Histidine supplementation alleviates inflammation in the adipose tissue of high-fat diet-induced obese rats via the NF-κB- and PPARγ-involved pathways

Xiaowei Sun†, Rennan Feng†, Yanchuan Li, Song Lin, Wei Zhang, Ying Li, Changhao Sun and Songtao Li*

Department of Nutrition and Food Hygiene, Public Health College, Harbin Medical University, 157 Baojian Road, Nangang District, Harbin, Heilongjiang Province 150081, People’s Republic of China

(Submitted 17 December 2013 – Final revision received 24 February 2014 – Accepted 18 March 2014 – First published online 15 May 2014)

Abstract

Obesity is considered to be accompanied by a chronic low-grade inflammatory state that contributes to the occurrence of many chronic diseases. Our previous study has demonstrated that histidine supplementation significantly ameliorates inflammation and oxidative stress in obese women. However, the in vitro potential mechanisms are not known. The present study was conducted to investigate the mechanisms underlying the effects of histidine on inflammation in a high-fat diet (HFD)-induced female obese rat model. An obese model was established in female Sprague–Dawley rats by HFD feeding for 8 weeks and followed by histidine supplementation for another 4 weeks. The results revealed that HFD-increased body weight and HFD-lowered serum histidine concentrations were significantly reversed by histidine supplementation (P≤0·05). In addition, the serum concentrations of TNF-α, IL-6, C-reactive protein (CRP) and malondialdehyde were significantly reduced and those of superoxide dismutase (SOD) were significantly increased by histidine supplementation when compared with those in obese rats (P<0·05). Correspondingly, the mRNA expressions of TNF-α, IL-6 and CRP in the adipose tissue were significantly down-regulated and that of CuZnSOD was significantly up-regulated by histidine supplementation (P<0·05). Histidine supplementation significantly reduced the HFD-induced translocation of NF-κB p65 into the nucleus (P=0·032) by reducing the phosphorylation of the inhibitor of κBα in the adipose tissue. The results also revealed that the expression of adiponectin was markedly increased both in the serum and in the adipose tissue after histidine supplementation, accompanied by the activation of PPARγ (P=0·021). These findings indicate that histidine is an effective candidate for ameliorating inflammation and oxidative stress in obese individuals via the NF-κB- and PPARγ-involved pathways.

Key words: Histidine; High-fat diets; Obesity; Inflammation

Obesity is a pro-inflammatory state characterised by an increased production of different cytokines by the adipose tissue. It has been reported that obesity-associated inflammation and oxidative stress are the key and early contributing factors for the occurrence of many chronic diseases, including type 2 diabetes, hypertension and CVD. Therefore, the suppression of low-grade chronic pro-inflammation and oxidative stress is an effective strategy for reducing the risk of these diseases.

Histidine is an important amino acid for humans. It has been reported that chronic kidney disease patients have a low plasma concentration of histidine, which is associated with protein-energy wasting, inflammation and oxidative stress. In a previous study, we had found that serum histidine concentrations in obese women were lower than those in non-obese women and had negative relationships with inflammation and oxidative stress. The recovery of serum histidine concentrations to normal levels through histidine supplementation could significantly attenuate inflammation and oxidative stress in obese women. In addition, plasma histidine concentrations have been found to be lower in diabetic BALB/c mice than in non-diabetic control mice, and histidine supplementation has been found to markedly reduce the concentrations of IL-6, TNF-α and C-reactive protein (CRP). Histidine has been reported to inhibit the TNF-α-induced IL-8 expression at the transcriptional level in intestinal...

Abbreviations: CRP, C-reactive protein; HFD, high-fat diet; H-His, high histidine dose group; HH DR, diet-restricted group for high histidine dose; κBα, inhibitor of κBα; OM, obese model group; OM DR, diet-restricted group for obese model; SOD, superoxide dismutase.

* Corresponding author: Dr S. Li, fax +86 451 87502885, email lisongtaoklds@126.com

† These authors contributed equally to the present study.
epithelial cells\(^{(3)}\). However, the potential in v i o mechanisms involved in the anti-inflammatory and anti-oxidative stress functions of histidine in the obese state are still unclear.

The transcription factor NF-κB is a central regulator of various cellular genes involved in immune and inflammatory responses\(^{(20,11)}\). Under basal conditions, NF-κB is an inactive cytoplasmic heterotrimer consisting of p50, p65 and inhibitor of κB (IκBκ) subunits. In response to stimulation by factors such as lipopolysaccharides and TNF-α, IκBκ undergoes phosphorylation and an ubiquitination-dependent degradation by a proteasome complex, which leads to the p65 subunit being transferred into the nucleus and stimulating the transcription of its target genes, such as IL-6, TNF-α and CRP\(^{(10)}\). The reported studies have revealed that the NF-κB signalling pathway could be a therapeutic target in chronic inflammation, evidenced by the results that the inhibition of this pathway could attenuate inflammatory responses\(^{(12,13)}\).

Adiponectin, one of the most abundant gene transcripts of the adipose tissue, is an important link among obesity, inflammation and chronic diseases\(^{(14,15)}\). It has been reported that an increase in adiponectin concentrations could attenuate inflammation in obese individuals\(^{(16)}\). In a previous study, we had found that histidine supplementation could increase the serum concentrations of adiponectin in obese women\(^{(7)}\). Therefore, we sought to study whether histidine could attenuate inflammation by increasing the serum concentrations of adiponectin. The expression of adiponectin has been found to be significantly enhanced by PPARγ at the transcriptional level\(^{(17)}\). PPARγ is a ligand-activated transcription factor that is most widely expressed in the adipose tissue. Importantly, PPARγ is a central regulator of adipocyte differentiation and controls many adipocyte genes by binding to specific PPAR response elements in the promoters of these genes\(^{(18)}\).

Therefore, in the present study, we focused on the NF-κB- and PPARγ-involved pathways to investigate the mechanisms underlying the effects of histidine on inflammation and oxidative stress in a high-fat diet (HFD)-induced female obese rat model.

**Experimental methods**

**Ethics statement**

All protocols used in the present study were approved by the Medical Ethics Committee of Harbin Medical University (Harbin, China) and were implemented in accordance with the National Institutes of Health regulations for the care and use of animals in research.

**Animals and obese model**

A total of fifty adult female Sprague–Dawley rats with body weight ranging from 160 to 200 g were purchased from Shanghai SLACK Laboratory Animal. The rats were allowed to acclimatise for 1 week before conducting the experiment. Among these rats, eight were randomly selected and fed the AIN-93M diet for 12 weeks until the end of the experiment\(^{(19)}\). The remaining forty-two rats were fed a HFD for 8 weeks to establish an obese model (OM group). The HFD was based on the AIN-93M diet with lard and maize starch contents being adjusted to 180 and 286·5 g/kg, respectively. To ensure that both diets had the same amount of amino acids, especially histidine, the average food intake per d of rats fed the AIN-93M diet was restricted to the same amount of food intake of the OM group, and the eight rats were designated as the diet-restricted group for obese model (OM DR group). The rats were housed individually in a temperature-controlled room under a 12 h light–12 h dark cycle and given free access to water.

**Histidine supplementation**

A total of ten HFD-fed rats with body weight less than the mean body weight plus 1-fold of the standard deviation of the OM DR group were considered to be obesity resistant and excluded from the study. The remaining obese rats (n 32) were randomly assigned to four groups: (1) OM group (no additional histidine included); (2) low-histidine dose group (histidine 0·375 g/kg·body weight); (3) high-histidine dose (H-His) group (histidine 1·875 g/kg·body weight); (4) diet-restricted group for high histidine dose (HH DR) group (no additional histidine included and with food intake the same as that of the H-His group). Histidine (purity ≥95 %) was purchased from Yuan Cheng Gong Chuang. The four groups were fed the same HFD mentioned above until the end of the experiment. Suspensions containing different doses of histidine in an aqueous solution of carboxymethyl cellulose were orally administered to rats at a dose of 1 ml/100 g·body weight. These doses were chose on the basis of the protocols described in previous reports\(^{(20,21)}\). Treatment was carried out for four consecutive weeks (Fig. 1). Food intake was recorded daily and body weight was measured weekly.

**Sample collection**

Tail blood samples were collected from each rat at the beginning and at the end of week 8. At week 12, the rats were killed after an overnight fast and pentobarbital anaesthesia. Blood samples were obtained from the abdominal aorta and centrifuged (3000 rpm for 15 min). Livers, kidneys and white adipose tissues (parametrium, perirenal fat and omental fat pads) were removed, weighed, quick-frozen in liquid N\(_2\) and stored at − 80°C for further analysis.

**Serum analysis**

The serum concentrations of histidine were measured at weeks 0, 8 and 12 according to the method reported previously\(^{(5)}\). The serum concentrations of TNF-α, IL-6, CRP and adiponectin were determined by ELISA using commercial kits (TNF-α and IL-6, R&D Systems Europe; CRP, Biocheck, Inc.; and adiponectin, AdipoGen) according to the manufacturers’ protocols. The serum concentrations of superoxide dismutase (SOD) and malondialdehyde were measured with enzymatic methods using commercial kits (Jiancheng Technology).
RNA isolation and real-time PCR

The mRNA levels of TNF-α, IL-6, CRP, adiponectin and CuZn-SOD in white adipose tissue were determined by real-time PCR. Total mRNA was extracted from the white adipose tissue using the TRIzol reagent (Invitrogen). Real-time PCR was carried out using the SYBR Green PCR Master Mix and the 7500 FAST Real-time PCR System (Applied Biosystems). Relative quantification of mRNA expression was performed using the \( \Delta\Delta C_t \) (\( 2^{-\Delta\Delta C_t} \)) method \( ^{22} \). Primer sequences used in the PCR are listed in Table 1. All reactions were carried out at least in triplicate.

Western blot analysis

Nuclear protein extracts and total protein extracts of the white adipose tissue were prepared using protein extraction kits (Biotechnology Institute of Biotechnology) according to the manufacturers’ protocol. Western blot analysis was carried out as described previously to measure the concentrations of proteins involved in the NF-κB and PPAR pathways \( ^{23} \). Antibodies used for protein detection were bought from the following sources: NF-κB p65, phospho-IkBa and IkBa from Cell Signaling Technology; PPARγ and Histone H3 from Abcam; β-actin from Santa Cruz Biotechnology, Inc.; secondary antibody from Promega Corporation. Data are presented as the relative intensity of the protein bands. Experiments were replicated at least three times, and representative blots are shown in the figures.

Statistical analysis

Data are presented as means with their standard errors. Data were analysed using one-way ANOVA followed by post hoc test, with \( P<0.05 \) considered to be significant. All \( P \) values were two-sided. Statistical analysis was carried out using the SPSS software (version 16; Beijing Stats Data Mining).

Results

Histidine reduces high-fat diet-induced body weight increase and food intake

An obese rat model was successfully established after 8 weeks of HFD feeding, evidenced by the obvious increase in body weight in the OM group when compared with that in the OM DR group (\( P<0.001 \); Table 2). After histidine supplementation for another 4 weeks, HFD-induced body weight increase was markedly reduced by high-dose histidine supplementation compared with that in OM group (\( P=0.042 \); Table 2). The food intake of the H-His group was significantly lower than that of the OM group from week 10 (\( P=0.026 \) after histidine supplementation (Fig. 2). However, no significant differences in body weight and food intake were observed between the H-His and HH DR groups.

Histidine supplementation reverses high-fat diet-lowered serum histidine concentrations in obese rats

There was no difference in serum histidine concentrations between the OM and OM DR groups at the start of the experiments. However, serum histidine concentration was markedly lower in obese rats (OM) than in normal rats (AIN-93M) (\( P<0.05 \); Table 1). Significant increases were observed in serum histidine concentration in both HH DR and H-His groups compared with that in OM group (\( P<0.001 \); Table 1). The histidine supplementation protocol is shown in Fig. 1.

Table 1. Primer sequences for TNF-α, IL-6, C-reactive protein (CRP), copper-zinc superoxide dismutase (CuZnSOD), adiponectin and β-actin used in the PCR

<table>
<thead>
<tr>
<th>Genes</th>
<th>Primer sequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNF-α</td>
<td>Forward: 5'-TGCTCAGCCTTCTTCATT-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 3'-CTCCGATGACTCGTCTTT-5'</td>
</tr>
<tr>
<td>IL-6</td>
<td>Forward: 5'-GATCCGTCCCTTCCCTATTCA-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 5'-GCCAGTGCCATCATCGTCTTT-3'</td>
</tr>
<tr>
<td>CRP</td>
<td>Forward: 5'-TTCCGAGGCGCCTCGTTTT-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 5'-GACAGTGCATCATCGTCTTT-3'</td>
</tr>
<tr>
<td>CuZnSOD</td>
<td>Forward: 5'-GATCCGAGGAGGCGGCTCC-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 5'-GATCCCGATGACTCGTCTTT-3'</td>
</tr>
<tr>
<td>Adiponectin</td>
<td>Forward: 5'-GACAGTGCATCATCGTCTTT-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 5'-GACAGTGCATCATCGTCTTT-3'</td>
</tr>
<tr>
<td>β-Actin</td>
<td>Forward: 5'-GACAGTGCATCATCGTCTTT-3'</td>
</tr>
<tr>
<td></td>
<td>Reverse: 5'-GACAGTGCATCATCGTCTTT-3'</td>
</tr>
</tbody>
</table>
Histidine alleviates high-fat diet-induced adverse changes in serum inflammatory and oxidative biomarkers

As shown in Fig. 3, compared with those in the OM DR group, the serum concentrations of inflammatory factors, including TNF-α, IL-6 and CRP, were significantly elevated by HFD feeding in the OM group (P<0·007, P<0·004 and P<0·005, respectively). The serum concentrations of adiponectin were reduced by HFD feeding (P<0·002). After histidine supplementation, inflammation was not significantly attenuated in the low-histidine dose group (P>0·05). The HFD-induced adverse changes in inflammatory factors mentioned above were significantly alleviated in the H-His group than in the HH DR group (P<0·05; ANOVA). The results also revealed that histidine supplementation significantly improved HFD-lowered SOD concentrations (P<0·019) and HFD-increased malondialdehyde concentrations (P<0·037; Table 2). Compared with those in HH DR group, the HFD-induced adverse changes in inflammatory factors mentioned above were significantly alleviated in the H-His group than in the HH DR group (P<0·032; Table 2). These results indicate that the histidine-inhibited NF-kB pathway contributes to its anti-inflammatory role in the adipose tissue.

Histidine induces PPARγ expression in the adipose tissue

After 8 weeks of HFD feeding, the protein expression of PPARγ in the adipose tissue of the OM group was decreased compared with that in the adipose tissue of the OM DR group (P<0·001). High-dose histidine supplementation significantly improved the HFD-down-regulated expression of PPARγ at the protein level (P<0·021), suggesting that the PPARγ pathway is probably involved in the up-regulation effects of histidine on adiponectin expression (Fig. 6A and B).

Table 2. Serum histidine concentration and body weight before and after histidine supplementation in rats

<table>
<thead>
<tr>
<th>Weeks</th>
<th>Groups</th>
<th>n</th>
<th>Histidine concentration (μmol/l)</th>
<th>Body weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mean SEM</td>
<td>Mean SEM</td>
</tr>
<tr>
<td>0</td>
<td>OM DR</td>
<td>8</td>
<td>97·70 3·37</td>
<td>184·9 4·2</td>
</tr>
<tr>
<td>8</td>
<td>OM DR</td>
<td>8</td>
<td>63·10 3·67</td>
<td>207·0 6·5</td>
</tr>
<tr>
<td>12</td>
<td>OM DR</td>
<td>8</td>
<td>68·59 2·59</td>
<td>299·5 5·6</td>
</tr>
<tr>
<td></td>
<td>L-His</td>
<td>8</td>
<td>55·78 1·97</td>
<td>347·3 5·3</td>
</tr>
<tr>
<td></td>
<td>H-His</td>
<td>8</td>
<td>57·97 2·49</td>
<td>324·9 4·7</td>
</tr>
<tr>
<td></td>
<td>HH DR</td>
<td>8</td>
<td>83·07 3·21</td>
<td>306·5 4·8</td>
</tr>
</tbody>
</table>

OM, obese model group; OM DR, diet-restricted group for obese model; L-His, low-histidine dose group; H-His, high-histidine dose group; HH DR, diet-restricted group for high histidine dose. Mean values were significantly different from those of the OM group: * P<0·05; ** P<0·01 (ANOVA).
Discussion

The present study demonstrates for the first time that histidine supplementation ameliorates HFD-induced inflammation in the adipose tissue of obese rats. The results of the present study revealed that histidine exerted its beneficial effects on obesity-associated inflammation by inactivating the NF-κB signalling pathway. The results also revealed that histidine reversed HFD-lowered adiponectin expression via a PPARγ-involved pathway, which might contribute to its role in anti-inflammation.

Histidine is generally considered to be a dietary essential amino acid for human infants and an important amino acid for adults. It has been reported that chronic kidney disease patients and obese and type 2 diabetic youth have low plasma concentrations of histidine(5,24). In our previous study, we had reported serum histidine concentrations were lower in obese women(6). A similar result was obtained in the present study, i.e. serum concentrations of histidine in the HFD-induced obese rats were lower than those in the normal diet-fed non-obese rats, suggesting that the serum amino acid metabolism is correlated with the occurrence of obesity. In addition, we also observed that food intake and weight gain were lower in the H-His group than in the OM group, which could probably be explained by the suppression of appetite by histidine through its conversion into neuronal histamine in the hypothalamus(25,26). To eliminate the food intake-induced disturbance, we established a HH DR group for further excluding the effects of the reduced body weight on the alleviation of inflammation and, thereby, focused on the inhibitory effects of histidine on inflammation and oxidative stress.

TNF-α, IL-6 and CRP are pro-inflammatory cytokines, and the elevation of their concentrations has been confirmed in obese subjects(1,2). Previous studies have suggested that TNF-α and IL-6 are involved in obesity-related insulin resistance and atherosclerosis(27,28). CRP is the most extensively

Fig. 3. Effects of histidine supplementation on serum inflammatory and oxidative biomarkers. The serum concentrations of (A) TNF-α, (B) IL-6, (C) C-reactive protein (CRP) and (D) adiponectin were determined using commercial ELISA according to the manufacturers’ protocols and those of (E) superoxide dismutase (SOD) and (F) malondialdehyde (MDA) were measured enzymatic methods using commercial kits. Values are means, with their standard errors represented by vertical bars. a, b Mean values with unlike letters were significantly different (P<0.05; ANOVA). OM, obese model group; OM DR, diet-restricted group for obese model; L-His, low-histidine dose group; H-His, high-histidine dose group; HH DR, diet-restricted group for high histidine dose.

Histidine alleviates adipose tissue inflammation 481

British Journal of Nutrition

Downloaded from https://www.cambridge.org/core. IP address: 54.70.40.41, on 24 Feb 2019 at 23:33:41, subject to the Cambridge Core terms of use, available at https://www.cambridge.org/core/terms.
studied marker of systemic inflammation in humans, which is also related to the insulin resistance syndrome and endothelial dysfunction (29). In the present study, HFD induced an increase in the serum concentrations of TNF-α, IL-6 and CRP in the OM group but not in the OM DR group. Moreover, we found that high-dose histidine supplementation could decrease the serum concentrations of TNF-α, IL-6 and CRP in the H-His group but not in HH DR group, in spite of the same amount of food being consumed by both groups. These results were consistent with the results of our previous study in which histidine supplementation was found to significantly lower the serum concentrations of the inflammatory biomarkers TNF-α and IL-6 in obese women (7). Correspondingly, a previous study has reported that plasma histidine concentration is significantly lower in chronic kidney disease patients with a history of CVD and inflammation, which is associated with inflammation, oxidative stress and mortality (5). The results of an animal study revealed that diabetic BALB/cA mice had

![Fig. 4. Effects of histidine supplementation on the mRNA expressions of inflammatory and oxidative biomarkers in the adipose tissue. Adipose tissue mRNA was extracted and the mRNA expressions of (A) TNF-α, (B) IL-6, (C) C-reactive protein (CRP), (D) adiponectin and (E) copper-zinc superoxide dismutase (CuZnSOD) were measured by quantitative real-time PCR. Expression was normalised to that of β-actin. Values are means, with their standard errors represented by vertical bars. a,b,c Mean values with unlike letters were significantly different (P < 0.05; ANOVA). OM, obese model group; OM DR, diet-restricted group for obese model group; L-His, low-histidine dose group; H-His, high-histidine dose group; HH DR, diet-restricted group for high histidine dose.](https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0007114514001056)

![Fig. 5. Inhibitory effects of histidine supplementation on the NF-κB-involved pathway in the adipose tissue. Nuclear protein extracts and total cell protein of the white adipose tissue were prepared and measured by Western blot analysis. (A) Blot depicting the reduction of p65 transference into the nucleus by histidine. (B) Quantification of the protein expression of p65 in the nucleus and cytoplasm shown as the relative intensity of the protein bands. (C) Blot showing the inhibition of the phosphorylation (p) of the inhibitor of NF-κB (IκBα) by histidine. (D) Quantification of the protein expression of p-IκBα shown as the relative intensity of the protein bands. a,b,c Mean values with unlike letters were significantly different (P < 0.05; ANOVA). OM, obese model group; OM DR, diet-restricted group for obese model; L-His, low-histidine dose group; H-His, high-histidine dose group; HH DR, diet-restricted group for high histidine dose.](https://www.cambridge.org/core/terms. https://doi.org/10.1017/S0007114514001056)
Histidine alleviates adipose tissue inflammation

Histidine can be a novel therapeutic agent for Crohn's disease by inhibiting NF-κB activation and down-regulating inflammatory cytokine production in macrophages\(^{(34)}\). Besides, in the previous study, we had observed that histidine could inhibit the translocation of NF-κB into the nucleus in human preadipocytes\(^{(37)}\). So, we quantified the expression of proteins involved in the NF-κB pathway in the adipose tissue by Western blot analysis, and the results revealed that histidine significantly inhibited NF-κB p65 translocation and κBα degradation, which suggests that NF-κB might be responsible for the anti-inflammatory effects of histidine.

Adiponectin is an anti-inflammatory factor secreted by adipocytes\(^{(16)}\). In contrast to most adipocyte hormones, the concentrations of circulating adiponectin are decreased in obesity and increased in response to weight loss\(^{(35)}\). We had found that histidine supplementation could increase the serum concentrations of adiponectin in obese women\(^{(7)}\). In the present study, we quantified the concentration of adiponectin in the serum and its mRNA expression in the adipose tissue. The results revealed that the expression of adiponectin was significantly increased by histidine supplementation. It is well accepted that the expression of adiponectin is markedly stimulated by the activation of PPAR\(\gamma\) in adipocytes\(^{(37)}\). So, we quantified the protein expression of PPAR\(\gamma\) in the adipose tissue, and the results revealed that the expression of PPAR\(\gamma\) was up-regulated by histidine supplementation, which might at least partially explain the results obtained for the effects of histidine supplementation on adiponectin. Moreover, PPAR\(\gamma\) and NF-κB interact in several ways to oppose their respective activities. PPAR\(\gamma\) can form a transcriptionally inhibitory complex with NF-κB in mouse macrophages\(^{(36)}\). Another study has revealed that the activation of PPAR\(\gamma\) suppresses cytokine-induced NF-κB transcriptional activity and target gene expression in skeletal muscle cells\(^{(35)}\). NF-κB also inhibits the binding of PPAR to genomic response elements, thereby reducing the transcriptional activity of PPAR and the expression of PPAR-related transcripts\(^{(39)}\).

In addition, histidine has been reported to protect human LDL against oxidation and glycation and to have beneficial effects on liver in rats with acetaminophen-induced liver injury through its actions against oxidative stress\(^{(8,20)}\). Histidine can also restrict the accumulation of free radicals and delay the activation of extracellular signal-regulated kinase and c-jun N-terminal kinase in neuronal cells\(^{(39)}\). Previous studies have suggested that the anti-oxidative effect of histidine is based on its free radical-scavenging and divergent metal ion-chelating abilities\(^{(40,41)}\). In the present study, we quantified two oxidative biomarkers, SOD and malondialdehyde, and the results revealed that the concentrations of SOD in the serum and the mRNA expression of Cu/ZnSOD in the adipose tissue were increased and the concentrations of malondialdehyde in the serum were decreased by histidine supplementation, indicating that histidine is a potential antioxidant in obese individuals.

All these findings indicate that histidine supplementation could attenuate inflammation and oxidative stress in obese women. The results of the present study also provide a new insight for understanding the relationship between amino
acid metabolism disorder and inflammation and/or oxidative stress, which suggests that more attention has to be paid to uncovering amino acid metabolism in obese individuals in a further study. In addition, previous studies have shown that women are more sensitive to dietary histidine and energy intake than men. Therefore, we chose female rats as the experimental animals in the present study. We established a HH DR group for excluding the effects of the reduced body weight on the alleviation of inflammation. However, artificially controlling food intake cannot completely imitate food intake reduction and body weight loss caused by histidine supplementation-induced appetite suppression. The suppression of appetite might lead to some unknown effects, which might be associated with the regulation of inflammation. Therefore, we cannot completely exclude the possibility that some of the findings might be related to the suppression of appetite, and more studies are required to be conducted in the future.

In summary, the present study provides evidence for the first time that by inhibiting NF-κB and activating PPARγ, histidine supplementation protects the adipose tissue from inflammation and oxidative stress induced by HFD feeding, suggesting that histidine is a potential candidate for ameliorating inflammation and oxidative stress in obese individuals.

Acknowledgements

The present study was supported by the National Natural Science Fund of China (81130049 and 81202184), the 12th China Five-Year Scientific and Technical Plan (grant no. 2012BAI02B00), and the Research Fund for Innovation Talents of Science and Technology in Harbin City (2013RFQX068).

The authors’ contributions are as follows: S. Li, Ying Li and C. S. were responsible for the study concept and design; X. S., R. F. and W. Z. performed the experiment and collected the data; Yanchuan Li and S. Lin carried out the analysis and interpretation of the data; S. Lin and W. Z. performed the statistical analysis; X. S. and R. F. wrote the article; Ying Li and C. S. were responsible for obtaining funds and supervision; S. Li, X. S. and C. S. also contributed to the critical revision of the manuscript for its intellectual content; X. S. and S. Li had primary responsibility for the final content. All authors read and approved the final manuscript.

None of the authors has any conflicts of interest to declare.

References


