Central and peripheral interleukin-1β and interleukin-1 receptor I expression and their role in the acute stress response of common carp, *Cyprinus carpio* L.

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Abstract

In fish, the hypothalamus–pituitary–interrenal axis (HPI-axis), the equivalent of the hypothalamus–pituitary–adrenal axis (HPA-axis) in mammals, is activated during stress and leads to production and release of cortisol by the interrenal cells in the head kidney. In mammals, the cytokine interleukin-1β (IL-1β) takes a key position in the innate immune and inflammatory responses and influences the HPA-axis. In fish, studies that address the effects of cytokines on HPI-axis activation are limited. We quantitatively assessed expression of IL-1β and its receptor, IL-1RI (the latter was cloned and sequenced), in an acute restraint stress paradigm in common carp, *Cyprinus carpio*. We also considered expression of the pituitary hormones prolactin (PRL) and GH that have been shown to be structurally related to cytokines and have immunomodulatory actions. Pituitary PRL expression increased fourfold during stress; GH mRNA levels were unaffected. Following restraint, hypothalamic IL-1β expression was upregulated; in head kidney and pituitary pars intermedia, IL-1RII expression significantly increased. We suggest that during acute stress IL-1β signalling in the HPI-axis becomes more sensitive, since both ligand and receptor expressions are enhanced. *In vitro*, recombinant carp IL-1β stimulates release of α-MSH and N-Ac β-endorphin from the pituitary gland. This observation concurs with increased *in vivo* plasma levels of α-MSH and N-Ac β-endorphin following restraint. Our findings combined lead us to conclude that IL-1β affects the activity of the HPI-axis and, in turn, expression profiles of genes encoding IL-1β and its receptor are modified during acute stress. Our study provides convincing evidence for bi-directional communication of the HPI-axis and the immune system in fish.


Introduction

In fish, neuroendocrine factors modulate the activity of the immune system, and conversely, signals from the immune system affect neuroendocrine activity (Harris & Bird 2000, Engelsma et al. 2002, Yada & Nakanishi 2002). These mutual interactions are increasingly investigated, profiting from the application of the ever increasing resolution of molecular biological techniques and publicly available databases of fish genome-sequencing projects (Huising et al. 2003a, 2004a). It is generally accepted that our understanding of mechanisms, which underlie immune–stress relations will improve our insights in health and welfare of fish in production systems, since stress is a potential factor causing increased susceptibility of fish to pathogens.

The hypothalamus–pituitary–interrenal axis (HPA-axis), the piscine equivalent of the hypothalamus–pituitary–adrenal axis (HPA-axis) in mammals, is activated during stress (Wendelaar Bonga 1997) and is considered the most important neuroendocrine modulatory system of the immune system. Corticotrophin-releasing hormone (CRH), released from the nucleus preopticus (NPO) of the hypothalamus (Huising et al. 2004b), stimulates synthesis of pro-opiomelanocortin (POMC) in the pituitary gland (Metz et al. 2004). POMC is the precursor for adrenocorticotropic hormone (ACTH), α-melanocyte-stimulating hormone (α-MSH) and β-endorphin. These peptides are released upon stimulation by CRH (Tran et al. 1990, Van den Burg et al. 2001, Metz et al. 2004) from the pars distalis (PD; ACTH) and pars intermedia (PI; α-MSH and β-endorphin). In the interrenal cells of the head kidney, ACTH stimulates the synthesis and release of cortisol, which in turn secures energy redistribution in the body to overcome the stressor (Wendelaar Bonga 1997, Gallo & Civinini 2003). This is brought about by gluconeogenesis in the liver and withdrawal of energy from physiological systems not directly influenced by the stressor, including the immune system, to the benefit of systems whose activity needs to be intensified. In particular, immunosuppressive effects of cortisol include a reduced number of circulating lymphocytes, inhibited lymphocyte proliferation and decreased numbers of antibody-producing cells and lower antibody production (reviewed by Harris & Bird 2000).
In mammals, a number of immune cells were shown to produce CRH, ACTH and β-endorphin (Lyons & Blalock 1997, Turnbull & Rivier 1999, Baigent 2001). A few studies report on production of these hormones by leukocytes of fish as well: POMC mRNA has been detected in goldfish phagocytes (Ottaviani et al. 1995), CRH-immunoreactivity is reported in the goldfish thymus (Ottaviani et al. 1998) and catfish leukocytes were shown to produce ACTH (Arnold & Rice 2000). The interaction of pituitary hormones with the immune system is not restricted to POMC-derived peptides: in mammals, as well as fish, it has been documented that growth hormone (GH) and prolactin (PRL) enhance various functions of immune cells, including phagocytic activity, immunoglobulin M (IgM) production and mitotic activity of leukocytes (Harris & Bird 2000, Yada et al. 2002, 2004). Indeed, PRL and GH are structurally related to a number of cytokines (Sprang & Bazan 1993) and are expressed in several lymphoid tissues, including head kidney (Yada et al. 2002).

We, therefore, also considered expression of these two hormones in the present study.

In mammals, communication of immune-derived signals with the HPA-axis occurs via interleukin-1β (IL-1β) and to a lesser extent IL-6 and tumour necrosis factor-α (TNF-α). These cytokines have been shown to influence neuroendocrine activity in mammals, resulting in increased activity of ACTH and cortisol during infection, inflammation and stress (Mastorakis et al. 1993, Shintani et al. 1995, Dunn 2000). In fish, studies that address effects of cytokines on HPI-axis activation are scarce, but it has been suggested that IL-1β activates the HPI-axis (Verburg-van Kemenade et al. 2001, Holland et al. 2002), as is the case in mammals.

IL-1β mediates its effects through the cell surface receptor type I (IL-1RI), which forms a receptor complex with recruit IL-1R accessory protein (IL-1Rap; Casadio et al. 2001, Dunne & O’Neill 2003, Subramaniam et al. 2004). IL-1RI contains extracellular immunoglobulin domains, a short transmembrane region and an intracellular Toll/IL1-receptor (TIR) domain (Sims 2002). To date, fish IL-1RI has been identified in rainbow trout (Holland et al. 2000), Atlantic salmon (Subramaniam et al. 2002), pufferfish and zebrasfish (Huising et al. 2004a). Following in vivo lipopolysaccharide (LPS) treatment, expression of IL-1RI is induced in liver, head kidney, spleen and gills (Subramaniam et al. 2002).

In this study, we investigated the neuroendocrine–immune interactions in common carp, Cyprinus carpio L. We cloned and sequenced the carp orthologue of the IL-1RI to be able to characterise cells and tissues that have the potential to respond to IL-1β. We quantitatively assessed the expression of IL-1β, IL1-RI, GH and PRL in hypothalamus, pituitary gland and head kidney of control and stressed fish. Finally, we present in vitro evidence that IL-1β targets melanotrope cells in the pituitary gland to release α-MSH and acetylated β-endorphin. The physiological role of this interaction between the immune and stress responses will be discussed.

### Materials and Methods

#### Animals

Common carp (C. carpio L.) of the R3×R8 strain (Huising et al. 2004b), weighing around 50 g, were produced by the De Haar Vissen facility in Wageningen, The Netherlands. Fish were reared in the Nijmegen facilities in 250 l tanks at 22 °C. Fish were fed commercial fish food (Trouvit, Trouw, Putten, The Netherlands) at a ration of 1.5% of the body weight per day. Prior to sampling, fish were anaesthetised in 0.1% (v/v) 2-phenoxyethanol (Sigma). Experimental protocols were according to Dutch legislation and approved by the ethical committee of the Radboud University Nijmegen.

#### Restraint stress experiment

Groups of eight carp were transferred from stock tanks to experimental tanks and acclimatised for at least 4 weeks. On the day of the experiment, eight fish at a time were confined in a net in their own aquarium. Controls were left undisturbed in another tank. After 24 h, fish were quickly caught, anaesthetised and sampled. Blood was taken by puncture of the caudal vessels with heparin as an antiagglutinant. Plasma was separated from blood cells by centrifugation (10 000 g, 10 min, 4 °C).

Brains, pituitary glands and head kidneys were collected. From the brains, a small cube of tissue containing the NPO was dissected. In carp, the NPO is situated rostrodorsally from the optic nerve (Metz et al. 2004). Dissection was performed in a standardised way by four cuts, using the optic nerve as a landmark (Fig. 1). From the pituitary glands, PD and PI were carefully separated. Under a stereomicroscope, pituitary PD (brightly white tissue) and PI (opaque) can easily be distinguished by colour. To verify proper separation, we homogenised three pituitary PDs and PIs in 0.01 M HCl. After centrifugation (15 000 g, 10 min, 4 °C) to remove...
cellular debris, supernatants were analysed for α-MSH and ACTH by RIAAs (Metz et al. 2004). Neither α-MSH immunoreactivity was detected in the PD, nor was ACTH detectable in the PI (data not shown).

**Quantitative expression**

Expression of IL-1β, IL-1RI, GH and PRL in the collected tissues was assessed by quantitative reverse transcriptase (RT)-PCR. Total RNA (1 μg), isolated from fresh tissues with TRIzol reagent (Invitrogen) according to the manufacturer’s instructions, was incubated with 1 U DNase I (Invitrogen) for 15 min at room temperature to ensure complete removal of trace genomic DNA. EDTA (1 mM), 50 ng random hexamers, 0.5 mM dNTPs, 10 U RNase inhibitor (Invitrogen), 10 mM dithiothreitol and 200 U Superscript II reverse transcriptase (Invitrogen) were used as template in 25 μl amplification mixture, containing the RNA, 300 ng random hexamers, 5 mM dNTPs, 10 U RNase inhibitor (Invitrogen), 10 mM dithiothreitol and 200 U Superscript II reverse transcriptase (Invitrogen).

For quantitative PCR analysis, 5 μl of five times diluted RT mix were used as template in 25 μl amplification mixture, containing 12.5 μl SYBR Green Master Mix (Applied Biosystems Benelux, Nieuwerkerk aan den IJssel, The Netherlands) and 3.75 μl of each primer (final concentration 300 nM). The primer sets were designed using Primer Express 2.0 Software (Applied Biosystems), synthesised by Biologio (Malden, The Netherlands) and are shown in Table 1. After an initial denaturation step at 95 °C for 10 min, a real-time PCR of 40 cycles was performed (GeneAmp 5700, Applied Biosystems), each cycle consisting of 15 s denaturation at 95 °C and 1-min annealing and extension at 60 °C. Cycle threshold (Ct) values were determined and expression was calculated as a percentage of the housekeeping genes β-actin or 40S (ΔΔCt; Pfaffl 2001). Results were confirmed to be similar following standardisation to either gene. For clarity, only results that are standardised for 40S expression are presented here.

**Cloning and sequencing**

Two oligonucleotide primers were designed based on a predicted zebrafish IL-1RI sequence (IL-1RI.fw, 5′-GCA GAA AAG GCA ATA CTT GAAC-3′; IL-1RI.rev2, 5′-TAG GCC AGA ACC AGA TCA AC-3′). PCR with these primers on a ZAP cDNA library of PMA-activated carp head kidney macrophages yielded a 745 bp product. PCRs were performed using 0.5 μl Taq DNA polymerase (Goldstar; Eurogentec, Seraing, Belgium) supplemented with 1.5 mM MgCl2, 200 μM dNTPs and 400 nM of each primer in a final volume of 25 μl. Cycling conditions were 94 °C for 2 min; 35 cycles of 94 °C for 30 s, 55 °C for 30 s and 72 °C for 1 min, followed by a final extension step of 72 °C for 10 min. PCR products were ligated and cloned into JM-109 cells using the pGEM-T-easy kit (Promega) according to the manufacturer’s protocol. Sequences were determined from both strands using T7 and SP6 primers and were carried out using the ABI Prism BigDye Terminator Cycle Sequencing Ready Reaction kit (Applied Biosystems). The rest of the sequence was obtained in a rapid amplification of cDNA ends (RACE) approach (GeneRacer, Invitrogen) according to the manufacturer’s instructions.

**Phylogenetic tree construction**

Multiple sequence alignments were carried out with the ClustalW program at http://www.ebi.ac.uk/clustalw/. A phylogenetic tree was constructed on the basis of amino acid difference (p-distance) by the neighbour-joining method (Saitou & Nei 1987) with MEGA version 2.1 (Kumar et al. 2001). Reliability of the tree was assessed by bootstrapping, using 1000 bootstrap replications.

**Cell isolation and in vitro stimulation**

Both carp head kidneys were removed and passed through a 50 μm nylon mesh with carp RPMI (cRPMI; RPMI 1640; Gibco) containing 10 U/ml heparin (Leo Pharmaceutical Products, Weesp, The Netherlands) and adjusted to carp
osmolarity (270 mOsm/kg). The cell suspension was layered on discontinuous Percoll (Amersham Pharmacia Biotech AB) gradient (1·02, 1·07 and 1·083 g/cm³). Following centrifugation (25 min at 800 g with brake disengaged) cells at the 1·07 g/cm³ interface (macrophage–enriched leukocytes) were collected and washed. Cells were suspended in cRPMI, supplemented with 0·5% pooled serum, 1% l-glutamine (Merck), 200 nM β-mercaptoethanol (Bio–rad), 1% penicillin G (Sigma) and 1% streptomycin sulphate (Sigma). Cells were seeded in a 24-well cell culture plate at a concentration of 4·5 × 10⁶ cells/ml in a volume of 400 μl per well (1·8 × 10⁶ cells/well) and cultured overnight at 27 °C, 5% CO₂. Following overnight culture, cells were stimulated for 4 h with 20 μg/ml concanavalin A (ConA; Sigma), 50 μg/ml lipopolysaccharide (LPS; Escherichia coli, Sigma) or 0·1 μg/ml phorbol 12-myristate 13-acetate (PMA; Sigma). Following in vitro stimulation, cells were harvested and total RNA was isolated with the RNeasy Mini Kit (Qiagen), according to the manufacturer’s instructions.

In vitro superfusion

Freshly isolated pituitary PI and head kidneys were placed on a cheese-cloth filter in a superfusion chamber. Tissues were superfused with carbogen-saturated 0·15 M HEPES/Tris-buffered medium (pH = 7·38), containing 128 mM NaCl, 2 mM KCl, 2 mM CaCl₂·2H₂O, 0·25% (w/v) glucose, 0·03% (w/v) BSA and 0·1 mM ascorbic acid. The flow was set at 30 μl/min. After 150 min, when hormonal release had reached an apparent steady state, the medium was supplemented with 100 ng/ml (5·3 nm) recombinant carp IL-1β (Yin & Kwang 2000) for 10 min. At t = 180 min, a 10-min control pulse was applied: pituitary glands were stimulated with 1×10⁻⁷ M thyrotrophin-releasing hormone (TRH; Biotrend, Köln, Germany) and head kidneys were stimulated with 5×10⁻⁸ M human ACTH (Sigma). Five- or fifteen-minute fractions were collected, immediately stored at −20 °C and analysed for α-MSH, N-Ac β-endorphin and cortisol by RIA.

RIAs for α-MSH, N-Ac β-endorphin and cortisol

α-MSH, N-Ac β-endorphin were measured by RIA with antibodies against synthetic human mono-Ac α-MSH (Van Zoest et al. 1989) and salmon N-Ac β-endorphin (Takahashi et al. 1984) respectively, according to the method described earlier (Van den Burg et al. 2005). Cortisol was measured using the manufacturer’s protocol of a commercially available kit (Campro Scientific, Veenendaal, The Netherlands).

Statistical analysis

The differences among groups in the relative expression data were assessed by the non-parametric Mann–Whitney U test. Significance was accepted at P<0·05. The values are expressed as means ± s.d.

Results

We detected basal expression of IL-1β in the NPO. The stress of 24-h restraint upregulated IL-1β expression significantly in this tissue (Fig. 2). In the pituitary PD and PI, IL-1β expression was not detected, either in the control or in stressed fish (not shown). In the PD, mRNA levels of PRL increased almost fourfold following restraint, while GH expression did not change (Fig. 2). In the head kidney, IL-1β expression significantly increased following 24-h restraint, while expression of TNF-α remained constant in this tissue (Fig. 2). We did not detect the expression of GH and PRL in head kidney (not shown).

To study the expression of the IL-1RI in carp, we used homology cloning based on the zebrafish IL-1RI sequence to obtain the carp sequence. This yielded a 1973 bp IL-1RI sequence encoding a 556 amino acid protein (sequences submitted to EMBL/Genbank database, accession number AJ843873). In line with the tetraploid nature of carp (Uyeno & Smith 1972), we found two IL-1RI sequences, which differ in seven nucleotides. The deduced amino acid sequence has moderate overall identity with salmon (33%) and human (23%) IL-1RI; identity is higher, however, if only the TIR domain is considered (47 and 33% respectively). To compare the carp sequence with that of other vertebrates, a multiple alignment was made (Fig. 3). Cysteine bonds, immunoglobulin-like regions, the trans-membrane segment and the TIR domain are indicated in the figure. A phylogenetic tree was constructed using the neighbour-joining method (Fig. 4). The human, rat and trout IL-1 receptor type II served as outgroup. The mammalian IL-1RI sequences are separated from the piscine sequences by chicken IL-1RI. Within the fish IL-1RI cluster, IL-1RI sequences from carp and salmonids cluster separately. Fugu IL-1RI clusters in proximity to the salmonid
**Figure 3** Multiple alignment of IL-1RI sequences of six different vertebrate species, including the newly identified putative carp IL-1RI. Identical amino acids are boxed in black, conservative substitutions in grey. The predicted Ig-like domains are indicated by dotted lines (⋯⋯), the transmembrane region with double lines (−−) and the TIR domain by a single black line ( – ) displayed above the sequences. Disulphide bonds are indicated by grey lines that connect cysteine residues. Amino acids involved in signal transduction are indicated by arrowheads (▲). The Fugu sequence was retrieved by BLAST searching of its complete genome at the Ensembl genome browser (http://www.ensembl.org). Accession numbers: carp, AJ843873; human, P14778; rat, Q02955; chicken, AAA48924; salmon, CAC83729; Fugu, SINFRRUP00000131701.
sequences, which resembles established patterns of piscine evolution.

The expression of IL-1RI was found in hypothalamus, both parts of the pituitary gland as well as in head kidney. Hypothalamic IL-1RI expression was not affected following restraint (Fig. 5). In the pituitary PI, restraint induced a significant increase in expression of IL-1RI (Fig. 6A), while expression in the PD remained constant (Fig. 6B). As shown in Fig. 7A, IL-1RI expression in head kidney also significantly increased following restraint. Four hours in vitro stimulation of isolated head kidney macrophages with ConA, LPS and PMA had no effect on expression of IL-1RI (Fig. 7B).

To investigate a functional role for this receptor in the pituitary gland and head kidney, an in vitro superfusion experiment was performed (Fig. 8). Tissues were stimulated with recombinant carp IL-1β; TRH and ACTH served as controls for tissue responsiveness of PI and head kidney respectively. In the PI, IL-1β induced a stimulation of α-MSH and N-Ac β-endorphin release; the stimulation of N-Ac β-endorphin was more profound than that of α-MSH (Fig. 8A). In the head kidney, stimulation with IL-1β had no detectable effect on cortisol release (Fig. 8B). Both tissues responded predictably to stimulation with TRH and ACTH. The stress of 24-h restraint induced elevated plasma α-MSH and N-Ac β-endorphin levels (Fig. 9).

### Discussion

This study provides four new major observations with regards to the role of IL-1β in the activation of the HPI-axis:

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**Figure 4** Phylogenetic tree of IL-1RI sequences constructed using the neighbour-joining method. Numbers at branch nodes represent the confidence levels of 1000 bootstrap replications. The human, rat and trout IL-1R type II (IL-1RII) served as outgroup. Accession numbers as in Fig. 3. Additional accession numbers: macaque, AAR88996; horse, BAA83730; mouse, P13504; trout, CAC82935; human IL-1RII, P27930; rat IL-1RII, P43303; trout IL-1RII, CAC19715.

**Figure 5** Expression of IL-1RI relative to 40S in NPO of control and stressed fish.

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**Figure 6** Expression of IL-1RI relative to 40S in pituitary (A) PI and (B) PD in control and stressed carp. *P<0.05.

**Figure 7** (A) Expression of IL-1RI relative to 40S in head kidneys (HK) of control and stressed fish. (B) IL-1RI expression in head kidney macrophages that were *in vitro* exposed to ConA, LPS and PMA. *P<0.05.
(i) hypothalamic expression of IL-1β, which is constitutively expressed, is upregulated during acute stress; (ii) IL-1RI expression is upregulated in head kidney and pituitary PI following restraint; (iii) recombinant carp IL-1β stimulates the in vitro release of α-MSH and β-endorphin from the pituitary PI. From these three findings combined, we propose that during acute stress, IL-1β signalling in the HPI-axis becomes more sensitive by enhanced expression of both ligand and receptor; (iv) the increased expression levels of IL-1β and IL-1RI in head kidney during acute stress indicate that the immune status is altered. These findings will be discussed separately.

IL-1β takes a key position in the innate immune and inflammatory response (Dinarello 1997, Secombes et al. 1999). We subjected fish to 24-h restraint to assess IL-1β expression levels during enhanced HPI-axis activity. As

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**Figure 8** (A) In vitro release of α-MSH and N-Ac β-endorphin from pituitary PI in a superfusion setup. Tissues were successively stimulated with 100 ng/ml (5·3 × 10⁻⁹ M) recombinant carp interleukin-1β and 1 × 10⁻⁷ M TRH as indicated by the shaded bars. (B) In vitro cortisol release by superfused head kidneys stimulated with 100 ng/ml recombinant carp interleukin-1β and 5 × 10⁻⁷ M ACTH respectively, as indicated by shaded bars.

**Figure 9** Plasma concentrations of α-MSH and N-Ac β-endorphin in control and 24-h restrained fish as determined by RIA. *P<0.05.
published earlier, these fish were indeed stressed, as judged by markedly increased plasma cortisol (176 ± 133 nM in controls vs 1319 ± 211 nM in restrained fish, P<0.001) and glucose levels (2.56 ± 0.46 mM in controls vs 9.22 ± 1.48 mM in restrained fish, P<0.001; Metz et al. 2004). Following 24-h restraint, we detected a twofold increase of IL-1RI expression in head kidney, but not of TNF-α, which indicates that stress leads to differential activation of specific immune signals. TNF-α is a well-established pro-inflammatory cytokine in mammals (Goetz et al. 2004) as well as fish (Zou et al. 2003), with effects on differentiation, survival and expression of pro-inflammatory factors in a variety of immune cells, most notably macrophages.

Expression of IL-1β in non-immune tissues such as the pituitary gland and brain, including hypothalamus, has been documented in both mammals (Shintani et al. 1995) and fish (Engelsma et al. 2001), albeit that expression in the pituitary gland of carp is very low (Engelsma et al. 2001). In mammals, acute stressors induce increased IL-1β mRNA and protein (O’Connor et al. 2003). We did not detect IL-1β expression in the pituitary PD and PI of control or stressed carp. In mammals IL-1β in the hypothalamus is associated with HPA-axis activation (Shintani et al. 1995). Moreover, glucocorticoids inhibit hypothalamic IL-1β expression in rat (Chai et al. 1996), which indicates the presence of a negative feedback mechanism. Similarly to our observations in carp, stress induced a 2.5-fold increase in IL-1β mRNA in the preoptic area of the rat (Tanebe et al. 2000). We, therefore, conclude that hypothalamic IL-1β fulfils a similar function in fish as it does in mammals and that this mechanism is phylogenetically conserved.

To study the targets for IL-1β, we cloned and identified a putative carp orthologue of the presumed receptor for IL-1β, viz. IL-1RI, which displays moderate amino acid homology with IL-1RI sequences of other vertebrate species. Although we realise that we have not considered the ability of the carp IL-1RI to actually bind IL-1β and therefore can only call it a putative IL-1RI, we take the following observations to suggest that the gene cloned indeed represents the IL-1RI orthologue: (1) protein structure resembles the characteristics of the IL-1 receptor family, which include extracellular immunoglobulin-like domains and a cytoplasmic TIR domain; (2) all seven amino acids that have been reported essential for signalling (Heguy et al. 1992), are conserved in the carp sequence; (3) in a neighbour-joining phylogenetic tree, as well as in a maximum parsimony tree, the carp IL-1RI sequence consistently clusters within the type I receptor clade of other fish species, which further confirms its identity as IL-1RI. Interestingly, in salmon, both the constitutive and LPS-stimulated expression profiles of this receptor resemble that of the mammalian IL-1RI and this suggests an analogous function (Subramaniam et al. 2002, Huising et al. 2004a).

The expression of IL-1RI in head kidney macrophages was not influenced by 4-h in vitro exposure to ConA, LPS and PMA. In Atlantic salmon, IL-1RI expression was increased in head kidney following systemic LPS treatment (Subramaniam et al. 2002). In our study, the stress of 24-h restraint induced an increase in IL-1RI expression in head kidney as well as in the pituitary PD; expression in the NPO and PD was unaffected. This tempts us to speculate that during stress, the role of IL-1β peripherally in the immune response as well as centrally in the activation of the HPI-axis, is crucial, as in both these systems expression levels of the signal as well as the receptor increase. Although we have no insight into the kinetics of altered expression levels, these observations seem to contrast with classical negative feedback loop situations. For example, during stress the expression of CRH in the NPO is upregulated, while its receptor in the pituitary gland is downregulated (Huising et al. 2004b). We cannot, at present, exclude the possibility that our observations on altered expression levels are a result of stress-induced redistribution of immune cells (Huising et al. 2003b).

A role for IL-1β in the activation of the HPI-axis is further corroborated by our observation that recombinant IL-1β is a very potent stimulator of α-MSH and N-Ac β-endorphin release from the pituitary PD in vitro. Strikingly, N-Ac β-endorphin release was more profoundly stimulated than α-MSH release. Although these peptides are derived from the same precursor, there is evidence that their release is not tightly coupled and differential release occurs in carp (Van den Burg et al. 2005). It must be noted though that we here present only a single experiment due to limited availability of recombinant carp IL-1β. This is, however, the first observation in fish which directly shows that a cytokine activates a component of the HPI-axis. Holland et al. (2002) suggested such a direct relation, but their suggestion was based on elevated plasma glucose and cortisol levels following injection with IL-1β, which to the best of our knowledge could also be an indirect effect. In line with the in vitro response, we observed elevated plasma levels of α-MSH and N-Ac β-endorphin in vivo, which further strengthens our extrapolation between the superfusion and in vivo stress experiment.

In mammals, IL-1β-driven activation of the HPA-axis mainly occurs via stimulation of CRH-producing cells in the hypothalamus (Turnbull & Rivier 1999). Presently, we cannot measure CRH in carp, but the presence of the IL-1RI in the NPO may suggest that IL-1β directly targets the CRH-producing neurons in carp. IL-1β has been shown to cross the blood–brain barrier (Banks et al. 2002) and may be produced locally. In addition, ACTH-producing cells of the pituitary PD have been documented to be a target for IL-1β in mammals (Kemppainen & Behrend 1998, Prickett et al. 2000). In our in vitro study, we considered only the melanotrope cells of the pituitary gland, which apparently are a target for IL-1β. We take the observation that IL-1β did not evoke a rise in cortisol release from superfused head kidney to conclude that IL-1RI is not present on interrenal cells but in the haematopoietic tissue, as corroborated by constitutive expression of this receptor in isolated carp head kidney macrophages (Engelsma et al. 2001; this study).
A 24-h restraint induced a significant decrease in plasma sodium levels from 115 to 97.5 mM (Metz et al. 2004). The same fish were used in this study to assess expression of GH and PRL in the pituitary PD. These cytokines are involved in osmoregulation (Sakamoto et al. 1997) and also in the modulation of immune responses (Yada et al. 2002). While GH expression was unaffected, PRL mRNA levels were greatly enhanced in the present study. The hyponatraemia observed may have led to upregulation of the PRL gene (McCormick 1995). Regarding the role of PRL and GH in the immune system, it has been shown that PRL prevents cortisol-induced apoptosis of in vitro cultured leukocytes in rainbow trout (Yada et al. 2004), with GH having no effect. These observations provide another example whereby stress induces a differential and specific signal to handle the imminent threats of stress.

Earlier, Weyts et al. (1998a, b) have shown that cortisol, end product of the HPI-axis, affects the immune system; it induces apoptosis in activated B-lymphocytes, while neutrophilic granulocytes, an important source of IL-1β, are rescued from apoptosis. In this study, we have shown that the cytokine IL-1β affects the activity of the HPI-axis and that in turn, expression profiles of genes encoding IL-1β and its receptor are modified during acute stress such that the responsiveness of the HPI-axis for IL-1β seems modulated during acute stress. The present study provides further evidence for bi-directional communication of the HPI-axis and the immune system in fish.

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