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

Xue Jiang, Jia Xiao, Mulan He, Ani Ma and Anderson O L Wong
School of Biological Sciences, University of Hong Kong, Pokfulam, Hong Kong

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...
et al. 2003, Cheng et al. 2009). 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 (Liang et al. 2014). 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) JAK2/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 (Metcalf 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 JAK2/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 idella) 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 spinoectomy according to the protocol approved for animal use at the University of Hong Kong. Test substances, including porcine GH, IL-1β, TNFα, 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-dimethylamine-1,2-diamine (IQDMA), P₃₈ MAPK inhibitor PD169316, MEK1/2 inhibitor U0126, PI3K inhibitor LY294002, and protein kinase B (Akt) inhibitor 1L6-hydroxymethylchiro-inositol-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>
<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>socs1/GU224284</td>
<td>F: 5'-CAGACAGCCAGCCATT-3'</td>
<td>94°C</td>
<td>55°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5'-GACCCGTTGCTCTCTTGT-3'</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>socs2/G478990</td>
<td>F: 5'-CGTCCGAGGGCACTTC-3'</td>
<td>94°C</td>
<td>55°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5'-CGGACTGCTGACACAG-3'</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>socs3/EU625352</td>
<td>F: 5'-GGTCCGAGATATGTTAGA-3'</td>
<td>94°C</td>
<td>55°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5'-CAGTGTGCTTGATGACAGTGTA-3'</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>cish/GU384205</td>
<td>F: 5'-AGAGCTTATTTGGTGTAC-3'</td>
<td>94°C</td>
<td>58°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5'-GGAAGCGTCAGACCTT-3'</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
<tr>
<td>β-actin/M25013</td>
<td>F: 5'-AGCTCATAGCCTTCTCCAG-3'</td>
<td>94°C</td>
<td>56°C</td>
<td>72°C</td>
</tr>
<tr>
<td>R: 5'-AGCTCATAGCCTTCTCCAG-3'</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
<td>30 s</td>
</tr>
</tbody>
</table>
Measurement of socs1–3 and cish mRNA expression in carp hepatocytes

Carp hepatocytes (with >95% viability) were prepared by collagenase digestion (Reindl et al. 2011), seeded in 24-well plates at ~0.7 × 10^6 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 PI3KAkt 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 STAT 5.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/10^6 cells/well. As 18S RNA did not exhibit notable changes

### Table 2

<table>
<thead>
<tr>
<th>Gene target</th>
<th>Primer sequence</th>
<th>PCR condition</th>
<th>Product size and Tm value</th>
</tr>
</thead>
<tbody>
<tr>
<td>socs1</td>
<td>F: 5′-CAGCAGGGGCAACCATTT-3′ R: 5′-GACCTGTGGTCTCTTGT-3′</td>
<td>94°C 49°C 72°C 80°C 35 232 bp and 83.1°C</td>
<td></td>
</tr>
<tr>
<td>socs2</td>
<td>F: 5′-CGTCGGAGGACACCATTT-3′ R: 5′-GGAGTAGCTGTAGCAG-3′</td>
<td>94°C 55°C 72°C 82°C 35 280 bp and 86.1°C</td>
<td></td>
</tr>
<tr>
<td>socs3</td>
<td>F: 5′-GTCGCG AGATATGGTGAATG-3′ R: 5′-CAGTGTTCTGTAGCAAGGTG-3′</td>
<td>94°C 55°C 72°C 82°C 35 240 bp and 84.8°C</td>
<td></td>
</tr>
<tr>
<td>cish</td>
<td>F: 5′-AGACGTCAATTATGTGATACT-3′ R: 5′-GGAAACGTCGCCGACTGACT-3′</td>
<td>94°C 58°C 72°C 84°C 35 328 bp and 85.2°C</td>
<td></td>
</tr>
<tr>
<td>igf1</td>
<td>F: 5′-TCTCAGCTGGTGCTGCTCT-3′ R: 5′-GGCTGTGAAAGGATGTCCTGC-3′</td>
<td>94°C 65°C 72°C 84°C 40 203 bp and 87.5°C</td>
<td></td>
</tr>
<tr>
<td>18S</td>
<td>F: 5′-AGCAACTTATTGATAACTT-3′ R: 5′-CTGAGAAACGGCTACCCATC-3′</td>
<td>94°C 64°C 72°C 79°C 40 210 bp and 85.0°C</td>
<td></td>
</tr>
</tbody>
</table>

http://joe.endocrinology-journals.org
DOI: 10.1530/JOE-15-0423
© 2016 Society for Endocrinology
Printed in Great Britain

Published by Bioscientifica Ltd.
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 \( sos\)–3 and \( c\)ish 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 BgIII, Xbal, BgII, StyII, and EcoR V, 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; however, hybridization signals were not apparent for Socs2 and Cish. Using RT-PCR, Socs3 and Cish signals were located ubiquitously in tissues including the gills, liver, kidney, gonad, intestine, spleen, pituitary, and heart as well as in brain areas including the olfactory bulbs, telencephalon, optic tectum, hypothalamus, cerebellum, medulla oblongata, and spinal cord (Fig. 2C). Similar findings were also noted for Socs1 and Socs2, except that Socs1 was not detected in the spleen and Socs2 signals could not be identified in the kidney, intestine, spleen, and telencephalon.

To confirm that type II SOCS are also expressed at the protein level, LC/MS/MS was performed in trypsin-digested lysate prepared from the carp liver (Supplemental Fig. 4A, B, C and D). Proteomic analysis of mass spectra of peptide fragments produced after trypsin digestion has 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

JAK2 inhibitor HEX, STAT 1 inhibitor FA, STAT 3 inhibitor ETDDC, or STAT5 inhibitor IQDMA (Fig. 5B). In these cases, attenuated or negated by the inhibitors targeting JAK 2/STAT 5 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/STAT3 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/STAT3-responsive reporter 8×GHRE.LUC, GH treatment could induce luciferase activity expression and this effect was suppressed by co-treatment with the JAK2 inhibitor HEX or STAT3 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 STAT3 signaling, STAT3 over-expression by transfection with STAT3.pcDNA was performed (Fig. 8B). In this case, a significant rise in luciferase activity expression was noted with STAT3.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/STAT3 in GHR signaling, the effect of STAT3 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 was blocked by co-treatment with the JAK2 inhibitor HEX (Fig. 9A) or STAT3 inhibitor IQDMA (Fig. 9B). Similar to the preceding studies with the JAK2/STAT3-responsive
Type II SOCS in GH-induced Igf1 expression

A

B

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 JAK2/STAT1 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 JAK2 inhibitor HEX (50 µM), STAT1 inhibitor FA (50 µM), STAT3 inhibitor ETDDC (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 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).
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. 2012), rainbow trout (Wang & Secombes 2008, Wang et al. 2014), yellow perch (Shepherd et al. 2007), and turbot (Zhang et al. 2007). This is different from grass carp, in which 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 Western blotting of \( \beta \)-actin as internal control) were quantified as the ratio of p- and t-form of the same protein (as ‘p:t ratio’). (B) Blocking MAPK and PI3K/Akt pathways on GH-induced Socs1–3 and Cish mRNA expression. Hepatocytes were challenged with GH (500 ng/mL) for 1 h without co-treatment of the MEK1/2 inhibitor U0126 (10 µM), P38MAPK inhibitor PD169316 (10 µM), PI3K inhibitor Ly294002 (10 µM), and Akt inhibitor HIMOC (20 µM) respectively. After that, total RNA was isolated and subjected to real-time PCR for quantitation of the respective transcripts of type II SOCS.

DOI: 10.1530/JOE-15-0423
http://joe.endocrinology-journals.org © 2016 Society for Endocrinology
Published by Bioscientifica Ltd.
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 JAK1/STAT1-responsive reporter 8xGHRE. LUC was conducted and GHR activation was induced by GH treatment (500 ng/mL) for 24 h. (B) Blocking JAK/STAT pathway in STAT1 signaling via GHR expressed in CHO cells. In CHO cells with GHR expression, transient transfection with the STAT1-responsive LUC reporter was performed followed by GHR induction (500 ng/mL) for 24 h with co-treatment of JAK1 inhibitor HEX (50 μM) or STAT1 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.

Type II SOCS in GH-induced Igf1 expression
with the expression of carp GHR, GH treatment or STAT3 over-expression was effective in activating a JAK2/STAT5-responsive reporter with GHR-responsive elements in its 5' promoter and the stimulatory effect by GH could be markedly enhanced by STAT5 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/STAT5-responsive reporter could be consistently inhibited by blocking JAK2 (by HEX) and STAT5 (by IQDMA) in our system, our results suggest that type II SOCS expression in carp model can inhibit JAK2/STAT5 signaling coupled to GHR. Our findings are comparable to the previous studies in 3T3-F442A cells, in which GH-induced activation of STAT5-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 STAT5 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 STAT5 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 STAT5 signaling. This idea is also consistent with our studies in CHO cells with GHR expression transfected with a luciferase-expressing reporter carrying the 1.07 kb grass carp Igf1 promoter. In this case, GH-induced Igf1 promoter activity could be reduced or negated by inhibiting JAK2 (by HEX) or STAT5 (by IQDMA), implying that JAK2/STAT5 pathway is involved in GH-induced igf1 gene transcription in carp model. Similar to our studies with JAK2/STAT5 reporter,
Type II SOCS in GH-induced Igf1 expression

X. JIANG and others

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 GH-induced 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.

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 JAK/STATs, 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 JAK/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 JAK/STATs signaling and igf1 gene transcription in the carp liver (Fig. 10). Probably, GHR activation could induce igf1 and type II SOCS gene expression via overlapping signal transduction pathways, and the subsequent rises in SOCS proteins might act as the negative feedback signals to inhibit GH-induced Igf1 expression at hepatic level. Whether type II SOCS can also contribute to the pulsatile pattern of Igf1 expression induced by GH (e.g., in rodents, Choi & Waxman 2000) is still unclear; however, our studies do provide (i) the evidence for the presence of an intracellular feedback for signal termination of GH in the carp liver and (ii) a new insight into the possible cross talk
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](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.

**Funding**
The project was supported by GRF Grants (780312, 781113, and 17128215) and NSFC/RGC Joint Research Scheme (N_HKU732/12) from the Research Grant Council, Hong Kong (to AOLW).

**Author contribution statement**
X J and X J 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 expression; A O L W was the PI and grant holder, and worked with X J on manuscript preparation and revision.

**Acknowledgements**
Financial support from School of Biological Sciences (University of Hong Kong, Hong Kong) in the form of postgraduate studentship (to X J, J X, and A M) is also acknowledged. We also thank Peter S Rotwein (Oregon Health and Science University, Portland, OR, USA) for sending us the JAK/STAT-responsive reporter and STAT, expression vector for testing of the functionality of type II SOCS expression in CHO cells.

**References**


Received in final form 8 February 2016
Accepted 14 March 2016
Accepted Preprint published online 14 March 2016