

RESEARCH

Open Access



Hepatic iron storage is related to body adiposity and hepatic inflammation

Chan Yoon Park¹, Jayong Chung², Kyung-Ok Koo², Min Soo Kim¹ and Sung Nim Han^{1,3*}

Abstract

Background: Obesity has been reported to be associated with iron deficiency. However, few studies have investigated iron status in low adiposity. To investigate whether body adiposity was associated with altered hepatic iron status, we compared liver iron levels and markers involved in inflammation and iron absorption in obese, control, and mildly calorie restricted mice.

Methods: Seven week old C57BL/6 mice were fed control (10% kcal fat, Control) or high fat (60% kcal fat, HFD) diets, or reduced amount of control diet to achieve 15% calorie restriction (CR) for 16 weeks. Hepatic non-heme iron content and ferritin protein level, and hematocrit and hemoglobin levels were determined to assess iron status. Hepatic expression of *Mcp-1* and *Tnf- α* were measured as hepatic inflammatory markers. Hepatic hepcidin (*Hamp*) and *Bmp6*, and duodenal *Dmt1*, *Dcyt1b*, hephaestin (*Heph*) and ferroportin mRNA levels were measured as factors involved in regulation of iron absorption.

Results: Hepatic non-heme iron and ferritin protein levels were significantly higher in the CR group compared with the Control group, and significantly lower in the HFD group. These two iron status markers showed significantly negative correlations with the amount of white adipose tissue ($r = -0.689$ for hepatic non-heme iron and $r = -0.740$ for ferritin). Hepatic *Mcp-1* and *Tnf- α* mRNA levels were significantly lower in the CR compared with the HFD (74 and 47% lower) and showed significantly negative correlations with hepatic non-heme iron levels (*Mcp-1*: $r = -0.557$, $P < 0.05$; *Tnf- α* : $r = -0.464$, $P < 0.05$). Hepatic *Hamp* mRNA levels were lower in the HFD and higher in the CR groups compared with the Control group, which could be a response to maintain iron homeostasis. Duodenal *Dcyt1b* mRNA levels were higher in the CR group compared with the HFD group and duodenal *Heph* mRNA levels were higher in the CR group than the Control group.

Conclusion: We showed that body adiposity was inversely correlated with liver iron status. Low inflammation levels in hepatic milieu and enhanced expression of duodenal oxidoreductases induced by calorie restriction could have contributed to higher iron status.

Keywords: Hepatic non-heme iron, Mild calorie restriction, Iron absorption, Duodenal iron transporter, Hepcidin, Body adiposity

Background

Iron deficiency is the most prevalent single nutrient problem and the most common cause of anemia. More than two billion people in both developing and industrialized countries are anemic due to iron deficiency [1]. Iron deficiency and obesity are often observed together and obesity has been reported as a possible factor leading

to under-nutrition of iron in recent years [2–8]. Although the etiology of iron deficiency associated with obesity is uncertain, many animal and clinical studies have reported reduced iron storage with obesity. Systemic chronic inflammation induced by obesity and higher hepcidin levels have been suggested as a reason for impaired iron absorption due to inhibition of iron transport across the basolateral enterocyte membrane by the action of hepcidin [3, 4, 9].

Hepcidin (*Hamp*) is the central regulator of iron homeostasis and is mainly released from the liver. When the iron level is high, iron activates the bone morphogenetic protein

* Correspondence: snhan@snu.ac.kr

¹Department of Food and Nutrition, College of Human Ecology, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea

³Research Institute of Human Ecology, Seoul National University, Seoul, South Korea

Full list of author information is available at the end of the article

(BMP) pathway and phosphorylates Smad to increase hepcidin expression. Hepcidin binds to ferroportin and induces its internalization, preventing efflux of iron from enterocyte to the circulation [10–12]. When the iron level is low, release of hepcidin from liver decreases [13]. Inflammatory states can also increase hepcidin expression. Lipopolysaccharide (LPS)-treatment increased *Hamp* mRNA levels in primary hepatocyte, Hep3B, and rat liver tissue [14, 15]. Obese patients with upregulated levels of serum C-reactive protein (CRP) and interleukin (IL)-6 had higher serum hepcidin levels [4, 5, 16]. Therefore, increased hepcidin expression mediated by inflammatory response has been suggested as one of the mechanisms for obesity related low iron level [11, 17, 18]. On the other hand, Sonnweber et al. [19] reported that iron deficiency observed with obesity was independent of hepcidin expression. Rather, it was suggested that decreased expression of iron absorption related duodenal enzymes, such as duodenal cytochrome B (*Dcyt1b*) and hephaestin, could affect iron deficiency in obesity. Other studies have reported that inflammatory markers, tumor necrosis factor alpha (*TNF- α*) and interferon gamma (*IFN- γ*), directly disturbed iron absorption into the enterocyte [4, 19–21].

Excess adiposity leads to chronic inflammatory responses by increasing macrophage infiltration into adipocytes. Growing evidence suggests that inflammation is one of the main contributors to iron deficiency [22, 23]. Calorie restriction has been reported to ameliorate inflammation through suppressing inflammatory cytokines. Monocyte chemoattractant protein 1 (*Mcp-1*), *Il-6* and *Tnf- α* mRNA and CRP protein levels in adipose tissue were lowered in rodents with 30% or more calorie restriction compared with those fed ad libitum [24, 25]. However, iron status was not measured in these calorie restricted animals. If chronic inflammation caused by excess adiposity is linked to iron deficiency, calorie restriction may have the potential to change iron status. Therefore, studies are required to examine whether alleviation of inflammation and further reduction of body weight achieved by calorie restriction has an impact on iron status.

This study compared hepatic iron levels using mildly calorie restricted, obese, and control mice to clarify the relationship between adiposity and iron status. To understand the mechanism responsible for differences in iron storage associated with body adiposity, the levels of hepcidin, pro-inflammatory markers, and duodenal enzymes involved in iron transport were determined.

Methods

Animals and diets

Male C57BL/6 N mice (7 weeks old) were purchased from Central laboratory Inc. (Seoul, Korea) and individually housed in the specific pathogen free (SPF) animal facility at Seoul National University. After 1 week of acclimation

with the control diet, mice were assigned to one of 3 dietary groups and fed experimental diets for 16 weeks: calorie restriction (CR, $n = 16$), control (Control, $n = 24$), and high fat (HFD, $n = 25$) diets. The Control group was fed the control diet (10% energy from fat, Research Diets, New Brunswick, NJ, USA, #D12450B) ad libitum and CR group was fed a reduced amount of control diet to achieve 15% calorie restriction. The HFD group was fed with a high fat diet (60% energy from fat, Research Diets, #D12492) ad libitum. After 16 weeks, mice were fasted for 12 h and euthanized by CO₂ asphyxiation. Blood, liver, duodenum and white adipose tissue were collected and samples were stored at -80 °C.

Determination of liver non-heme iron content

Hepatic non-heme iron levels were measured using the colorimetric method as previously described by Brain et al. [26]. Liver samples (100 mg) were homogenized and hydrolyzed in 2 ml of acidic solution (mixture of 3 mol/L HCl and 10% trichloroacetic acid). After 20 h incubation, supernatant was collected and mixed with chromogen reagent containing bathophenanthroline sulfonate. After 10 min incubation, absorbance was measured at 535 nm. Iron concentration was expressed as microgram of iron per gram of wet tissue.

Determination of liver protein oxidation

Hepatic protein oxidation was determined using the Oxyblot™ Protein Oxidation Detection kit (S7150; Millipore, Billerica, MA, USA) based on Western blot analysis. Protein oxidation was detected by measuring carbonyl groups in the protein side chain derived from the oxygen free radicals. Briefly, liver protein was extracted and derivatized to 2, 4-dinitrophenylhydrazone (DNP-hydrazone), separated by SDS-PAGE, then transferred onto PVDF membrane. Membranes were incubated with rabbit anti-DNP (1:150) to detect DNPH-derivatized proteins, washed, then incubated with goat anti-rabbit IgG (1:300). After the reaction with chemiluminescent reagent, DNPH derivatized proteins were detected and analyzed using a mixture of standard proteins as the loading control.

RNA preparation and real time PCR

RNA was extracted using TRIZOL reagent (Invitrogen, CA, USA) from liver and duodenum. Reverse transcription was performed using the PrimeScript™ 1st strand cDNA synthesis kit (Takara bio Inc., Japan). mRNA levels of *Hamp*, *Mcp-1*, *Tnf- α* in liver, *Fpn*, *Dmt1*, *Dcyt1b*, and *Heph* in duodenum were determined by real-time PCR with a SYBR Premix Ex Taq (Takara bio Inc.) and StepOne Real-time PCR System (Applied Biosystems, CA, USA). The relative expression of each gene was calculated from $2^{-\Delta\Delta CT}$. All values were normalized to the levels of *Gapdh* and expressed as relative mRNA

level compared to the average level of the Control group.

Western blot analysis

Protein was isolated from liver tissue using RIPA lysis buffer and protein concentration was determined by Bradford assay (Bio-Rad Laboratories, CA, USA). Fourty μ l of protein was separated by electrophoresis on a 10% SDS-polyacrylamide gel. Separated proteins were blotted onto a PVDF membrane and blocked in Tris buffered saline/0.1% Tween-20 (TBST, pH 7.6), containing 5% skim milk. Membrane was incubated with sheep anti-human ferritin (The Binding site Ltd., Birmingham, UK), washed, then incubated with HRP-conjugated donkey anti-sheep IgG (Santa Cruz, CA, USA). Membrane bound antibodies were visualized with enhanced chemiluminescence (ECL) solution (Santa Cruz). Band density was analyzed using QuantityOne software (Bio-Rad Laboratories) with β -actin as the loading control.

Statistical analysis

One-way analysis of variance (ANOVA) was used to determine overall differences among groups, followed by Fisher's least significant difference (LSD) test for individual group comparisons. Pearson's correlation was used to determine the association between parameters. The results from all comparisons were considered significant at $P < 0.05$. Data were reported as mean \pm SEM. All data were analyzed using the SPSS 21.0 program (SPSS Inc., IL, USA).

Results

Body weight and adipose tissue weight

After 16 weeks of feeding, body weights were significantly different among groups ($P < 0.001$). Body weight of the HFD group (48.80 ± 0.49 g) was higher than those of the Control (37.08 ± 0.56 g) and CR (27.53 ± 0.76 g) groups, and the CR group had lower body weight than the Control group. White adipose tissue weight was lower in the CR group than the Control (55% lower, $P < 0.001$) and HFD (74% lower, $P < 0.001$) groups, and it was lower in the

Control group than the HFD group (43% lower, $P < 0.001$). Liver weight per body weight (g liver weight/100 g body weight) was also different among groups, and significantly lower in the CR group compared with the Control ($P < 0.01$) and HFD ($P < 0.001$) groups (Table 1).

Serum hemoglobin and hematocrit levels

Hemoglobin and hematocrit levels were not different among groups (Table 2).

Liver non-heme iron concentrations and ferritin protein levels

Hepatic non-heme iron concentrations were significantly different among groups ($P < 0.001$). The CR group had significantly higher non-heme iron level (291.20 ± 26.48 μ g/g tissue) compared with the Control (136.21 ± 16.99 μ g/g tissue) and HFD (89.92 ± 9.52 μ g/g tissue) groups (Fig. 1a). Hepatic ferritin protein levels were higher in the CR group than the Control (70% higher, $P < 0.001$) and HFD (207% higher, $P < 0.001$) groups. The HFD group's ferritin level was significantly lower than that of the Control group (45% lower, $P < 0.001$) (Fig. 1b). Hepatic non-heme iron levels correlated negatively with white adipose tissue weights ($r = -0.689$, $P < 0.001$), and body weights ($r = -0.711$, $P < 0.001$) (Fig. 2a). Hepatic ferritin protein levels also showed negative correlations with white adipose tissue amount ($r = -0.740$, $P < 0.001$), and body weights ($r = -0.708$, $P < 0.001$) (Fig. 2b).

Hepcidin (*Hamp*) and bone morphogenic protein (*Bmp6*) mRNA levels in liver

Hepatic *Hamp* mRNA levels were significantly different among groups. The CR group had higher *Hamp* mRNA levels than the Control (95% higher) and HFD (242% higher) groups and the Control group had higher mRNA levels than the HFD group (76% higher, $P = 0.073$) (Fig. 3a). The mRNA levels of *Bmp6* which regulates hepcidin expression were higher in the CR group compared with the Control (206% higher) and HFD (151% higher) groups. There was no significant difference in *Bmp6* mRNA levels between Control and HFD groups (Fig. 3a). Hepatic

Table 1 Body weight and weight gain of mice in the CR, Control, and HFD groups¹

	CR (n = 16)	Control (n = 24)	HFD (n = 25)	P value
Body weight at 0 week (g)	22.68 \pm 0.20	22.40 \pm 0.22	22.26 \pm 0.21	0.44
Body weight at 16 week (g)	27.53 \pm 0.76 ^a	37.08 \pm 0.56 ^b	48.80 \pm 0.49 ^c	<0.001
Body weight gain (g)	4.8 \pm 0.8 ^a	14.7 \pm 0.5 ^b	26.5 \pm 0.5 ^c	<0.001
Daily calorie intake (kcal/day)	11.43 \pm 0.16 ^a	13.49 \pm 0.14 ^b	15.59 \pm 0.15 ^c	<0.001
White adipose tissue (g) ²	1.76 \pm 0.14 ^a	3.94 \pm 0.15 ^b	6.87 \pm 0.11 ^c	<0.001
Liver weight per body weight (g/100 g body weight)	4.18 \pm 0.15 ^a	5.11 \pm 0.11 ^b	5.58 \pm 0.23 ^b	<0.001

¹One-way ANOVA followed by Fisher's LSD multiple comparison was used to determine significant differences

²White adipose tissue weight included epididymal, subcutaneous, retroperitoneum, and perinephric fat

^{abc}Different superscript letters indicate significant differences at $P < 0.05$

Table 2 Levels of hemoglobin and hematocrit of mice in the CR, Control, and HFD groups¹

	CR (n = 16)	Control (n = 24)	HFD (n = 25)	P value
Hemoglobin (g/dl)	14.66 ± 0.21	14.42 ± 0.13	14.28 ± 0.21	0.409
Hematocrit (%)	49.31 ± 1.12 ^a	47.01 ± 0.92 ^b	46.92 ± 0.56 ^c	0.124

¹One-way ANOVA followed by Fisher's LSD multiple comparison was used to determine significant differences

^{abc}Different superscript letters indicate significant differences at $P < 0.05$

Hamp and *Bmp6* mRNA levels showed positive correlations with non-heme iron levels (*Hamp*: $r = 0.600$, $P < 0.001$; *Bmp6*: $r = 0.707$, $P < 0.001$, data not shown). On the other hand, negative correlations were observed between white adipose tissue weights and hepatic *Hamp* and *Bmp6* mRNA levels (*Hamp*: $r = -0.567$, $P < 0.001$; *Bmp6*: $r = -0.559$, $P < 0.01$, data not shown).

Pro-inflammatory cytokines mRNA levels in liver

Figure 3b shows hepatic *Mcp-1* and *Tnf- α* mRNA levels. *Mcp-1* mRNA levels were lower in the CR group compared with other two groups (63% lower than Control, $P < 0.05$ and 74% lower than HFD, $P < 0.001$). *Tnf- α* mRNA levels were lower in the CR group than the HFD group (47% lower, $P < 0.05$). The mRNA levels of *Mcp-1* and *Tnf- α* negatively correlated with liver iron concentration ($r = -0.557$, $P < 0.01$; $r = -0.464$, $P < 0.05$, respectively) (Fig. 2c and d).

Oxidation status of proteins in liver

Hepatic protein oxidation levels were not significantly different among groups (Fig. 4).

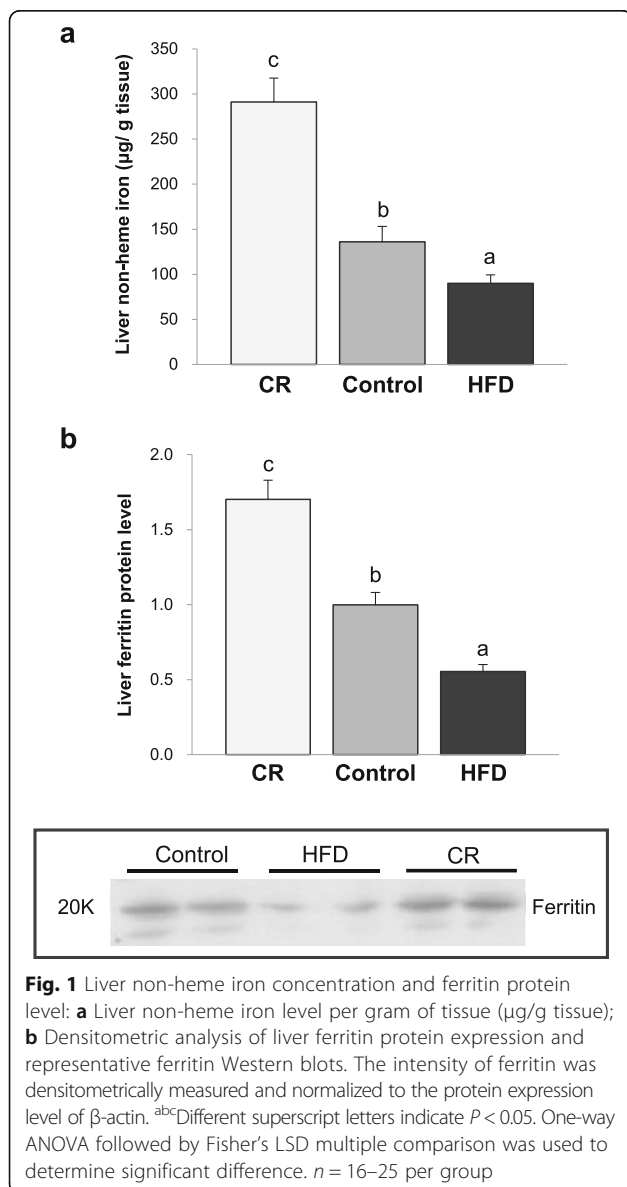
Iron transporters, oxidoreductases and ferritin mRNA levels in duodenum

To investigate whether HFD induced obesity and calorie restriction affected iron absorption, mRNA levels of duodenal enzymes involved in iron transport, divalent metal transporter1 (*Dmt1*), ferroportin (*Fpn*), duodenum cytochrome 1b (*Dcyt1b*), and hephaestin (*Heph*) were measured (Fig. 5). mRNA levels of *Dmt1* and *Fpn* were not significantly different among groups. However, oxidoreductase *Dcyt1b* expression was significantly higher in the CR (229% higher) and Control (204% higher) groups compared with the HFD group. *Heph* expression was significantly higher in the CR (85% higher) and HFD (63% higher) groups compared with the Control group. There was no significant difference in duodenal ferritin (*Fth1*) mRNA levels among groups.

Discussion

The present showed that liver iron levels were inversely associated with body weights and white adipose tissue amount. The study showed not only that hepatic iron storage was lower in the HFD group, which is consistent with previous findings [3], but also that lower body weight achieved by mild calorie restriction resulted in higher non-heme iron concentration and hepatic ferritin protein level in comparison with Control animals. Inflammation in hepatic milieu and levels of duodenal oxidoreductases appear to be involved in the adiposity related differences in liver iron status.

To achieve mild calorie restriction, the CR group were fed 15% reduced amount of control diet without



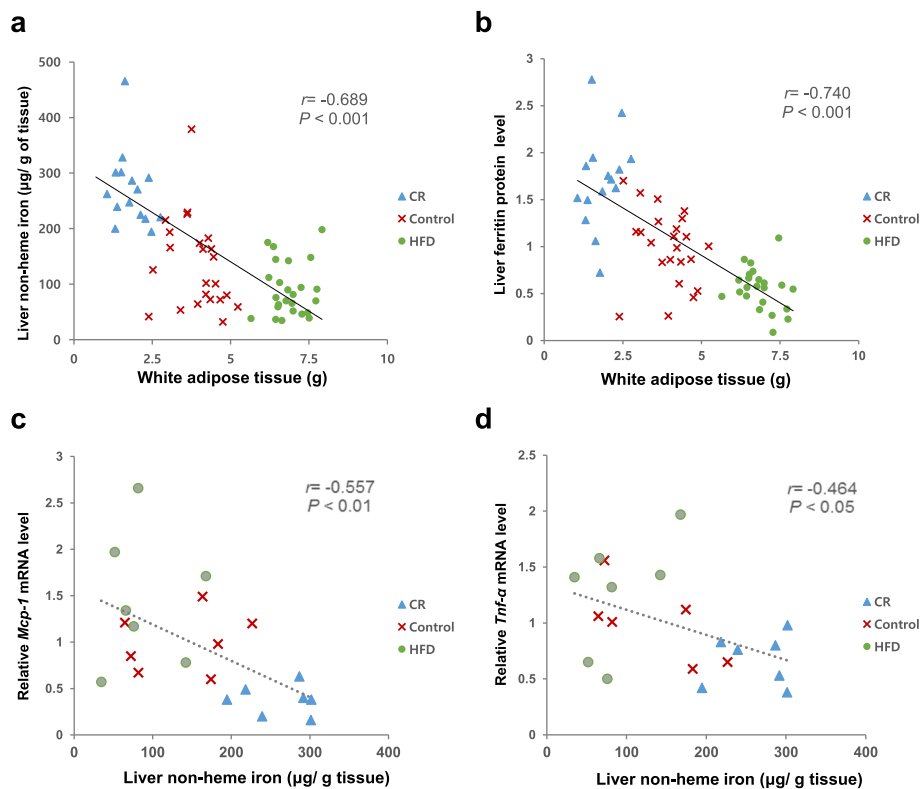


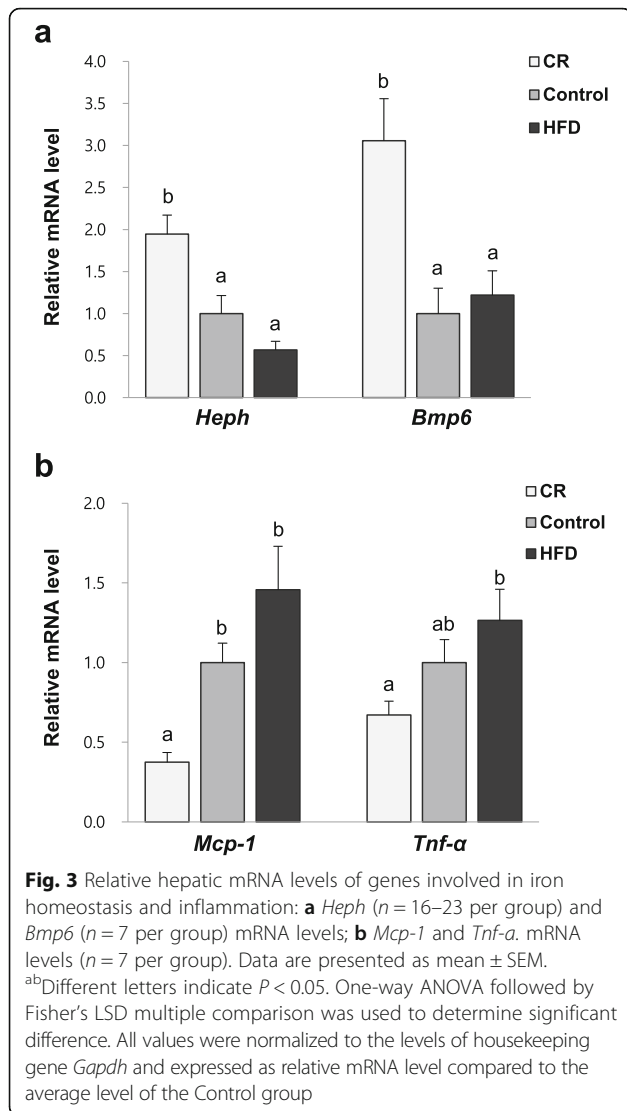
Fig. 2 Correlations between liver iron levels and white adipose tissue or hepatic inflammatory markers: **a** Liver non-heme iron level ($\mu\text{g/g}$ tissue) and white adipose tissue weight (g), $n = 63$; **b** Liver ferritin protein level and white adipose tissue weight (g), $n = 63$; **c** Hepatic *Mcp-1* mRNA level and non-heme iron level ($\mu\text{g/g}$ tissue), $n = 21$; **d** Hepatic *Tnf- α* mRNA level and non-heme iron level ($\mu\text{g/g}$ tissue), $n = 21$; Pearson correlation coefficient, r , and P value are indicated for each graph

additional supplements. Iron levels of the experimental diets were 35 mg Fe/kg in the control diet, the NRC suggested requirement for iron [27], and 48 mg Fe/kg in the high fat diet. Considering daily diet intake of each group, actual average iron intake was 104 μg Fe/day in the CR group, 15% lower than that in the Control group (123 μg Fe/day). Sorbie and Valberg [28] reported that diets containing 25–100 mg Fe/kg diet could support normal growth and hematopoiesis of C57BL/6 J mice. Therefore, a 15% decrease in dietary iron intake is unlikely to affect normal growth and metabolism.

Despite a lower dietary iron intake, hepatic non-heme iron levels were 114% higher and ferritin protein levels were 60% higher in the CR group compared with the Control group. On the other hand, the HFD group showed 34% lower non-heme iron levels and 45% lower ferritin protein levels compared with the Control group, although their iron intake was 16% higher than the Control group. Human and animal studies have also reported reduced iron status with obesity [3, 4, 29]. Restoration of serum iron and hemoglobin levels after weight loss in obese people has been observed in several studies, which suggest an association between adiposity and iron status

[30, 31]. Higher iron status in very lean mice from the CR group compared with the control animals further supports the close association between adiposity and iron levels.

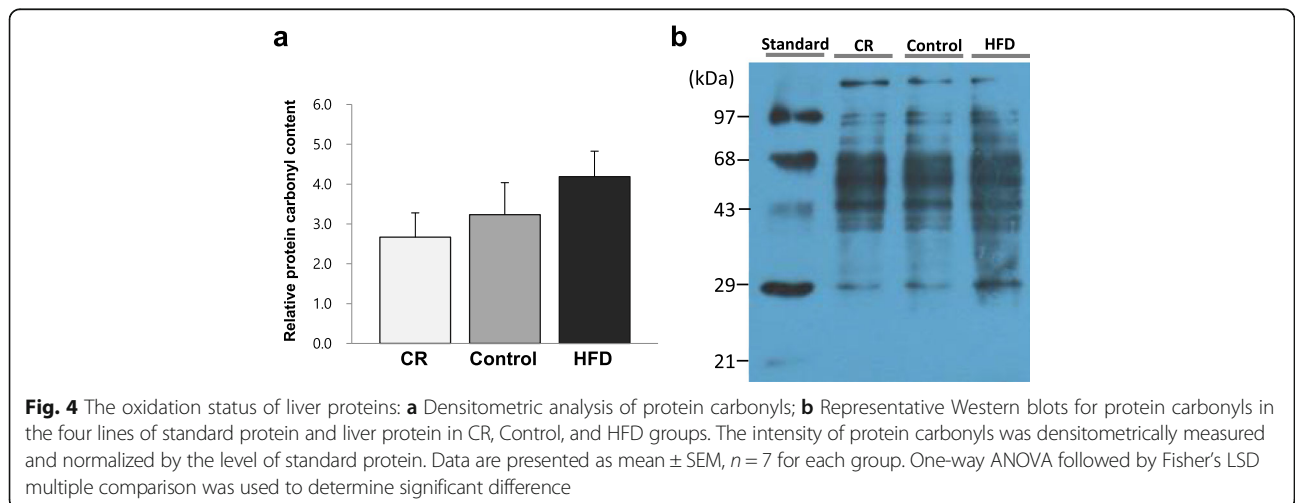
Obesity could lead to chronic inflammation and oxidative stress; due to macrophage recruitment into adipose tissue and release of pro-inflammatory cytokines through various signals. Reactive oxygen species (ROS) production is also increased by these cytokines and overconsumption of oxygen during obesity [32–34]. On the other hand, calorie restriction has been reported to alleviate inflammation and ROS production [24, 35, 36]. In this study, mRNA levels of *Tnf- α* and *Mcp-1* showed positive correlations with white adipose tissue amount, and expression of these cytokines were significantly higher in the HFD group than the CR group. However, degrees of oxidative stress, examined by determination of protein oxidative carbonyl content, were not significantly different among the groups. According to the review by Dixon et al. [37], iron and iron derivatives were essential for ROS producing enzyme function and they contributed to formation of ROS. Higher non-heme iron and ferritin levels in the CR group could have led to higher redox-active iron pools which would contribute to



the ROS formation. Therefore, lower inflammation in the CR group did not result in significant reduction of oxidative stress.

Not only hepatic iron concentration but also hepatic ferritin protein levels, which are both involved in iron storage, showed negative correlations with hepatic *Mcp-1* and *Tnf-α* levels. TNF- α has been reported to induce hypoferremia by inhibiting iron absorption through the small intestine in mice [20, 38]. *Mcp-1* has been reported as a TNF- α induced gene [39]. Although the mechanism has not been explicitly elucidated, Laftah et al. [38] reported that mucosal transfer of iron was reduced in TNF- α treated mice and was associated with increased level of duodenal ferritin that could trap ferric iron within the enterocyte. In this study, although not statistically significant ($P = 0.102$), mean duodenal *Fth1* mRNA level was higher in the HFD group compared with the Control and CR groups, which was opposite to the case of ferritin protein levels in liver. In this regard, increased *Tnf-α* and *Mcp-1* expression could be responsible for decreased iron absorption throughout the enterocyte.

Many previous studies that reported iron deficiency with obesity suggested that hepcidin was responsible for obesity driven iron shortage and hepcidin was upregulated by inflammatory signals [9]. However, in the present study, the mRNA levels of *Hamp* and *Bmp6* were lowest in the HFD group and highest in the CR group. Hepcidin is the main regulator of systemic iron homeostasis by reducing total iron content and its expression is regulated by *Bmp6* [12, 17]. Hepcidin synthesis is increased by excess iron levels or inflammatory signals and decreased by iron deficiency, hypoxia, or erythroid [40]. Darshan et al. [14] showed that inflammation induced by LPS increased *Hamp* expression in normal mice, while this mechanism was blunted in LPS stimulated mice with iron deficiency, as their *Hamp* levels were decreased. They concluded that severe iron deficiency



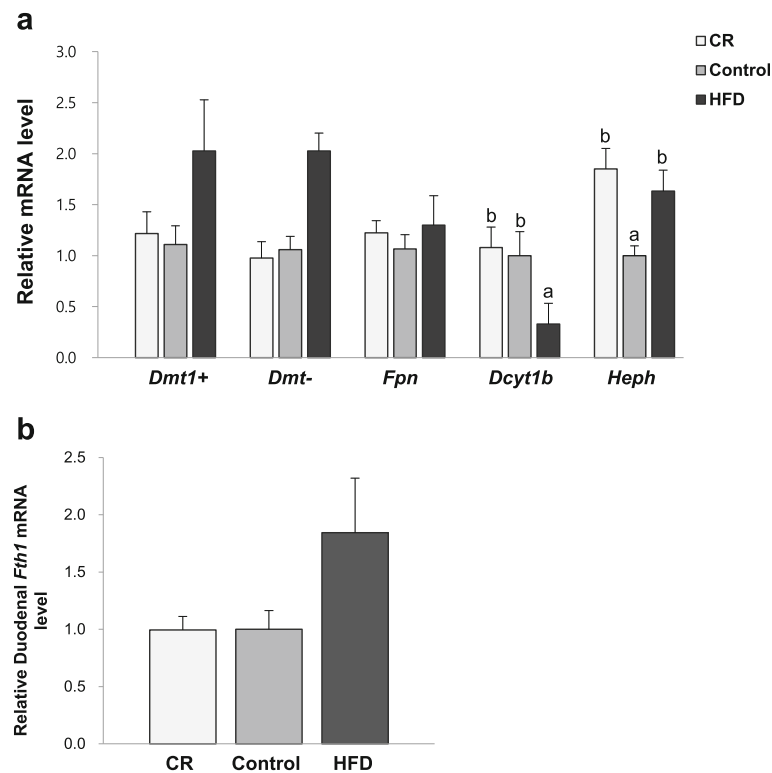


Fig. 5 Relative duodenal mRNA levels of ferritin and enzymes involved in iron transport: **a** *Dmt1*, *Fpn*(ferroportin), *Heph*(hephaestin), and *Dcyt1b* mRNA levels; **b** *Fth1*(ferritin) mRNA levels. Data are presented as mean \pm SEM, $n = 7-12$ for each group. ^{ab}Different letters indicate $P < 0.05$. One-way ANOVA followed by Fisher's LSD multiple comparison was used to determine significant difference. All values were normalized to the levels of housekeeping gene *Gapdh* and expressed as relative mRNA level compared to the average level of the Control group

could ameliorate hepcidin expression in response to LPS. In this study, although *Mcp-1* and *Tnf- α* mRNA levels were higher in the HFD group, indicative of increased inflammatory response, hepcidin levels were lower than the other groups. Lower iron levels in the HFD group could have overridden the effect of these inflammatory mediators on hepcidin expression. Thus, hepcidin levels seemed to be mainly regulated by bodily requirements for iron in this study.

Expression of iron absorption related enzymes in duodenum tissue was determined to investigate the association between adiposity and iron status. mRNA levels of *Dcyt1b* and *Heph*, which is located at both sides of enterocyte and facilitate iron transport, were highest in the CR group. *Dcyt1b* is the ferric reductase that converts ferric iron to the ferrous state that enables iron to enter the apical side of enterocyte through the *Dmt1*, and hephaestin is the ferroxidase at the basolateral side of the enterocyte [41, 42]. Calorie restriction could have promoted iron absorption by upregulating those duodenal enzymes that enable the physical state of iron to enter the enterocyte. Sonnweber et al. [19] reported lowered *Dcyt1b* and *Heph* mRNA levels in obese mice compared with control mice. They suggested that decreased levels of

ferroxidases were associated with iron deficiency in obesity. In this study, *Dcyt1b* expression was lowest in the HFD group and it showed significant negative correlation with white adipose tissue amount ($r = -0.509$), however, hephaestin level was upregulated in the HFD group compared with the Control group. Considering that hephaestin is affected by stored iron amount rather than by instant dietary iron intake [41], low iron status in the HFD group could have influenced *Heph* expression and led to higher expression in the HFD group. However, further research is needed to identify the relationship between adiposity and duodenal iron absorption and to find obesity related factors that regulate expression of iron transport enzymes.

Conclusions

This study confirmed that liver iron status has an inverse relationship with body adiposity. More importantly, we showed that liver iron levels could be upregulated in low adiposity through mild calorie restriction. Low inflammatory state induced by calorie restriction could be responsible for higher hepatic iron storage. Upregulated duodenal iron transport enzymes appeared to contribute to higher hepatic iron levels in the CR group.

Abbreviations

ANOVA: One-way analysis of variance; BMP: Bone morphogenetic protein; CR: Calorie restriction; CRP: C-reactive protein; DCYT1B: Duodenum cytochrome 1b; DMT1: Divalent metal transporter1; ECL: Enhanced chemiluminescence; HFD: High fat diet; IFN- γ : Interferon gamma; IL-6: Interleukin-6; LPS: Lipopolysaccharide; LSD: Least significant difference; MCP-1: Monocyte chemoattractant protein 1; ROS: Reactive oxygen species; SPF: Specific pathogen free; TNF- α : Tumor necrosis factor alpha

Acknowledgements

Not applicable.

Funding

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2010-0024878 and NRF-2010-0011226).

Availability of data and materials

The datasets used and/or analysed during this study available from the corresponding author on reasonable request.

Authors' contributions

CYP, JC, MSK, KK and SNH designed and performed the experiments. CYP, JC, and SNH analyzed the data. CYP, JC, and SNH wrote the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Consent for publication

Not applicable.

Ethics approval and consent to participate

This study was approved by the Seoul National University (approval no. SNU-090710-1). All of the animal experiments were approved by the Institutional Animal Care and Use Committee of Seoul National University.

Author details

¹Department of Food and Nutrition, College of Human Ecology, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, South Korea.

²Department of Food and Nutrition, College of Human Ecology, Kyung Hee University, Seoul, South Korea. ³Research Institute of Human Ecology, Seoul National University, Seoul, South Korea.

Received: 28 November 2016 Accepted: 6 February 2017

Published online: 13 February 2017

References

- World Health Organization. Micronutrient deficiencies. Iron deficiency anaemia. World Health Organization. 2015.
- Aeberli I, Hurrell RF, Zimmermann MB. Overweight children have higher circulating hepcidin concentrations and lower iron status but have dietary iron intakes and bioavailability comparable with normal weight children. *Int J Obes*. 2009;33:1111–7.
- Chung J, Kim MS, Han SN. Diet-induced obesity leads to decreased hepatic iron storage in mice. *Nutr Res*. 2011;31:915–21.
- Herter-Aeberli I, Thankachan P, Bose B, Kurpad AV. Increased risk of iron deficiency and reduced iron absorption but no difference in zinc, vitamin A or B-vitamin status in obese women in India. *Eur J Nutr*. 2016;55:2411–21.
- Lailou A, Yakes E, Le TH, Wieringa FT, Le BM, Moench-Pfanner R, et al. Intra-individual double burden of overweight and micronutrient deficiencies among Vietnamese women. *PLoS One*. 2014;9:e110499.
- Lecube A, Carrera A, Losada E, Hernandez C, Simo R, Mesa J. Iron deficiency in obese postmenopausal women. *Obesity (Silver Spring)*. 2006;14:1724–30.
- Pinhas-Hamiel O, Newfield RS, Koren I, Agmon A, Lilos P, Phillip M. Greater prevalence of iron deficiency in overweight and obese children and adolescents. *Int J Obes Relat Metab Disord*. 2003;27:416–8.
- Wenzel BJ, Stults HB, Mayer J. Hypoferraemia in obese adolescents. *Lancet*. 1962;2:327–8.
- McClung JP, Karl JP. Iron deficiency and obesity: the contribution of inflammation and diminished iron absorption. *Nutr Rev*. 2009;67:100–4.
- Nemeth E, Tuttle MS, Powelson J, Vaughn MB, Donovan A, Ward DM, et al. Hepcidin regulates cellular iron efflux by binding to ferroportin and inducing its internalization. *Science*. 2004;306:2090–3.
- Pigeon C, Ilyin G, Courselaud B, Leroyer P, Turlin B, Brissot P, et al. A new mouse liver-specific gene, encoding a protein homologous to human antimicrobial peptide hepcidin, is overexpressed during iron overload. *J Biol Chem*. 2001;276:7811–9.
- Andriopoulos Jr B, Corradini E, Xia Y, Faasse SA, Chen S, Grgurevic L, et al. BMP6 is a key endogenous regulator of hepcidin expression and iron metabolism. *Nat Genet*. 2009;41:482–7.
- Frazer DM, Wilkins SJ, Becker EM, Vulpe CD, McKie AT, Trinder D, et al. Hepcidin expression inversely correlates with the expression of duodenal iron transporters and iron absorption in rats. *Gastroenterology*. 2002;123:835–44.
- Darshan D, Frazer DM, Wilkins SJ, Anderson GJ. Severe iron deficiency blunts the response of the iron regulatory gene *Hamp* and pro-inflammatory cytokines to lipopolysaccharide. *Haematologica*. 2010;95:1660–7.
- Nemeth E, Rivera S, Gabayan V, Keller C, Taudorf S, Pedersen BK, et al. IL-6 mediates hypoferrremia of inflammation by inducing the synthesis of the iron regulatory hormone hepcidin. *J Clin Invest*. 2004;113:1271–6.
- Bekri S, Gual P, Anty R, Luciani N, Dahman M, Ramesh B, et al. Increased adipose tissue expression of hepcidin in severe obesity is independent from diabetes and NASH. *Gastroenterology*. 2006;131:788–96.
- Atanasiu V, Manolescu B, Stoian I. Hepcidin-central regulator of iron metabolism. *Eur J Haematol*. 2007;78:1–10.
- Ganz T. Hepcidin, a key regulator of iron metabolism and mediator of anemia of inflammation. *Blood*. 2003;102:783–8.
- Sonnweber T, Röss C, Nairz M, Theurl I, Schroll A, Murphy AT, et al. High-fat diet causes iron deficiency via hepcidin-independent reduction of duodenal iron absorption. *J Nutr Biochem*. 2012;23:1600–8.
- Sharma N, Laftah AH, Brookes MJ, Cooper B, Iqbal T, Tselepis C. A role for tumour necrosis factor alpha in human small bowel iron transport. *Biochem J*. 2005;390:437–46.
- Wessling-Resnick M. Iron homeostasis and the inflammatory response. *Annu Rev Nutr*. 2010;30:105–22.
- Tussing-Humphreys LM, Liang H, Nemeth E, Freels S, Braunschweig CA. Excess adiposity, inflammation, and iron-deficiency in female adolescents. *J Am Diet Assoc*. 2009;109:297–302.
- Yanoff LB, Menzie CM, Denkinger B, Sebring NG, McHugh T, Remaley AT, et al. Inflammation and iron deficiency in the hypoferrremia of obesity. *Int J Obes*. 2007;31:1412–9.
- Huang P, Li S, Shao M, Qi Q, Zhao F, You J, et al. Calorie restriction and endurance exercise share potent anti-inflammatory function in adipose tissues in ameliorating diet-induced obesity and insulin resistance in mice. *Nutr Metab (Lond)*. 2010;7:59.
- Park S, Park NY, Valacchi G, Lim Y. Calorie restriction with a high-fat diet effectively attenuated inflammatory response and oxidative stress-related markers in obese tissues of the high diet fed rats. *Mediators Inflamm*. 2012;2012:984643.
- Brain JD, Heilig E, Donaghey TC, Knutson MD, Wessling-Resnick M, Molina RM. Effects of iron status on transpulmonary transport and tissue distribution of Mn and Fe. *Am J Respir Cell Mol Biol*. 2006;34:330–7.
- Subcommittee on Laboratory Animal Nutrition, Committee on Animal Nutrition, Board on Agriculture, National Research Council. *Nutrient Requirements of Laboratory Animals, Fourth Revised Edition*. Washington, D.C.: National Academies Press (US); 1995.
- Sorbie J, Valberg LS. Iron balance in the mouse. *Lab Anim Sci*. 1974;24:900–4.
- Zimmermann MB, Zeder C, Muthayya S, Winichagoon P, Chaouki N, Aeberli I, et al. Adiposity in women and children from transition countries predicts decreased iron absorption, iron deficiency and a reduced response to iron fortification. *Int J Obes*. 2008;32:1098–104.
- Amato A, Santoro N, Calabro P, Grandone A, Swinkels DW, Perrone L, et al. Effect of body mass index reduction on serum hepcidin levels and iron status in obese children. *Int J Obes*. 2010;34:1772–4.
- Dao MC, Meydani SN. Iron biology, immunology, aging, and obesity: four fields connected by the small peptide hormone hepcidin. *Adv Nutr*. 2013;4:602–17.
- Tilg H, Moschen AR. Adipocytokines: mediators linking adipose tissue, inflammation and immunity. *Nat Rev Immunol*. 2006;6:772–83.
- Fantuzzi G. Adipose tissue, adipokines, and inflammation. *J Allergy Clin Immunol*. 2005;115:911–9.
- Furukawa S, Fujita T, Shimabukuro M, Iwaki M, Yamada Y, Nakajima Y, et al. Increased oxidative stress in obesity and its impact on metabolic syndrome. *J Clin Invest*. 2004;114:1752–61.

35. Gonzalez O, Tobia C, Ebersole J, Novak MJ. Caloric restriction and chronic inflammatory diseases. *Oral Dis.* 2012;18:16–31.
36. Qiu X, Brown K, Hirschey MD, Verdin E, Chen D. Calorie restriction reduces oxidative stress by SIRT3-mediated SOD2 activation. *Cell Metab.* 2010;12:662–7.
37. Dixon SJ, Stockwell BR. The role of iron and reactive oxygen species in cell death. *Nat Chem Biol.* 2014;10:9–17.
38. Laftah AH, Sharma N, Brookes MJ, McKie AT, Simpson RJ, Iqbal TH, et al. Tumour necrosis factor alpha causes hypoferraemia and reduced intestinal iron absorption in mice. *Biochem J.* 2006;397:61–7.
39. Ping D, Boekhoudt G, Zhang F, Morris A, Philipsen S, Warren ST, et al. Sp1 binding is critical for promoter assembly and activation of the MCP-1 gene by tumor necrosis factor. *J Biol Chem.* 2000;275:1708–14.
40. Huang H, Constante M, Layoun A, Santos MM. Contribution of STAT3 and SMAD4 pathways to the regulation of hepcidin by opposing stimuli. *Blood.* 2009;113:3593–9.
41. Frazer DM, Wilkins SJ, Becker EM, Murphy TL, Vulpe CD, McKie AT, et al. A rapid decrease in the expression of DMT1 and Dcytb but not Ireg1 or hephaestin explains the mucosal block phenomenon of iron absorption. *Gut.* 2003;52:340–6.
42. Lane DJ, Bae DH, Merlot AM, Sahni S, Richardson DR. Duodenal cytochrome b (DCYTB) in iron metabolism: an update on function and regulation. *Nutrients.* 2015;7:2274–96.

Submit your next manuscript to BioMed Central and we will help you at every step:

- We accept pre-submission inquiries
- Our selector tool helps you to find the most relevant journal
- We provide round the clock customer support
- Convenient online submission
- Thorough peer review
- Inclusion in PubMed and all major indexing services
- Maximum visibility for your research

Submit your manuscript at
www.biomedcentral.com/submit

