Anti-diabetic activity of chromium picolinate and biotin in rats with type 2 diabetes induced by high-fat diet and streptozotocin

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Abstract

The objective of the present study was to evaluate anti-diabetic effects of chromium picolinate (CrPic) and biotin supplementations in type 2 diabetic rats. The type 2 diabetic rat model was induced by high-fat diet (HFD) and low-dose streptozotocin. The rats were divided into five groups as follows: (1) non-diabetic rats fed a regular diet; (2) diabetic rats fed a HFD; (3) diabetic rats fed a HFD and supplemented with CrPic (80 μg/kg body weight (BW) per d); (4) diabetic rats fed a HFD and supplemented with biotin (300 μg/kg BW per d); (5) diabetic rats fed a HFD and supplemented with both CrPic and biotin. Circulating glucose, cortisol, total cholesterol, TAG, NEFA and malondialdehyde concentrations decreased (P<0·05), but serum insulin concentrations increased (P<0·05) in diabetic rats treated with biotin and CrPic, particularly with a combination of the supplements. Feeding a HFD to diabetic rats decreased PPAR-γ expression in adipose tissue and phosphorylated insulin receptor substrate 1 (p-IRS-1) expression of liver, kidney and muscle tissues, while the supplements increased (P<0·001) PPAR-γ and p-IRS-1 expressions in relevant tissues. Expression of NF-κB in the liver and kidney was greater in diabetic rats fed a HFD, as compared with rats fed a regular diet (P<0·01). The supplements decreased the expression of NF-κB in diabetic rats (P<0·05). Results of the present study revealed that supplementing CrPic and biotin alone or in a combination exerts anti-diabetic activities, probably through modulation of PPAR-γ, IRS-1 and NF-κB proteins.

Key words: Chromium; Biotin; Glucose; Insulin; PPAR-γ; Phosphorylated insulin receptor substrate-1; NF-κB

Insulin resistance has a principal importance for the development and progression of diabetes as well as the metabolic syndrome, obesity, hypertension and CVD(1,2). Cr is considered an essential factor for optimal insulin activity and normal carbohydrate/lipid mechanism(3). Biotin is an essential cofactor for a number of carboxylases that are important in carbohydrate and lipid metabolism, including acetyl-CoA carboxylase and methylcrotonyl-CoA carboxylase. Biotin stimulates the activity of glucokinase in the liver and improves pancreatic β islet cell function to enhance insulin regulation(4).

In vitro data have suggested that the combination of 10 ng/ml chromium picolinate (CrPic) with 50 mg/kg biotin greatly enhances glucose uptake and glycogen production in a human skeletal muscle culture(5). It was reported that CrPic, and the combination of CrPic and biotin, are capable of enhancing glucose disposal, lowering total cholesterol (TC) levels and increasing HDL-cholesterol levels in people with type 2 diabetes(6). The combination of CrPic and biotin has also been reported to improve glycaemic control in overweight uncontrolled type 2 diabetes(7–9). In human studies, CrPic and biotin reduced cholesterol levels(7) and atherogenic index in plasma(10). The mechanism by which Cr and biotin exert their anti-diabetic effects has not been studied in detail. PPAR-γ and insulin receptor substrate 1 (IRS-1) are important biomarkers involved in insulin signalling and resistance as well as in inflammation(11,12). NF-κB is another biomarker involved in cellular responses to stimuli such as stress and free radicals(13). Hua et al(14) stated that Cr

Abbreviations: AIN, American Institute of Nutrition; BW, body weight; CISI, composite insulin sensitivity index; CrPic, chromium picolinate; HFD, high-fat diet; HOMA-IR, homeostasis model assessment-estimated insulin resistance; IRS-1, insulin receptor substrate 1; MDA, malondialdehyde; p-IRS-1, phosphorylated insulin receptor substrate 1; STZ, streptozotocin; TC, total cholesterol.

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down-regulates proteins such as IRS-1 involved in insulin resistance. Similarly, Sharma et al.\(^{(15)}\) found that improved glycaemic control is associated with increased PPAR-\(\gamma\) and decreased NF-\(\kappa B\) protein expression in high-fat diet (HFD)-streptozotocin (STZ)-induced type 2 diabetic rats. Therefore, the aim of the present study was to evaluate the anti-diabetic properties of CrPic and biotin and their action of mechanism by looking at the changes in biomarkers such as PPAR-\(\gamma\), IRS-1 and NF-\(\kappa B\) proteins, antioxidant status measured as malondialdehyde (MDA), metabolic parameters, as well as tissue histopathological changes in STZ-induced type 2 diabetic rats fed a HFD.

**Experimental design**

The rats weighing 200–220 g (8 weeks old, \(n\) 75) were divided according to BW, which were similar, into five equal groups containing fifteen rats each. The groups were as follows: group 1: normoglycaemic rats, fed a regular diet (normal control) and injected with buffer solution as placebo; group 2: diabetic rats, fed a HFD without any supplementation (diabetic control); group 3: diabetic rats, fed a HFD supplemented with CrPic (80 \(\mu g/kg\)BW per d); group 4: diabetic rats, fed a HFD supplemented with biotin (300 \(\mu g/kg\) BW per d); group 5: diabetic rats, fed a HFD supplemented with both CrPic (80 \(\mu g/kg\)BW per d) and biotin (300 \(\mu g/kg\) BW per d). The CrPic and biotin supplements were dissolved in drinking-water and offered to rats. CrPic was supplemented to provide 8 \(\mu g\) Cr/d, which is an equivalent dose of 560 \(\mu g\) Cr for a 70 kg adult human. Chromium picolinate and biotin were supplied by Nutrition 21, Inc. The study was carried out for 10 weeks. At the end of the experiment, all rats were killed by cervical dislocation. Blood samples were taken from rats in the morning, after overnight fasting, and the tissues from the pancreas, liver, kidney and muscles from the hind limb, including biceps femoris, gastrocnemius and soleus, were removed and processed for biochemical, Western blot and histopathological examination. Fat was trimmed off from the muscles. Feed intake and BW were measured twice weekly.

**Laboratory analyses**

Blood samples were centrifuged at 3000 \(g\) for 10 min and analysed for TC, TAG, insulin, cortisol, urea and MDA. Estimation of insulin sensitivity from an oral glucose tolerance test, blood glucose and plasma insulin profiles were performed using the composite insulin sensitivity index (CISI) proposed by Matsuda & De Fronzo\(^{(17)}\). Calculation of the index was made according the following equation:

\[
\text{CISI} = 10,000/((\text{FPG} \times \text{FPI}) \times (\text{MG} \times \text{MI}))^{1/2},
\]

where FPG and FPI are fasting plasma glucose and insulin concentrations, respectively, and MG and MI are the mean glucose and insulin concentrations, respectively, over the course of the oral glucose tolerance test.

At 1 week before surgical preparation, an oral glucose tolerance test was performed after 12–14 h of fasting on all animals. Blood glucose was measured in triplicate before (baseline) and 5, 15, 30, 45, 60, 90 and 120 min after the administration of 20% (w/v) d-glucose solution (1 g/kg BW) by oral administration. Blood was obtained from the tail vein and glucose was assessed using a glucometer (Accu-Chek Active; Roche Diagnostics).

A computer-solved model called the homeostasis model assessment-estimated insulin resistance (HOMA-IR) was calculated, as proposed by Muniyappa et al.\(^{(18)}\), using the following equation:

\[
\text{HOMA-IR} = \frac{\text{fasting glucose (mmol/l)}}{\text{fasting insulin (\(\mu lU/ml\))}/22.5}.
\]

**Table 1. Macronutrient composition of the control and high-fat diet (HFD) fed to rats**

<table>
<thead>
<tr>
<th>Diet composition (% energy)</th>
<th>Control</th>
<th>HFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protein</td>
<td>28</td>
<td>20</td>
</tr>
<tr>
<td>Carbohydrate</td>
<td>60</td>
<td>38</td>
</tr>
<tr>
<td>Fat</td>
<td>12</td>
<td>42</td>
</tr>
</tbody>
</table>
Serum glucose concentrations were measured by using ACCU-Chek Active (Roche Diagnostics). Serum insulin levels were measured using the Rat Insulin Kit (Linco Research, Inc.) by ELISA (Els-800; Bio-Tek Instruments, Inc.). Cortisol concentration was determined by ELISA using a commercially available kit, according to the manufacturer’s protocol (Cortisol ELISA Kit no. 402710, assay range 0·05–5·0 ng/ml; Neogen Corporation). Serum concentrations of TC and TAG were measured using the diagnostic kits (Sigma Diagnostics, Inc.). NEFA levels were measured by a diagnostic kit (Boehringer Mannheim, GmbH). Serum urea and creatinine concentrations and aspartate aminotransferase and alanine aminotransferase activities were measured using a biochemical analyser (Olympus AU-660, Olympus).

Lipid peroxidation was measured in terms of MDA formation, which is the major product of membrane lipid peroxidation, using a previously described method(19) with slight modification. MDA concentration of kidney tissue was measured by HPLC (Shimadzu) using a Shimadzu UV-vis SPD-10 AVP detector and a C18-ODS-3, 5 m column. The mobile phase was 30 m M-KH2PO4–methanol containing 0·1 mM-EDTA, 1 mM-DTT, 0·1 mM-phenylmethylsulfonyl fluoride. To the homogenate, 30 mM-KH2PO4–methanol (82·5:17·5, v/v, pH 3·6) and the flow rate was 1·2 ml/min. Chromatograms were monitored at 250 nm and the injection volume was 20 µl.

**Western blot**

Protein extraction was performed by homogenising the rat adipose, liver and kidney tissues in 1 ml ice-cold hypotonic buffer A containing 10 mm-HEPES (pH 7·8), 10 mm-KCl, 2 mm-MgCl2, 1 mm-dithiothreitol (DTT), 0·1 mm-EDTA and 0·1 mm-phenylmethylsulfonyl fluoride. To the homogenate, 80 µl of 10 % Nonidet P-40 solution were added and the mixture was centrifuged for 2 min at 14 000 g. The precipitates, containing nuclei, were washed once with 500 µl of buffer A plus 40 µl of 10 % Nonidet P-40, centrifuged, resuspended in 200 µl of buffer C (50 mm-HEPES (pH 7·8), 50 mm-KCl, 300 mm-NaCl, 0·1 mm-EDTA, 1 mm-DTT, 0·1 mm-phenylmethylsulfonyl fluoride and 20 % glycerol) and centrifuged for 5 min at 14 800 g. The supernatant proteins were collected for PPAR-γ, IRS-1 and NF-κB. Equal amounts of protein (50 µg) were electrophoresed and subsequently transferred to nitrocellulose membrane (Schleicher and Schuell, Inc.). The antibody against PPARγ phosphorylated tyrosine 612 IRS1 (Tyr162) and NF-κB were purchased from Santa Cruz Biotechnology, Inc. Primary antibody was diluted (1:1000) in the same buffer containing 0·05 % Tween-20. Protein loading was controlled using a monoclonal mouse antibody against β-actin antibody (A5316; Sigma). Bands were analysed densitometrically using an image analysis system (Image J; National Institutes of Health).

**Histopathological examination**

Following laparotomy, the tissues (liver, kidney and pancreas) of each rat were first examined grossly. The tissues were then removed for histological examination. Formaldehyde (10 %)-fixed pancreas, liver and kidney tissues were embedded in paraffin and serial sections (3 mm) were cut using a microtome. Each section was stained with haematoxylin and eosin for histological examination according to a standard procedure(20). The histological analyses were performed by the same person who was blinded to the group that each sample came from.

**Statistical analysis**

Sample size was calculated based on a power of 85 % and a P value of 0·05. On the basis of this assumption, a sample size of fifteen per treatment was used. The data were analysed using the general linear model procedure of SAS (SAS Institute Inc.). Differences between groups were analysed using Fisher’s multiple comparison test followed by Fisher’s post hoc test for all groups.

**Results**

**Effects of chromium picolinate and biotin on glucose, insulin, lipid profile and serotonergic properties**

Feed intake and final BW were greater in diabetic rats fed either feeds supplemented with CrPic or biotin alone or as a combination (P<0·05). The effects of CrPic and biotin supplementation alone or in a combination on the serum glucose, insulin, cortisol and lipid profile of diabetic rats are presented in Table 2. After 10 weeks of feeding the HFD along with intra-peritoneal injection of STZ, serum glucose, cortisol, TC, TAG and NEFA levels were elevated by 4·6-, 1·6-, 2·6-, 2·9- and 2·4-fold, respectively, in diabetic control rats, compared with the normal controls (P=0·0001). However, serum insulin and C ISI values were reduced by 2·1- and 3·2-fold in diabetic control rats, compared with rats fed a regular diet (P=0·0001). Diabetic rats fed a diet supplemented with CrPic or biotin had greater C ISI, but lower HOMA-IR (P<0·05). Either in combination or alone, CrPic and biotin decreased blood glucose, serum insulin, TC, TAG and NEFA concentrations (P=0·0001), but increased serum insulin and C ISI concentrations in diabetic rats (P=0·0001). The effect of combination of CrPic and biotin was more pronounced on these parameters. In addition, except total TC concentration, CrPic was more effective compared with biotin on these parameters.

Diabetic rats had increased levels of alanine aminotransferase and aspartate aminotransferase and also urea and creatinine, compared with normal (non-diabetic) rats (Table 3). We found a 1·9-fold increase in serum urea, a 1·7-fold increase in creatinine, a 2·1-fold increase in alanine aminotransferase and a 1·9-fold increase in aspartate aminotransferase in HFD–STZ-treated diabetic control rats, compared with normal controls (P=0·0001). CrPic and biotin supplemendations, alone or in combination, decreased serum urea, creatinine, aspartate aminotransferase and alanine aminotransferase levels in diabetic rats. The effect of the combination of CrPic and biotin was more pronounced on these parameters. Although not significant, CrPic was more effective on these parameters compared with biotin.
Serum, liver and kidney MDA levels were increased upon feeding the HFD in diabetic rats \((P = 0.0001; \text{Table 4})\). The effect of the combination of CrPic and biotin was more pronounced on these parameters. In addition, except for liver MDA levels, CrPic was more effective compared with biotin on these parameters.

**Effects of chromium picolinate and biotin on protein expression of PPAR-\(\gamma\), insulin receptor substrate 1 and NF-\(\kappa\)B in tissues of diabetic rats**

As shown in Fig. 1, feeding a HFD to rats decreased PPAR-\(\gamma\) expression in adipose tissue, while CrPic or biotin, each alone or their combination, increased \((P < 0.001)\) PPAR-\(\gamma\) expression in this tissue. The level of phosphorylated IRS-1 (p-IRS-1) (Tyr162) in liver, kidney and muscle tissues of diabetic control rats was reduced to 52.33\% of that in normal control rats \((P < 0.05)\) (Fig. 2). CrPic or biotin alone similarly increased the p-IRS-1 expression, but the magnitude of the increase was more in case of the combination of supplements. Expression of NF-\(\kappa\)B in the liver and kidney tissues was greater in rats fed a HFD, as compared with rats fed a regular diet \((P < 0.01)\) (Fig. 3). Supplementing CrPic or biotin, or a combination of them, resulted in a decrease in expression of NF-\(\kappa\)B in diabetic rats \((P < 0.05)\).

**Effects of chromium picolinate and biotin on histopathology of tissues**

Histopathological evaluation of various liver, kidney and pancreatic segments of the rats fed a regular diet and rats fed a HFD are presented in Fig. 4. **Liver.** Normal histology and normal hepatocellular architecture with a normal central vein were observed in non-diabetic rats. Hepatocytes having pink eosinophillic cytoplasm without any inclusions and with mostly central single nuclei were observed in non-diabetic rats. These cells had well-defined cell borders, polygonal in shape and arranged in sheets. Liver sinusoids were not dilated. There were no areas of haemorrhage or fibrosis. In diabetic rats, hepatocytes had vacuolated eosinophillic cytoplasm with a ground glass appearance and with fatty inclusions. The nuclei were enlarged, displaced and vacuolated. There were several pycnotic nuclei, suggesting significant hepatocellular

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**Table 2. Effects of chromium picolinate (CrPic) and biotin supplementation on glucose, insulin and lipid profile in diabetic rats**

(Mean values with their standard errors of fifteen rats from each group)

<table>
<thead>
<tr>
<th>Item</th>
<th>Control HFD/STZ</th>
<th>HFD/STZ + CrPic</th>
<th>HFD/STZ + biotin</th>
<th>HFD/STZ + CrPic + biotin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean    SE</td>
<td>Mean  SE</td>
<td>Mean  SE</td>
<td>Mean  SE</td>
</tr>
<tr>
<td>Final body weight (g)</td>
<td>320·47d 5·22</td>
<td>216·25c 3·51</td>
<td>240·20b 3·17</td>
<td>235·60b 7·57</td>
</tr>
<tr>
<td>Feed intake (g/d)</td>
<td>29·08e 0·53</td>
<td>19·53h 0·32</td>
<td>21·82e 0·29</td>
<td>20·46f 0·73</td>
</tr>
<tr>
<td>Glucose (mg/dl)</td>
<td>1030a 5·7</td>
<td>4690b 27·8</td>
<td>2870c 8·6</td>
<td>4190b 8·7</td>
</tr>
<tr>
<td>Insulin (mg/dl)</td>
<td>486·0c 3·2</td>
<td>232·1b 1·6</td>
<td>258·7c 1·7</td>
<td>246·0b 1·9</td>
</tr>
<tr>
<td>C ISI</td>
<td>2·68a 0·01</td>
<td>0·83b 0·01</td>
<td>1·28c 0·01</td>
<td>1·21d 0·01</td>
</tr>
<tr>
<td>HOMA-IR</td>
<td>12·35b 0·11</td>
<td>26·85b 0·26</td>
<td>18·31c 0·11</td>
<td>25·43b 0·23</td>
</tr>
<tr>
<td>Cortisol (mg/dl)</td>
<td>82·1d 0·6</td>
<td>134·3c 1·3</td>
<td>115·5b 1·3</td>
<td>121·1b 1·2</td>
</tr>
<tr>
<td>TC (mg/dl)</td>
<td>950·7b 8·0</td>
<td>2503·8b 12·5</td>
<td>2280·0d 7·0</td>
<td>2230·0c 7·0</td>
</tr>
<tr>
<td>TAG (mg/dl)</td>
<td>1350·7d 18·1</td>
<td>3902·5d 27·5</td>
<td>3659·0b 18·3</td>
<td>3700·0b 13·4</td>
</tr>
<tr>
<td>NEFA (mmol/l)</td>
<td>1·60d 0·06</td>
<td>3·90a 0·08</td>
<td>3·31b 0·08</td>
<td>3·49b 0·08</td>
</tr>
</tbody>
</table>

**Table 3. Effects of chromium picolinate (CrPic) and biotin supplementation on urea, creatinine, aspartate aminotransferase (AST) and alanine aminotransferase (ALT) levels in diabetic rats**

(Mean values with their standard errors of fifteen rats from each group)

<table>
<thead>
<tr>
<th>Item</th>
<th>Control HFD/STZ</th>
<th>HFD/STZ + CrPic</th>
<th>HFD/STZ + biotin</th>
<th>HFD/STZ + CrPic + biotin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean    SE</td>
<td>Mean  SE</td>
<td>Mean  SE</td>
<td>Mean  SE</td>
</tr>
<tr>
<td>Urea (mmol/l)</td>
<td>12·16d 0·19</td>
<td>23·29a 0·27</td>
<td>17·53b 0·22</td>
<td>17·89b 0·23</td>
</tr>
<tr>
<td>Creatinine ((\mu)mol/l)</td>
<td>36·24d 0·86</td>
<td>61·88a 0·79</td>
<td>49·50b 0·83</td>
<td>51·27b 0·98</td>
</tr>
<tr>
<td>AST (UI/l)</td>
<td>115·27d 1·73</td>
<td>241·25a 2·34</td>
<td>189·00b 2·86</td>
<td>193·00b 1·51</td>
</tr>
<tr>
<td>ALT (UI/l)</td>
<td>80·00d 0·87</td>
<td>150·00a 1·49</td>
<td>131·00b 1·13</td>
<td>135·00b 1·38</td>
</tr>
</tbody>
</table>

HFD, high-fat diet; STZ, streptozotocin; C ISI, composite of insulin sensitivity index; HOMA-IR, homeostasis model assessment-estimated insulin resistance; TC, total cholesterol.

\(a,b,c,d,e\) Mean values within a row with unlike superscript letters were significantly different \((P < 0.05)\).

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degeneration. The cells were irregular in size, shape and orientation. Moderate macrovesicular fatty degeneration of liver with dilated sinusoids was observed. In CrPic or biotin, or the combination of supplements groups, lobules with normal hepatocellular architecture with a normal central vein were observed. Hepatocytes had pink eosinophillic cytoplasm without any inclusions and with mostly central single nuclei. These cells had well-defined cell borders, polygonal in shape and arranged in sheets. Liver sinusoids were not dilated. There were no areas of haemorrhage or fibrosis.

Kidney. In diabetic (fat-fed/STZ) rats, renal parenchyma showing significant vacuolar degeneration of renal tubular cells with displaced pycnotic nuclei was observed. Renal glomeruli showing mesangial hyperplasia and eosinophillic fibrinous deposits were observed. Diffuse infiltration of monomorphonuclear cells in renal parenchyma and the glomeruli was observed. Tubulointerstitial nephropathy with significant mesangial proliferation in glomeruli was observed. In CrPic and biotin treatment or in combination groups, normal renal tubular architecture and normal glomeruli were observed.

Pancreas. Non-diabetic rats had normal exocrine pancreatic acinar architecture and pancreatic islets, showing predominantly insulin-producing β-cells with granular basophilic cytoplasm and few eosinophillic glucagon-producing α-cells. In diabetic rats, pancreatic islets showed a relatively decreased population of insulin-producing β-cells with granular basophilic cytoplasm and several eosinophillic glucagon-producing α-cells. There were areas of eosinophillic amorphous deposits within islets, suggesting cellular necrosis. Degenerative changes and islet cell necrosis in endocrine pancreas were observed. In supplemental groups (CrPic or biotin or a combination of them), normal exocrine pancreatic acinar architecture was observed.

Discussion

Diabetes is the most common metabolic disorder worldwide and is associated with profound alterations in glucose, insulin, cortisol, lipid and lipoprotein profiles. In the present study, Cr and biotin supplementation, each alone or together, ameliorated insulin resistance, dyslipidaemia, hepatic and renal damage and pathological changes in liver, kidney and pancreas tissues in HFD-STZ-induced type 2 diabetic rats. Similar to results of the present investigation, a number of studies have indicated that CrPic and biotin administration, each alone or together, can act as anti-diabetic agents and decrease TC concentration. Previous studies have also demonstrated that animals, when fed a HFD and injected with a low dose of STZ, display many characteristics of insulin resistance, including hyperglycaemia and hyperinsulinaemia, decreased hyperlipidaemia, liver and kidney damage. The effect of a combination of CrPic and biotin in the present study was more pronounced for all metabolic parameters, as well as MDA, and CrPic was more effective compared with biotin on most of the parameters in diabetic rats. Similarly, previous studies indicated that a combination of CrPic and biotin worked synergistically to produce positive effects on insulin function, blood glucose and lipid metabolism in people with type 2 diabetes and in an animal model of insulin-resistant obesity. In accordance with other metabolic parameters of the present study, diabetic rats fed a diet supplemented with CrPic or biotin had a greater GSI but lower HOMA-IR. Feed intake and final BW of diabetic rats were paralleled in a way that greater feed intake resulted in a greater final BW.

The present study provided evidence of a specific association between a combination of CrPic and biotin supplementation and MDA in diabetic rats. Lower levels of MDA were observed...
in diabetic animals receiving CrPic and biotin supplementation. Cr, through playing an important role against insulin resistance, is postulated to augment the antioxidant defence system(23). A decrease in hepatic thiobarbituric acid reactive substances formation by supplementation of CrPic and chromium nicotinate has been reported in rats(24). It was also found that chromium dinicocysteinate supplementation in rats significantly lowered C-reactive protein and lipid peroxidation and increased vitamin C and adiponectin levels(25). Oxidative stress associated with overproduction of reactive oxygen species plays an important role in the development of diabetic complications, including diabetic nephropathy(26).

PPAR is a member of a nuclear receptor superfamily. Due to its role in decreasing insulin resistance and inflammation, PPAR has been involved in the pathology of numerous diseases, including obesity, diabetes and atherosclerosis(15,27). PPAR exist as three different subtypes in mammals, namely, PPARα, PPARδ and PPARγ. PPARγ, widely expressed in adipose tissue, is the central regulator of insulin and glucose metabolism, leading to improved insulin sensitivity in type 2 diabetic patients as well as in diabetic rodent models(21). Several studies have shown that PPAR-γ agonists may be effective in reducing renal cortical lipid content and proteinuria by a mechanism independent of their hypoglycaemic property(28–30). In the present study, CrPic and biotin, as well as their combination, regulated (increased) PPAR-γ expression in adipose tissue, which may exert a potent insulin-sensitising effect and may improve insulin resistance in a rat model of type 2 diabetes mellitus. It has been demonstrated that a combination of lipoic acid, acetyl-l-carnitine, nicotinamide and biotin treatment significantly increased mRNA levels of PPAR-γ in skeletal muscles of type 2 diabetic Goto–Kakizaki rats(31). Additionally, it has been reported that anti-lipidaemic and anti-inflammatory effects of drugs, such as *Semecarpus anacardium* nut milk extract treatment, increase the mRNA expression of PPAR-γ(32).

Studies in diabetic mice and rat models have found that supplementing CrPic and biotin increases insulin sensitivity(23,33,34). IRS-1 appears to play a central role in the insulin-stimulated signal transduction pathway and links the insulin receptor to its final biological actions via a series of intermediate effectors(35). Studies have shown that differential regulation of IRS-1 in the liver and muscle tissues were observed in diabetic animals, which may produce differential alterations in insulin signalling in these two tissues and contribute to hepatic and muscular insulin resistance(12). In the present study, decreases of IRS-1 expression in the liver, kidney and muscle tissues were observed in diabetic rats. These results suggest that the favourable impact of CrPic and biotin on hyperlipidaemia was probably associated with the improvement of insulin signal transduction in target tissues, which plays an important role in regulating glucose metabolism. Consistent with the present findings, Jain et al.(25) reported that chromium dinicocysteinate supplementation increased IRS-1 activation in the liver tissues of type 2 diabetic rats. Similarly, Wang et al.(36) reported that obese rats treated with CrPic had significantly improved glucose disposal rates and demonstrated a significant increase in insulin-stimulated p-IRS-1 and phosphatidylinositol-3 kinase activity in skeletal muscles compared with obese controls.

NF-κB, one of the transcription factors, is responsible for controlling DNA transcription and is involved in cellular responses to a number of stimuli including free radicals(13). Hyperglycaemia-induced reactive oxygen species and advanced glycation end products stimulate the signal transduction pathway for the activation of the transcription factor NF-κB(37). The results of the present study also showed that CrPic and biotin, as well as their combination, decreased NF-κB level in the liver and kidney tissues of the rats with diabetes.
HFD/STZ-induced diabetes. In parallel with the results of the present study, Kuhad et al.\(^{580}\) reported that NF-κB p65 subunit was significantly elevated in the kidneys of diabetic animals. Results of the present investigation are also consistent with previous studies reporting that the levels of NF-κB p65 in the kidneys were distinctly increased in a lower-dose STZ-induced diabetic rat model fed a HFD.\(^{597}\) Tuzcu et al.\(^{400}\) also reported a decrease in liver NF-κB expression by supplementation of CrPic in rats fed a HFD. In addition, Jain et al.\(^{25}\) found that chromium dinicocysteinate is a potent hypoglycaemic compound, with anti-inflammatory activity apparently mediated by elevated blood vitamin C and inhibition of NF-κB, Akt and GLUT-2 in the livers of type 2 diabetic rats. It can be postulated from the present investigation and results from the reported studies\(^{25,39,40}\) that amelioration of insulin resistance by CrPic and biotin might be directly or indirectly associated with modulation of NF-κB expression.

Data found in the present study also provided evidence that HFD-STZ treatment produces liver, kidney and pancreatic lesions in rats because of associated hyperinsulinaemia, hyperlipidaemia, hyperglycaemia and increased oxidative stress. However, CrPic and biotin alone or in combination prevented these pathological alterations due to their insulin-sensitising, anti-inflammatory, anti-dyslipidaemia and antioxidant activity. Animal studies strongly support the hypoglycaemic action of biotin and CrPic via improved glucose tolerance and decreased insulin resistance\(^{23,34,41}\).

The present study clearly showed that supplementing CrPic or biotin alone or in a combination exerts antioxidant, anti-hyperlipidaemic, anti-inflammatory and anti-hyperglycaemic effects, and increases the level of insulin in diabetic rats. These changes may be related to the elevation of the levels of PPAR-γ and p-IRS-1 in the liver, kidney and muscle tissues. The combination of CrPic and biotin in the present study was more effective for all metabolic parameters, as well as on MDA, PPAR-γ, p-IRS-1 and NF-κB. CrPic supplementation was more effective, compared with biotin supplementation, on most of the parameters in diabetic rats. Therefore, a nutritional supplement containing CrPic and biotin is highly recommended for individuals having metabolic diseases, diabetes in particular. CrPic and biotin supplementations could exert their health-benefiting roles in regulating diabetes via activation of PPAR-γ, IRS-1 and NF-κB proteins and its associated complications in the tissues. The present doses of CrPic and biotin provided positive results, but dose-dependent responses could also be investigated as a further study.

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