Increased FNDC5 is associated with insulin resistance in high fat-fed mice

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Abstract
FNDC5/irisin, has recently been identified as a novel protein that stimulates the “browning” of white adipose by inducing thermogenesis via increased uncoupling protein 1 (UCP1). We tested the hypothesis that high fat diet-induced prediabetic mice would exhibit increased FNDC5 and this effect would be attenuated by chronic exercise. C57BL/6 mice were randomized into three groups for the 4 week intervention: Standard diet (Std, n = 12), High fat diet (HF, n = 14), or High fat diet and free access to a running wheel (HFEX, n = 14). Body weight, glucose, insulin, and the homeostatic model assessment of insulin resistance (HOMA-IR) were greater in HF compared to Std and HFEX after the 4 week intervention. In support of our hypothesis, FNDC5 was higher in HF in both skeletal muscle and adipose compared to Std and was lower in adipose only in HFEX compared to HF mice. Following the same pattern, PGC-1α was significantly higher in HF compared to Std in skeletal muscle and significantly lower in HFEX compared to HF in adipose. UCP1 was significantly lower in HFEX versus Std (in skeletal muscle) and versus HF (in adipose). HOMA-IR was significantly correlated with FNDC5 protein levels in adipose. Increased FNDC5 in adipose and skeletal muscle may be a compensatory mechanism to offset high fat diet-induced weight gain and insulin resistance by increasing energy expenditure.

Introduction
Irisin has recently been identified as a novel exercise-inducible myokine that may hold therapeutic potential for both obesity and diabetes. Fibronectin type III domain-containing protein 5 (FNDC5) is released from muscle and then cleaved to irisin, the soluble peptide hormone. FNDC5 is upregulated in response to acute exercise (Bostrom et al. 2012; Brenmoehl et al. 2014; Norheim et al. 2014; Nygaard et al. 2015) and chronic exercise (Bang et al. 2014; Norheim et al. 2014) in humans and animals. Exercise-induced expression of FNDC5/irisin in muscle has been shown to be dependent on increased PGC-1α (Bostrom et al. 2012; Brenmoehl et al. 2014; Norheim et al. 2014).

Irisin’s actions include “browning” of white adipose tissue (WAT) via increased uncoupling protein 1 (UCP1) levels, a specialized mitochondrial protein that converts
WAT to brown adipose tissue (BAT) by dissipating energy in the form of heat (Bostrom et al. 2012; Wu et al. 2014). Browning of WAT has the potential to increase total energy expenditure (Wu et al. 2014) and suggests a role for FNDC5/irisin in treatment of obesity and obesity-related diseases such as type II diabetes.

The impact of exercise on FNDC5/irisin is somewhat contradictory and the different views may be due to variability in exercise mode, intensity, frequency, duration, and whether exercise was chronic or acute. Following acute endurance exercise, FNDC5/irisin levels are significantly elevated, resulting in increased energy expenditure in mice (Bostrom et al. 2012; Brenmoehl et al. 2014; Norheim et al. 2014) and humans (Norheim et al. 2014; Nygaard et al. 2015). This increased energy expenditure is proposed to be mediated by increased browning of WAT via increased UCP1 levels (Bostrom et al. 2012; Wu et al. 2014). However, other studies have shown no effect of acute (Czarkowska-Paczez et al. 2014) or chronic endurance exercise on skeletal muscle FNDC5 or circulating irisin (Hecksteden et al. 2013; Kurdiova et al. 2014; Seo et al. 2014). Norheim et al. demonstrated that combined chronic endurance and resistance training increased both PGC-1α and FNDC5 skeletal muscle mRNA, whereas circulating irisin increased only in response to acute combined endurance and resistance exercise (Norheim et al. 2014). Further study is needed to differentiate the effects of acute and chronic exercise on FNDC5 and irisin.

In addition to its role as an exercise-inducible myokine, it has been purported that irisin may play a compensatory role as an adipokine released in response to obesity and/or insulin resistance. Mice fed high fat diets have higher serum irisin levels than their lean counterparts (Seo et al. 2014; Wu et al. 2014). Similarly, humans that consume a caloric excess diet and have elevated fasting glucose levels exhibit elevated serum irisin levels (Huerta et al. 2015; Schlogl et al. 2015). Furthermore, plasma irisin levels are positively associated with body mass index (Stengel et al. 2013) as well as fat mass (Pardo et al. 2014). Congruently, weight loss induced by bariatric surgery or diet/exercise intervention has resulted in associated reductions in plasma irisin levels (Huh et al. 2012; Sharma et al. 2012; Crujeiras et al. 2014).

Although initial investigations focused on the impact of exercise on FNDC5/irisin, irisin has recently been proposed to have a compensatory role as an adipokine released in response to metabolic disturbance (Novelle et al. 2013). FNDC5 and irisin have been assessed in the context of a high fat diet (Seo et al. 2014; Wu et al. 2014; Yang et al. 2015), obesity (Stengel et al. 2013; Yamvmini et al. 2013), and insulin resistance (Choi et al. 2013; Moreno-Navarrete et al. 2013; Park et al. 2013; Crujeiras et al. 2014; Ebert et al. 2014; Kurdiova et al. 2014; Sesti et al. 2014; Yang et al. 2015; Hu et al. 2016; Huh et al. 2016; Shi et al. 2016), but results are contradictory. Although several studies have shown irisin to be positively associated with insulin resistance (Park et al. 2013; Crujeiras et al. 2014; Ebert et al. 2014; Sesti et al. 2014; Huh et al. 2016), others have shown decreased irisin in type 2 diabetic patients (Choi et al. 2013; Moreno-Navarrete et al. 2013; Hu et al. 2016) and rodents (Yang et al. 2015). It is plausible that these conflicting results are associated with differences in the severity or duration of insulin resistance.

In addition, the majority of previous studies showing an association between FNDC5/irisin and insulin resistance have used an estimate of insulin sensitivity such as an oral glucose tolerance test (Moreno-Navarrete et al. 2013) or HOMA-IR (Park et al. 2013; Crujeiras et al. 2014; Ebert et al. 2014; Hu et al. 2016). Only one study has directly assessed insulin’s action using insulin signaling via Akt activation (Yang et al. 2015). In light of irisin’s potential role as a pharmacotherapeutic treatment for insulin resistance, it is critical to understand irisin’s role in insulin resistance. Here, we tested the hypothesis that high fat diet-induced prediabetic mice increases FNDC5 and this effect would be attenuated by chronic exercise. Importantly, we report the effects of a high fat diet and exercise on skeletal muscle Akt activation and FNDC5 protein expression in adipose and skeletal muscle.

Methods

Animals, diet, and voluntary exercise

Male 7-week old C57BL/6NCrl mice were obtained from Charles River (Washington, MA) and were kept in controlled illumination on a 12-h light: 12-h dark cycle at the University of Kansas Medical Center laboratory animal resources facility. Mice were randomized to one of three treatment groups that are abbreviated throughout as follows: standard diet sedentary (Std), high fat diet sedentary (HF), and high fat diet exercise (HFEX). Sedentary mice were housed two per cage in a pathogen-free vivarium and had ad libitum access to both water and food that included either a standard diet (8604; Harlan Teklad, Madison Wisconsin; 14% kcals from fat, 32% from protein, and 54% from carbohydrates) or a high fat diet (07011; Harlan Teklad; 54% kcals from fat comprised of both vegetable shortening and corn oil, 21% protein, and 24% kcals from carbohydrate). Exercised mice were caged individually and had ad libitum access to a running wheel for the entire 4 weeks of the study. The Vital View Data Acquisition System (Mini...
Mitter, Bend, OR) was used to record each wheel revolution in thirty-minute intervals and quantify daily running distance. Daily running distance was calculated by multiplying the number of wheel turns by the diameter of the wheel in a 24 h period. Mice were removed from running wheels 24 h prior to tissue harvest in order to eliminate the acute effects of exercise.

All procedures were approved by the University of Kansas Medical Center Animal Use and Care Committee and were compliant with the National Research Council of the National Academies’ Guide for the Care and Use of Laboratory Animals (2011).

### Glucose, insulin, and HOMA-IR

Following a 3-h fast, blood was collected at baseline and at the end of the 4-week study immediately before insulin stimulation. Samples were assayed for glucose using glucose diagnostic reagents (Sigma, St. Louis, MO). For insulin measurements, blood was collected into a heparinized microcapillary tube, then pipetted into an Eppendorf tube, and centrifuged for 15 min at 3000g. Plasma was removed and frozen at −80°C. Insulin levels were measured using ELISA (mouse insulin Elisa, Alpco, Salem, NH). Fasting insulin and fasting glucose levels were used to calculate the homeostatic model assessment of insulin resistance (HOMA-IR), a measure of insulin resistance. The following equation was used to calculate HOMA-IR values: Blood (Glucose (mg/dL) × (Serum Insulin (μU/mL))/405 (Kim et al. 2008).

### Insulin stimulation

Following a three hour fast, sterile PBS (vehicle) or 10 U/kg Humulin R insulin was administered to mice from the SS, HS, and HE groups. Humulin R insulin was diluted to 0.001 U/μL in sterile PBS and 10 μL/g was injected via a single intra-peritoneal injection. Thirty minutes after insulin injection, mice were anesthetized with isofluorane and decapitated. Blood was collected from the decapitation pool for post-insulin stimulation glucose quantification.

### Western immunoblotting

After the 30-min vehicle PBS or insulin stimulation period, mice were euthanized as described above and the gastrocnemius muscle and epididymal fat pad were snap frozen in liquid nitrogen, and stored at −80°C. Only tissues from PBS injected mice were used for the FNDC5, UCP1, and PGC-1α western blots. Tissues were lysed with cell lysis buffer (137 mmol/L NaCl, 20 mmol/L Tris [pH 8.0], 1% NP40, and 10% glycerol) containing protease inhibitors (0.5 mm sodium vanadate, 1 μg/mL leupeptin, 10 μg/mL aprotinin, and 1 mmol/L PMSF) and protein was extracted while tissue lysates were kept on ice for 1 h and vortexed every 10 min. Samples were then centrifuged at 10,000g for 10 min at 4°C and the protein concentration of the supernatant was measured with a Bradford assay (Bio-Rad, Hercules, CA). Samples were prepared to achieve equivalent protein concentrations then boiled at 95–100°C with Lane Marker Reducing Sample Buffer (Thermo Scientific, Waltham, MA) for 3 min. Samples were separated by electrophoresis (35 mA/gel, 0.75 h, 4°C) on 4–15% gradient tris-glycine polyacrylamide gels (Bio-Rad). Samples for Akt quantification were transferred onto nitrocellulose membranes (400 mA, 1.5 h, 4°C) and samples for FNDC5, UCP1, and PGC-1α were transferred onto polyvinylidene difluoride (PVDF) membranes using Bio-Rad Trans Blot Turbo (2 gels/cassette, 25 mA, 7 min). Membranes were blocked for 1 h at room temperature in blocking solution (5% non-fat powdered milk and 0.05% Tween-20 in 0.1 mol/L phosphate buffered saline [PBST, pH 7.4]), followed by overnight incubation (4°C) in primary antibody diluted in blocking solution (1% non-fat powdered milk and 0.05% 0.1 mol/L PBS (pH 7.4)).

Membranes were probed using following antibodies: total Akt (C67E7 rabbit mAb #4691; Cell Signaling Technology, Danvers, MA), phospho (Ser473) Akt (rabbit mAb #4060; Cell Signaling), FNDC5 (ab174833; Abcam, Cambridge, MA), PGC-1α (ab72230, Abcam), UCP1 (ab10983; Abcam), α-tubulin (T-5168), and β-actin (#5125; Cell Signaling). Following PBST washes, membranes were incubated at room temperature for 1 h at room temperature using goat anti-rabbit horseradish peroxidase-conjugated (HRP) secondary antibodies (sc-2004; Santa-Cruz Biotechnology, Dallas, TX). All bands were visualized by enhanced chemiluminescence (ECL) using Supersignal West (Femto or Pico) Substrate (Pierce, Rockford, IL). Total Akt and pAkt bands were detected on X-ray film, and quantified via densitometry using NIH Image J software. FNDC5, UCP1, and PGC-1α bands were detected and quantified using Bio-Rad ChemiDoc MP Imaging System with Image Software Lab.

### Statistical analysis

Data are presented as a mean ± SEM. Data were analyzed using a two-factor analysis of variance (ANOVA) or repeated measures ANOVA with Fisher’s test of least square difference post hoc comparisons. Pearson correlations using two-tailed P-values were performed to assess the relationship between FNDC5 protein levels in skeletal muscle and adipose and body weight, body weight...
Results

Bodyweight, glucose, insulin

Sedentary mice fed the HF diet had increased body weight (Fig. 1A), glucose (Fig. 1B) and insulin levels (Fig. 2A), and HOMA-IR (Fig. 2B) and greater daily caloric intake compared to Std sedentary mice. Elevations in glucose and insulin levels in HF mice indicated that these mice were prediabetic but not overtly diabetic (Fig. 2B). Body weight (Fig. 1A), glucose (Fig. 1B), insulin (Fig. 2A), and HOMA-IR (Fig. 2B) in HFEX mice were not different from Std sedentary mice, thus voluntary running wheel exercise prevented deleterious changes in all of these metabolic variables, despite significantly greater daily caloric intake in HFEX (18.4 ± 1.9 kcal/d) compared to Std (12.7 ± 2.5 kcal/d, \( P < 0.001 \)) and HF (14.0 ± 1.1 kcal/d, \( P < 0.001 \)).

Exercise distance

HFEX mice had ad libitum access to a running wheel in their individual cages 24 h per day, 7 days per week. However, due to their nocturnal nature, mice used the running wheels primarily during the dark portion of the 12 h light/dark cycle from 6 PM to 6 AM. On average, all mice ran 9.9 km per 24 h.

Akt activation

After insulin stimulation, insulin action was evaluated by quantification of Akt activation (pAkt/total Akt) in the gastrocnemius muscle. In Std, HF, and HFEX, insulin injection elicited a significant increase in Akt activation compared to PBS injection in the corresponding group (Fig. 3). Akt activation was significantly blunted in the gastrocnemius of HF compared to Std mice (Fig. 3). Akt activation was significantly higher in HFEX compared to HF mice, indicating that exercise attenuated the deleterious effects of the high fat diet on insulin signaling in muscle (Fig. 3). However, HFEX mice nevertheless had significantly lower Akt activation than Std, revealing that 4 weeks of exercise did not completely restore Akt activation to normal levels (Fig. 3).

FNDC5, UCP1, and PGC-1α protein levels

In the gastrocnemius muscle, FNDC5 and PGC-1α protein levels were significantly higher in HF compared to the Std mice (Fig. 4A and C). UCP1 levels were higher in the Std compared to HFEX mice (Fig. 4B).
Consistent with skeletal muscle, FNDC5 in adipose was significantly higher in HF compared to Std mice (Fig. 5A). In addition, adipose levels of FNDC5, UCP1, and PGC-1α were significantly higher in HF compared to HFEX mice (Fig. 5A–C). Adipose PGC-1α was also significantly higher in Std compared to HFEX mice (Fig. 5C).

**Correlations between FNDC5 and variables associated with insulin resistance**

Considering the role that activation of the PGC-1α-FNDC5/irisin pathway may have in response to insulin resistance, Pearson correlations were performed between FNDC5 protein levels in muscle or adipose and body weight, fasting blood glucose, and HOMA-IR. Neither muscle nor adipose FNDC5 protein levels were significantly correlated with body weight or fasting blood glucose. However, adipose FNDC5 was significantly correlated ($P = 0.04$, $R = 0.16$) with HOMA-IR (Fig. 6A). In addition, body weight change, an indicator of energy balance, was significantly correlated with adipose FNDC5 (Fig. 6B, $P = 0.01$, $R = 0.48$) and HOMA-IR (Fig. 6C, $P = 0.005$, $R = 0.50$).
Discussion

The current experiments reveal the impact of exercise on the FNDC5/PGC-1α pathway in high fat-fed prediabetic mice with impaired insulin action. FNDC5 was increased in both skeletal muscle and adipose in high fat-fed, overweight, prediabetic mice compared to mice fed a standard diet. Exercise prevented the increase in body weight, glucose, HOMA-IR, FNDC5, and attenuated the loss of skeletal muscle insulin action (Akt activation) in high fat-fed mice. These results indicate a potential compensatory increase in FNDC5 to counteract body weight gain and loss of insulin sensitivity in high fat-fed mice. Furthermore, our results contribute new evidence that irisin acts in a homeostatic fashion in metabolic conditions such as obesity and prediabetes. However, the precise role of the PGC-1α-FNDC5/irisin pathway in regulation of energy metabolism remains elusive.

Exercise did not increase PGC-1α, FNDC5, or UCP1

Irisin was initially identified as a PGC-1α-dependent exercise-inducible myokine that stimulated the browning of adipose tissue via increased thermogenesis (Bostrom et al. 2012). Previous studies demonstrate increased FNDC5/irisin in response to chronic exercise (Bostrom et al. 2012; Roca-Rivada et al. 2013; Norheim et al. 2014; Wu et al. 2014) and increased PGC-1α following acute (Bostrom et al. 2012; Norheim et al. 2014) and chronic (Norheim et al. 2014; Wu et al. 2014) endurance exercise. Conversely, in the current study, 4 weeks of chronic running wheel exercise did not induce a significant increase in FNDC5 or PGC-1α protein levels in skeletal muscle or adipose compared to sedentary mice. PGC-1α in adipose was actually lower in HF fed exercised mice compared to both sedentary mice fed the standard diet or HF diet and this pattern was consistent with lower FNDC5 levels in adipose in the HFE group compared to HF.

Importantly, others have reported that PGC-1α and FNDC5 peak a few hours after an acute endurance exercise and return to baseline levels within 24 h (Bostrom et al. 2012; Brenmoehl et al. 2014; Norheim et al. 2014; Nygaard et al. 2015). In order to ameliorate the acute effects of exercise, mice in the current study were removed from exercise wheels 24 h before sacrifice. This may, in part, explain the lack of increase in FNDC5 in the exercised mice. In addition, exercised mice in the current study were also on a high fat diet, and previous studies showing increased FNDC5 in exercised mice were in...
mice fed a standard diet (Boström et al. 2012; Brenmoehl et al. 2014). Consistent with our findings, Wu et al. demonstrated endurance training had no effect on skeletal muscle FNDC5 levels in rats fed a high or low fat diet (Wu et al. 2014). Furthermore, Perhaps acute exercise increases PGC-1α and subsequently increases FNDC5 in skeletal muscle. It may be that these effects are transient as PGC-1α and FNDC5 levels return to baseline within hours after exercise, thus explaining the lack of increased skeletal muscle PGC-1α and FNDC5 in the current study.

Notably, skeletal muscle and adipose UCP1 levels were significantly lower in HFEX compared Std mice in muscle and HF mice in adipose. This pattern reflects the lack of increase in muscle PGC-1α and FNDC5 in HFEX (vs. Std) and significantly lower adipose PGC-1α in HFEX (vs. Std and HF) and adipose FNDC5 in HFEX (vs. Std and HF). However, previous studies report exercise training induced increased UCP1 levels predominantly in inguinal white adipose tissue (iWAT), opposed to epididymal adipose, which was used in the current study (Roca-Rivada et al. 2013; Wu et al. 2014; Claycombe et al. 2015). Interestingly, Roca-Rivada et al. reported UCP1 in BAT decreased after 3 weeks of endurance exercise (Roca-Rivada et al. 2013). Furthermore, Wu et al. (2014) reported chronic exercise in rats increased UCP1 content and subsequent browning primarily in subcutaneous adipose tissue, however, these effects were attenuated by a high fat diet.

A progressive reduction in UCP1 in BAT during chronic endurance exercise suggests an adaptive response to chronic exercise. Myo-adipokine cross-talk may exist in which exercise initially stimulates browning of adipose tissue, but chronic exercise training eventually results in an adaptive halt with reduction in UCP1 expression due to less “necessity” for energy expenditure. This view agrees with our findings in which HFEX exhibited substantially lower UCP1 levels in adipose and skeletal muscle compared to the Std and HF groups respectively. Thus, exercise may prevent an increase in UCP1 and BAT development, contrary to previous thought. This view is consistent with the idea that the PGC-1α-FNDC5/irisin pathway may be increased transiently in response to exercise.

**FNDC5 and PGC-1α were increased in high fat-fed sedentary mice**

Although initially identified as a myokine (Boström et al. 2012), FNDC5/irisin has also been identified as an adipokine, with increased release stimulated by atypical metabolic disturbances such as obesity and insulin resistance (Kleiner et al. 2012; Roca-Rivada et al. 2013; Stengel et al. 2017).
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Our results are congruent with previous reports in both animals and humans that suggest the PGC-1α-FNDC5/irisin pathway is upregulated in response to chronically elevated blood glucose as well as HOMA-IR (Huh et al. 2012; Kleiner et al. 2012; Crujeiras et al. 2014; Keuper et al. 2014; Yang et al. 2015; Xin et al. 2016; Zhang et al. 2016). Additionally, Zhang et al. reported a positive correlation between circulating irisin and HbA1c levels in diabetic humans (Zhang et al. 2016). Furthermore, Crujeiras et al. found that individuals who regain weight after initial weight loss had increased irisin levels corresponding with increased bodyweight, fat mass, fasting glucose, insulin, and HOMA-IR compared to those maintaining a normal weight (Crujeiras et al. 2014).

Our results indicate that HF feeding resulted in reduced Akt activation and increased PGC-1α and FNDC5 in skeletal muscle and adipose, which were all attenuated by exercise. We postulate that insulin resistance stimulates activation of the PGC-1α/FNDC5 pathway as a compensatory response in effort to increase insulin sensitivity and attenuate impaired insulin signaling. In support of this idea, Xin et al. reported that HF-diet induced diabetic mice treated with irisin showed dramatically improved glucose tolerance and glucose uptake with increased translocation of GLUT4 in skeletal muscle along with a myriad of other benefits including increased UCP1 in adipose and increased fatty acid oxidation (Xin et al. 2016). Intriguingly, Yang et al. found that irisin treatment recovered impaired Akt and Erk phosphorylation in palmitic-acid induced insulin resistant myocytes (Yang et al. 2015). These studies and our results support our hypothesis that FNDC5 levels in both skeletal muscle and adipose tissue are increased as an adaptive response in prediabetic mice to counteract the deleterious effects of excess adiposity and perturb metabolic derangements such as insulin resistance. The present findings suggest that the role of irisin as a protective myo-adipokine in atypical metabolic situations needs further examination, but provides promising support for the potential pharmacotherapeutic use of irisin in the treatment of obesity and type 2 diabetes.

Conclusion

A high fat diet and chronic exercise significantly impacts the irisin/PGC-1α pathway, insulin sensitivity, and insulin action in prediabetic mice. FNDC5 and PGC-1α protein levels were elevated in skeletal muscle and adipose in HF sedentary mice and compared to Std sedentary mice (in muscle) and HF exercised mice (in adipose). Importantly, adipose FNDC5 was positively correlated with HOMA-IR.
Taken together, these data indicate that exercise may transiently increase these proteins, however, metabolic disturbances such as high fat diet-induced obesity and insulin resistance may have a greater role in upregulating this pathway in skeletal muscle and adipose. We propose that PGC-1α-FNDC5/irisin pathway may be upregulated as a compensatory mechanism to induce browning of adipose and subsequently increase energy expenditure to oppose increased adiposity and insulin resistance. This concept suggests FNDC5/irisin may have an important role as a protective myo-adipokine opposing the development of insulin resistance in the stages of prediabetes and provides further support for the use of FNDC5/irisin as a potential therapeutic treatment for obesity and related metabolic disorders.

Conflict of Interest

None declared.

References

Bang, H. S., D. Y. Seo, Y. M. Chung, K. M. Oh, J. J. Park, F. Arturo, et al. 2014. Ursolic Acid-induced elevation of serum irisin augments muscle strength during resistance training in men. Korean J. Physiol. Pharmacol. 18:441–446. 
Bostrom, P., J. Wu, M. P. Jedrychowski, A. Korde, L. Ye, J. C. Lo, et al. 2012. A PGC1-alpha-dependent myokine that drives brown-fat-like development of white fat and thermogenesis. Nature 481:463–468. 
Brenmoehl, J., E. Albrecht, K. Komolka, L. Schering, M. Langhammer, A. Hoeflich, et al. 2014. Irisin is elevated in skeletal muscle and serum of mice immediately after acute exercise. Int. J. Biol. Sci. 10:338–349. 
Choi, Y. K., M. K. Kim, K. H. Bae, H. A. Seo, J. Y. Jeong, W. K. Lee, et al. 2013. Serum irisin levels in new-onset type 2 diabetes. Diabetes Res. Clin. Pract. 100:96–101. 
Claycombe, K. J., E. E. Vomhof-DeKrey, J. N. Roemmich, T. Rhen, and O. Ghribi. 2015. Maternal low-protein diet causes body weight loss in male, neonate Sprague-Dawley rats involving UCP-1-mediated thermogenesis. J. Nutr. Biochem. 26:729–735. 
Cruejeiras, A. B., M. A. Zulet, P. Lopez-Lagarrea, R. de la Iglesia, M. Pardo, M. C. Carreira, et al. 2014. Association between circulating irisin levels and the promotion of insulin resistance during the weight maintenance period after a dietary weight-lowering program in obese patients. Metabolism 63:520–531. 
Cruejeiras, A. B., M. Pardo, and F. F. Casanueva. 2015. Irisin: ‘fat’ or artefact. Clin. Endocrinol. (Oxf) 82:467–474. 
Czarkowska-Paczek, B., M. Zendzian-Piotrowska, K. Gala, M. Sobol, and L. Paczek. 2014. One session of exercise or endurance training does not influence serum levels of irisin in rats. J. Physiol. Pharmacol. 65:449–454. 
Ebert, T., D. Focke, D. Petroff, U. Wurst, J. Richter, A. Bachmann, et al. 2014. Serum levels of the myokine irisin in relation to metabolic and renal function. Eur. J. Endocrinol. 170:501–506. 
Hecksteden, A., M. Wegmann, A. Steffen, J. Kraushaar, A. Morsch, S. Ruppenthal, et al. 2013. Irisin and exercise training in humans - results from a randomized controlled training trial. BMC Med. 11:235. 
Hu, W., R. Wang, J. Li, J. Zhang, and W. Wang. 2016. Association of irisin concentrations with the presence of diabetic nephropathy and retinopathy. Ann. Clin. Biochem. 53(Pt 1):67–74. 
Huerta, A. E., P. L. Prieto-Hontoria, M. Fernandez-Galilea, N. Sainz, M. Cuervo, J. A. Martinez, et al. 2015. Circulating irisin and glucose metabolism in overweight/obese women: effects of alpha-lipoic acid and eicosapentaenoic acid. J. Physiol. Biochem. 71:547–558. 
Huh, J. H., S. V. Ahn, J. H. Choi, S. B. Koh, and C. H. Chung. 2016. High Serum Irisin Level as an Independent Predictor of Diabetes Mellitus: A Longitudinal Population-Based Study. Medicine (Baltimore) 95:e3742. 
Huh, J. Y., G. Panagiotou, V. Mougios, M. Brinkoetter, M. T. Vamvini, B. E. Schneider, et al. 2012. FNDC5 and irisin in humans: I. Predictors of circulating concentrations in serum and plasma and II. mRNA expression and circulating concentrations in response to weight loss and exercise. Metabolism 61:1725–1738. 
Keuper, M., M. Jastroch, C. X. Yi, P. Fischer-Posovszky, M. Wabitsch, M. H. Tschop, et al. 2014. Spare mitochondrial respiratory capacity permits human adipocytes to maintain ATP homeostasis under hypoglycemic conditions. FASEB J. 28:761–770. 
Kim, M. K., Y. N. Chae, M. H. Son, S. H. Kim, J. K. Kim, H. S. Moon, et al. 2008, PAR-5359, a well-balanced PPARalpha/gamma dual agonist, exhibits equivalent antidiabetic and hypolipidemic activities in vitro and in vivo. Eur. J. Pharmacol. 595:119–125. 
Kleiner, S., R. J. Mepani, D. Lazznik, L. Ye, M. J. Jurczak, F. R. Jornayvaz, et al. 2012. Development of insulin resistance in mice lacking PGC-1alpha in adipose tissues. Proc. Natl. Acad. Sci. USA 109:9635–9640. 
Kurdiova, T., M. Balaz, M. Vician, D. Maderova, M. Vlcek, L. Valkovic, et al. 2014. Effects of obesity, diabetes and exercise on Fndc5 gene expression and irisin release in human skeletal muscle and adipose tissue: in vivo and in vitro studies. J. Physiol. 592:1011–1107. 
Lopez-Lagarrea, P., R. de la Iglesia, A. B. Cruejeiras, M. Pardo, F. F. Casanueva, M. A. Zulet, et al. 2014. Higher baseline irisin concentrations are associated with greater reductions in glycaemia and insulinemia after weight loss in obese subjects. Nutr. Diabetes 4:e110. 
Moreno-Navarrete, I. M., F. Ortega, M. Serrano, E. Guerra, G. Pardo, F. Tinahones, et al. 2013. Irisin is expressed and produced by human muscle and adipose tissue in...
association with obesity and insulin resistance. J. Clin. Endocrinol. Metab. 98:E769–778.
National Research Council (US) Committee for the Update of the Guide for the Care and Use of Laboratory Animals (2011). Guide for the care and use of laboratory animals. National Academies Press. Washington DC.
Norheim, F., T. M. Langleite, M. Hjorth, T. Holen, A. Kielland, H. K. Stadheim, et al. 2014. The effects of acute and chronic exercise on PGC-1alpha, irisin and browning of subcutaneous adipose tissue in humans. FEBS J. 281:739–749.
Novelle, M. G., C. Contreras, A. Romero-Pico, M. Lopez, and C. Dieguez. 2013. Irisin, two years later. Int. J. Endocrinol. 2013:746281.
Nygaard, H., G. Slettalokken, G. Vegge, I. Hollan, J. E. Whist, T. Strand, et al. 2015. Irisin in blood increases transiently after single sessions of intense endurance exercise and heavy strength training. PLoS ONE 10:e0121367.
Pardo, M., A. B. Crujeiras, M. Amil, Z. Aguera, S. Jimenez-Murcia, R. Banos, et al. 2014. Association of irisin with fat mass, resting energy expenditure, and daily activity in conditions of extreme body mass index. Int. J. Endocrinol. 2014:857270.
Park, K. H., L. Zaichenko, M. Brinkoetter, B. Thakkar, A. Sahin-Efe, K. E. Joung, et al. 2013. Circulating irisin in relation to insulin resistance and the metabolic syndrome. J. Clin. Endocrinol. Metab. 98:4899–4907.
Roca-Rivada, A., C. Castelao, L. L. Senin, M. O. Landrove, J. Baltar, A. Belen Crujeiras, et al. 2013. FNDC5/irisin is not only a myokine but also an adipokine. PLoS ONE 8:e60563.
Schlogl, M., P. Piaggi, S. B. Votruba, M. Walter, J. Krakoff, and M. S. Thearle. 2015. Increased 24-hour ad libitum food intake is associated with lower plasma irisin concentrations the following morning in adult humans. Appetite 90:154–159.
Seo, D. Y., H. B. Kwak, S. R. Lee, Y. S. Cho, I. S. Song, N. Kim, et al. 2014. Effects of aged garlic extract and endurance exercise on skeletal muscle FNDC-5 and circulating irisin in high-fat-diet rat models. Nutr Res Pract 8:177–182.
Sesti, G., F. Andreozzi, T. V. Fiorentino, G. C. Mannino, A. Sciacqua, M. A. Marini, et al. 2014. High circulating irisin levels are associated with insulin resistance and vascular atherosclerosis in a cohort of nondiabetic adult subjects. Acta Diabetol. 51:705–713.
Sharma, N., C. M. Castorena, and G. D. Cartee. 2012. Greater insulin sensitivity in calorie restricted rats occurs with unaltered circulating levels of several important myokines and cytokines. Nutr. Metab. (Lond) 9:90.
Shi, X., M. Lin, C. Liu, F. Xiao, Y. Liu, P. Huang, et al. 2016. Elevated circulating irisin is associated with lower risk of insulin resistance: association and path analyses of obese Chinese adults. BMC Endocr. Disord. 16:44.
Srinivasa, S., C. Suresh, J. Mottla, S. R. Hamarneh, J. E. Irazoqui, W. Frontera, et al. 2016. FNDC5 relates to skeletal muscle IGF-1 and mitochondrial function and gene expression in obese men with reduced growth hormone. Growth Horm. IGF Res. 26:36–41.
Stengel, A., T. Hofmann, M. Goebel-Stengel, U. Elbelt, P. Kobelt, and B. F. Klapp. 2013. Circulating levels of irisin in patients with anorexia nervosa and different stages of obesity–correlation with body mass index. Peptides 39:125–130.
Vamvini, M. T., K. N. Aronis, G. Panagiotou, J. Y. Huh, J. P. Chamberland, M. T. Brinkoetter, et al. 2013. Irisin mRNA and circulating levels in relation to other myokines in healthy and morbidly obese humans. Eur. J. Endocrinol. 169:829–834.
Wu, M. V., G. Bikopoulos, S. Hung, and R. B. Ceddia. 2014. Thermogenic capacity is antagonistically regulated in classical brown and white subcutaneous fat depots by high fat diet and endurance training in rats: impact on whole-body energy expenditure. J. Biol. Chem. 289:34129–34140.
Xin, C., J. Liu, J. Zhang, D. Zhu, H. Wang, L. Xiong, et al. 2016. Irisin improves fatty acid oxidation and glucose utilization in type 2 diabetes by regulating the AMPK signaling pathway. Int. J. Obes. (Lond) 40:443–451.
Yang, Z., X. Chen, Y. Chen, and Q. Zhao. 2015. Decreased irisin secretion contributes to muscle insulin resistance in high-fat diet mice. Int. J. Clin. Exp. Pathol. 8:6490–6497.
Zhang, S., L. Yang, P. Chen, H. Jin, X. Xie, M. Yang, et al. 2016. Circulating Adipocyte Fatty Acid Binding Protein (FABP4) Levels Are Associated with Irisin in the Middle-Aged General Chinese Population. PLoS ONE 11:e0146605.