An extract of chokeberry attenuates weight gain and modulates insulin, adipogenic and inflammatory signalling pathways in epididymal adipose tissue of rats fed a fructose-rich diet

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Abstract
Chokeberries are a rich source of anthocyanins, which may contribute to the prevention of obesity and the metabolic syndrome. The aim of the present study was to determine if an extract from chokeberries would reduce weight gain in rats fed a fructose-rich diet (FRD) and to explore the potential mechanisms related to insulin signalling, adipogenesis and inflammatory-related pathways. Wistar rats were fed a FRD for 6 weeks to induce insulin resistance, with or without chokeberry extract (CBE) added to the drinking-water (100 and 200 mg/kg body weight, daily: CBE100 and CBE200). Both doses of CBE consumption lowered epididymal fat, blood glucose, TAG, cholesterol and LDL-cholesterol. CBE consumption also elevated plasma adiponectin levels and inhibited plasma TNF-α and IL6, compared with the control group. There were increases in the mRNA expression for Irs1, Irs2, Glut1, Glut4 and Gys1, and decreases in mRNA levels of Gsk3β. The protein and gene expression of adiponectin and Ppara mRNA levels were up-regulated and Fabp4, Fas and Lpl mRNA levels were inhibited. The levels of gene expression of inflammatory cytokines, such as Il1β, Il6 and Tnfα were lowered, and protein and gene expression of Zfp36 (zinc finger protein) were enhanced in the epididymal adipose tissue of the rats that consumed the CBE200 extract. In summary, these results suggest that the CBE decreased risk factors related to insulin resistance by modulating multiple pathways associated with insulin signalling, adipogenesis and inflammation.

Key words: Chokeberry extract: Insulin signalling: Adipogenesis: Inflammation

Chokeberry, known as Aronia melanocarpa, is found in the eastern parts of North America, as well as Northern and Eastern Europe. Although usually consumed as a fruit, it has also been used in traditional medicine to treat hypertension and atherosclerosis in Russia and Eastern European countries1. Chokeberry has attracted scientific interest because of its high content of phenolic phytochemicals. The active compounds found in chokeberry include anthocyanins and flavonoids, some at concentrations over five times greater than those found in cranberries2,3. A comparative in vitro study has shown that chokeberries display higher antioxidant activity with the oxygen radical absorption capacity assay than that obtained with blueberries, cranberries or lingonberries4.

Anthocyanins and anthocyanin-rich extracts exhibit diverse potential health benefits in animal and human studies, including cardioprotective5, anti-diabetic6,7 and anti-inflammatory properties8. Although it has been reported that anthocyanins are poorly absorbed and circulate in the blood exclusively as unmetabolised parent glycosides9, Kay et al.10 observed that in human subjects, anthocyanins exist in the circulation primarily as metabolites, and cyanidin 3-glycosides are absorbed and transported in human serum and urine primarily as glucuronide and methyl glucuronide derivatives. Moreover, recent studies in rodents have shown that anthocyanins are rapidly absorbed from both the stomach and small intestine11, with derivatives found in multiple organs, including adipose tissue12.

Adipocyte and adipose tissue dysfunction are primary defects in obesity and may link obesity to several health problems, including increased risk of type 2 diabetes, hypertension, dyslipidaemia and atherosclerosis13,14. In cultured adipocytes, anthocyanins enhance adiponectin secretion15,

Abbreviations: CBE, chokeberry extract; CBE100, group fed chokeberry extract at 100 mg/kg body weight daily added to drinking water; CBE200, group fed chokeberry extract at 200 mg/kg body weight daily added to drinking water; CON, group fed with water alone; EAT, epididymal adipose tissues; FABP4, fatty acid-binding protein 4; FAS, fatty acid synthase; FRD, fructose-rich diet; Irs, insulin receptor substrate; LPL, lipoprotein lipase; ZFP36, zinc protein finger 36.

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regulate the expression of multiple adipocyte-specific genes\(^{(15,16)}\) and also reverse TNF-\(\alpha\)-induced insulin resistance\(^{(17)}\). In addition, dietary anthocyanins were shown to suppress obesity when administered to mice fed high-fat diets\(^{(18,19)}\).

The aim of the present study was to investigate whether feeding an extract of chokeberry improved metabolic parameters in rats fed a fructose-rich diet (FRD) to induce insulin resistance. Effects on body weight gain and epididymal fat accumulation and the underlying molecular mechanisms of action on the expression of the adipose genes involved in insulin signalling, adipogenic and inflammation pathways were evaluated.

Materials and methods

According to the manufacturer, the chokeberry extract (CBE) used was prepared from frozen Aronia berries from Northern Europe. Berries were stirred at room temperature with 4-fold excess by weight of 60% ethanol–water for 3–4 h. The mixture was then centrifuged and the supernatant was spray-dried (CellBerry\(^{\text{\textregistered}}\), the dried CBE, was provided by Integrity Nutraceuticals International (Spring Hill, TN, USA)). This extract contained at least 10% anthocyanins based on HPLC and MS analyses (lot no. TGB-071020).

Animals

Male Wistar rats (5 weeks old) were housed in a temperature-controlled room according to the Guidelines for Animal Care of the Beltsville Area Animal Care and Use Committee. After a 1-week acclimatisation period, rats were assigned randomly to receive either the CBE at 100 or 200 mg/kg body weight/d (\(n = 6\) for each group: CBE100 and CBE200) added to drinking-water or water alone (CON) group. All rats were placed on a FRD for 6 weeks. The diet contained (g/kg diet): casein, 207; d-i-methionine, 30; fructose, 600; lard, 50; cellulose, 79.8; AIN mineral mix, 50.0; zinc carbonate, 0.4; AIN vitamin mix, 10.0; and green food colour 0.15 (89 247-Teklad Animal Diets, Madison, WI, USA). During the experimental period, the consumption of food and fluid and body weight were monitored every other day. At the termination of the feeding experiment, following an overnight fast, blood glucose levels were tested from blood collected from the tail vein. Rats were then anaesthetised and blood was collected from the portal vein in pre-cooled tubes containing EDTA and centrifuged at 5000 rpm for 15 min at 4°C. The epididymal adipose tissues (EAT) were carefully removed and weighed before being snap-frozen in liquid N\(_2\) and stored at \(-80°C\) until analysed.

Immunoblotting

For the immunooanalysis of adipose tissue, approximately 100 mg of EAT were homogenised at 4°C for 30 s in lysis buffer containing 20 mM-Tris (pH 7.4), 2 mM-EDTA, 50 mM-NaF, 200 mM-Na\(_3\)VO\(_4\), 250 mM-phenylmethylsulfonyl fluoride, 1 mM-leupeptin, 1 mM- pepstatin and 0.36 mM-aprotinin. Protein concentrations were determined by a commercial assay (Bio-Rad D). Gene expression in epididymal adipose tissues

Total RNA was isolated from EAT using Trizol reagent (Invitrogen, Carlsbad, CA, USA). RNA concentrations and integrity were determined using RNA 6000 Nano Assay Kit and the Bioanalyzer 2100, according to the manufacturer’s instructions (Agilent, Santa Clara, CA, USA). The complementary DNA was synthesised from total RNA using SuperScript II RT (Invitrogen). The primers used are described in our previous study\(^{(20)}\) and included in Table 1. Real-time quantitative PCR was performed using SYBR Green PCR Master Mix (ABI, Forster, CA, USA). The expression of the housekeeping gene, peptidylprolyl isomerase A, was used to normalise the expression of target genes.

Biochemistry

Plasma adiponectin was determined with a rat ultrasensitive EIA (Phoenix Pharm, Burlingame, CA, USA). Plasma NEFA were measured using a colorimetric assay (Wako, Richmond, VA, USA). Serum TNF-\(\alpha\) and IL-6 were determined with a rat ultrasensitive EIA (Alpco, Salem, NH, USA). Measurement of blood glucose, insulin, TAG and cholesterol were performed as described\(^{(20,21)}\).

Statistical analyses

Data were analysed by one-way ANOVA followed by the least square difference (LSD) test. \(P\) values <0.05 were considered significant.

### Table 1. Real-time PCR primers

<table>
<thead>
<tr>
<th>Gene</th>
<th>Sequence (5’ to 3’ forward)</th>
<th>Sequence (5’ to 3’ reverse)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AdipoQ</td>
<td>AGGAAACTTGTGACAGGTGGA</td>
<td>GAAACCTTGAGTTCTCCCTT</td>
</tr>
<tr>
<td>Lpl</td>
<td>TGGAGCCCAATGCTGCTG</td>
<td>CAAGCCAGTAATCTTATGACCTC</td>
</tr>
<tr>
<td>Fas</td>
<td>GCCCTACTCCGGAGGAACAAACA</td>
<td>CCCGGCTACGAAGATGTTGCCA</td>
</tr>
<tr>
<td>Fabp4</td>
<td>GAAATGAGGTAGTCGCTTT</td>
<td>TTATGTTGCTCTTGACTTCCCT</td>
</tr>
</tbody>
</table>

AdipoQ, adiponectin; Lpl, lipoprotein lipase; Fas, fatty acid synthase; Fabp4, fatty acid-binding protein 4.
Results

General observations and plasma biochemistry

Food intake and water consumed did not differ among the three groups. Body weight gain and epididymal adipose weight were reduced at both levels of CBE intake (Table 2, \(P < 0.05\)). Fasting blood glucose and plasma insulin, TAG, total cholesterol, LDL-cholesterol and plasma NEFA levels were all reduced in animals consuming both levels of CBE. CBE consumption increased the plasma adiponectin and HDL-cholesterol levels (Table 3). In addition, a significant reduction in the plasma IL-6 and TNF-\(\alpha\) occurred in both the CBE groups (Table 3).

Chokeberry extract altered mRNA expression in the insulin signalling pathway and glucose uptake in epididymal adipose tissues

As shown in Fig. 1(a), CBE consumption (CBE200) with the FRD enhanced mRNA levels of components of the insulin signalling pathway, including increases in mRNA levels of insulin receptor substrate 1 (\(Irs1\)) (2.3-fold), \(Irs2\) (1.8-fold) and phosphatidylinositol 3 kinase regulatory subunit 1 (\(Pi3kr1\)) (1.5-fold), and inhibited phosphatase and tensin homolog (\(Pten\)) mRNA levels (0.61-fold), compared with the FRD-fed control rats.

As shown in Fig. 1(b), CBE consumption (CBE200) induced an increase in \(Glut1\) (1.6-fold), \(Glut4\) (1.5-fold) and glycogen synthase (\(Gys\)) (1.5-fold) mRNA expression, and inhibited glycogen synthase kinase 3 \(\beta\) (\(Gsk3\beta\)) mRNA levels (0.62-fold), compared with the FRD-fed control rats. Similar trends were observed in the CBE100 group but values were not significant (data not shown).

Consumption of chokeberry extract modulated the expression of genes and proteins involved in epididymal adipose adipogenesis

As shown in Fig. 2(a) and (b), CBE consumption (CBE200) caused a significant increase in adiponectin (\(AdipoQ\)) mRNA levels (2.1-fold) and adiponectin protein levels (169 %), compared with the FRD-fed control rats (\(P < 0.05\), both). CBE also induced \(Ppar\) mRNA expression (1.6-fold) and inhibited fatty acid binding protein 4 (\(Fabp4\)) (0.7-fold), fatty acid synthase (\(Fas\)) (0.63-fold) and \(Lpl\) (0.65-fold) mRNA expression (Fig. 2(c)), but did not significantly affect fatty acid translocase (\(Cd36\)) mRNA expression. Changes in the CBE100 group were not significant (data not shown).

Chokeberry extract inhibited the epididymal adipose inflammation gene expression and induced ZFP36 expression

As shown in Fig. 3(a), CBE consumption (CBE200) caused a significant decrease in \(Tnf\alpha\) (0.52-fold), \(Ilb\) (0.38-fold) and \(Il6\) (0.45-fold) mRNA levels, compared with the FRD-fed control rats.

Table 2. Effects of chokeberry extract (CBE) on body weight and epididymal pad weight

<table>
<thead>
<tr>
<th></th>
<th>CON</th>
<th>CBE100</th>
<th>CBE200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial body weight (g)</td>
<td>181 ± 3</td>
<td>183 ± 2</td>
<td>180 ± 1</td>
</tr>
<tr>
<td>Final body weight (g)</td>
<td>416 ± 6</td>
<td>402 ± 5</td>
<td>398 ± 4</td>
</tr>
<tr>
<td>Body weight gain (g)</td>
<td>236 ± 5</td>
<td>219 ± 5</td>
<td>217 ± 4</td>
</tr>
<tr>
<td>Epididymal adipose weight (g)</td>
<td>9.2 ± 0.2</td>
<td>8.3 ± 0.2</td>
<td>8.0 ± 0.2</td>
</tr>
</tbody>
</table>

CON, group fed with water alone; CBE100, group fed CBE at 100 mg/kg body weight daily added to drinking water; CBE200, group fed CBE at 200 mg/kg body weight daily added to drinking water.

Table 3. Effects of chokeberry extract (CBE) on blood and plasma parameters in the fasted state

<table>
<thead>
<tr>
<th></th>
<th>CON</th>
<th>CBE100</th>
<th>CBE200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood glucose (mmol/l)</td>
<td>4.9 ± 0.2</td>
<td>4.4 ± 0.2</td>
<td>4.3 ± 0.3</td>
</tr>
<tr>
<td>Insulin (ng/ml)</td>
<td>1.3 ± 0.12</td>
<td>0.95 ± 0.06</td>
<td>0.91 ± 0.09</td>
</tr>
<tr>
<td>TAG (mmol/l)</td>
<td>1.92 ± 0.15</td>
<td>1.25 ± 0.11</td>
<td>1.15 ± 0.13</td>
</tr>
<tr>
<td>Cholesterol (mmol/l)</td>
<td>2.35 ± 0.19</td>
<td>1.65 ± 0.18</td>
<td>1.58 ± 0.14</td>
</tr>
<tr>
<td>LDL-C (mmol/l)</td>
<td>1.18 ± 0.13</td>
<td>0.83 ± 0.13</td>
<td>0.75 ± 0.13</td>
</tr>
<tr>
<td>HDL-C (mmol/l)</td>
<td>0.46 ± 0.03</td>
<td>0.62 ± 0.04</td>
<td>0.70 ± 0.02</td>
</tr>
<tr>
<td>NEFA (mmol/l)</td>
<td>0.75 ± 0.07</td>
<td>0.48 ± 0.03</td>
<td>0.43 ± 0.05</td>
</tr>
<tr>
<td>Adiponectin ((\mu)g/ml)</td>
<td>19.8 ± 2.1</td>
<td>27.3 ± 2.4</td>
<td>29.8 ± 2.6</td>
</tr>
<tr>
<td>IL-6 (pg/ml)</td>
<td>220 ± 10</td>
<td>158 ± 7</td>
<td>81 ± 5</td>
</tr>
<tr>
<td>TNF-(\alpha) (pg/ml)</td>
<td>353 ± 9</td>
<td>190 ± 10</td>
<td>103 ± 6</td>
</tr>
</tbody>
</table>

CON, group fed with water alone; CBE100, group fed CBE at 100 mg/kg body weight daily added to drinking water; CBE200, group fed CBE at 200 mg/kg body weight daily added to drinking water; LDL-C, LDL-cholesterol; HDL-C, HDL-cholesterol.

a,b,c Mean values within a row with unlike superscript letters were significantly different (\(P < 0.05\)).
Control rats. In contrast to these inflammatory factors, CBE consumption enhanced \(Zfp36\) mRNA and \(ZFP36\) protein expression (Fig. 3(b) and (c), 1.45-fold and 139%). Changes in the CBE100 group were not significant (data not shown).

**Discussion**

Consumption of a FRD contributes to insulin resistance, hyperinsulinaemia, dyslipidaemia and hypertension in animal models\(^{22–24}\). Furthermore, consumption of a FRD leads to abdominal adipose tissue endocrine dysfunction in normal rats, and increased adipose tissue mass and adipocyte size\(^{25}\). Growing evidence suggests that adipose tissue plays a crucial role in the regulation of systemic energy homoeostasis, insulin sensitivity and lipid/carbohydrate metabolism\(^{26}\). In the present study, we found that consumption of a CBE, rich in anthocyanins, improved the impaired gene expression related to insulin signalling and glucose uptake in EAT, and up-regulated adiponectin levels and decreased plasma TNF-\(\alpha\) and IL-6 levels. In addition, we demonstrated that consumption of CBE significantly increased plasma adiponectin and down-regulated the decreased \(Irs1\), \(Irs2\), and \(Plk3r1\) mRNA expression and the expression of other genes related to carbohydrate metabolism, such as \(Glut1\), \(Glut4\), and \(Gys1\). CBE also inhibited the expression of \(Irs2\) and \(Gsk3\) in adipose tissue. In contrast to many other factors derived from adipose tissue, circulating adiponectin and adipose adiponectin expression are increased in insulin resistance\(^{35,43}\). In most clinical reports, primate studies and genetic models, adiponectin levels have been reported to be negatively correlated with body weight, visceral fat mass and resting insulin levels\(^{35–37}\). Transgenic mice overexpressing \(AdipoQ\) have increased insulin sensitivity and improved glucose tolerance and TAG clearance\(^{38}\). We have reported previously that FRD feeding significantly decreased plasma adiponectin and \(AdipoQ\) mRNA expression\(^{24}\). In the present study, we observed that feeding CBE significantly increased plasma adiponectin levels and mRNA and protein expression of adipose adiponectin of FRD-fed rats (Fig. 2). These results support the previous finding in human subjects that combination therapy of statins with an extract of chokeberry and animal studies demonstrated that loss of body weight is associated with an increase of insulin sensitivity\(^{26,28,29}\).

In the present study, we found that consumption of a CBE, high in polyphenols, reduced weight gain and epididymal fat accumulation, and improved systemic insulin sensitivity-related factors, such as fasting glucose, plasma insulin and lipids. At the molecular level, although the FRD impaired insulin signalling pathways in multiple tissues, such as liver\(^{30}\), skeletal muscle\(^{25}\) and adipose tissue\(^{24}\), the consumption of CBE improved the impaired gene expression related to insulin signalling and glucose uptake in EAT, and up-regulated adiponectin levels have been reported to be negatively correlated with body weight, visceral fat mass and resting insulin levels\(^{35–37}\). Transgenic mice overexpressing \(AdipoQ\) have increased insulin sensitivity and improved glucose tolerance and TAG clearance\(^{38}\). We have reported previously that FRD feeding significantly decreased plasma adiponectin and \(AdipoQ\) mRNA expression\(^{24}\). In the present study, we observed that feeding CBE significantly increased plasma adiponectin levels and mRNA and protein expression of adipose adiponectin of FRD-fed rats (Fig. 2). These results support the previous finding in human subjects that combination therapy of statins with an extract of chokeberry...
increased plasma adiponectin levels in patients after myocardial infarction\(^\text{(8)}\). Adiponectin possesses insulin sensitising and anti-atherogenic properties\(^\text{(35)}\).

It is well known that increased adipose tissue mass and adipocyte dysfunction associated with obesity are linked to the abnormal regulation of adipogenesis\(^\text{(39)}\). PPAR\(\gamma\), a master regulator of adipogenesis\(^\text{(40)}\), plays a critical role in glucose metabolism and energy homeostasis\(^\text{(41,42)}\). Fructose feeding induced a lower Pparg mRNA expression in white adipose tissue, and a PPAR ligand reversed the down-regulated expression of Pparg and systemic insulin resistance\(^\text{(43)}\). In the present study, we observed that CBE consumption increased Pparg mRNA expression in EAT. PPAR\(\gamma\) regulates multiple genes in the adipose tissue regulating adipogenesis, including those encoding the adipocyte fatty acid-binding protein 4 (FABP4), fatty acid synthase (FAS) and lipoprotein lipase (LPL). FABP4 is postulated to be an early marker of the metabolic syndrome in plasma and modulated multiple signalling pathways related to adipose dysfunction in an animal model. The present findings suggest that CBE consumption increased adipose Zfp36 mRNA and protein expression, which is consistent with CBE feeding-induced decreases in TNF-\(\alpha\) and IL-6 expression and increases in adiponectin expression in plasma and adipose tissue.

In summary, the present study provides evidence that an anthocyanin-rich extract of chokeberry reduced body weight gain and abdominal fat, improved the risk factors related to the metabolic syndrome in plasma and modulated multiple signalling pathways related to adipose dysfunction in an animal model. The present findings suggest that chokeberry or its extract might be beneficial in preventing or decreasing obesity and the metabolic syndrome. Further studies are needed in human volunteers at increased risks for diet-related chronic disease to ascertain the beneficial effects from consumption of polyphenols such as those found in chokeberry.

Studies have shown that polyphenols from cinnamon and green tea also inhibit Lpl mRNA expression and other genes of lipogenesis\(^\text{(24,49)}\). In the present study, the data show that feeding polyphenols from chokeberry suppressed Fabp4, Fas and Lpl mRNA levels in EAT. CD36, referred to as fatty acid translocase, is a transmembrane protein present in many tissues that is believed to play a role in facilitating fatty acid transport\(^\text{(50)}\). In ob/ob mice, and FRD-fed rats, CD36 mRNA\(^\text{(51)}\) and protein\(^\text{(49)}\) levels in the adipose tissue were increased. CBE consumption did not affect CD36 mRNA expression in the adipose tissue.

Substantial evidence indicates that a state of low-grade chronic inflammation typically is associated with obesity, and the increased production of pro-inflammatory cytokines by adipose tissue plays a crucial role in the development of insulin resistance\(^\text{(52,53)}\). FRD feeding also induces the overexpression of plasma TNF-\(\alpha\) and IL-6, which both contribute to the development of CVD by promoting insulin resistance, dyslipidaemia and endothelial dysfunction\(^\text{(54)}\). TNF-\(\alpha\) is known to be a potent negative regulator of adipogenesis and PPAR\(\gamma\) function\(^\text{(55)}\). The present results suggest that consumption of CBE not only inhibited the plasma levels of TNF-\(\alpha\) and IL-6 but also induced a decrease of mRNA expression of Tnfa and Il1b and Il6. This is in agreement with a human study in which chronic chokeberry consumption reduced the severity of plasma inflammation, increased anti-inflammatory factor and increased plasma adiponectin levels\(^\text{(8)}\). Previous studies suggested that Zfp36, an anti-inflammatory protein, increased Tnf mRNA degradation by binding to its 3' untranslated region\(^\text{(56)}\), and that omental adipose Zfp36 mRNA levels were correlated with insulin, insulin resistance index and adiponectinaemia in women\(^\text{(57)}\). In the present study, we found that CBE consumption increased adipose Zfp36 protein and mRNA expression, which is consistent with CBE feeding-induced decreases in TNF-\(\alpha\) expression and increases in adiponectin expression in plasma and adipose tissue.

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evaluation of the study and writing of the manuscript. B. Q. was involved in all phases of the study. B. Q. is a visiting scientist, working at the USDA/ARS Beltsville Human Nutrition Research Center, and employed by Integrity Nutraceuticals International; R. A. A. has no conflicts of interest to declare. Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture. The USDA is an equal opportunity provider and employer.

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