Type II SOCS as a feedback repressor for GH-induced Igf1 expression in carp hepatocytes

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Abstract
Type II suppressor of cytokine signaling (SOCS) serve as feedback repressors for cytokines and are known to inhibit growth hormone (GH) actions. However, direct evidence for SOCS modulation of GH-induced insulin-like growth factor 1 (Igf1) expression is lacking, and the post-receptor signaling for SOCS expression at the hepatic level is still unclear. To shed light on the comparative aspects of SOCS in GH functions, grass carp was used as a model to study the role of type II SOCS in GH-induced Igf1 expression. Structural identity of type II SOCS, Socs1–3 and cytokine-inducible SH2-containing protein (Cish), was established in grass carp by 5′/3′-RACE, and their expression at both transcript and protein levels were confirmed in the liver by RT-PCR and LC/MS/MS respectively. In carp hepatocytes, GH treatment induced rapid phosphorylation of JAK2, STATs, MAPK, PI3K, and protein kinase B (Akt) with parallel rises in socs1–3 and cish mRNA levels, and these stimulatory effects on type II SOCS were shown to occur before the gradual loss of igf1 gene expression caused by prolonged exposure of GH. Furthermore, GH-induced type II SOCS gene expression could be negated by inhibiting JAK2, STATs, MEK1/2, P38MAPK, PI3K, and/or Akt respectively. In CHO cells transfected with carp GH receptor, over-expression of these newly cloned type II SOCS not only suppressed JAK2/STAT5 signaling with GH treatment but also inhibited GH-induced grass carp Igf1 promoter activity. These results, taken together, suggest that type II SOCS could be induced by GH in the carp liver via JAK2/STATs, MAPK, and PI3K/Akt cascades and serve as feedback repressors for GH signaling and induction of igf1 gene expression.

Introduction
The members of suppressor of cytokine signaling (SOCS) are key regulators of innate (Strebovsky et al. 2012) and adaptive immune systems (Tamiya et al. 2011). In mammals, at least eight members of SOCS family, including Socs1–7 and cytokine-inducible SH2-containing protein (Cish), have been identified (Jin et al. 2008). All of them share the common features with a SH2 domain in the central core followed by a highly conserved SOCS box in the C-terminus. Socs1 and Socs3 also have the additional kinase inhibitory region (KIR) and extended SH2 motif (ESS) upstream of SH2 domain, which are absent in other SOCS members (Piessevaux et al. 2008b). SOCS proteins are widely expressed at tissue level (Delgado-Ortega et al. 2011), and their production can be induced by microbial/viral infection or by cytokine treatment (Hebenstreit...
At cellular level, SOCS expression is well documented to serve as the feedback repressor for cytokine signaling via inhibition of JAK/STAT pathway (Croker et al. 2008) and plays a protective role in preventing hyperactivation of immune system, which can lead to autoimmune/inflammatory disorders (Li et al. 2003, Cheng et al. 2009). In mammals, SOCS proteins can also act as negative modulators for growth hormone (GH) actions (Birzniece et al. 2009) and contribute to the cross talk between immune system and somatotropic axis (Ahmed & Farquharson 2010). In rodents, GH treatment is known to induce Socs2, Socs3, and Cish expression in the liver, both in vivo and in vitro (Adams et al. 1998, Tollet-Egnell et al. 1999). Given that (i) JAK3/STAT3 pathway is a key component of GH signaling (Vijayakumar et al. 2010); (ii) Socs1–3 and Cish expression can inhibit JAK2 activity, STAT3 phosphorylation, and GH-responsive promoters (Greenhalgh & Alexander 2004, Greenhalgh et al. 2005); and (iii) Socs2 knockout can lead to gigantism in mouse model (Metcalf et al. 2000) and the growth enhancement is dependent on STAT3 (Greenhalgh et al. 2002a), SOCS proteins, especially Socs2, are proposed to be the feedback repressors for GH signaling, which may contribute to the pulsatile actions of GH on Igf1 production at the hepatic level (Choi & Waxman 2000).

Of note, conflicting results against the role of SOCS as a ‘signal terminator’ for GH actions have also been reported. In mice, SOCS2 over-expression could induce gigantism with accelerated growth as in the case of Socs2 knockout (Greenhalgh et al. 2002b). Besides, serum levels and hepatic content of Igf1 in Socs2-null mice were found to be similar to those of wild-type littermates (Metcalfe et al. 2000). In the same study, the role of SOCS2 in GH-induced Igf1 production and body growth was also questioned, as most of the organs in Socs2-null mice were enlarged without parallel rise in Igf1 expression. In transfection studies with cell lines (e.g., HEK293 cells), SOCS2 over-expression could induce dual effects on GH signaling, being inhibitory at low doses but stimulatory at high doses (Favre et al. 1999). In 3T3-F442A adipocytes, however, SOCS2 and CISH expressions had no effects on GH-induced promoter activity in GH-responsive genes (e.g., Spi-2.1) (Adams et al. 1998). Although the mechanisms for SOCS inhibition of JAK/STAT pathway through KIR inhibition of Janus kinase (JAK) activity, blocking signal transducer and activator of transcription (STAT) recruitment by SH2 domain, and decaying activated receptor complex via SOCS box have been documented (Greenhalgh & Alexander 2004, Greenhalgh et al. 2005), except for a single report in C2C12 myoblasts, suggesting that mitogen-activated protein kinases (MAPK) and phosphoinositide 3-kinase (PI3K) activation may inhibit GH-induced SOCS2 and CISH expression (Sadowski et al. 2001), not much is known for the post-receptor signaling for GH-induced SOCS expression, especially in the liver with relevance to IGF1 production. To date, the direct evidence for SOCS modulation of IGF1 expression induced by GH is still lacking.

In recent years, SOCS proteins have been cloned in fish models, e.g., trout (Wang et al. 2010, Maehr et al. 2014), salmon (Skjesol et al. 2014), catfish (Yao et al. 2015), turbot (Zhang et al. 2011), and zebrafish (Wang et al. 2011). Data mining of genome databases not only reveals the orthologues of mammalian SOCS but also reveals new paralogues of Cish, Socs3, and Socs5 unique to fish species (Jin et al. 2008, Wang et al. 2011), which are presumably the result of fish-specific 3R genome duplication (Kassahn et al. 2009). Based on the phylogenetic analysis of the new sequences with those reported in invertebrates, two families of SOCS, type I and type II SOCS, have been proposed (Jin et al. 2008). Type I SOCS (including Socs4–7, Socs5b, and Socs9 found in both vertebrates and invertebrates) represents the lineage closely related to the ancestral SOCS, whereas type II SOCS (including Socs1–5, Cish, and the CISH homologue Socs9) can be identified only in vertebrates and believed to be derived from type I SOCS by gene duplication (Jin et al. 2007, 2008). Functional studies in fish models also reveal that type II SOCS (e.g., Socs1–3 and Cish) are highly responsive to microbial infection or exposure to endotoxin/cytokines, whereas the corresponding responses for type I SOCS are marginal/undetectable (Wang et al. 2010, 2011). For the role of SOCS in GH signaling, notable rises of socs1 and socs3 mRNA could be found in the liver of zebrafish with GH transgene. However, Igf1 expression was reduced with no effects on body growth or JAK/STAT, signaling components (Studzinski et al. 2009). Recently, elevations of socs1 and socs2 transcripts have also been reported in trout liver during cortisol inhibition of GH-induced Igf1 expression (Philip et al. 2015), suggesting that SOCS proteins may play a role in Igf1 regulation by GH in fish model.

To shed light on the role of SOCS in GH functions in fish model, type II SOCS, including Socs1–3 and Cish, were cloned in grass carp and their gene copy number and tissue expression, especially in the liver, were determined. Using carp hepatocytes, the possible involvement of JAK/STAT, MAPK, and PI3K/Akt cascades in GH-induced type II SOCS expression was examined. Using transfection...
studies in CHO cells, the effects of over-expression of grass carp type II SOCS on (i) JAK2/STAT5 signaling coupled to carp GH receptor (GHR) and (ii) GH-induced grass carp Igf1 promoter activity were also investigated. Our studies for the first time elucidate the post-receptor signaling for GH-induced type II SOCS expression at the hepatic level and provide evidence that Socs1–3 and Cish can act as feedback repressors for GH signaling and induction of igf1 gene transcription in the carp liver.

Materials and methods

Animal and test substances

One-year-old grass carp (Ctenopharyngodon idellus) with body weight 2.0–2.5 kg were obtained from local markets, housed in 250L aquaria at 20°C under 12 h light:12 h darkness photoperiod, and fed to satiation twice daily for at least 7 days before experimentation. As the fish at this stage were pre-pubertal and sexual dimorphism was not apparent, grass carp of mixed sexes were used for tissue sampling and hepatocyte preparation. During the process, the fish was killed by MS222 anesthesia (0.05%; Sigma) followed by spinosectomy according to the protocol approved for animal use at the University of Hong Kong. Test substances, including porcine GH, IL-1β, TNF-α, lipopolysaccharide (LPS), JAK 2 inhibitor 1,2,3,4,5,6-hexabromocyclohexane (HEX), STAT1 inhibitor fludarabine (FA), STAT 3 inhibitor ethyl-1-(cyano-2,3,5,6-tetrafluorophenyl)-6,7,8-trifluoro-4-oxo-1,4-dihydroquinoline-3-carboxylate (ETDDC), STAT5 inhibitor N1-(11H-Indolo[3,2-c]quinolin-6-yl)-N2,N2-dimethylthylamine-1,2-diamine (IQDMA), P38MAPK inhibitor PD169316, MEK1/2 inhibitor U0126, PI3K inhibitor LY294002, and protein kinase B (Akt) inhibitor 1L6-hydroxymethyl-chirolinositol-2-O-methyl-3-O-octadecyl-sn-glycero carbonate (HIMOC), were obtained from Calbiochem. For transfection studies, the JAK2/STAT5-responsive 8×GHRE. LUC reporter and STAT5 expression vector STAT5.pcDNA were generous gifts from Peter S Rotwein (Oregon Health & Science University, Portland, OR, USA).

Molecular cloning, copy number, and tissue expression of Socs1–3 and Cish

For molecular cloning of type II SOCS, total RNA was extracted from the carp liver and subjected to 5′/3′-RACE using primers designed based on zebrafish Socs1–3 and Cish. Sequence alignment, 3D protein modeling, and phylogenetic analysis were conducted using CLUSTAL-W, SWISS-MODEL, and MEGA 6.0 respectively. To deduce gene copy number of Socs1–3 and Cish, Southern blot was performed in genomic DNA isolated from carp blood (Lin et al. 2015). For tissue expression of type II SOCS, northern blot was conducted in total RNA prepared from the carp liver and pituitary, whereas RT-PCR was examined in selected tissues/brain areas using primers for respective gene targets with PCR conditions described in Table 1. Using LC/MS/MS, protein expression of Socs1–3 and Cish was also evaluated in the carp liver using a SCIEX TripleTOF-5600 system (AB SCIEX, Concord, ON, Canada) as described previously (Wong et al. 2013).

Table 1 Primer sequences and PCR conditions for RT-PCR of type II SOCS.

<table>
<thead>
<tr>
<th>Gene target/accession No</th>
<th>Primer sequence</th>
<th>PCR condition</th>
<th>Cycle no.</th>
<th>Product size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genomic DNA</td>
<td>Southern blot</td>
<td>Denaturing</td>
<td>Annealing</td>
<td>Extension</td>
</tr>
<tr>
<td>socs1/GU224284</td>
<td>F: 5′-CAGCAGCGAGCCATT-3′</td>
<td>94°C</td>
<td>49°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5′-GACAGCTGTTGCTCTTTG-3′</td>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>socs2/GQ478990</td>
<td>F: 5′-CGTCGAGGGGACACATT-3′</td>
<td>94°C</td>
<td>55°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5′-CGGAGCTGTTGGACGACAG-3′</td>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>socs3/EU625352</td>
<td>F: 5′-GTCTCGAGAGCTTTATG-3′</td>
<td>94°C</td>
<td>55°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5′-AGTGGCTGTTATGACAAAGTGA-3′</td>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>cish/GU384205</td>
<td>F: 5′-AGAGGCTATTTTGCTGATAC-3′</td>
<td>94°C</td>
<td>58°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5′-GGAAAGCTCGAGACTGAC-3′</td>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>β-actin/M25013</td>
<td>F: 5′-CGGTGATTCTGGATGACT-3′</td>
<td>94°C</td>
<td>56°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5′-AGCTCATAGCCTTCCACAG-3′</td>
<td></td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
</tbody>
</table>
Carp hepatocytes (with >95% viability) were prepared by collagenase digestion (Reindl et al. 2011), seeded in 24-well plates at ~0.7 × 10⁶ cells/mL/well at 28 °C, and challenged with test substances for the duration as indicated. Individual experiments were repeated with hepatocytes obtained from three to four cell preparation and each of them was conducted with quadruplicates in the same study. After treatment, total RNA (4 μg/well, OD260/280 of ~2.0) was isolated, digested with DNase I, and subjected to real-time PCR according to the conditions described in Table 2 using a RotorGene-Q System (Qiagen). Serial dilutions of plasmid DNA with ORF of target genes were used as the standards for standard curve construction for data calibration using RotorGene Q-Rex software and parallel measurement of 18S RNA was used as an internal control (for the details of cell preparation and experiments, see Supplemental Fig. 1, see section on supplementary data given at the end of this article).

Western blot of post-receptor signaling targets in carp hepatocytes

To examine GH action on JAK/STAT, MAPK, and PI3K/Akt cascades, Western blot was performed in carp hepatocytes after GH treatment as described previously (Jiang & Wong 2013) with antibodies for the phosphorylated form and total protein of MEK1/2 (1:1000), ERK1/2 (1:5000), P38MAPK (1:1000), Akt (1:1000), JAK2 (1:1000), STAT1 (1:1000), STAT3 (1:1000), and STAT5 (1:1000) respectively (Cell Signaling). Parallel blotting of β-actin was used as the loading control.

Functional expression of Socs1–3 and Cish in CHO cells

To characterize the functionality of grass carp type II SOCS, the ORF of the respective gene targets was subcloned into pcDNA3.1 (Invitrogen) to generate the expression vectors for Socs1–3 and Cish respectively. To study the effects of type II SOCS on GH signaling, CHO cells with stable expression of grass carp GHR were used as the host cells for transient transfection of 8×GHRE.LUC, TK-Renilla (as internal control), and expression vectors for the respective type II SOCS with either GH treatment or co-transfection with STAT5.pcDNA by the protocol as described previously (Sun et al. 2014). In parallel studies, a 1.07 kb grass carp Igf1 promoter was cloned into the LUC reporter pGL3.basic and substituted for 8×GHRE.LUC in transfection study with CHO cells with GH treatment in the presence of JAK2/STAT5 inhibitors or co-transfection with the expression vectors for type II SOCS. After that, firefly and renilla luciferase activities expressed in CHO cells were measured using a Dual-Glo Luciferase Assay Kit (Promega).

Data transformation and statistics

Transcript expression of igf1, socs1–3, and cish was measured in terms of femtomole transcript detected/10⁶ cells/well. As 18S RNA did not exhibit notable changes.
Figure 1
Phylogenetic analysis and in silico protein modeling of grass carp Socs1–3 and Cish. (A) Unrooted analysis of the phylogenetic relationship of carp Socs1–3 and Cish with the corresponding sequences identified in other vertebrates using neighbor-joining method by MEGA 6.0. The scale bar represents the evolutionary distance, and bootstrap values for individual nodes in the guide tree (in the range of 76–100%) have been omitted for clarity. (B) Protein modeling of carp SOCS1–3 and CISH by SWISS-MODEL using crystal structures of their human counters as the templates. The α-helices (in red) and β-sheets (in blue) forming the SH2 domain and SOX box within the respective type II SOCS in grass carp were mapped according to the corresponding structures in human SOCS1–3 and CISH, respectively.
in our experiments, the raw data for target mRNA were simply transformed as a percentage of the mean value in control group (as ‘%Ctrl’). For Western blot, signals detected by X-ray film were quantified by densitometry scanning and the ratio of phosphorylated form and total protein of respective kinases (as ‘p:t ratio’) was used as an index for their activation. For transfection studies, the raw data for firefly luciferase (in ALU) was normalized as a ratio of renilla luciferase data detected in the same sample. The normalized data were then expressed as fold increase compared with the mean value in the control group (as ‘fold induction’). Data presented (mean ± s.e.m.) were pooled from four experiments and analyzed by Student’s t-test or ANOVA followed by Newman–Keuls test with difference considered as significant at P<0.05.

Results

Molecular cloning, copy number, and tissue expression of Socs1–3 and Cish

To establish the structural identity of type II SOCS in grass carp, full-length cDNAs for socs1–3 and cish were cloned in the carp liver (Supplemental Fig. 2), and phylogenetic analysis by neighbor-joining method revealed that these grass carp cDNAs could be grouped in the respective clades of type II SOCS with very close evolutionary relationship to the corresponding zebrafish sequences (Fig. 1A). The deduced protein sequences of grass carp Socs1–3 and Cish were found to be highly homologous to the respective targets in other vertebrates, especially in SH2 domain and SOCS box (also for KID & ESS motifs in
Socs1 and Socs3, Supplemental Fig. 3). Protein modeling also revealed that the spatial arrangement of α-helical and β-sheet structures in the newly cloned Socs1–3 and Cish, which form the basis of SH2 domain and SOCS box, was highly comparable to their human counterparts (Fig. 1B).

As shown in Fig. 2A, Southern blot with carp genomic DNA digested with BglIII, XbaI, BglII, StyII, and EcoRV, respectively, consistently produced a single band after hybridization with the probes for the respective type II SOCS, implying that Socs1–3 and Cish are single-copy genes in carp genome. For tissue expression of type II SOCS, northern blot was performed in the carp liver and pituitary (Fig. 2B). In the two tissues examined, a single transcript of 7.0 and 1.8 kb in size were detected with the probes for Socs1 and Socs3, respectively, consistently produced a single band after DNA digested with BgIII, XbaI, BgII, StyII, and EcoRV, which form the basis of SH2 domain and SOCS box, was highly comparable to their human counterparts (Fig. 1B). Protein modeling also revealed that the spatial arrangement of α-helical and β-sheet structures in the newly cloned Socs1–3 and Cish, which form the basis of SH2 domain and SOCS box, was highly comparable to their human counterparts (Fig. 1B).

To elucidate the signal transduction mediating GH-induced type II SOCS expression, Western blot revealed the presence of peptide products of grass carp type II SOCS (with 19 peptides for Socs1, 14 peptides for Socs2, 28 peptides for Socs3, and 23 peptides for Cish with confident level for target identification at 99%) and protein coverage of respective type II SOCS ranging from 61.8 to 88.9%, indicating that the socs1–3 and cish transcripts detected can be translated into respective proteins in the carp liver.

### Signal transduction for GH-induced type II SOCS mRNA expression in carp hepatocytes

To examine type II SOCS expression at hepatic level, carp hepatocytes were used as a cell model, and treatment with IL-1β and TNFα or the endotoxin LPS was effective in elevating the mRNA levels of socs1–3 and cish in this cell culture system (Fig. 3A). In carp hepatocytes, GH treatment also induced igf1 transcript expression with notable loss of Igf1 responsiveness at high dose (1 µg/mL)/prolonged exposure (≥24 h) to GH (Fig. 3B and C). As shown in Fig. 4A, GH could also up-regulate type II SOCS expression with different kinetics, with (i) transient rises in socs1 and socs3 mRNA levels peaked at 1 h after GH induction and (ii) gradual elevation of socs2 and cish mRNA levels up to 6 h or longer with GH exposure. By fixing the duration of GH treatment at 1 h, increasing doses of GH (1–1000 ng/mL) were also found to stimulate socs1–3 and cish mRNA expression in a concentration-related fashion (Fig. 4B).

To elucidate the signal transduction mediating GH-induced type II SOCS expression, Western blot
Type II SOCS in GH-induced Igf1 expression

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A

B

Figure 4

GH stimulation of type II SOCS mRNA expression in carp hepatocytes. (A) Time course and (B) dose dependence of GH treatment on Socs1–3 and cish mRNA expression in carp hepatocytes. The dose of GH was used at 500 ng/mL for the time course, whereas the duration of drug treatment was fixed at 1 h for dose-dependent study. After treatment, total RNA was extracted and subjected to real-time PCR for Socs1–3 and cish mRNA measurement. Groups denoted by different letters represent a significant difference at P < 0.05 (ANOVA followed by Newman–Keuls test).

was conducted in carp hepatocytes to test whether GH stimulation could activate the JAK/STAT pathway. As shown in Fig. 5A, GH treatment induced rapid phosphorylation of JAK2, STAT1, STAT3, and STAT5 with the highest responses observed for STAT5 (close to 40-fold increase). In parallel studies, hepatocytes were challenged with GH with simultaneous treatment of the JAK inhibitor HEX, STAT1 inhibitor FA, STAT3 inhibitor ETDDC, or STAT5 inhibitor IQDMA (Fig. 5B). In these cases, GH-induced Socs1–3 and cish mRNA expression was either attenuated or negated by the inhibitors targeting JAK2/STATs pathway. In carp hepatocytes, a 10-min exposure to GH was found to induce MEK1/2, ERK1/2, P38MAPK, and Akt phosphorylation (Fig. 6A). Co-treatment with the MEK1/2 inhibitor U0126 or P38MAPK inhibitor PD169316 also reduced or abolished GH-induced Socs1–3 and cish mRNA expression. Treatment with the PI3K inhibitor Ly294002 or Akt inhibitor HIMOC, interestingly, could inhibit GH-induced Socs3 mRNA expression but had no effects on the corresponding responses of other type II SOCS (Fig. 6B).

Socs1–3 and Cish expression on GHR signaling via JAK2/STAT5 pathway

As the pharmacological tools for SOCS are not yet available, a molecular approach was used to examine Socs1–3 and Cish expression on GHR signaling in grass carp. In CHO cells with grass carp GHR expression and transfection with the JAK2/STAT5-responsive reporter p8 × GHRE.LUC, GH treatment could induce luciferase activity expression and this effect was suppressed by co-treatment with the JAK2 inhibitor HEX or STAT5 inhibitor IQDMA (Fig. 7). In this cell model, transfection with increasing levels of the respective expression vectors for carp Socs1–3 and Cish also induced a dose-dependent inhibition on basal as well as GH-induced luciferase activity expression (Fig. 8A). To test whether the effects of type II SOCS were mediated by targeting STAT5 signaling, STAT5 over-expression by transfection with STAT5 pcDNA was performed (Fig. 8B). In this case, a significant rise in luciferase activity expression was noted with STAT5 pcDNA transfection and this stimulatory action was reduced dose-dependently by over-expression of carp Socs1–3 and Cish respectively. Consistent with the role of JAK2/STAT5 in GHR signaling, the effect of STAT5 over-expression on luciferase activity was markedly enhanced by GH, and again, this potentiating effect was also sensitive to the inhibition by over-expression of type II SOCS (Fig. 8C).

Socs1–3 and Cish expression on GH-induced Igf1 promoter activity

In CHO cells with GHR expression, Igf1 promoter activity was examined by transfection with the pGL3.basic reporter carrying a 1.07 kb grass carp Igf1 promoter. In this case, luciferase activity mediated by Igf1 promoter could be induced by GH treatment, and this stimulation was blocked by co-treatment with the JAK2 inhibitor HEX (Fig. 9A) or STAT5 inhibitor IQDMA (Fig. 9B). Similar to the preceding studies with the JAK2/STAT5-responsive
reporter 8×GHRE.LUC, both basal and GH-induced luciferase activity expression mediated by Igf1 promoter could be reduced or negated in a dose-related fashion by co-transfection with increasing levels of the expression vectors for grass carp type II SOCS (Fig. 9C, D, E and F).

Discussion

As a first step to study the role of type II SOCS in GH functions in carp model, Socs1–3 and Cish were cloned in grass carp, and phylogenetic analysis of their cDNA sequences has confirmed that they could be clustered in the clades of respective subfamilies of type II SOCS. As revealed by sequence alignment and protein modeling, the protein structures of Socs1–3 and Cish were found to be highly conserved, especially in the SH2 domain and SOCS box. The spatial arrangement of β-sheets and α-helices forming the two domains in carp Socs1–3 and Cish is highly comparable with their human counterparts. In mammals, SH2 domain is a target recognition motif commonly found in tyrosine kinases and involved in protein–protein interaction with phosphotyrosine residues (Machida & Mayer 2005). Previous studies (e.g., in hepatocytes and lymphocytes) have shown that SH2 domain in SOCS proteins is essential for their association with JAK2 (Machida & Mayer 2005, Liu et al. 2006) and can compete with STAT1, binding for cytokine receptors to inhibit JAK/STAT signaling (Hilton 1999). Similar to SH2 domain, SOCS box also plays a role in SOCS inhibition of cytokine signaling as it can interact with elongin B/C, culin B, and Ring-box 2 to form a complex with E3 ubiquitin ligase activity (Yoshimura et al. 2007) and trigger proteasomal degradation of JAK2 by SOCS binding (Piessevaux et al. 2008a). The presence of structural motifs in grass carp Socs1–3 and Cish mRNA expression. Hepatocytes were incubated with GH (500 ng/mL) for 1 h with/ without co-treatment of JAK, inhibitor HEX (50 µM), STAT, inhibitor FA (50 µM), STAT, inhibitor ETD (300 nM), and STAT, inhibitor IQDMA (50 µM) respectively. After that, total RNA was isolated and used for real-time PCR measurement of socs1–3 and cish mRNA expression.

As revealed by genomic Southern blot, the newly cloned type II SOCS are confirmed to be single-copy genes in the carp genome. Expression profiling using RT-PCR also reveals that Socs1–3 and Cish are widely expressed at tissue level as well as in various brain areas in grass carp. Although the four type II SOCS could all be located in the liver and pituitary by RT-PCR, northern blot signals for the respective transcripts were detected only for Socs1 (7.0 kb) and Socs3 (1.8 kb) but not Socs2 and Cish, suggesting that Socs1 and Socs3 are the major forms of type II SOCS expressed in these two tissues. Recently, tissue expression
of SOCS has also been reported in fish models, including salmon (Skjesol et al. 2014), yellow perch (Shepherd et al. 2012), rainbow trout (Wang & Secombes 2008, Wang et al. 2010), puffer fish (Jin et al. 2007), and turbot (Zhang et al. 2011). Similar to grass carp, SOCS expression was found to be widely expressed, e.g., in the gills, spleen, gut, liver, kidney, muscle, and brain. However, species-specific variations could still be noted. For examples, in rainbow trout, notable levels of SOCS and Cish gene expression could be located in the spleen and kidney with little/low levels of signal found in the liver (Wang & Secombes 2008, Wang et al. 2010). This is different from grass carp, in which Socs1–3 and Cish were readily detectable in the liver; however, Socs1 and Socs2 signals in the spleen and kidney were low/undetectable. The different patterns of type II SOCS expression observed suggest that the functional dominance of individual SOCS may vary at the tissue level among different species. In mammals, hepatic expression of SOCS has also been reported and found to have tumor suppressor activity (Miyoshi et al. 2005) and modulatory effects on liver regeneration (Brand et al. 2007). However, the biological actions of SOCS in the liver of fish species have yet to be characterized.

In mammals, up-regulation of SOCS expression is well documented after microbial/viral infection or cytokine treatment (Strebovsky et al. 2012), and these SOCS responses constitute an intracellular feedback to turn off/tune down cytokine signaling via the JAK/STAT pathway and prevent overshot of proinflammatory activities (Tamiya et al. 2011). Cytokine induction of SOCS can not only be found in immune tissues but also be found in the liver (Tollet-Egnell et al. 1999). The liver not only represents a key component of the somatotropic axis but also an immunological organ for antigen presentation, NK/T cell priming, and production of complement factors (Racanelli & Rehermann 2006). In this study, Socs1–3 and Cish expression, both for transcripts (by RT-PCR & real-time PCR) and proteins (by
Figure 7
JAK/STAT pathway coupled to carp GHR. (A) Functional expression of carp GHR in CHO cells. Stable transfection of CHO cells with the expression vector for grass carp GHR was performed (with parallel transfection of the blank vector as a control). After the line of CHO cells with GHR expression was selected, transient transfection with the JAK/STAT pathway-responsive reporter 8×GHRE-LUC was conducted and GHR activation was induced by GH treatment (500 ng/mL) for 24 h. (B) Blocking JAK/STAT pathway in STAT signaling via GHR expressed in CHO cells. In CHO cells with GHR expression, transient transfection with the STAT-responsive LUC reporter was performed followed by GH induction (500 ng/mL) for 24 h with co-treatment of JAK inhibitor HEX (50 μM) or STAT inhibitor IQDMA (50 μM). In these studies, cell lysate was prepared after drug treatment and used for luciferase activity measurement as described in ‘Materials and methods’ section.

LC/MS/MS), have been confirmed in the carp liver, and mRNA levels of these type II SOCS could be increased in carp hepatocytes by LPS exposure or treatment with IL-1β and TNFα. These findings indicate that hepatic expression of type II SOCS could be induced by endotoxin and cytokines, which may serve as feedback repressors for immune responses occurring in the carp liver. In fish models, LPS/cytokine-induced socs1–3 gene expressions have been reported in the head kidney of puffer fish (Jin et al. 2007) and trout monocytes/macrophages (Wang & Secombes 2008), corroborating with the idea that the role of SOCS as signal terminators for cytokine actions is well conserved in vertebrate evolution (Wang et al. 2011). In carp hepatocytes, GH consistently induced Igf1 mRNA expression in a time- and dose-dependent manner. Of note, down-regulation of Igf1 responses was also observed with high concentration/prolonged exposure to GH, suggesting the presence of intrinsic mechanisms to turn off/tune down GH signaling. As socs1–3 and cish mRNA expression could be elevated by GH treatment in carp hepatocytes and these stimulatory effects occurred before/during Igf1 down-regulation with prolonged incubation with GH, the possible involvement of type II SOCS in signal termination for GH-induced Igf1 expression cannot be excluded. In rodents, hepatic expression of Socs2–3 and Cish can be induced by GH both in vivo and in vitro (Tollet-Egnell et al. 1999, Greenhalgh & Alexander 2004) and deregulation of GH signaling by Socs1–3 has been reported in cell lines, e.g., F442A fibroblasts (Greenhalgh & Alexander 2004). However, direct evidence showing SOCS inhibition of GH-induced Igf1 expression has not been documented.

Although the signal transduction for GH-induced SOCS/CISH expression at the hepatic level is still unknown, Socs2 interaction with GHR (Greenhalgh et al. 2002a) and Socs1 and Socs3 inhibition of JAK2 activation (Hansen et al. 1999) and GH-responsive promoters (Adams et al. 1998) have been reported in various cell models. Recently, down-regulation of GH signaling by SOCS2 via SOCS box-dependent ubiquitination and proteasomal degradation of GHR has been demonstrated in mouse liver (Vesterlund et al. 2011). In our studies, GH treatment induced rapid phosphorylation of JAK2, STAT1, STAT3, MEK1/2, ERK1/2, and P38MAPK in carp hepatocytes. Furthermore, GH-induced socs1–3 and cish mRNA expression was also sensitive to the blockade of JAK2 (by HEX), STAT1 (by FA), STAT3 (by ETDDC), STAT5 (by IQDMA), MEK1/2 (by U0126), and P38MAPK (by PD169316), implying that GH-induced type II SOCS expression in the carp liver is mediated by JAK2/STATs and MAPK cascades. Although Akt phosphorylation was also noted after GH induction, except for the drop in transcript level for socs3, GH-induced socs1–2, and cish mRNA expression were not affected by blocking PI3K (by Ly294002) or Akt (by H110). Apparently, the PI3K/Akt pathway is involved in GH-induced socs3, but not socs1–2 and cish gene expression. Our results are consistent with GHR coupling to JAK2/STATs, MAPK, and PI3K/Akt signaling reported in mammals (Miuet et al. 2010). Recently, GH activation of STAT5, ERK1/2, and Akt and their involvement in GH-induced Igf1 expression have also been demonstrated in trout hepatocytes (Reindl et al. 2011). To our knowledge, our study represents the first report to elucidate the post-receptor signaling for GH-induced type II SOCS expression at the hepatic level.

In mammals, SOCS expression induced by cytokines is known to inhibit STAT1 activation as well as transcription of STAT-responsive genes, e.g., ALS and Spil-2.1 genes (Adams et al. 1998, Boisclair et al. 2000). As the JAK2/STAT5 pathway is also a key component of the post-receptor signaling for GH-induced Igf1 expression at the hepatic level (Choi & Waxman 2000, Davey et al. 2001), it would be logical to assume that SOCS expression could also down-regulate GH-induced Igf1 gene transcription via interference of JAK2/STAT5 signaling. In CHO cells...
Type II SOCS expression in GH-induced Igf1 expression

with the expression of carp GHR. GH treatment or STAT3 over-expression was effective in activating a JAK2/STAT3-responsive reporter with GHR-responsive elements in its 5' promoter and the stimulatory effect by GH could be markedly enhanced by STAT3 over-expression. These stimulatory actions, however, could be dose dependently suppressed by over-expression of grass carp Socs1–3 and Cish. As GH activation of the JAK2/STAT3-responsive reporter could be consistently inhibited by blocking JAK2 (by HEX) and STAT3 (by IQDMA) in our system, our results suggest that type II SOCS expression in carp model can inhibit JAK2/STAT3 signaling coupled to GHR. Our findings are comparable to the previous studies in 3T3-F442A cells, in which GH-induced activation of STAT3-responsive Spi-2.1 promoter could be negated by Socs1 and Socs3 over-expression (Adams et al. 1998). To examine the role of type II SOCS on GH-induced Igf1 expression in fish model, the full gene of grass carp igf1 was cloned and a well-conserved STAT3 binding site was mapped in close proximity to a HNF1α binding site located in its proximal promoter region (A O L Wong & W W Wong, unpublished data). Similar bipartite pattern of STAT3 and HNF1α binding sites has also been reported in Igf1 promoter of common carp (Vong et al. 2003) and salmon (Moghadam et al. 2007), implying that gene transcription of igf1 in fish models is also responsive to STAT3 signaling. This idea is also consistent with our studies in CHO cells with GHR expression transfected with a luciferase-expressing reporter 8×GHRE.LUC with/without co-transfection of increasing amount of the expression vectors for carp Socs1–3 and Cish respectively. Treatment was initiated for 24 h with (A) static incubation with GH (500 ng/mL), (B) over-expression of STAT3, by co-transfection with STAT3 expression vector, and (C) STAT3 over-expression with GH treatment (500 ng/mL). After that, cell lysate was prepared from CHO cells and assayed for luciferase activity as an index for JAK2/STAT3 reporter activation as described in ‘Materials and methods’ section.
Type II SOCS expression on Igf1 promoter activation via JAK2/STAT5 signaling coupled to GHR. CHO cells with GHR expression were transfected with pGL3.basic carrying the 5’ promoter of grass carp igf1 gene. The cells were then challenged with GH (500 ng/mL) in the presence of (A) the JAK2 inhibitor HEX, (B) the STAT5 inhibitor IQDMA, or (C, D, E and F) with co-transfection of increasing amount of the expression vectors for carp Socs1–3 and Cish respectively. After 24-h treatment, lysate was prepared from CHO cells and assayed for luciferase activity as an index for Igf1 promoter activation as described in ‘Materials and methods’ section.

Figure 9

Both basal and GH-induced Igf1 promoter activity could be suppressed in a dose-related manner by over-expression of Socs1–3 and Cish. These results, as a whole, provide evidence for the first time that type II SOCS expression was effective in blocking GH-induced igf1 gene transcription via inhibition of JAK2/STAT5 signaling.

In summary, we have cloned the type II SOCS, including Socs1–3 and Cish, in grass carp and characterized their gene copy number and tissue expression profiles. In carp hepatocytes, GH treatment could induce transcript expression of these type II SOCS via JAK2/STAT5, MAPK, and/or PI3K/Akt cascades, and these effects were shown to occur before/during Igf1 down-regulation induced by prolonged exposure to GH. In CHO cells with GHR expression, GH could not only activate JAK2/STAT5 signaling but also up-regulate grass carp Igf1 promoter activity. These stimulatory actions, however, could be suppressed by over-expression of carp Socs1–3 and Cish. These findings, taken together, suggest that type II SOCS may serve as feedback repressors for GH activation of JAK2/STAT5 signaling and igf1 gene transcription in carp hepatocytes.

Figure 10

Working model for GH-induced type II SOCS expression and their effects on JAK2/STATs, signaling and igf1 gene transcription in carp hepatocytes. In carp hepatocytes, GH stimulation can induce gene expression of type II SOCS including Socs1–3 and Cish via JAK2/STATs, MAPK and/or PI3K/Akt cascades functionally coupled to GHR. The JAK2/STATs pathway is also a major component in the post-receptor signal transduction for GH-induced Igf1 promoter activation and gene expression. Subsequent protein translation following the rises of type II SOCS mRNA induced by GH could elevate the levels of corresponding SOCS proteins in carp hepatocytes, which may serve as the intracellular feedback repressors to inhibit JAK2/STATs pathway and lead to the down-regulation of Igf1 promoter activity and igf1 gene transcription occurred during the prolonged period of GHR activation. This intracellular feedback may constitute the intrinsic mechanisms acting at the hepatic level for signal termination of GH in the somatotropic axis in carp species.
between immune system and somatotropic axis in fish model. As GH resistance caused by bacterial/viral infection is known to compromise the overall productivity of fish farming, our findings may have potential application in developing new strategy targeting type II SOCS expression for growth promotion in commercial fish.

Supplementary data
This is linked to the online version of the paper at http://dx.doi.org/10.1530/JOE-15-0423.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

Author contribution statement
X J and J X were responsible for molecular cloning, gene copy number determination, tissue distribution, and transcript expression for grass carp type II SOCS; A M was in charge of hepatocyte preparation and GH-induced Igf1 gene expression; M H took care of LC/MS/MS for protein expression of type II SOCS and Western blot for signaling kinases; A O L W was the PI and grant holder, and worked with X J on manuscript preparation and revision.

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