

RESEARCH OUTPUTS / RÉSULTATS DE RECHERCHE

Ex vivo approach supports both direct and indirect actions of melatonin on immunity in pike-perch *Sander lucioperca*

Baekelandt, Sébastien; Cornet, Valérie; Mandiki, Robert; Lambert, Jérôme; Dubois, Mickaël; Kestemont, Patrick

Published in:
Fish & Shellfish Immunology

DOI:
[10.1016/j.fsi.2021.03.005](https://doi.org/10.1016/j.fsi.2021.03.005)

Publication date:
2021

Document Version
Peer reviewed version

[Link to publication](#)

Citation for pulished version (HARVARD):
Baekelandt, S, Cornet, V, Mandiki, R, Lambert, J, Dubois, M & Kestemont, P 2021, 'Ex vivo approach supports both direct and indirect actions of melatonin on immunity in pike-perch *Sander lucioperca*', *Fish & Shellfish Immunology*, vol. 112, pp. 143-150. <https://doi.org/10.1016/j.fsi.2021.03.005>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Ex vivo* approach supports both direct and indirect actions of melatonin on immunity in pike-perch *Sander lucioperca

Sébastien Baekelandt *, Valérie Cornet, Syaghalirwa N.M. Mandiki, Lambert Jérôme, Dubois Mickaël, Patrick Kestemont

Research Unit in Environmental and Evolutionary Biology (URBE), Institute of Life, Earth & Environment, University of Namur, Rue de Bruxelles 61, B-5000, Belgium

*Corresponding author. Tel.: +32 81 72 42 84 Email address: sebastien.baekelandt@unamur.be

9 **ABSTRACT**

10 The melatonin hormone, which is a multifunctional molecule in vertebrates, has been shown to
11 exert complex actions on the immune system of mammals. In teleosts, the immunomodulatory
12 capacity of this hormone has seldom been investigated. In the present experiment, we exposed
13 *ex vivo* spleen and head kidney tissues of pike-perch to melatonin (Mel) and cortisol (Cort). We
14 applied three concentrations of both hormones, alone and in combination, namely (1) Mel (10,
15 100 or 1000 pg mL⁻¹) (2) Cort (50, 500 or 5000 ng mL⁻¹) (3) Mel+Cort (10+50, 100+500 or
16 1000 pg mL⁻¹+5000 ng mL⁻¹). Pure medium without Mel or Cort served as control. After 15 h
17 of incubation, we assessed the expression of a set of immunity-related genes, including genes
18 encoding for pro-inflammatory proteins (*il-1 β* , *cxcl8* and *tnf- α*), acute-phase proteins (*fgl2*, *fth1*,
19 *hepc*, *hp* and *saa1*) and key factors of the adaptive immune system (*fkbp4* and *tcrg*). Both Mel
20 and Cort, when used alone or combined at physiological concentrations, significantly
21 influenced immune gene expressions that may lead to a global immune stimulation. Our results
22 support both, an indirect action of the Mel hormone on the immune system through the
23 regulation of intermediates such as Cort, as well as a direct action on immune targets through
24 specific receptors.

25 **Keywords:** Melatonin; Immunity; Gene expression; Cortisol; Pike-perch

1. INTRODUCTION

In response to a growing market demand, aquaculture has strongly developed over the last few decades. In order to improve productivity and profitability in fish culture, stocking density is usually increased, with up to several hundred kg/m³ of fish. However, overcrowding in production units tends to affect fish health, enhancing the susceptibility of fish to infections which is a major bottleneck of aquaculture development (Conde-Sieira et al., 2014). Various efforts have been undertaken to limit disease outbreaks by developing antibiotics and vaccines. However, drug-resistant bacteria and limitations of vaccination have stimulated research on alternatives based on the improvement of immunocompetence of cultured fish species through the use of immunostimulants and the enhancement of fish welfare (Abarike et al., 2018). Improving our knowledge on fish immunity is thus of great interest in order to optimize management strategies and to limit disease outbreaks in fish farms.

Immune-neuroendocrine interactions in vertebrates have been at the center of interest for decades and it has become evident that a bi-directional communication between the immune and neuroendocrine systems is essential for the maintenance of homeostasis (Guerrero and Reiter, 2002; Esteban et al., 2006; Mathieu et al., 2014). In fish, the effects of several hormones, including cortisol (Cort), reproductive hormones (17 β -estradiol, testosterone, 11-ketotestosterone, ...), growth hormone (GH) and prolactin (PRL), on immune functions have been extensively documented (Harris and Bird, 2000; Cuesta et al, 2006; Yada, 2007; Paredes et al., 2013; Nardocci et al., 2014; Chaves-Pozo et al., 2018). However, the immune modulation by the melatonin hormone (Mel), a multifunctional molecule in vertebrates, is less understood and merits more attention.

In vertebrates, the Mel hormone, a key hormone of the circadian axis, is mainly produced and secreted by the pineal gland during the dark phase of the photoperiod (Vera et al. 2007; Confente et al., 2010; Falcon et al., 2010). Through this daily rhythm, it relays information about the time of the day and year to cells and organs (Kulczykowska et al., 2006; Migaud et al., 2007; López-Patiño et al., 2014). This indoleamine is also known to regulate important physiological functions like thermoregulation and reproduction in a wide range of vertebrates, as well as immunity in mammals (Carrillo-Vico et al., 2005; Dumbell et al., 2016). In teleosts, Mel also acts on important functions such as reproduction, smoltification, osmoregulation and development (Downing et al., 2002; Falcon et al., 2007; 2010). Contrary to mammals, its potential immunomodulatory capacity in teleosts has been rarely investigated (Cuesta et al.,

2008). The few available evidence suggest that Mel may act as an important fish immune regulator. This action on immune cells and tissues could involve specific Mel receptors and/or the regulation of the secretion of intermediates (glucocorticoids, GH, PRL) known to act on immune functions (Esteban et al., 2006; Cuesta et al., 2008; Falcon et al., 2010; Esteban et al., 2013).

As the main glucocorticoid in vertebrates, Cort is recognized also in teleosts to play a role in stress responses and to be a crucial immunomodulator with complex actions (Esteban et al., 2004; Cuesta et al., 2006; Oliveira et al., 2013). Depending on the type and intensity of stress, Cort may act as an immune activator or suppressor, with acute stress generally resulting in immune-enhancing processes and chronic stress generally leading to immunosuppression (Tort, 2011; Nardocci et al., 2014). Since a mutual inhibition has been characterized between stress and circadian axes (López-Patiño et al., 2013; 2014; Conde-Sieira et al., 2014), Cort is a potential intermediate of the indirect immunomodulation by Mel.

Over the last few years, pike-perch (*Sander lucioperca*) has become the most promising teleost species of European inland aquaculture thanks to its fast growth and high-quality flesh (Dalsgaard et al., 2013; Overton et al., 2015). However, percid fish seem to be more sensitive to husbandry stressors than other species with a longer history of domestication (Jentoft et al., 2005), which consequently may alter its immune functions (Mathieu et al., 2014). Efforts have thus been deployed to improve pike-perch welfare to optimize its management in aquaculture.

Previous studies have proven that the light environment affects pike-perch stress status as well as melatonin release by the pineal gland and that it further modulates its innate immune functions (Baekelandt et al., 2019a,b; 2020). So far, no investigations exist on the mode of action of the melatonin hormone on immune tissues of teleosts. We thus aimed to investigate the direct action of Mel, with and without combination of Cort, on the expression of immune-relevant genes in head kidney and spleen of pike-perch using an *ex vivo* approach. The selected genes encode for pro-inflammatory proteins (*il-1 β* , *cxcl8* and *tnf- α*), acute-phase proteins (*fgl2*, *fth1*, *hepc*, *hp* and *saal*) and key factors of the adaptive immune system (*fkbp4* and *tcrg*).

2. Materials and methods

2.1. Animals and rearing conditions

The present protocol (19 002 KE) has been carried out in agreement with the local Ethics Committee for Animal Experiments. A stock of 200 pike-perch juveniles (120 ± 10 g) from the Aquaculture Experimental Platform of the University of Lorraine, France, was transferred to URBE facilities at the University of Namur, Belgium. They were maintained in 4 indoor 400-L tanks of a recirculating aquaculture system for 4 weeks. Environmental conditions were kept constant during that period. These were light intensity of 10 lux at water surface, photoperiod of 12L_(8:00 - 20:00)/12D, water temperature at 16°C, oxygen saturation of 90%, and a feeding scheme twice a day with commercial pellets at 2% biomass.

2.2. Sampling procedures and incubation

On March 4th and 7th 2019, ten fish from each tank were randomly removed and euthanized (overdose of anesthetic MS-222, 250 mg L⁻¹) before extracting the spleen and the head kidney. Considering the two sampling days, 80 fish were collected in total. Organs were washed thrice with Hanks' balanced salt solution (HBSS, Fisher Scientific, USA). They were then transferred on 12-well culture plates, filled with HBSS supplemented with bovine serum albumin (BSA, 0.1%, Fisher Scientific, USA) and ascorbic acid (50 µM, Sigma-Aldrich, USA). The following treatments were applied: (1) Mel (10, 100 or 1000 pg mL⁻¹) (2) Cort (50, 500 or 5000 ng mL⁻¹) (3) Mel+Cort (10+50, 100+500 or 1000 pg mL⁻¹+5000 ng mL⁻¹). Medium without Mel or Cort served as control. Thus, for one sampling day, each treatment was applied to 4 spleen and 4 head kidney tissues. The Mel and Cort doses were selected to according to existing literature, considering 2 physiological and 1 pharmacological dose with a 10-fold factor between them. The lowest concentrations of Mel (10 and 100 pg mL⁻¹) correspond to diurnal and nocturnal levels of plasma melatonin for pike-perch maintained under steady conditions (Baekelandt et al., 2019b). The lowest concentrations of Cort (50 and 500 ng mL⁻¹) consider plasma cortisol levels under normal conditions and in response to acute stress (Baekelandt et al., 2019b). After 5 and 10 h of incubation, culture media were stored at -80°C and replaced with fresh media. After 15h, culture media and organs were frozen in liquid nitrogen and transferred to -80°C until further analysis.

2.3. Gene expression analysis

Total RNA isolation was performed using Extract-all® reagent (Eurobio, Paris, France) following the manufacturer's instructions. Tissues were homogenized using a Bullet Blender Storm 24 (NextAdvance, New York, USA) in tubes containing 0.5 mm zirconium oxide beads (Dutscher, Brumath, France). Total RNA was resuspended in 100 µl of RNase-free water. Each RNA sample was subjected to DNase treatment (DNase Ambion, Life Technologies) and reverse-transcription (RevertAid™ H Minus First Strand cDNA Synthesis Kit, Thermo Scientific) following the manufacturer's instructions. cDNA was then diluted 25 times for RT-qPCR analysis and kept at -80°C.

The relative expression of targeted genes was investigated by RT-qPCR using specific primers (Table 1, sequences published in Swirplies et al., 2019 and Baekelandt et al., 2019b). Primer efficiencies were validated when ranging between 95 and 106 %. qPCR was performed using SYBR® Green Supermix (Biorad, California, USA). A four-step experimental run protocol was followed: denaturation (10 min at 95 °C), amplification (40 cycles, 10 s at 95 °C, 30 s at 60 °C), melting curve (60 to 95 °C, heating rate 0.075°C s⁻¹) and a final cooling step (4°C) using a QuandStudio™ 5 real-time PCR machine (Applied Biosystems).

Relative fold gene expression was calculated following the 2^{-ΔΔCt} method (Livak and Schmittgen, 2001). Ct values were normalized with the geometric mean for *rna-18s*, *β-actin* and *efl-α* whose expressions were stable under tested conditions. Values are expressed as fold change, with the control equaling 1. Among the 10 immune genes targeted, 5 were detected in both organs while the other 5 five were only detected in the head kidney (Table 1).

2.4. Lactate dehydrogenase activity

In order to evaluate the presence of damage and toxicity of tissues, lactate dehydrogenase (LDH) activity was quantified using LDH Assay Kit (ab102526, Abcam, UK). Activity was assayed according to the manufacturer's instructions. The analysis was performed twice in media collected after 15 h of incubation.

2.5. Levels of hormones in culture medium

After 0, 5, 10 and 15 h of incubation, Mel and Cort concentrations were measured in the culture medium using a Melatonin ELISA Kit (E-EL-M0788; Elabscience Biotechnology CO.) and a Cortisol ELISA kit (DRG, EIA-1887, DRG International, USA).

2.6. Statistical analysis

Data are expressed as the mean \pm standard error of the mean (SEM). Kolmogorov and Smirnov's test was used to assess the normality of data sets ($p < .05$) and Bartlett's test was conducted to evaluate variance homogeneity ($p < .05$). Logarithmic transformations were made to achieve normality and homoscedasticity when necessary. No significant differences were detected between tanks (the fish were captured in 4 different tanks of the same RAS) or between sampling days (the experiment was conducted on two different dates). Results were then analyzed with a one-way ANOVA considering treatment as a fixed factor. When significant ($p < .05$), a Tukey's HSD post-hoc test was applied ($p < .05$). When the data, even after log-transformation, did not meet the assumptions for the parametric tests, a Kruskal-Wallis test for nonparametric analysis was applied, followed by a pairwise comparison using Dunn tests. The statistical tests and graphs were performed using JMP 12.1 Software (SAS Institute Inc., North Carolina, USA) and GraphPad Prism V5.04 (California, USA), respectively.

In addition, a redundancy analysis (RDA) and a hierarchical ascending classification (HAC), considering the Ward's distance, were performed with R software (package ade4) in order to characterize the samples' distribution regarding gene expression and treatment for both, kidney and spleen tissues. RDA and clustering analysis such as HAC have proven their value in omics' research (D'Haeseleer, 2005; Csala et al, 2017; Gold-Bouchot et al, 2017). The Ward's distance criteria achieved through the clustering enable to minimize the variance within each group formed by the clustering analysis (Shimodaira, 2002).

Table 1: Sequences of primers used for gene expression quantification in spleen and head kidney (HK), published in Swirplies et al. (2019) and Baekelandt et al. (2019b).

Gene	Sense primer (5' to 3')	Antisense primer (5' to 3')	Efficiency (%)
Reference genes			
<i>β-actin</i>	CGACATCCGTAAGGACCTGT	GCTGGAAGGTGGACAGAGAG	100
<i>efl-α</i>	TGATGACACCAACAGCCACT	AAGATTGACCGTCGTTCTGG	101
<i>rna-18s</i>	GCGGTAATTCCAGCTCCAATAG	GCGGGACACTCAGTTAAGAGC	98
Target genes			
- in spleen & HK			
<i>cxcl8</i>	AACAGGGATGAGTCTGAGAAGC	GCTTGGAATGAAGTCTTACATGA	100
<i>fgl2</i>	ACTTTGAGGGTGTTCGGGAGTA	ACATATCGTTGTGCGGGTCGG	105
<i>fth1</i>	ATTGAGACACACTACCTGGATGA	ACGGATTAGCTGCTTTCTTTGC	106

<i>fkbp4</i>	ACTGTAGGTGGAAGTGTGTTGAAT	AAAAAGCTGTGTCTGGATGTGTTA	105
<i>il-1β</i>	TTTCCCATCATCCACTGACA	ATTCACACACGCACACCATT	102
- in HK			
<i>hepc</i>	CCGTCGTGCTCACCTTTATT	GCCACGTTTGTGTCTGTTGT	97
<i>hp</i>	GCTGAAACTGGGGACATTTACG	GAGCGCAGAGCAGACGATTTTC	104
<i>saal</i>	CTGAAGGAGCTGGTGATATGTG	CTACTCTTTGCTTTTCACCTGATA	105
<i>tcrγ</i>	GTAATGTCTCTGTTGTGCCATATT	TCTCAGAGCAAATGCCATGGTC	99
<i>tnf-α</i>	CTGATTTCGCCTCAACGTGTA	GGAGATGGGTCATGAGGAGA	99

168 3. RESULTS

169 Levels of hormones in culture medium

170 Every 5 h of incubation (before collection and renewal with fresh media), Mel and Cort
 171 concentrations were assessed in the culture media (Table 2), as well as in the stock solutions.
 172 No significant differences were detected between organs of the same treatment or between post-
 173 exposition time points.

174
 175 Table 2: Melatonin (Mel, pg mL⁻¹) and cortisol (Cort, ng mL⁻¹) concentrations in culture media of stock solutions
 176 and in culture media after 5, 10 and 15 h of *ex vivo* exposition of spleen and head kidney (HK) from pike-perch.

	Stock solution	5 h	10 h	15 h
Mel10				
Spleen	12 ± 3	9 ± 2	8 ± 3	9 ± 1
HK		11 ± 2	7 ± 3	8 ± 2
Mel100				
Spleen	108 ± 8	92 ± 12	87 ± 7	91 ± 15
HK		102 ± 9	92 ± 13	89 ± 22
Mel1000				
Spleen	981 ± 27	934 ± 33	961 ± 42	943 ± 52
HK		969 ± 46	932 ± 75	961 ± 41
Cort50				
Spleen	68 ± 13	52 ± 24	61 ± 20	46 ± 17
HK		56 ± 17	48 ± 8	43 ± 16
Cort500				
Spleen	541 ± 62	480 ± 75	502 ± 39	482 ± 74
HK		512 ± 42	458 ± 21	462 ± 46
Cort5000				
Spleen	4780 ± 165	4530 ± 256	4620 ± 218	4490 ± 320
HK		4610 ± 184	4580 ± 312	4720 ± 162
Mel10/Cort50				
Spleen	14 ± 3/61 ± 9	11 ± 2/64 ± 11	9 ± 2/48 ± 9	8 ± 3/46 ± 10
HK		11 ± 2/58 ± 8	10 ± 3/47 ± 12	10 ± 2/52 ± 13
Mel100/Cort500				
Spleen	112 ± 10/512 ± 48	94 ± 15/481 ± 59	95 ± 18/473 ± 62	87 ± 8/504 ± 71
HK		92 ± 10/462 ± 68	106 ± 9/493 ± 36	93 ± 16/477 ± 35
Mel1000/Cort5000				
Spleen	1110 ± 59/5120 ± 306	1084 ± 78/4720 ± 256	960 ± 102/4840 ± 184	914 ± 96/4630 ± 317

HK	1060 ± 68/4950 ± 192	944 ± 138/4920 ± 281	983 ± 92/5030 ± 127
----	----------------------	----------------------	---------------------

Lactate dehydrogenase activity

After 15 h of incubation, no differences in lactate dehydrogenase activity were detected between treatments and control condition, for both organs.

Gene expression

The RDA and clustering analysis of kidney tissues revealed four distinct groups (**Fig. 1**) according to the following treatments: (A) Mel100; (B) Mel10 and Mel+Cort (10+50); (C) Cort500; (D) Control, Mel1000, Cort50, Cort5000, Mel+Cort (100+500) and Mel+Cort (1000+5000). The group “A” is mainly characterized by differentially expressed genes, including *tnf-α*, *saal* and *fkbp4*. The “B” group is defined by *fth1*, *hepc* and *fkbp4*, and the “C” group by *hp* and *tnf-α*. Concerning spleen tissue (**Fig. 2**), 3 groups can be distinguished: (A) Mel10 and Cort50; (B) Mel+Cort (10+50; 100+500; 1000+5000); (C) Control, Cort500, Cort5000, Mel100 and Mel1000. The dispersion, mainly defined on axis 1, is explained by *fgl2*, and to a lesser extent by *il-1β*, *fth1* and *fkbp4* genes.

In the head kidney tissue, gene expression of *il-1β* and *fgl2* increased with the lowest Cort concentration. A similar observation was made for *tnf-α*, *il-1β* and *hp* with Cort at 500 ng mL⁻¹ (**Fig. 3**). Mel treatments also significantly increased some gene expressions in comparison to the control, including *fgl2*, *il-1β* and *fth1* at 10 pg mL⁻¹, *tnf-α*, *saal* and *il-1β* at 100 pg mL⁻¹ and *il-1β* at 1000 pg mL⁻¹. Finally, the mix Cort+Mel significantly increased *fth1* and *il-1β* at the lowest concentration, as well as *fgl2* at pharmacological doses. On the contrary, the latter concentration reduced *fth1* expression.

Concerning the spleen tissue (**Fig. 4**), several gene expressions increased significantly, including *fth1*, *il-1β*, *fgl2* and *fkbp4* when exposed to Mel or Cort at the lowest concentration (10 pg mL⁻¹ and 50 ng mL⁻¹, respectively). With the exception of *il-1β*, whose expression decreased with Cort (5000 ng mL⁻¹), higher concentrations of Mel or Cort had no significant effects compared to the control. Similarly, the mix Mel+Cort, whatever the concentration, did not influence immune gene expressions in spleen. However, a significant difference was detected for *il-1β* between the lowest and the highest concentrations.

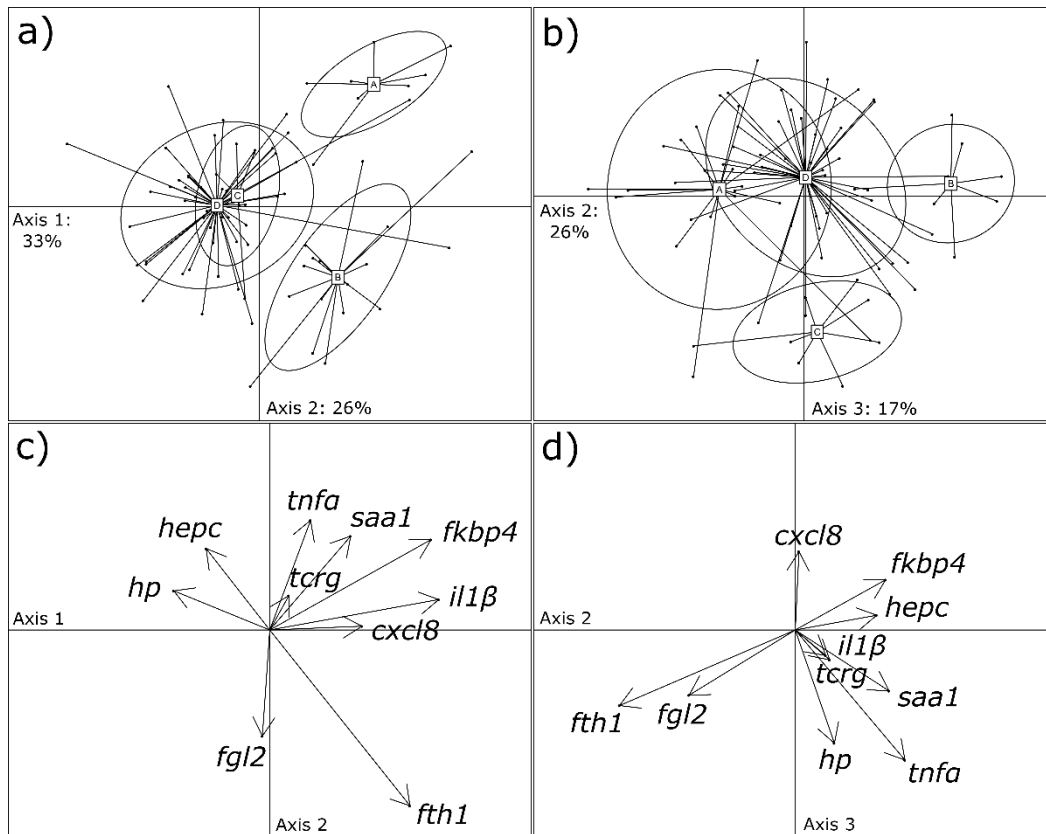


Fig. 1: Projection and clustering, on axes (a) 1 and 2 or (b) 2 and 3 of the redundancy analysis, of 80 head kidney tissues according to their gene expression profiles after *ex vivo* hormonal treatments. Projection of gene expression outputs on axes (c) 1 and 2 or (d) 2 and 3 of the redundancy analysis. The cumulative projected inertia of axes 1, 2 and 3 reaches 76%. Clustering revealed four groups: [A] Mel100; [B] Mel10 and Mel+Cort (10+50); [C] Cort500; [D] Control, Mel1000, Cort50, Cort5000, Mel+Cort (100+500) and Mel+Cort (1000+5000). For each experimental condition, n=8.

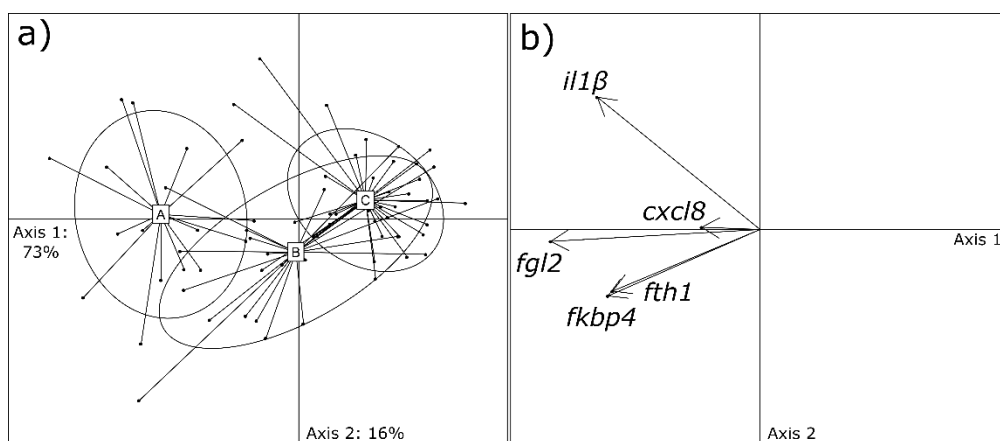


Fig. 2: Projection and clustering (a), on axes 1 and 2 of the redundancy analysis, of 80 spleen tissues according to their gene expression profiles after *ex vivo* hormonal treatments. Projection (b) of gene expression outputs on axes 1 and 2 of the redundancy analysis. The cumulative projected inertia of axes

1 and 2 is 89%. Clustering revealed three groups: [A] Mel10 and Cort50; [B] Mel+Cort (10+50; 100+500; 1000+5000); [C] Control, Cort500, Cort5000, Mel100 and Mel1000. For each experimental condition, n=8.

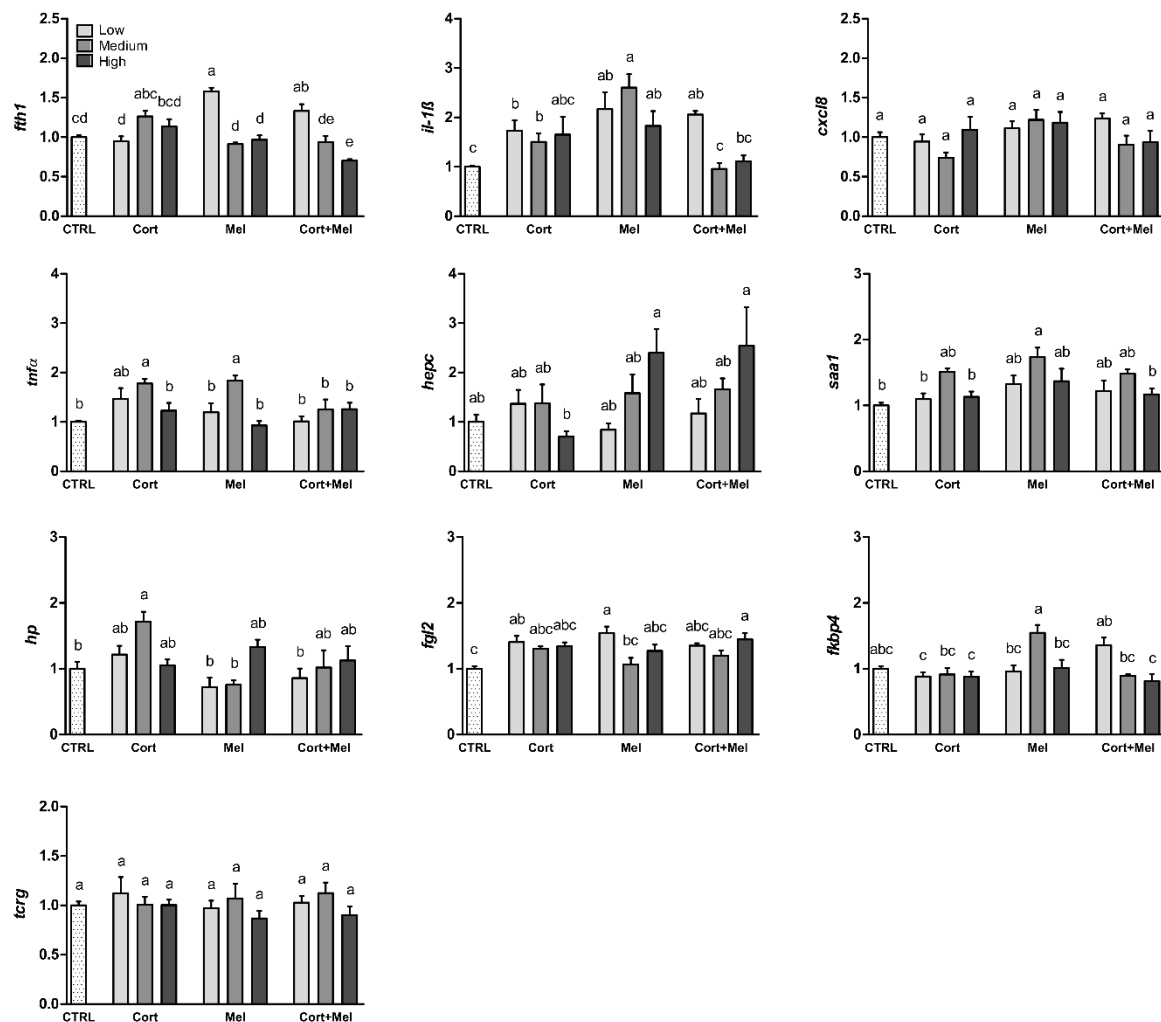


Fig. 3: Relative expression of immune-relevant genes in head kidney tissue of pike-perch exposed *ex vivo* to melatonin and cortisol. Treatments, tested in 3 concentrations (Low, Medium and High), included (1) Mel (10, 100 or 1000 $\mu\text{g mL}^{-1}$), (2) Cort (50, 500 or 5000 ng mL^{-1}) and (3) Mel+Cort (10+50, 100+500 or 1000 $\mu\text{g mL}^{-1}$ +5000 ng mL^{-1}). Medium without Mel or Cort was used as a control. Data are expressed as means \pm SEM (n = 8). Lower case letters indicate significant differences at $p < .05$.

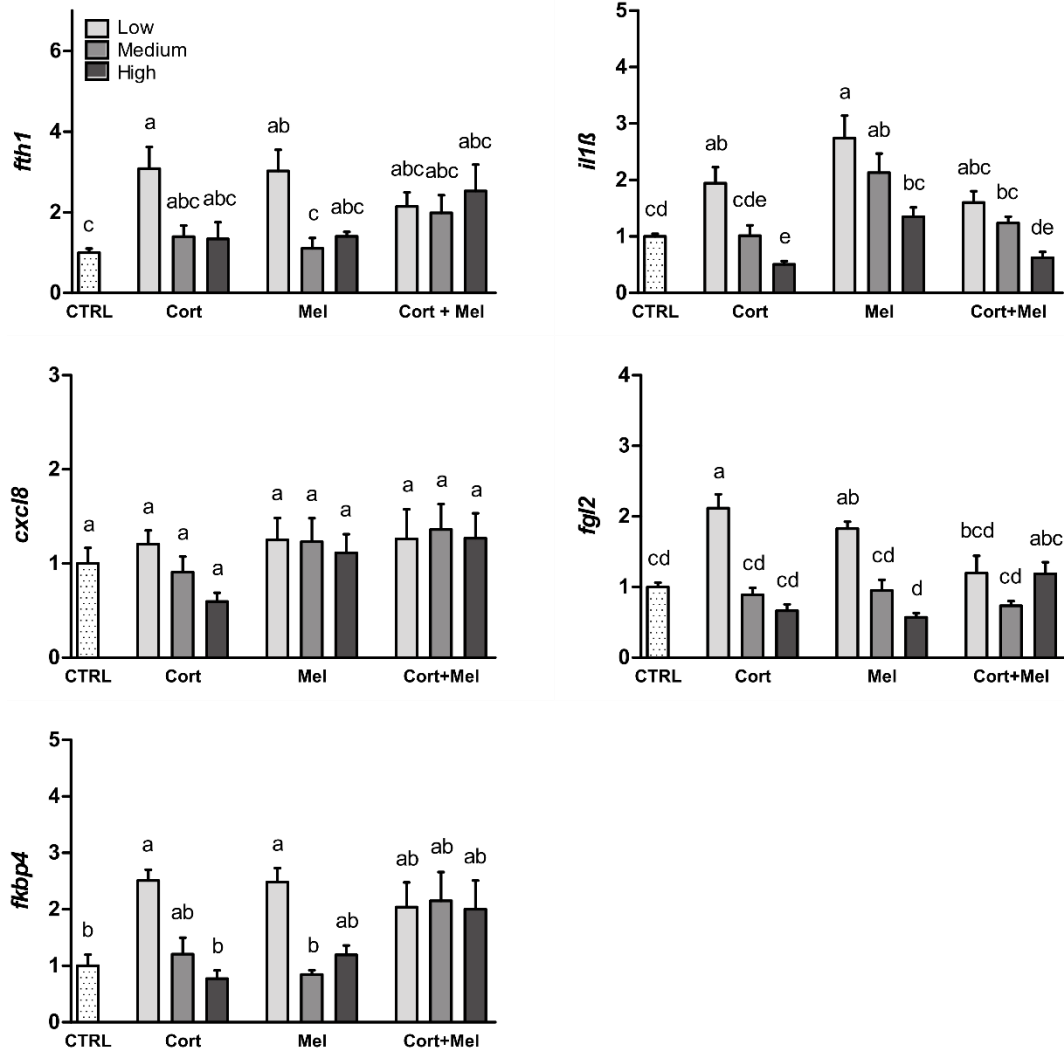


Fig. 4: Relative expression of immune-relevant genes in spleen tissue of pike-perch exposed *ex vivo* to melatonin and cortisol. Treatments, tested in 3 concentrations (Low, Medium and High), included (1) Mel (10, 100 or 1000 pg mL^{-1}) (2) Cort (50, 500 or 5000 ng mL^{-1}) (3) Mel+Cort (10+50, 100+500 or 1000 pg mL^{-1} +5000 ng mL^{-1}). Medium without Mel or Cort was used as a control. Data are expressed as means \pm SEM ($n = 8$). Lower case letters indicate significant differences at $p < .05$.

4. DISCUSSION

The actions of melatonin, with or without combination of cortisol, on immunity were investigated by analyzing immune-related gene expressions in the main fish lymphoid organs, the head kidney and the spleen. Both organs were exposed *ex vivo* to several concentrations of Mel and/or Cort. The present protocol ensured constant concentrations of both hormones in culture media throughout the experiment. Furthermore, the LDH activity revealed no damage or toxicity of tissues following 15 h of hormonal treatments.

Globally, the most positively influenced gene expressions following Mel treatments included two pro-inflammatory genes, namely *tnf- α* and *il-1 β* , three acute-phase protein (APP) genes, *saal*, *fgl2* and *fh1*, as well as *fkbp4*, a gene involved in the regulation of immune gene expression in B and T lymphocytes. Mel has been characterized as an immunostimulant molecule under basal or immunosuppressive conditions, as demonstrated by enhanced immune functions following its injection or ingestion in various vertebrates, such as fish (Cuesta et al., 2008; Ren et al., 2015), birds (Brennan et al., 2002; Singh et al., 2010) and mammals (Liu et al., 2001; Peña et al., 2007; Ahmad and Halder, 2010). However, in the case of inflammatory responses, Mel exerts anti-inflammatory properties to protect the organism from host tissue damage (Carrillo-Vico et al., 2013; Tarocco et al., 2019). This anti-inflammatory function has mainly been described in mammals (Lin et al., 2011; Xia et al., 2012) but only once in teleost. In common carp (*Cyprinus carpio*), its administration during zymosan-induced peritonitis reduced leukocyte migration to the peritoneum and induced a decrease of the respiratory burst activity in peritoneal leukocytes (Kepka et al., 2015).

Considering pro-inflammatory and APP genes, the present results support the immunoenhancing properties of the molecule under basal conditions (unstimulated immunity). In pike-perch, it has been hypothesized that Mel would act on inflammatory cytokines since *in vivo*, the daily cyclic release of Mel by the pineal gland were correlated with the day-night variations of *tnf- α* and *il-1 β* gene expressions in the head kidney (Baekelandt et al., 2019). Moreover, exogenous Mel has been described to increase *il-1 β* expression in the head kidney of gilthead seabream (*Sparus aurata*) (Cuesta et al., 2008).

The acute-phase response is a series of non-specific and complex reactions occurring soon after the onset of stress, injury, trauma, infection and inflammation, which aim to eliminate the infectious agents and to restore homeostasis (Tothova et al., 2014; Yu et al., 2017). So far, the only data showing an impact of Mel on APPs concern mammals. In castrated dogs, exogenous

Mel significantly reduced APPs and inflammatory cytokines, including SAA, CRP, IL-1 β and TNF- α (Nazifi et al., 2020). In bovine mammary epithelial cells, Mel decreased LPS-induced expression of pro-inflammatory cytokines (TNF- α , IL-1 β , IL-6), chemokines (chemokine CC motif ligand (CCL)2, CCL5) and positive APPs (SAA, haptoglobin, C-reactive protein, ceruloplasmin, α -1 antitrypsin) (Yu et al., 2017). While these studies defined a negative regulation of acute-phase response during inflammatory processes, our results are consistent with immunoenhancing properties of Mel under basal conditions.

In mammals, Mel influences the acquired immune response. T lymphocytes were shown to be modulated by melatonin, from its development in thymus to its differentiation and even memory (Garcia-Mauriño et al. 1999; Guerrero and Reiter, 2002; Glebezdina et al., 2019; Luo et al., 2020). Several studies concluded that melatonin also plays a critical role in regulating the activation of B cells (Yu et al., 2000; Cernysiov et al., 2009; Luo et al., 2020). The only study considering potential Mel actions on T and B cells in teleosts revealed no effect on specific markers at the transcript level (TCR α - T cell receptor alpha chain - and IgM, respectively), suggesting a lack of effects on lymphocyte activation or proliferation (Cuesta et al., 2008). However, the modulation of *fkbp4* following Mel treatment in this study may suggest an action on fish specific immunity, as observed in other vertebrates like birds and mammals (Kharwar et al., 2015; Li et al., 2015; Chen et al., 2016). Nevertheless, further investigations considering the acquired immunity are needed.

No information was available about the potential direct and/or indirect actions of Mel on these immune markers. In both organs, Mel activated a set of immune-related genes supporting the hypothesis that Mel may act through specific receptors that are located on fish immune cells. In vertebrates, several G protein-coupled membrane receptors with high affinity for Mel have been identified, namely MT1 and MT2 (Dubocovich and Markowska., 2005). In addition, a third melatonin receptor, Mel1c, was found exclusively in fish (*Xenopus* sp.) and birds (Dufourny et al., 2008). The Mel receptors in mammals are expressed by numerous tissues such as immune cells and tissues. In the human immune system, they are distributed in B and T lymphocytes, monocytes, NK cells and mast cells (Carrillo-Vico et al., 2003; Pozo et al., 2004; Lardone et al., 2009; Maldonado et al., 2010). They have further been detected in spleen, thymus and lymphocytes of various vertebrates (rats, mice and birds, see Pozo et al., 1997; Carrillo-Vico et al., 2003; Sanchez-Hidalgo et al., 2008; Wronka et al., 2008; Singh et al., 2016). Concerning fish, Park et al. (2006) and Confente et al. (2010) described MT2 and MT1

in spleen of rabbitfish and Senegalese sole, respectively. However, their function in spleen remains unclear and further characterization of Mel receptors in fish immune tissues are needed.

While the pineal gland is the main source of Mel, several extrapineal sources of this indoleamine have been identified in several vertebrates like the retina, skin and gastrointestinal tract (Wiechmann et al., 2013; Acuña-Castroviejo et al., 2014). Mel production has also been detected in immune cells and tissues, including human lymphocytes, macrophages and Jurkat cells (Carrillo-Vico et al., 2004; Lardone et al., 2006; Markus et al., 2017), murine thymus, spleen, bone marrow cells and RAW264.7 macrophages (Gómez-Corvera et al., 2009; Muxel et al., 2012) and rat mast cells and macrophages (Martins et al., 2004; Maldonado et al., 2010). Considering that Mel receptors are found in immune cells and tissues, this immune-synthesized Mel seems to play paracrine, autocrine and intracrine functions. In teleosts, the production of Mel by immune cells and tissues has not yet been investigated, but following the results of our gene expression experiment, its potential production and subsequent effects on immunity cannot be excluded.

Cortisol is considered as the main hormone of stress responses. It is produced by interrenal cells located in the head kidney of teleosts (Tort et al., 2011). The functions of cortisol during stress reactions are numerous and include physiological, endocrine and immunological responses (Tort et al., 2011; Cortés et al., 2013; Mathieu et al., 2014). Many studies have focused on the regulation of immune defense through corticosteroids and both, activation and inhibition of immune mediators have been described, depending on the stress event. While acute stress is usually associated to immune activation, chronic stress is characterized by long-term exposure to cortisol with subsequent immune depression or suppression (for further information see Tort et al., 2011; Nardocci et al., 2014). In the present experiment, Cort influenced several immune gene expressions in both, spleen and head kidney, depending on concentration. On the one hand, in spleen, the lowest physiological Cort concentration led to an increase of pro-inflammatory gene *il-1 β* , acute-phase genes *fgl2* and *fth1* as well as *fkbp4*. On the other hand, *il-1 β* expression decreased with the pharmacological dose of Cort. Such action on pro-inflammatory cytokine *il-1 β* has already been described *in vivo* in rainbow trout (*Oncorhynchus mykiss*) following Cort application (Cortés et al., 2013). This effect may be explained by an inhibition of NF- κ B signaling, leading to a decrease in the production of pro-inflammatory cytokines such as IL-1 (Sternberg, 2006). In the head kidney tissue, only the high physiological dose of Cort (500 ng mL⁻¹) led to a different expression profile, with increases in acute-phase and pro-inflammatory genes, i.e. *fth1*, *il-1 β* , *tnf- α* and *hp*. While in spleen a stimulatory effect

was mainly observed at 50 ng mL⁻¹, which was lost at higher concentrations, in head kidney tissues, stimulation was only observed at a concentration of 500 ng mL⁻¹. These different sensitivities may be explained by different expressions or activities of glucocorticoids receptors (GR). Both GR and mineralocorticoids receptors (MR) are capable of binding cortisol and, in fish, four cortisol receptors (GR1a, GR1b, GR2 and MR) have been described whose activations are concentration-dependent (Stolte et al., 2008; Nardocci et al., 2013). In addition, the dual endocrine and hematopoietic functions of the head kidney tissue must be considered and potential production and release of cortisol by the organ may have influenced the results.

In conclusion, both hormones at physiological concentrations significantly influenced the immune-related genes in the present *ex vivo* experiment. In both organs, Mel treatment led to an increase in immune-related genes, including genes involved in the inflammatory process, acute-phase response and acquired immune response. These results confirm the immunoenhancing properties of Mel under basal immune conditions in teleost. We further demonstrated a direct action of Mel on immune organs. An indirect action of possibly even greater importance, needs to be addressed in studies on melatonin-immunity interactions. In addition, future investigations should consider the actions of the potential immune-derived melatonin on the immunity of teleosts.

5. ACKNOWLEDGMENT

This work was supported by the FRIA (Fonds de la Recherche dans l'Industrie et l'Agriculture, Wallonia-Brussels Federation), providing a grant to S.B.

358 6. REFERENCES

- 359 Abarike ED, Cai J, Lu Y, Yu H, Chen L, Jian J, Tang J, Jun L, Kuebutornye FKA (2018).
 360 Effects of a commercial probiotic BS containing *Bacillus subtilis* and *Bacillus*
 361 *licheniformis* on growth, immune response and disease resistance in Nile tilapia,
 362 *Oreochromis niloticus*. *Fish Shellfish Immunol.*, 82, 229–238.
- 363 Acuna-Castroviejo D, Escames G, Venegas C, Diaz-Casado M, Lima-Cabello E, Lopez LC,
 364 Rosales-Corral S, Tan DX, Reiter RJ (2014). Extrapineal melatonin: sources, regulation,
 365 and potential functions. *Cell. Mol. Life Sci.*, 71, 2997–3025.
- 366 Ahmad Z, Haldar C (2010). Melatonin and androgen receptor expression interplay modulates
 367 cell-mediated immunity in tropical rodent *Funambulus pennanti*: an in-vivo and in-vitro
 368 study. *Scand. J. Immunol.*, 71(6), 420–430.
- 369 Baekelandt S, Mandiki SNM, Schmitz M, Kestemont P (2019). Influence of the light spectrum
 370 on the daily rhythms of stress and humoral innate immune markers in pikeperch *Sander*
 371 *luciperca*. *Aquaculture*, 499, 358–363.
- 372 Baekelandt S, Mandiki SNM, Kestemont P (2019b). Are cortisol and melatonin involved in the
 373 immune modulation by the light environment in pike-perch *Sander luciperca*? *J. Pineal*
 374 *Res.*, 67(e12573).
- 375 Baekelandt S, Milla S, Cornet V, Flamion E, Ledoré Y, Redivo B, Antipine S, Mandiki SNM,
 376 Houndji A, El Kertaoui N, Kestemont P (2020). Seasonal simulated photoperiods influence
 377 melatonin release and immune markers of pike-perch *Sander luciperca*. *Scientific*
 378 *Reports*, 10(2650).
- 379 Brennan CP, Hendricks GL, El-Sheikh TM, Mashaly MM (2002). Melatonin and the
 380 enhancement of immune responses in immature male chickens. *Poult. Sci.*, 81(3), 371–
 381 375.
- 382 Carrillo-Vico A, García-Pergañeda A, Naji L, Calvo JR, Romero MP, Guerrero JM (2003).
 383 Expression of membrane and nuclear melatonin receptor mRNA and protein in the mouse
 384 immune system. *Cell. Mol. Life Sci.*, 60, 2272–2278.
- 385 Carrillo-Vico A, Calvo JR, Abreu P, Lardone PJ, Garcia-Maurino S, Reiter RJ, Guerrero JM
 386 (2004). Evidence of melatonin synthesis by human lymphocytes and its physiological
 387 significance: possible role as intracrine, autocrine, and/or paracrine substance. *FASEB J.*,
 388 1, 537–539.
- 389 Carrillo-Vico A, Guerrero JM, Lardone PJ, Reiter RJ (2005). A Review of the Multiple Actions
 390 of Melatonin on the Immune System. *Endocrine*, 27(2), 189–200.
- 391 Carrillo-Vico A, Lardone PJ, Álvarez-Sánchez N, Rodríguez-Rodríguez A, Guerrero JM
 392 (2013). Melatonin: Buffering the immune system. *Int. J.Mol. Sci.*, 14(4), 8638–8683.
- 393 Cernysiov V, Gerasimcik N, Mauricas M, Girkontaite I (2009). Regulation of T-cell-
 394 independent and T-cell-dependent antibody production by circadian rhythm and melatonin.
 395 *Int. Immunol.*, 22(1), 25–34.

396 Chaves-Pozo E, Garcia-Ayala A, Cabas I (2018). Effects of sex steroids on fish leukocytes.
397 *Biology (Basel)*, 7(1): 9.

398 Chen F, Reheman A, Cao J, Wang Z, Dong Y, Zhang Y, Chen Y (2016). Effect of melatonin
399 on monochromatic light-induced T-lymphocyte proliferation in the thymus of chickens. *J.*
400 *Photochem. Photobiol. B*, 161, 9–16.

401 Conde-Sieira M, Muñoz JL, López-Patiño MA, Gesto M, Soengas JL, Míguez JM (2014). Oral
402 administration of melatonin counteracts several of the effects of chronic stress in rainbow
403 trout. *Domest. Anim. Endocrinol.*, 46:26-36.

404 Confente F, Carmen M, Besseau L, Falcón J, Muñoz-Cueto JA (2010). Melatonin receptors in
405 a pleuronectiform species, *Solea senegalensis*: cloning, tissue expression, day–night and
406 seasonal variations. *Gen. Comp. Endocrinol.*, 167(2):202-214.

407 Cortés R, Teles M, Trídico R, Acerete L, Tort L (2013). Effects of cortisol administered through
408 slow-release implants on innate immune responses in rainbow trout (*Oncorhynchus*
409 *mykiss*). *Int. J. Genomics.*, ID 619714.

410 Csala A, Voorbraak FPJM, Zwinderman AH, Hof MH (2017). Gene expression Sparse
411 redundancy analysis of high-dimensional genetic and genomic data. *Bioinformatics*,
412 33(20):3228–3234.

413 Cuesta A, Laiz-Carrión R, Arjona F, Del Rio MP, Meseguer J, Mancera JM, Esteban MA
414 (2006). Effect of PRL, GH and cortisol on the serum complement and IgM levels in
415 gilthead seabream (*Sparus aurata* L.). *Fish Shelfish Immunol.*, 20(3):427-432.

416 Cuesta A, Cerezuela R, Esteban MA, Meseguer J (2008). In vivo actions of melatonin on the
417 innate immune parameters in the teleost fish gilthead seabream. *J. Pineal Res.*, 45(1):70-
418 78.

419 Dalsgaard J, Lund I, Thorarinsdottir R, Drengstig A, Arvonen K, Pedersen PB (2013). Farming
420 different species in RAS in Nordic countries: current status and future perspectives. *Aquac.*
421 *Eng.* 53:2-13.

422 D’haeseleer P (2005). How does gene expression clustering work? *Nat. Biotechnol.*,
423 23(12):1499–1501.

424 Downing G (2002). Impact of spectral composition on larval haddock, *Melanogrammus*
425 *aeglefinus* L., growth and survival. *Aquac. Res.*, 33(4):251-259.

426 Dubocovich ML, Markowska M (2005). Functional MT1 and MT2 melatonin receptors in
427 mammals. *Endocrine*, 27(2), 101–110.

428 Dumbell R, Matveeva O, Oster H (2016). Circadian clocks, stress, and immunity. *Front.*
429 *Endocrinol.*, 7, 37.

430 Esteban MA, Rodriguez A, Ayala AG, Meseguer J (2004). Effects of high doses of cortisol on
431 innate cellular immune response of seabream (*Sparus aurata* L.). *Gen. Comp. Endocrinol.*,
432 137(1):89-98.

433 Esteban MA, Cuesta A, Rodríguez A, Meseguer J (2006). Effect of photo- period on the fish
434 innate immune system: a link between fish pineal gland and the immune system. *J. Pineal*
435 *Res.*, 41(3):261-266.

436 Esteban MÁ, Cuesta A, Chaves-pozo E, Meseguer J (2013). Influence of melatonin on the
437 immune system of fish: a review. *Int. J. Mol. Sci.*, 14(4):7979-7999.

438 Falcón J, Besseau L, Sauzet S, Boeuf G (2007). Melatonin effects on the hypothalamo-pituitary
439 axis in fish. *Trends Endocrinol. Metab.*, 18(2):81–88.

440 Falcón J, Migaud H, Munoz-Cueto JA, Carrillo M (2010). Current knowledge on the melatonin
441 system in teleost fish. *Gen. Comp. Endocrinol.*, 165(3):469-482.

442 Garcia-Mauriño S, Pozo D, Carrillo-Vito A, Calvo JR, Guerrero JM (1999). Melatonin activates
443 Th1 lymphocytes by increasing IL-12 production. *Life Sci.*, 65(20), 2143–2150.

444 Glebezdina NS, Olina AA, Nekrasova IV, Kuklina EM (2019). Molecular mechanisms of
445 control of differentiation of regulatory T-lymphocytes by exogenous melatonin. *Dokl.*
446 *Biochem. Biophys.*, 484(2), 13–16.

447 Gold-bouchot G, Rubio-Piña J, Montero-Muñoz J, Ramirez-Miss N, Echeverría-García A,
448 Patiño-Suarez V, Puch-Hau CA, Zapata-Pérez O (2017). Pollutants and biomarker
449 responses in two reef fish species (*Haemulon aurolineatum* and *Ocyurus chrysurus*) in the
450 Southern Gulf of Mexico. *Mar. Pollut. Bull.*, 116(1-2):249-257.

451 Gomez-Corvera A, Cerrillo I, Molinero P, Naranjo MC, Lardone PJ, Sanchez-Hidalgo M,
452 Carrascosa-Salmoral MP, Medrano-Campillo P, Guerrero JM, Rubio A (2009). Evidence
453 of immune system melatonin production by two pineal melatonin deficient mice, C57BL/6
454 and Swiss strains. *J. Pineal Res.*, 47(1):15–22.

455 Guerrero JM, Reiter RJ (2002). Melatonin-immune system relationships. *Curr. Top. Med.*
456 *Chem.*, 2(2):167–179.

457 Harris J, Bird DJ (2000). Modulation of the fish immune system by hormones. *Vet. Immunol.*
458 *Immunopathol.*, 77(3-4):163-176.

459 Jentoft S, Aastveit AH, Torjesen PA, Andersen Ø (2005). Effects of stress on growth, cortisol
460 and glucose levels in non-domesticated Eurasian perch (*Perca fluviatilis*) and domesticated
461 rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol. A Mol Integr. Physiol.*,
462 141(3):353–358.

463 Kepka M, Szejser E, Pijanowski L, Kemenade VBM, Chadzinska M (2015). A role for
464 melatonin in maintaining the pro- and anti-inflammatory balance by influencing leukocyte
465 migration and apoptosis in carp. *Develop. Comp. Immunol.*, 53(1):179–190.

466 Kharwar RK, Haldar C, Singh S (2015). Mel1b receptor mediated action of melatonin in
467 regulation of lung associated immune system (LAIS) of *Perdicula asiatica*: An *in vitro*
468 study. *Biologia*, 70(11), 1537–1544.

469 Kulczykowska E, Kalamarz H, Warne JM, Balment RJ (2006). Day-night specific binding of
470 2-[125I]iodomelatonin and melatonin content in gill, small intestine and kidney of three
471 fish species. *J Comp Physiol B.*, 176(4):277-285.

472 Lardone PJ, Carrillo-Vico A, Naranjo MC, de Felipe B, Vallejo A, Karasek M, Guerrero JM
473 (2006). Melatonin synthesized by Jurkat human leukemic T cell line is implicated in IL-2
474 production. *J. Cell Physiol.*, 206(1):273–279.

475 Lardone PJ, Carrillo-Vico A, Molinero P, Rubio A, Guerrero JM (2009). A novel interplay
476 between membrane and nuclear melatonin receptors in human lymphocytes: significance
477 in IL-2 production. *Cell Mol. Life Sci.*, 66(3):516–525.

478 Li J, Cao J, Wang Z, Dong Y, Chen Y (2015). Melatonin plays a critical role in inducing B
479 lymphocyte proliferation of the bursa of Fabricius in broilers via monochromatic lights. *J.*
480 *Photochem. Photobiol. B*, 142, 29–34.

481 Lin XJ, Mei GP, Liu J, Li YL, Zuo D, Liu SJ, Zhao TB, Lin MT (2011). Therapeutic effects of
482 melatonin on heatstroke-induced multiple organ dysfunction syndrome in rats. *J. Pineal*
483 *Res.*, 50, 436–444.

484 Livak KJ, Schmittgen TD (2001). Analysis of relative gene expression data using real-time
485 quantitative PCR and the 2(-Delta Delta C(T)) Method. *Methods*, 25(4):402-408.

486 Liu F, Ng TB, Fung MC (2001). Pineal indoles stimulate the gene expression of
487 immunomodulating cytokines. *J. Neural Transm.*, 108, 397–405.

488 López-patiño MA, Conde-Sieira M, Gesto M, Librán-Pérez M, Soengas JL, Míguez JM (2013).
489 Melatonin partially minimizes the adverse stress effects in Senegalese sole (*Solea*
490 *senegalensis*). *Aquaculture*, 388–391:165–172.

491 Lopez-Patino MA, Gesto M, Conde-Sieira M, Soengas JL, Miguez JM (2014). Stress inhibition
492 of melatonin synthesis in the pineal organ of rainbow trout (*Oncorhynchus mykiss*) is
493 mediated by cortisol. *J. Exp. Biol.*, 217(8):1407-1416.

494 Luo J, Zhang Z, Sun H, Song J, Chen X, Huang J, Lin X, Zhou R (2020). Effect of melatonin
495 on T/B cell activation and immune regulation in pinealectomy mice. *Life Sci.*, 242(117191).

496 Maldonado MD, Mora-Santos M, Naji L, Carrascosa-Salmoral MP, Naranjo MC, Calvo JR
497 (2010). Evidence of melatonin synthesis and release by mast cells. Possible modulatory
498 role on inflammation. *Pharmacol. Res.*, 62(3):282–287.

499 Markus RP, Fernandes PA, Kinker GS, Cruz-Machado SS, Marçola M (2018). Immune-pineal
500 axis – acute inflammatory responses coordinate melatonin synthesis by pinealocytes and
501 phagocytes. *Br. J. Pharmacol.*, 175(16):3239-3250.

502 Martins E Jr., Ferreira AC, Skorupa AL, Afeche SC, Cipolla-Neto J, Costa Rosa LF (2004).
503 Tryptophan consumption and indoleamines production by peritoneal cavity macrophages.
504 *J. Leukoc. Biol.*, 75(6):1116-1121.

505 Mathieu C, Milla S, Mandiki SNM, Doux fils J, Kestemont P (2014). In vivo response of some
506 immune and endocrine variables to LPS in Eurasian perch (*Perca fluviatilis*, L.) and
507 modulation of this response by two corticosteroids, cortisol and 11-deoxycorticosterone.
508 *Comp. Biochem. Physiol. Part A.*, 167:25–34.

509 Migaud H, Daive A, Martinez Chavez CC, Al-Khamees S (2007). Evidence for differential
510 photic regulation of pineal melatonin synthesis in teleosts. *J. Pineal Res.*, 43(4):327–335.

511 Miller SC, Pandi PSR, Esquifino AI, Cardinali DP, Maestroni GJM (2006). The role of
512 melatonin in immuno-enhancement: potential application in cancer. *Int. J. Exp. Pathol.*,
513 87(2):81–87.

514 Muxel SM, Pires-Lapa MA, Monteiro AWA, Cecon E, Tamura EK, Floeter-Winter LM,
515 Markus RP (2012). NF-kB Drives the synthesis of melatonin in RAW 264.7 macrophages
516 by inducing the transcription of the arylalkilamine-N-acetyltransferase (AA-NAT) gene.
517 *PLoS One*, 7(12):e52010.

518 Nardocci G, Navarro CG, Cortés PP, Imarai M, Montoya M, Valenzuela B, Picas PJ, Acuña C,
519 Fernandez R (2014). Neuroendocrine mechanisms for immune system regulation during
520 stress in fish. *Fish Shellfish Immunol.*, 40(2),531–538.

521 Nazifi S, Mogheiseh A, Tabrizi AS, Rayat MH (2020). Effect of oral melatonin administration
522 on inflammatory cytokines and acute phase proteins after the castration of dogs. *Comp.*
523 *Clin. Path.*, 29:829-836.

524 Oliveira CC, Aparício R, Blanco-Vives B, Chereguini O, Martín I, Sánchez-Vazquez FJ (2013).
525 Endocrine (plasma cortisol and glucose) and behavioral (locomotor and self-feeding
526 activity) circadian rhythms in Senegalese sole (*Solea senegalensis* Kaup 1858) exposed to
527 light/dark cycles or constant light. *Fish Physiol Biochem.*, 39(3):479-487.

528 Overton JL, Toner D, Policar T, Kucharczyk D (2015). Environmental biology of Percid fishes.
529 In: Kestemont P, Dabrowski K, Summerfelt RC, eds. *Biology and Culture of Percid Fishes*.
530 Dordrecht, the Netherlands: Springer Science+Business Media; 881-889.

531 Paredes M, Gonzalez K, Figueroa J, Motiel-Eulefi E (2013) Immunomodulatory effect of
532 prolactin on Atlantic salmon (*Salmo salar*) macrophage function. *Fish Physiol. Biochem.*,
533 39(5):1215–1221.

534 Park YJ, Park JG, Kim SJ, Lee YD, Rahman SM, Takemura A (2006). Melatonin receptor of a
535 reef fish with lunar-related rhythmicity: cloning and daily variations. *J. Pineal Res.*,
536 41(2):166-174.

537 Peña C, Rincon J, Pedreanez A, Viera N, Mosquera J (2007). Chemotactic effect of melatonin
538 on leukocytes. *J. Pineal Res.*, 43, 263–269.

539 Pozo D, Deldago M, Fernandez-Santos JM, Calvo JR, Gomariz RP, Martin-Lacave I, Ortiz GG,
540 Guerrero JM (2018). Expression of the Mella-melatonin receptor mRNA in T and B
541 subsets of lymphocytes from rat thymus and spleen. *FASEB J.*, 11(6):466–473.

542 Pozo D, Garcia-Maurino S, Guerrero JM, Calvo JR (2004). mRNA expression of nuclear
543 receptor RZR/RORalpha, melatonin membrane receptor MT, and hydroxindole-O-
544 methyltransferase in different populations of human immune cells. *J. Pineal Res.*,
545 37(1):48–54.

546 Ren DL, Li YJ, Hu BB, Wang H, Hu B (2015). Melatonin regulates the rhythmic migration of
547 neutrophils in live zebrafish. *J. Pineal Res.*, 58(4):452–460.

Sanchez-Hidalgo M, Guerrero MJM, Carrasco-Salmoral MP, Naranjo GMC, Lardone PJ, de la Lastra Romero CA (2009). Decreased MT1 and MT2 melatonin receptor expression in extrapineal tissues of the rat during physiological aging. *J. Pineal Res.*, 46(1):29–35.

Shimodaira H (2002). An Approximately Unbiased Test of Phylogenetic Tree Selection. *Syst. Biol.*, 51(3), 492–508.

Singh SS, Yadav SK, Halder C (2010). Effect of glucocorticoid and melatonin on immune function of an indian tropical bird, *Perdica asiatica*: an *in vivo* and *in vitro* study. *Eur. J. Inflam.*, 8(2), 89–97.

Singh SS, Deb A, Sutradhar S (2016). Dexamethasone modulates melatonin MT2 receptor expression in splenic tissue and humoral immune response in mice. *Biol. Rhythm Res.*, 48(3):425-435.

Sternberg EM (2006). Neural regulation of innate immunity: a coordinated nonspecific host response to pathogens. *Nat. Rev. Immunol.*, 6(4):318-328.

Stolte EH, de Mazon AF, Leon-Koosterziel KM, Jesiak M, Bury NR, Sturm A, Savelkoul HF, van Kemenade BM, Flik G (2008). Corticosteroid receptors involved in stress regulation in common carp, *Cyprinus carpio*. *J. Endocrinol.*, 198(2):403-417.

Swirplies F, Wuertz S, Baßmann B, Orban A, Schäfer N, Brunner RM, Hadlich F, Goldammer T, Rebl A (2018). Identification of molecular stress indicators in pikeperch *Sander lucioperca* correlating with rising water temperatures. *Aquaculture*, 501:260–271.

Tarocco A, Caroccia N, Morciano G, Wieckowski MR, Ancora G, Garani G, Pinton P (2019). Melatonin as a master regulator of cell death and inflammation: molecular mechanisms and clinical implications for newborn care. *Cell Death Dis.*, 10(4), 317.

Tort L (2011). Stress and immune modulation in fish. *Dev. Comp. Immunol.*, 35(12):1366-1375.

Tothova C, Nagy O, Kovac G (2014). Acute phase proteins and their use in the diagnosis of diseases in ruminants: a review. *Vet. Med.-Czech*, 59:163–180.

Vera LM, De Oliveira C, Lopez-Olmeda JF, Ramos J, Mañanos E, Madrid JA, Sanchez-Vazquez FJ (2007). Seasonal and daily plasma melatonin rhythms and reproduction in Senegalese sole kept under natural photoperiod and natural or controlled water temperature. *J. Pineal Res.*, 43(1):50–55.

Wiechmann AF, Sherry DM (2013). Role of Melatonin and Its Receptors in the Vertebrate Retina. *Int. Rev. Cell. Mol. Biol.*, 300:211-242.

Wronka M, Maleszewska M, Stepinska U, Markowska M (2008). Diurnal differences in melatonin effect on intracellular Ca²⁺ concentration in chicken spleen leukocytes *in vitro*. *J. Pineal Res.*, 44(2):134–140.

Xia MZ, Liang YL, Wang H, Chen X, Huang YY, Zhang ZH, Chen YH, Zhang C, Zhao M, Xu DX, Song LH (2012). Melatonin modulates TLR4-mediated inflammatory genes through MyD88- and TRIF-dependent signaling pathways in. *J. Pineal Res.*, 53(4), 325–334.

- 585 Yada T (2007). Growth hormone and fish immune system. *Gen. Comp. Endocrinol.*, 152:353–
586 358.
- 587 Yu Q, Miller SC, Osmond DG (2000). Melatonin inhibits apoptosis during early B-cell
588 development in mouse bone marrow. *J. Pineal Res.*, 29, 86–93.
- 589 Yu GM, Kubota H, Okita M, Maeda T (2017) The anti-inflammatory and antioxidant effects of
590 melatonin on LPS-stimulated bovine mammary epithelial cells. *PLoS One*,
591 12(5):e0178525.