Glutamate ameliorates copper-induced oxidative injury by regulating antioxidant defences in fish intestine

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(Submitted 26 September 2015 – Final revision received 8 March 2016 – Accepted 23 March 2016)

Abstract
The objective of this study was to determine the protective effect of glutamate (Glu) in Cu-induced oxidative injury in fish intestine in vitro and enterocytes in vivo. The results indicated that exposure to 6 mg/l Cu for 72 h induced the production of reactive oxygen species, thereby increasing protein oxidation and lipid peroxidation in enterocytes of grass carp in vitro. Cells exposed to Cu alone resulted in a significant increase in lactate dehydrogenase release, which is accompanied by depletions of antioxidants, including total superoxide dismutase (T-SOD), glutathione S-transferase (GST), glutathione reductase (GR), anti-superoxide anion (ASA), anti-hydroxy radical (AHR) activities and GSH content. Pre-treatment with Glu remarkably prevented the toxic effects of Cu on the T-SOD, GST, GR, AHR, and ASA activities and GSH content in enterocytes. However, Cu induced an adaptive increase in the activities of catalase and glutathione peroxidase (GPx). Glu supplementation further increased GPx activity in enterocytes. Interestingly, the experiment in vivo showed that Glu pre-supplementation significantly elevated SOD, GPx, GST, GR, ASA and AHR activities, as well as GSH content. Further results showed that pre-treatment with Glu could alleviate Cu-induced oxidative injury by elevating antioxidant enzyme activities through regulating the expression of NF-E2-related nuclear factor 2 (Nrf2) mRNA. Together, these results indicated that Glu could attenuate Cu-induced cellular oxidative damage in fish intestine, likely mediated through Nrf2 signalling pathways regulating mRNA expressions of antioxidant enzyme genes and synthesis of GSH.

Key words: Glutamate; Copper; Oxidative injury; Antioxidants; NF-E2-related nuclear factor 2; Intestine

α-L-Glutamate (Glu) is a non-essential amino acid with versatile functions in animal physiology and metabolism(1–3). Glu has an important role in the amino acid metabolism through its conversion to α-ketoglutarate or other amino acids, including alanine, aspartate, ornithine and proline in intestine(2,3). Thus, Glu can serve both locally inside enterocytes and through the production of other amino acids in an interorgan metabolic perspective(2). In addition, Glu is a key transamination partner and is required for the synthesis of GSH, which is an important component in the defence against oxidative stress(4–6). Our previous studies demonstrated that dietary Glu supplementation increased intestinal anti-superoxide anion (ASA), anti-hydroxy radical (AHR), glutathione reductase (GR), catalase (CAT) and total superoxide dismutase (T-SOD) activities, and GSH content in grass carp Ctenopharyngodon idella(5), improved antioxidant capacity and regulated antioxidant-related signalling molecule expression of fish enterocytes(6). Sivakumar et al.(7) reported that Glu alleviated isoproterenol-induced oxidative stress in rats by increasing antioxidant enzyme activities and GSH content from exogenous Glu. These results suggested that Glu could offer protection during intestinal oxidative stress.

Cu is known for its essentiality for living organisms, including fish, which is required for maintaining cellular function and acting as a cofactor for a number of key metabolic enzymes(8,9). Nevertheless, Cu is one of the most important pollution-causing metals, because it is commonly released into the environment through industrial wastes and used in the form of copper

Abbreviations: AHR, anti-hydroxy radical; AKP, alkaline phosphatase; ASA, anti-superoxide anion; CAT, catalase; DMEM, Dulbecco’s Modified Eagle’s Medium; Glu, glutamate; GPx, glutathione peroxidase; GR, glutathione reductase; GST, glutathione S-transferase; LDH, lactate dehydrogenase; MDA, malondialdehyde; MTS, 5-(5-(tetramethylthiazol-2-yl)-2-(5-carboxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium; Nrf2, NF-E2-related nuclear factor 2; OD, optical density; PC, protein carbonyl; ROS, reactive oxygen species; SOD, superoxide dismutase.

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sulphate as algaecide, fungicide, bactericide and herbicide. In fish culture systems, Cu is regularly used in the form of copper sulphate (CuSO₄) to control algal blooms and aquatic macrophyte infestations. Recently, aquatic organisms may suffer from exposure to Cu concentrations that might be ten to fifty times higher than the required concentrations. The danger of Cu is aggravated by their almost indefinite persistence in water because they cannot be destroyed biologically but are only transformed from one state to another. Also, high concentrations of waterborne Cu can be toxic, because perturbations in Cu homeostasis result in oxidative stress and increased free-radical production. The intestine is very sensitive to a wide range of stressors. The recent reports show that the intestine is a major target for waterborne Cu toxicity in both freshwater and seaweed fish. Although Cu uptake is via gills, Cu exposure highly elevates fish intestinal Cu load. In grass carp, accumulation of Cu in intestine is higher than that in gill. Our previous study demonstrated that Cu exposure could induce oxidative stress in intestine and the enterocytes of juvenile Jian carp Cyprinus carpio var. Jian. However, few studies examined how to efficiently protect the intestine against Cu-induced oxidative damage. Given the increasing release of Cu into the environment and its potentially harmful effects on the intestine, it is important to expand our knowledge of how to protect fish against Cu toxicity. Some nutrients could prevent Cu-induced oxidative damage and change antioxidant capacity in fish enterocytes.

Piscine antioxidant capacity can be assessed by the content of non-enzymatic compounds (e.g. GSH) and activities of antioxidant enzymes including superoxide dismutase (SOD), CAT and glutathione peroxidase (GPx), glutathione S-transferase (GST) and GR. These antioxidant compounds and enzymes have key roles in eliminating the reactive oxygen species (ROS) in fish. ROS are generated during normal cellular function, but high doses and/or inadequate removal of ROS results in oxidative stress that may cause severe metabolic malfunctions and impair cell health status. NF-E2-related nuclear factor 2 (Nrf2) is an important transcription factor that can bind to the antioxidant responsive element (ARE) and induce transcription of antioxidant enzymes genes. Kelch-like ECH-associated protein 1 (Keap1) was identified as an Nrf2-binding protein, which depresses Nrf2 translocation to the nucleus. Our previous report showed that antioxidant enzyme activities were regulated by the Nrf2 and Keap1 signalling molecules in fish. Our recent study showed that Glu could regulate Nrf2 and Keap1a gene expression, might mediating the signal transduction involved in increased gene expressions of antioxidant enzymes in fish enterocytes.

The present study was designed to investigate whether Glu could attenuate Cu-induced cellular oxidative damage, mediating through Nrf2 signalling pathways regulating mRNA expressions of antioxidant enzymes genes and synthesis of GSH in fish intestine.

### Methods

#### In vivo experiments

**Animal collection and acclimation conditions.** Animal Care advisory Committee of Sichuan Agricultural University specifically approved this study. Yong grass carp were obtained from Tong Wei fisheries and acclimated for 4 weeks. Dissolved O₂ was not <6 mg/l. Water temperature and pH were 24 (SEM 3) °C and 7.5 (SEM 0.5), respectively.

**Protective effect of glutamate in copper-induced oxidative stress in the intestine.** The formulations of the basal and experimental diets (Table 1) were similar as in our previous study. In brief, it contained 280 g of crude protein/kg diet. The basal diet was Glu unsupplemented control (Ctrl). Glu was added to the basal diet to provide 8 g Glu/kg diet, which was the required Glu concentration for optimal growth established by our previous study. Procedures for diet preparation and storage were the same as those described by Shiau & Su. A total of 180 fish with an average initial weight of 247 (SEM 7.5) g from the acclimation tank were randomly assigned into two groups of three replicates each. The groups were fed either the Ctrl diet or the Glu diet for 56 d. The experimental conditions were the same as in our previous study.

At the end of the feeding trial, the fish in each tank were weighed and collected for Cu exposure. Fish with a similar body weight from both the Ctrl and Glu groups were exposed to 0.7 mg Cu/l water for 96 h, which has been proved to induce oxidative stress in grass carp according to our previous study.

#### Table 1. Feed formulation and chemical composition of diets

<table>
<thead>
<tr>
<th>Diets</th>
<th>Ctrl group</th>
<th>Glu group</th>
<th>Ctrl group</th>
<th>Glu group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formulation (g/kg diet)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soyabean meal</td>
<td>200</td>
<td>200</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>Rapeseed meal</td>
<td>220</td>
<td>220</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Cotton meal</td>
<td>92</td>
<td>92</td>
<td>9.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Wheat flour</td>
<td>424</td>
<td>416</td>
<td>9.2</td>
<td>9.3</td>
</tr>
<tr>
<td>Soya oil</td>
<td>10</td>
<td>10</td>
<td>15.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Monocalcium phosphate</td>
<td>18</td>
<td>18</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Choline chloride</td>
<td>6</td>
<td>6</td>
<td>8.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Vitamin premix*</td>
<td>10</td>
<td>10</td>
<td>4.8</td>
<td>9.2</td>
</tr>
<tr>
<td>Mineral premix†</td>
<td>20</td>
<td>20</td>
<td>11.8</td>
<td>11.6</td>
</tr>
<tr>
<td>L-Glu</td>
<td>0</td>
<td>8</td>
<td>40.5</td>
<td>47.4</td>
</tr>
</tbody>
</table>

**Analysed chemical composition (g/kg DM)**

<table>
<thead>
<tr>
<th>Proximate nutrients</th>
<th>Cly</th>
<th>Prox</th>
<th>Cly</th>
<th>Prox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude protein</td>
<td>266</td>
<td>277</td>
<td>13.4</td>
<td>13.5</td>
</tr>
<tr>
<td>Crude lipid</td>
<td>37.5</td>
<td>37.2</td>
<td>12.5</td>
<td>12.3</td>
</tr>
<tr>
<td>Crude ash</td>
<td>73.1</td>
<td>74.1</td>
<td>5.5</td>
<td>5.9</td>
</tr>
</tbody>
</table>

1. Vitamin premix (g/kg): retinyl acetate (150 g/kg), 0.80 g; cholecalciferol (12.5 g/kg), 0.48 g; D-α-tocopheryl acetate (500 g/kg), 2000 g; menadione (230 g/kg), 0.22 g; thiamine hydrochloride (980 g/kg), 0.12 g; riboflavin (800 g/kg), 0.99 g; pyridoxine hydrochloride (980 g/kg), 0.62 g; cyanocobalamin (10 g/kg), 0.10 g; niacin (990 g/kg), 2.58 g; α-tocopherol (20 g/kg), 5.00 g; meso-inositol (990 g/kg), 52.33 g; folic acid (960 g/kg), 0.52 g; ascorbic acid (930 g/kg), 7.16 g; calcium-D-pantothenate (900 g/kg), 2.78 g. All ingredients were diluted with maize starch to 1 kg.

2. Mineral premix (g/kg): FeSO₄.7H₂O, 25.00 g; CuSO₄.5H₂O, 0.60 g; ZnSO₄.7H₂O, 4.35 g; MnSO₄.H₂O, 2.04 g; KI, 1.10 g; NaSeO₃, 2.50 g; MgSO₄.7H₂O, 230.67 g. All ingredients were diluted with CaCO₃ to 1 kg.
In addition, the Ctrl/Ctrl treatment (fish from the Ctrl) was performed by exposing the fish from the Glu unsupplemented group to Cu-free water. Therefore, there were three different pre-treatment/exposure groups, Ctrl/Ctrl, Ctrl/Cu and Glu/Cu, with three replicates per group and twelve fish per replicate (thirty-six fish for each group) (Fig. 1). During the Cu exposure period in replicates, the experimental conditions were the same as those in the growth trial, but no food was provided and the water was not renewed\(^{16}\). At the end of the challenge trial, all of those in the growth trial, but no food was provided and the period in replicates, the experimental conditions were the same exposure, it was not necessary to empty the intestinal lumen\(^{32}\). Therefore, there were three different groups to Cu-free water. Therefore, there were three different pre-treatment/Cu exposure: Ctrl/Ctrl, Ctrl/Cu, 2mmol/l Glu/Cu, 4mmol/l Glu/Cu, 6mmol/l Glu/Cu, 8mmol/l Glu/Cu, 10mmol/l Glu/Cu and 12mmol/l Glu/Cu. At the end of the exposure, the MTS assay was performed. Cytotoxicity was determined by measuring lactate dehydrogenase (LDH) activity and malondialdehyde (MDA) in the culture media supernatants. Cell lysates were collected to detect protein carbonyl (PC) and GSH contents, alkaline phosphatase (AKP), ASA, AHR, SOD, CAT, GPx, GST and GR activities, and CAT, GPx, GST, GR, Nrf2 and Keap1a mRNA expression.

**Analysis and measurement**

**Cell viability and differentiation assays.** Cell viability in vivo experiments were quantified using the CellTiter 96\(^{®}\) AQueous One Solution cell proliferation assay kit (Promega). In brief, at the end of the experiment, 40 μl of MTS working solution was added to each well. After incubation for 2h, the amount of formazan was determined by measuring the optical density (OD) at 490 nm on a plate reader (Wellscan MK3; Labsystems). AKP activity was assayed according to Krogdahl et al.\(^{35}\). Lactate dehydrogenase, malondialdehyde, protein carbonyl and antioxidant parameter analysis. Cu-induced cytotoxicity was quantified by measuring the amounts of LDH released into the culture medium from injured cell in vitro experiments\(^{26,37}\). The amount of LDH released was measured using the method of Muller et al.\(^{50}\). MDA content was analysed as described by Zhang et al.\(^{39}\) using the thiobarbituric acid reaction. The content of PC was determined according to the method described by Armenteros et al.\(^{40}\) using 2,4-dinitrophenylhydrazine reagent. The activities of SOD, CAT and GPx were determined by the method described by Chen et al.\(^{26}\). GST and GR activities were measured by the method described by Pandey et al.\(^{41}\) with minor modification. GSH contents were determined by using the method described by Chen et al.\(^{26}\) with a minor modification. The method is based on the formation of yellow colour when dithio nitrobenzoic acid reacts with compounds containing sulphydryl groups. The amount of GSH was expressed as nmol of GSH per mg protein. ASA (anti-superoxide anion) and AHR (anti-hydroxy radical) activities were assayed according to the method described by Jiang et al.\(^{42}\).

ASA was determined using the Superoxide Anion Free Radical Detection Kit (Nanjing Jiancheng Bioengineering Institute).
Superoxide anion (O$_2^-$) were generated by the action of xanthine and xanthine oxidase. When the electron acceptor added, a coloration reaction is developed using the nitro blue tetrazolium. The coloration degree is directly proportional to the quantity of superoxide anion in the reaction. If the sample has anti-superoxide anion activity, the superoxide anion in the reaction will decrease, so the coloration will be week; if the sample can promote the production of superoxide anion, the coloration will be strong. The superoxide anion can be measured by colorimetry, and then ASA of the homogenate was calculated by the following formula: 

\[
ASA = \frac{(OD_{\text{control}} - OD_{\text{blank}}) \times V_C}{OD_{\text{standard}} - OD_{\text{blank}}} 
\]

where $OD_{\text{control}}$ and $OD_{\text{blank}}$ are the absorbance readings of the control and blank samples, respectively, $V_C$ is the volume of the sample, and $OD_{\text{standard}}$ and $OD_{\text{blank}}$ are the absorbance readings of the standard H$_2$O$_2$ concentration.

AHR was determined using the Hydroxyl Radical Detection Kit (Nanjing Jiancheng Bioengineering Institute). It was on the basis of Fenton reaction (Fe$^{2+}$ + H$_2$O$_2$ → Fe$^{3+}$ + OH$^-$/OH). According to the principle, hydroxyl radicals are generated by Fenton reaction. When the electron acceptor added, a coloration reaction is developed using the nitro blue tetrazolium. The coloration degree is directly proportional to the quantity of hydroxyl radicals in the reaction. If the sample has anti-hydroxy radical activity, the hydroxyl radicals in the reaction will decrease, so the coloration will be weak; if the sample has anti-superoxide anion activity, the superoxide anion in the reaction will decrease, so the coloration will be week; if the sample can promote the production of superoxide anion, the coloration will be strong.

Table 2. The primers and annealing temperatures used in real-time quantitative PCR

<table>
<thead>
<tr>
<th>Names</th>
<th>Sequence (5′–3′)</th>
<th>Annealing temperature (°C)</th>
<th>GenBank ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAT</td>
<td>QF-GGAATTCTACACCGATGAGG CR-CCAGAAATCCCCAACCAT</td>
<td>58.7</td>
<td>FJ560431</td>
</tr>
<tr>
<td>GR</td>
<td>QF-GTTGTCACCTTCTCTCGTG OR-ATCTTGAGGTGCTCAAAACGC</td>
<td>59.4</td>
<td>JX854448</td>
</tr>
<tr>
<td>GPx</td>
<td>QF-GGCTCTGTTATTCGTGCG OR-AGGCCATGTCATTCCTTGTC</td>
<td>61.5</td>
<td>EU828796</td>
</tr>
<tr>
<td>GST</td>
<td>QF-TCTCAAGGAAACCGCTG OR-CAAGATTCGCTCCCAAAAC</td>
<td>58.4</td>
<td>EU107283</td>
</tr>
<tr>
<td>Nrf2</td>
<td>QF-CTGGAGGAGGAGCTGGA OR-ATCGTGCTGAGGTGGAAC</td>
<td>62.5</td>
<td>KF733814</td>
</tr>
<tr>
<td>Keap1a</td>
<td>QF-TTCCACGCCTCCTACA OR-TGACTCCTCCCGCTGAT</td>
<td>63.0</td>
<td>KF811013</td>
</tr>
<tr>
<td>β-Actin</td>
<td>QF-GGCTGTGCGTCTCCTGTA OR-GGCCATACCCCTCCTGTA</td>
<td>61.4</td>
<td>M25013</td>
</tr>
</tbody>
</table>

CAT, catalase; GR, glutathione reductase; GPx, glutathione peroxidase; GST, glutathione S-transferase; Nrf2, NF-E2-related nuclear factor 2; Keap1, Kelch-like ECH-associated protein 1.

Statistical analysis

A $t$ test was used for comparisons between two groups in the growth trial. The other data were analysed by one-way ANOVA using SPSS 13.0 (SPSS Inc.). Duncan’s multiple-range test was used to determine significant differences. Data are presented as means with their standard errors. $P<0.05$ was considered to be statistically significant.

Results

Glutamate prevented copper-induced oxidative damage of the intestine in vivo

Dietary supplementation with Glu significantly increased the growth of grass carp when compared with the Ctrl group – final weight: 614 (sae 12.2) g: 560 (sae 5.6) g ($P<0.05$). The effects of Glu on MDA, PC, SOD, CAT, GPx, GST, GR, ASA, AHR and GSH contents in intestine of grass carp under Cu exposure are
Table 3. Malondialdehyde (MDA), protein carbonyl (PC) and GSH contents (nmol/mg protein), anti-superoxide anion (ASA), anti-hydroxy radical (AHR), superoxide dismutase (SOD), catalase (CAT), glutathione peroxidase (GPx), glutathione S-transferase (GST), glutathione reductase (GR) activities (U/mg protein) in the intestine of grass carp-fed diets containing different glutamate levels for 56 d, followed by exposure to 0.7 mg/l Cu for 96 h (Mean values with their standard errors, n 6)

<table>
<thead>
<tr>
<th>Groups</th>
<th>MDA Mean SEM</th>
<th>PC Mean SEM</th>
<th>ASA Mean SEM</th>
<th>AHR Mean SEM</th>
<th>SOD Mean SEM</th>
<th>CAT Mean SEM</th>
<th>GPx Mean SEM</th>
<th>GST Mean SEM</th>
<th>GR Mean SEM</th>
<th>GSH Mean SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctrl/Ctrl</td>
<td>1.50a 0.08</td>
<td>2.76b 0.14</td>
<td>358c 13.4</td>
<td>531c 11.7</td>
<td>62.5c 2.9</td>
<td>50.7c 3.3</td>
<td>93.6c 4.6</td>
<td>191b 15.1</td>
<td>106b 11.5</td>
<td>132c 1.4</td>
</tr>
<tr>
<td>Ctrl/Cu</td>
<td>2.59c 0.12</td>
<td>3.72b 0.18</td>
<td>261a 13.0</td>
<td>310a 15.2</td>
<td>41.8a 4.0</td>
<td>67.0b 2.7</td>
<td>58.9b 5.5</td>
<td>143a 6.1</td>
<td>65.7a 4.7</td>
<td>4.7 5.52a 0.61</td>
</tr>
<tr>
<td>8 g/kg Glu/Cu</td>
<td>1.65b 0.14</td>
<td>2.82a 0.13</td>
<td>319b 16.4</td>
<td>406b 13.7</td>
<td>56.4b 3.0</td>
<td>54.1a 4.1</td>
<td>78.7b 6.3</td>
<td>189b 9.2</td>
<td>112b 10.8</td>
<td>11.1b 1.1</td>
</tr>
</tbody>
</table>

*Mean values within a column with unlike superscript letters were significantly different (P < 0.05).

Table 4. Effect of different concentrations of glutamate on lactate dehydrogenase (LDH) activity and malondialdehyde (MDA) content in media, 3-(4, 5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2-(4-sulfophenyl)-2H-tetrazolium optical density (MTS OD), alkaline phosphatase (AKP) activities and protein carbonyl (PC) content in copper-exposed grass carp enterocytes* (Mean values with their standard errors, n 6)

<table>
<thead>
<tr>
<th>Groups</th>
<th>MTS OD Mean SEM</th>
<th>AKP (U/g protein) Mean SEM</th>
<th>LDH (U/g protein) Mean SEM</th>
<th>MDA (nmol/ml) Mean SEM</th>
<th>PC (nmol/mg protein) Mean SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ctrl/Ctrl</td>
<td>0.189d 0.005</td>
<td>2.09c 0.17</td>
<td>37.0b 2.8</td>
<td>1.53a 0.12</td>
<td>0.27a 0.01</td>
</tr>
<tr>
<td>Ctrl/Cu</td>
<td>0.157a 0.009</td>
<td>1.71a 0.09</td>
<td>47.3a 2.3</td>
<td>2.86a 0.18</td>
<td>0.40d 0.02</td>
</tr>
<tr>
<td>2 mmol/l Glu/Cu</td>
<td>0.152b 0.005</td>
<td>1.88b 0.10</td>
<td>43.3a 1.9</td>
<td>2.78a 0.18</td>
<td>0.39d 0.02</td>
</tr>
<tr>
<td>4 mmol/l Glu/Cu</td>
<td>0.160a 0.006</td>
<td>1.97c 0.09</td>
<td>39.5a 1.4</td>
<td>2.72d 0.08</td>
<td>0.36c 0.01</td>
</tr>
<tr>
<td>6 mmol/l Glu/Cu</td>
<td>0.169d 0.005</td>
<td>2.03e 0.09</td>
<td>37.0b 1.1</td>
<td>2.45b 0.10</td>
<td>0.31b 0.02</td>
</tr>
<tr>
<td>8 mmol/l Glu/Cu</td>
<td>0.173c 0.008</td>
<td>2.04c 0.09</td>
<td>31.1a 2.4</td>
<td>2.31c 0.10</td>
<td>0.29a 0.02</td>
</tr>
<tr>
<td>10 mmol/l Glu/Cu</td>
<td>0.175d 0.006</td>
<td>2.07c 0.16</td>
<td>29.6a 1.9</td>
<td>2.15b 0.07</td>
<td>0.29a 0.02</td>
</tr>
<tr>
<td>12 mmol/l Glu/Cu</td>
<td>0.176c 0.007</td>
<td>2.04c 0.13</td>
<td>32.0a 1.9</td>
<td>2.15b 0.09</td>
<td>0.28a 0.03</td>
</tr>
</tbody>
</table>

*Mean values within a column with unlike superscript letters were significantly different (P < 0.05).

Glutamate reduced copper-induced oxidative damage of enterocytes in vitro

The present study has investigated the protective effects of Glu pre-treatment on Cu-induced enterocyte oxidative stress. The Cu exposure (Ctrl/Cu) significantly increased LDH release, MDA content in the medium and PC content in enterocytes as compared with the unexposed Ctrl group (Ctrl/Ctrl) (P < 0.05) (Table 4). However, pre-treatment with 6–12 mmol/l before exposure to Cu significantly reduced LDH release, MDA generation and PC formation induced by Cu (P < 0.05) (Table 4). Exposure to Cu was shown to cause a significant decrease in MTS OD values and AKP activity compared with that of the Ctrl (P < 0.05) (Table 4). As expected, pre-treatment with Glu partially prevented the decrease in cell viability and AKP activity induced by Cu (P < 0.05) (Table 4). ASA and AHR activities of enterocytes are shown in Fig. 2. Cu exposure alone significantly decreased ASA and AHR activities in enterocytes. When cells were pre-treated with increasing doses of Glu, before Cu stress, ASA and AHR activities were increased in a dose-dependent manner (P < 0.05).

The effects of Glu on antioxidant parameters in enterocytes under Cu exposure are displayed in Table 5. The T-SOD, GST and GR activities and GSH content were significantly decreased in cells exposed to Cu as compared with the unexposed Ctrl treatment (P < 0.05). However, pre-treatment with Glu partially prevented a marked reduction in T-SOD, GST and GR activities and GSH content induced by Cu (P < 0.05) (Table 5). In contrast, Cu exposure alone significantly increased the CAT and GPx activities. However, pre-treatment with Glu partially prevented the increase in CAT activity. Interestingly, cells pre-treated with Glu further increased high GPx activity (Table 5).

Effects of glutamate on antioxidant-related and NF-E2-related nuclear factor 2 signalling molecule gene expression in the intestine in vivo

As shown in Fig. 3, the Ctrl/Cu treatment increased the relative mRNA expression levels of CAT in the intestine of grass carp...
compared with the Ctrl/Ctrl group (P<0.05). Dietary Glu treatment (Glu/Cu) significantly prevented the up-regulation of CAT mRNA expression (P<0.05). The Ctrl/Cu treatment caused a significant decrease in GR, GPx and GST mRNA expression in the intestine when compared with the Ctrl/Ctrl (P<0.05). Pretreatment with Glu prevented down-regulation of the GR, GPx and GST mRNA expression (P<0.05). The effects of Glu on Nrf2 and Keap1a mRNA expression in the intestine of fish following Cu exposure are presented in Fig. 3. Fish exposed to Cu showed a decrease in Nrf2 mRNA expression of intestine as compared with the Ctrl/Ctrl group (P<0.05), and Glu markedly inhibited down-regulation of Cu-induced Nrf2 mRNA expression (P<0.05). Exposure to Cu significantly increased Keap1a transcript abundances in intestine of grass carp compared with the untreated control (P<0.05). Pre-treatment with Glu decreased Keap1a mRNA expression (P<0.05).

**Effects of glutamate on antioxidant enzyme genes and NF-E2-related nuclear factor 2 signalling molecule in vitro**

Relative gene expressions of CAT, GPx, GST, GR, Nfr2 and Keap1a in enterocytes were presented in Fig. 4. Cu exposure alone significantly increased CAT and GPx mRNA expression (P<0.05). Pre-treatment with Glu resulted in a significant increase of levels of GPx mRNA as compared with the Cu stress treatment. However, GST and GR mRNA expression were significantly decreased by Cu stress alone, and Glu markedly inhibited Cu-induced down-regulation of GST and GR mRNA expression (P<0.05). The relative expression level of Nfr2 in enterocytes was significantly down-regulated by Cu stress alone (P<0.05). Pre-treatment with Glu before Cu exposure significantly depressed Cu-induced down-regulation of Nfr2 mRNA (P<0.05). Cu exposure significantly increased the...
relative mRNA expression levels of Keap1a in enterocytes (P < 0.05). Pre-treatment of cells with Glu partially prevented the increase in Cu-induced relative mRNA expression of Keap1a (P < 0.05).

Discussion

Cu is an essential nutrient, which has numerous functions in cellular biochemistry (such as a cofactor for many different enzymes). However, Cu at higher concentrations may be toxic. The toxicity of Cu is suggested to be mainly caused by oxidative stress in fish. It was demonstrated that Cu exposure could induce oxidative stress in zebrafish hepatocytes, rainbow trout gill cell, and carp enterocytes. Oxidative damage in cultured cells has been assessed by LDH release. The extent of cell damage was assessed by measuring the release of the cytosolic enzyme LDH from damaged cells to the bathing medium. The present study demonstrated that Cu exposure significantly increased LDH levels in the medium, indicating severe enterocyte damage. The colorimetric assay using MTS can rapidly quantify the cell viability of fish enterocyte. AKP serves as an enterocyte differentiation marker and is considered to be involved in the absorption of nutrients. In the present study, Cu exposure significantly decreased cell viability and AKP activity. Interestingly, treatment of Cu-exposed enterocytes with some concentrations of Glu depressed LDH release, and elevated cell viability and AKP activity. MDA and PC contents were widely used as biochemical indicators of oxidative damage. Exposure of enterocytes to 6 mg/l Cu was shown to cause a significant increase in MDA and PC contents, suggesting that Cu exposure caused lipid and protein oxidative damage in enterocytes, which may be attributed to the increase of ROS production. ROS are produced in response to metals. Increasing the levels of ROS can lead to severe cell injury or death. Superoxide anions can cause a wide range of oxidative damage within the cell. The present study showed that MDA and PC contents were decreased in cells treated with Glu in a dose-dependent manner. The result suggested that Glu may exert potent protection of the intestine against Cu-induced oxidative damage. To our knowledge, no study has investigated the protective effects of Glu against metal toxicity. This is the first report demonstrating that Glu could attenuate Cu-induced cellular damage.

To investigate the potential protective effects of Glu against Cu-induced oxidative damage, the antioxidant enzymes such as SOD, CAT, GPx, GST, GR and GSH content were determined. The SOD is the first enzyme to respond against O2 radicals and important endogenous antioxidants for protection against oxidative stress. CAT has been implicated as an essential defence against the potential toxicity of hydroxyl radicals. The GSH-dependent enzymes (GST, GPx and GR) are able to counteract peroxidative damage. GSH is the major endogenous antioxidant scavenger that protects cells from oxidative stress, and GSH/GSSG represents the major cellular redox buffer and therefore is a representative indicator for the redox environment of the cell. In the present study, a significant decrease in SOD and GR activities and GSH content was found.

![Fig. 3. Relative gene expression (shows to be relative to Ctrl/Ctrl), which was set at 1.0, in arbitrary units of catalase (CAT), glutathione reductase (GR), glutathione peroxidase (GPx), glutathione S-transferase (GST), NF-E2-related nuclear factor 2 (Nrf2) and Kelch-like ECH-associated protein 1 (Keap1) in the intestine of young grass carp (Ctenopharyngodon idellus) fed diets containing different Glu levels for 56 d, followed by exposure to 0.7 mg/l Cu for 96 h. Values are means of six replicates, with their standard errors. Mean values with unlike letters were significantly different (P < 0.05).](image-url)

![Fig. 4. Relative expression (shows to be relative to Ctrl/Ctrl), which was set at 1.0, in arbitrary units of catalase (CAT), glutathione reductase (GR), glutathione peroxidase (GPx), glutathione S-transferase (GST), NF-E2-related nuclear factor 2 (Nrf2) and Kelch-like ECH-associated protein 1 (Keap1) mRNA in enterocytes cultured with medium containing graded levels of Glu for 72 h, followed by exposure to 6 mg/l Cu for 24 h. Values are means of six replicates, with their standard errors. Mean values with unlike letters were significantly different (P < 0.05).](image-url)
in cells exposed to Cu. The result demonstrated that Cu-induced enterocyte oxidative damage may be partly related to disturbance of the antioxidant system. Glu pre-treatment prevented a Cu-induced decrease of these antioxidant enzyme activities. This may suggest that the antioxidant effect of Glu may be attributed to its ability to maintain the activity of radical scavenging enzymes. A variety of citrate cycle intermediates such as fumarate, oxalacetate, malate and succinate were shown to modulate lipid peroxide production by interacting with endogenous iron ions, thus adjusting the iron redox cycle and, subsequently, free-radical generation\(^{(59)}\). Glu can form α-ketoglutarate by deamination and enter into the citrate cycle to promote the production of citrate cycle intermediates\(^{(53)}\). Hence, the reduction in lipid peroxides with an increase in GSH on Glu pre-treatment could be because of the antioxidant effect of citrate cycle intermediates formed from Glu. Further, GSH was produced from exogenous Glu\(^{(2)}\). However, Cu exposure significantly elevated CAT and GPx activities. Glu pre-treatment of enterocytes further increased GPx activities. The reason might be attributed to an adaptive mechanism against stress. The enterocytes were directly exposed to Cu; increased CAT and GPx activities were required to inhibit the Cu-induced oxidative stress. The ASA and AHR activity are two indexes used to evaluate the total capacity of scavenging superoxide and hydroxyl radical, respectively\(^{(22)}\). To investigate how Glu inhibited the Cu-induced oxidative damage in fish, we determined the ASA and AHR activities. Our results showed that Cu exposure significantly decreased the ASA and AHR activities in enterocytes. Glu pre-treatment prevented the Cu-induced decrease of ASA and AHR activities in a dose-dependent manner. These results indicated that the protective effects of Glu on Cu-induced oxidative damage may, at least in part, be because of the increased ASA and AHR activities.

The activities of antioxidant enzymes can be affected by the mRNA levels in fish\(^{(27)}\). To further elucidate whether Glu regulated antioxidant enzyme activities at the gene level in fish, the mRNA levels of antioxidant enzyme of enterocytes after being challenged against Cu were investigated. The results of the current study demonstrated that Cu exposure significantly increased mRNA levels of CAT and GPx in enterocytes. Glu pre-treatment blocked the increase in CAT mRNA expression induced by Cu. However, Glu pre-treatment further elevated mRNA expression of GPx gene induced by Cu. The antioxidant enzyme gene expression exhibited a same pattern with their respective enzyme changes. The regulation of antioxidant gene mRNA levels may result from activating the antioxidant-related signalling molecules. Nrf2 is a master regulator of the antioxidant response through regulating the transcription of antioxidant gene in fish, including \(SO{D}, \ \textit{CAT}, \ \textit{GPx}, \ \textit{GR}\) and \(\textit{GST}\)\(^{(26)}\). The present study showed that Cu exposure down-regulated the \(\textit{Nrf2}\) gene expression in enterocytes. The result is very well in agreement with our previous report, which showed that Cu exposure markedly decreased the binding of nuclear Nrf2 to ARE\(^{(59)}\). In addition, the negative effects of Cu-induced antioxidant gene mRNA expression may be partly ascribed to a decrease in Nrf2 nuclear translocation. Keap1 is identified as an Nrf2-binding protein that prevents Nrf2 translocation to the nucleus and promotes the ubiquitination-proteasomal degradation of Nrf2\(^{(26)}\). Our study also showed that Cu induces the up-regulation of \(\textit{Keap1a}\) mRNA level in enterocytes\(^{(6)}\). Glu pre-treatment elevated \(\textit{Nrf2}\) mRNA expression and blocked the increase in \(\textit{Keap1a}\) mRNA expression\(^{(6)}\). These results suggested that the antioxidant effect of Glu is mediated at least in part by Nrf2 signalling pathways in fish. To date, no information is available about the effect of Glu on \(\textit{Nrf2}\) gene mRNA expression in fish enterocytes. The underlying mechanism needs further investigation.

On the basis of the beneficial effects of Glu against Cu-induced oxidative damage in the enterocytes, it was reasonable to hypothesise that Glu can protect fish against Cu-induced intestinal oxidative damage \textit{in vivo}. The present study showed that Cu exposure could induce intestinal oxidative stress in grass carp. Similar results were observed that Cu exposure could induce oxidative stress in juvenile \textit{Epinephelus coioides} intestine\(^{(60)}\) and pacu \textit{Piaractus mesopotamicus} liver\(^{(41)}\). The antioxidant enzyme activities of intestine were elevated in response to Glu supplementation. The \(\textit{GR}, \ \textit{GPx}\) and \(\textit{GST}\) mRNA abundance in intestine was enhanced by Glu pre-treatment. The positive effects of Glu on antioxidant enzyme mRNA expression may be partly ascribed to promote Nrf2 nuclear translocation by down-regulating \(\textit{Keap1a}\) mRNA expression. In the present study, a significant increase in mRNA levels of \(\textit{Nrf2}\) was observed in the grass carp intestine with Glu supplementation. In contrast, Glu pre-treatment significantly decreased \(\textit{Keap1a}\) mRNA expression. These results were in agreement with the present study statements \textit{in vitro}. Studies from rats also indicated that Glu supplementation alleviates oxidative damage induced by isoproterenol\(^{(77)}\). However, it is of interest that the \textit{in vivo} GPx activity in intestine was decreased by Cu exposure, which was the reverse of the pattern observed in enterocytes. The reason for these results is unclear. The differences may be because, in this study, the enterocytes were directly exposed to Cu, whereas the intestine is indirectly exposed to Cu. In other words, because the enterocytes were directly exposed to Cu, increased GPx activity was required to inhibit the Cu-induced oxidative stress. The previous study in grass carp showed that dietary Cu content (5-25 mg/kg), beyond requirement (4-78 mg/kg), induced intestinal oxidative stress, but increased GPx activity\(^{(9)}\). In addition, higher doses of Cu (6-70-8-33 mg/kg) induced intestinal oxidative stress and decreased the GPx activity at the same time\(^{(9)}\). Therefore, the enterocytes directly exposed to a certain amount of Cu by culture \textit{in vitro} and oral administration \textit{in vivo} can both induce oxidative stress, as well as increase GPx activity in fish intestine.

In conclusion, Cu exposure could induce oxidative damage, resulting in lipid peroxidation, protein oxidation and antioxidant enzymes activity alterations in intestine and the enterocytes of grass carp. Cu exposure down-regulated the mRNA abundance of \(\textit{GR}, \ \textit{GPx}\) and \(\textit{GST}\) in the intestine of grass carp. Dietary and medium pre-supplementation with Glu could alleviate Cu-induced oxidative damage in fish intestine and the enterocytes, respectively. The protective effects of Glu on Cu-induced oxidative damage are associated with up-regulating the expression of antioxidant enzymes gene by regulating mRNA abundance of signalling molecule \(\textit{Nrf2}\). It provides a
theoretical basis for reducing oxidative stress of Cu in cultured fish by means of nutrition.

Acknowledgements

The authors would like to express their sincere thanks to the personnel of these teams for their kind assistance.

This study was financially supported by the Youth Foundation Program of the Education Department of Sichuan Province, China (grant no. 14ZB0021) and the Applied Basic Research Programs of Science and Technology Commission Foundation of Sichuan Province, China (grant no. 2015JY0067).

J. J. and X.-Y. W. conducted the trial, performed the RT-PCR experiments and wrote the manuscript. Y. Z. and X.-Q. Z. contributed to the design of the study. L. F. and W.-D. J. assisted in the manuscript preparation. Y. L. assisted with all data analysis. P. W. assisted with the trail.

The authors declare that there are no conflicts of interest.

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