc, mc1r, mc2r and mc4r following the acute stress application.** Figures 3 shows the α-MSH and cortisol response and the expression profile of the pomc, mc1r, mc2r and mc4r genes prior to (0 h) and after (0.5 h, 1 h, 2 h and 24 h) the application of a stressor at the stage of the formation of all fins. A statistically significant effect of the stressor on α-MSH concentrations was observed (Fig. 3a) with a pattern characterized by a gradual increase to a maximum at 2 h (855.7 ± 84.7 pg g\(^{-1}\)) followed by a minimum (190.6 ± 31.9 pg g\(^{-1}\)) at 24 h post stress (F4,10 = 19.07; P < 0.001). Whole-body cortisol content (Fig. 3b) was 4.58 ± 0.7 ng g\(^{-1}\) at 0 h, to increase to 20.75 ± 0.9 ng g\(^{-1}\) at 0.5 h, reach a maximum at 2 h (39.93 ± 1.6 ng g\(^{-1}\)) after stress, and then returned to basal values at 24 h (10.11 ± 4.3 ng g\(^{-1}\)) (F4,10 = 62.14; P < 0.001).

Transcripts levels of pomc (Fig. 3c) showed a statistically significant 1.9-fold upregulation at 1 h post stress compared to controls (F4,15 = 6.67; P < 0.05) that dropped to resting values at 24 h post stress. The acute stress application had no effect on mc1r (Fig. 3d). The pattern observed for mc2r (Fig. 3e) expression after the acute stress application consisted of low basal values at 0 h that increased at 0.5 h and at 1 h post stress (3.8-fold up-regulation) which returned to basal values at 2 h and 24 h post stress (F4,15 = 12.55; P < 0.001). This expression pattern of mc2r after the acute stress application parallels with the changes observed in whole body cortisol concentrations post stress. Transcript levels of mc4r (Fig. 3f) were affected by the applied stressors, showing a 2-fold up-regulation at 1 h post stress, to gradually reach basal values at 24 h post stress (F4,15 = 6.78; P < 0.05).

**Discussion**

During ontogenesis of sea bass, temporal changes in whole-body α-MSH levels showed a gradual increase from low levels during the first stages to maximum values at the stages of flexion and development of all fins. Our immunohistochemistry showed that no significant α-MSH positive cells were observed outside of the pars intermedia. There are very few data available on α-MSH during early ontogeny apart from a study carried out during the early developmental stages in scyliorhinid dogfish (Scyliorhinus torazame) that showed a gradual increase of the α-MSH-producing cells in the adenohypophysis\(^\text{28}\). The observed increase in whole-body α-MSH concentrations at the advanced stages of early development reported here may reflect the involvement of α-MSH in the formation of melanophores and the coloring of the body\(^\text{29-31}\), which takes place in the period around the
Figure 1. Temporal patterns of α-MSH content and gene expression at early ontogeny of European sea bass. Changes in resting whole body (a) α-MSH and mRNA transcript levels of (b) *pomc*, (c) *mc1r*, (d) *mc2r* and (e) *mc4r* at the different developmental points/stages (embryos-EM, hatch-HAT, mouth opening-MO, first feeding-FF, flexion-FLX, formation of all fins-FINS). Means with different letters differ significantly from one another (*P* < 0.05).
formation of the fins. Expression of pomc increases at the stage of flexion and its peak is in line with the first statistically significant elevation of α-MSH levels. Abundance of mc2r remains at low levels until the stage of first feeding where it reaches a maximum and then decreases gradually at the later stages of development. Previous studies of our group have shown that sea bass larvae begin to synthesize cortisol around the stage of first feeding26,27, which coincides with the expression profile observed for mc2r. Similar results have been obtained in zebrafish, where the expression of mc2r is upregulated immediately before the rise in whole-body larvae cortisol concentrations33. Expression of mc1r was not altered depending on the developmental stage, whereas expression levels of mc4r was low in the embryo stage until mouth opening showing an increase at the stage of first feeding and remained at similar levels thereafter till the stage of the full formation of all fins. The acute stress challenge at the stage of the formation of all fins involved an elevation of α-MSH and cortisol levels with a peak at 2 h after application of the stressor. These results are supported by studies in adult gilthead sea bream (Sparus aurata) and rainbow trout (Oncorhynchus mykiss), studies that showed that the application of severe acute stress leads to an increase of α-MSH levels18,19. This pattern of the α-MSH response to stress is rather similar to the pattern observed post-stress for whole body cortisol concentrations at the same developmental stage, where low basal values increase at 0.5 h and 1 h to reach a maximum at 2 h post-stress (Fig. 3a).

α-MSH is a POMC-derived peptide, so to reveal the molecular mechanisms related to the onset of the α-MSH stress response, qPCR experiments were carried out to analyze transcript levels of pomc. We would emphasize that we do not – as of yet – know how the measured transcripts are reflected in peptide levels of ACTH and α-MSH. Expression levels of pomc after the acute stress application appear to be altered at the stage of the formation of all fins where the pattern of pomc stress response is characterized by maximum values at 1 h post stress that gradually drop to resting levels at 24 h (Fig. 3c) and this could concern both the ACTH and the MSH signal. However, the mRNA expression of pomc is upregulated along with α-MSH levels, indicating a strong relation between pomc mRNA expression and α-MSH production. These results are in accordance with the results obtained from a study in adult channel catfish (Ictalurus punctatus), where an up-regulation of pomc mRNA was observed in response to low-water stress, showing peak values at 1 h post stress which at 3 h declined to the level of the control group34. The melanocortins exert their physiological role by binding to melanocortin receptors (MC1R-MC5R). MC2R plays a critical role in the HPI axis35 and is specifically activated by ACTH, while the other MCRs can be activated by the MSHs as well as ACTH7. The acute stress application at the stage of the formation of all fins resulted in altered transcript levels of mc2r which showed an up-regulation after application of the stressor, with peak values at 0.5 h and 1 h post stress to return to basal levels at 2 h and 24 h post stress (Fig. 3e) showing a similar pattern with the observed cortisol pattern obtained under the same conditions (Fig. 3b). The observed up-regulation of mc2r after stress at the stages of flexion and development of all fins is in accordance with the data obtained in a study conducted in rainbow trout where application of an acute stressor led to increased levels of mc2r transcripts32. Up-regulation of mc2r after acute stress is further supported by a study by Tokarz and colleagues in zebrafish36, where the expression level of mc2r increased significantly until about 30 min after the stressor and subsequently decreased to the mRNA levels of unstressed fish. Both mc1r and mc4r are activated by α-MSH and

Figure 2. α-MSH radioimmunoassay. Representative images of transverse sections of (A) mouth open, (B) first feeding, (C) flexion and (D) all fins stages. Arrows indicate α-MSH positive cells in the pars intermedia. The scale bar represents 100 μm (A) or 200 μm (B–D).
are involved in the control of the pigmentation and the modulation of food intake, respectively. Expression of \(mc1r\) in this study was not altered following application of the stressor (Fig. 3d), whereas \(mc4r\) expression appeared to be affected by stress at the stage of the full formation of all the fins where transcript levels peaked at...
1 h post stress and fell back to resting levels at 24 h post stress (Fig. 3f). It thus seems likely that MSH also through MC4R may play a role in the responses to stress.

In summary, we characterized for the first time in a Mediterranean marine teleost, the European sea bass, the temporal pattern of whole body α-MSH and the expression profile of pomc, mc1r, mc2r and mc4r genes during early ontogeny. Additionally, sea bass larvae at the stage of the full formation of all fins were exposed to acute stressors and the temporal patterns of whole body α-MSH and cortisol and the expression profiles of pomc, mc1r, mc2r and mc4r genes prior to and after application of the stressor, were determined. Overall, these data, combined with data on the cortisol response during early ontogeny give us for the first time a more thorough view on the two mechanisms involved in the stress response in sea bass with similar patterns observed for α-MSH and cortisol. Alpha-MSH is a truly pleiotropic hormone, with, among others, effects on skin coloration, feed intake and metabolism. To what extent α-MSH contributes to each of these processes remains to be determined, but our results indicate an involvement of α-MSH in the stress response, a response requiring adjustment of energy flow and distribution. Whether MSH acts on the interrenal and/or on brain centers controlling feed intake remains to be determined.

Materials and Methods

Animals and husbandry conditions. Batches of fertilized European sea bass eggs were obtained from a private fish farm (DIAS S.A.) and transferred to the installations of the Institute of Aquaculture, Hellenic Center for Marine Research (Heraklion, Crete). Larval rearing was performed applying the pseudogreen-water technique, in 500 L cylindro-conical tanks, with an initial density of 100 eggs l⁻¹. Animals in testing, in accordance to Greek (PD 56/2013) and EU (Directive 63/2010) legislation on the care and use of animals in testing, in accordance to Greek (PD 56/2013) and EU (Directive 63/2010) legislation on the care and use of experimental animals.

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Experimental design. Samples were collected at six different points/stages during early life development (embryos, hatching, mouth opening, first feeding, flexion and formation of all fins). Additionally, at the stage of the formation of all fins additional samples were also collected at 0.5 h, 1 h, 2 h and 24 h post stress. The antibody used in the present study is highly specific for alpha-MSH.

α-MSH radioimmunoassay. Samples were homogenized in 0.01 M HCl (1:1 (v/w) HCl/body weight). Whole-body α-MSH concentrations were then measured with a radioimmunoassay; α-MSH was labeled with ¹²⁵I using the iodogen method. Labeled α-MSH was purified by solid phase extraction (C8 Bakerbond column, J.T. Baker, Center Valley, PA, USA). The antiserum shows 100% cross reactivity with des-, mono- and di-acetyl- α-MSH, and was used in a final concentration of 1:22,500. The second antibody to precipitate immune-complexes was a sheep-anti-rabbit anti-body (Fitzgerald, Acton, MA, USA) and was used at a final dilution of 1:15. Radioimmunoassay analyses using recombinant ACTH peptides demonstrated no binding of the antibody to all (0% cross-reactivity). Mammalian as well as fish ACTH peptides were used, which all share a sequence similarity between 80–95% with sea bass ACTH. Moreover, alpha-MSH is acetylated N-terminally, and the antibody shows 100% cross-reactivity between des-, mono- and di-acetyl alpha-MSH, indicating that the epitope of the antibody lies in the C-terminal region of the protein. This region is not available for antibody binding in ACTH and not present in CLIP, nor any other POMC-derived peptides. Therefore, we are confident that the antibody used in the present study is highly specific for alpha-MSH.
α-MSH immunohistochemistry. Samples of mouth opening, first feeding, flexion and all fins were fixed in Bouin’s fixative for 6 hours and wash thoroughly in 70% ethanol afterwards. For sectioning, samples were dehydrated trough gradually increasing ethanol series and embedded in paraffin. Sections (7 μm) were cut, mounted on glass slides coated with poly-L-lysine and dried overnight at 37°C. Next day the sections were deparaffinized in xylene, rehydrated through gradually decreasing ethanol series and incubated with 1% H2O2 to block endogenous peroxidase activity. Non-specific antigenic sites were blocked with 2% Normal Donkey Serum (NDS, Jackson Immuno Research, West Grove, PA) followed by overnight incubation with 1:1000 α-MSH antibody29. After 1 h incubation with 1:200 biotinylated Donkey Anti Rabbit IgG (Jackson Immuno Research, West Grove, PA) secondary antibody, 1:200 Avidin–Biotin–HRP Complex (ABC, Vector Laboratories, Burlingame, CA) was added and incubated for 1 h. Staining was performed using 0.025% 3,3’-diaminobenzidine (DAB) and 0.005% H2O2.

Cortisol determination. Whole body cortisol extraction was performed according to Pavlidis et al.26. Briefly, body samples were partially thawed on ice and homogenized in 5 x (w/v), ice-cold phosphate-buffered saline (pH 7.4). Cortisol was extracted from 2 x 250 μL of homogenate with 3 mL of diethyl ether. The extract was allowed to freeze by placing tubes in a deep freezer (−80°C), the diethyl ether layer (above the frozen water layer) was transferred into a new tube and evaporated by placement of tubes in a 45°C water bath for 1 h and in room temperature for an additional 3 h. Samples were then reconstituted in 250 μL of immunoassay buffer and cortisol was quantified by the use of a commercial enzyme immunoassay kit (Cayman Chemical, MI, USA). All samples were tested in duplicate.

RNA purification and cDNA synthesis. Samples of embryos, pre-larvae and larvae were let to thaw on ice, disrupted and homogenized using the TissueRuptor (Qiagen, Hilden, Germany) for 20 s in 600 μL RLT plus buffer (RNeasy Plus Mini Kit Qiagen, Valencia, USA). Total RNA was isolated with the RNeasy Plus Mini Kit (Qiagen, Valencia, USA). RNA yield and purity was determined by measuring the absorbance at 260 and 280 nm using a Nanodrop® ND-1000 UV–Vis spectrophotometer (Peqlab, Erlangen, Germany), and its integrity was allowed to freeze by placing tubes in a deep freezer (−80 °C), the diethyl ether layer (above the frozen water layer) was transferred into a new tube and evaporated by placement of tubes in a 45°C water bath for 1 h and in room temperature for an additional 3 h. Samples were then reconstituted in 250 μL of immunoassay buffer and cortisol was quantified by the use of a commercial enzyme immunoassay kit (Cayman Chemical, MI, USA). All samples were tested in duplicate.

The forward primer for pomc has the sequence 5′-CATCTACGCCTTCCGCATTG 3′ while the reverse 5′-ACCTCCTGTGCCTTCTCCTC 3′ pair was required to have a linear standard curve with an r2 value above 0.98 and primer amplification efficiency of the dilution factor against the relative cycle threshold value. To be considered suitable for analysis, each primer constructed for each gene, using 4 serial dilutions (1:5) of a pool of all cDNA samples by graphing the negative log of the dilution factor against the relative cycle threshold value. Statistical analysis. All statistical analyses were performed with SigmaPlot 11.0 (Jandel Scientific). Data are presented as means ± standard deviation (SD). Statistical comparisons of α-MSH concentration and gene expression of unstressed specimens (0 h) between the different developmental points/stages and statistical comparisons of temporal patterns of α-MSH and cortisol concentrations and gene expression between the different time points following exposure to a stressor at the stage of the formation of all fins were made using one-way ANOVA. Holm-Sidak’s honestly significant difference test for multiple comparisons was used to determine significant differences among groups. The significance level was set at P < 0.05.

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Author Contributions
A.T. and M.P. wrote the main manuscript. A.T. and N.P. carried out larvae rearing and sampling. M.G., G.F. and T.P. carried out α-MSH localization experiments and prepared Fig. 2. A.T. carried out cortisol measurements, primer design and qPCR experiments. A.T. prepared Figs 1 and 3. All authors reviewed the manuscript.

Additional Information
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