Renal dopamine D₁ receptor dysfunction is acquired and not inherited in obese Zucker rats

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Renal dopamine D₁ receptor dysfunction is acquired and not inherited in obese Zucker rats. Am J Physiol Renal Physiol 287: F109–F116, 2004. First published April 6, 2004; 10.1152/ajprenal.00396.2003.—In essential hypertension, the defect in renal dopamine (DA) D₁ receptor function is intrinsic to proximal tubules as this phenomenon is also seen in primary proximal tubule cultures from spontaneously hypertensive rats (SHR) and essential hypertensive patients. Previously, a defect was reported in renal D₁ receptor function in obese Zucker rats. In the present study, we sought to determine whether this D₁ receptor dysfunction is intrinsic in these animals. In primary proximal tubular epithelial cells (PTECs) from lean and obese rats, DA inhibited Na-K-ATPase (NKA) activity in PTECs from both groups of rats. Basal NKA activity, D₁ receptor protein expression, and their coupling to G proteins were similar in cells from both groups. However, when PTECs from lean and obese rats were cultured in 20% serum from obese rats, DA failed to inhibit NKA activity, which was accompanied by a reduction in D₁ receptor expression and a defect in D₁ receptor-G protein coupling. No such defects in the inhibitory effect of DA on NKA activity, D₁ receptor numbers, or coupling were seen when PTECs from both lean and obese rats were grown in 20% serum from lean or rosiglitazone-treated obese (RTO) rats. RTO rat serum had normal blood glucose and reduced plasma levels of insulin compared with serum from obese rats. Furthermore, chronic insulin treatment of PTECs from lean and obese rats caused an attenuation in DA-induced NKA inhibition, a decrease in D₁ receptor expression, and D₁ receptor-G protein uncoupling. These results suggest that defective D₁ receptor function in obese Zucker rats is not inherited but contributed to by hyperinsulinemia and/or other circulating factors associated with obesity.

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We examined D1 receptor function in lean and obese Zucker rat primary proximal tubule cells (1) grown under similar culture conditions, 2) grown in serum from lean, obese, and rosiglitazone-treated obese (RTO) Zucker rats, and 3) grown under similar culture conditions followed by chronic insulin exposure.

**METHODS**

**Materials.** Cell culture media were purchased from GIBCO BRL. R(+)-1-phenyl-2.3.4,5-tetrahydro-(1H)-3-benazepine-7,8-diol hydrochloride (SKF-38393 hydrochloride), a D1-receptor agonist and active enantiomer of (±)-SKF-38393, was purchased from Sigma (RBI). 86RbCl, R(+)-2,3,4,5-tetrahydro-3-methyl-5-phenyl-1H-3-benazepine-7-ol hydrochloride ([H]SKF-23390 hydrochloride), a D1-receptor antagonist, and 35S-labeled guanosine 5’-(γ-thio)triphosphate ([35S]-GTPyS) were purchased from New England Nuclear Life Sciences. Antibodies were purchased from Alpha Diagnostic and Calbiochem-Novabiochem. All other chemicals of the highest purity available were purchased from Sigma.

**Rosiglitazone treatment.** Nine-week-old male obese and lean Zucker rats (Harlan, Indianapolis, IN) were housed in plastic cages with free access to normal rodent chow and tap water. Obese rats were divided into two groups; one was treated with rosiglitazone (10 μM cold GTP), and other treated with vehicle (1% aqueous carboxymethyl cellulose, n = 10) served as the control. The rats were dosed (3 mg·ml⁻¹·kg⁻¹) daily via oral gavage for 2 wk. Lean Zucker rats received no treatment. At the end of the treatment, blood was collected from the aorta in EDTA-coated tubes for plasma insulin measurement and in glass ment. At the end of the treatment, blood was collected from the aorta for 24 h. Cells starved in DMEM-F-12 served as the control. Cells were incubated without culture conditions, 1 experimental groups comprised lean and obese Zucker rat PTECs (2).

We examined D1 receptor function in lean and obese Zucker rats. Plasma insulin levels in obese rats were about eight times higher compared with lean rats, whereas plasma glucose was ~50% higher in obese rats than in lean rats. These data confirm that obese Zucker rats are hyperinsulinemic with moderate hyperglycemia. Also, the blood TG levels in obese rats were 10 times higher than in lean rats, suggesting defective lipid metabolism, a hallmark of obesity and insulin resistance. Rosiglitazone completely normalized the plasma glucose levels, as there was no significant difference in plasma glucose levels in lean or RTO rats. Furthermore, treatment of obese rats with rosiglitazone reduced plasma insulin and TG levels by 73 and 50%, respectively (Table 1).

**RESULTS**

As shown in Table 1, the body weights of 11- to 12-wk-old obese and RTO rats were significantly higher than those of lean rats. Plasma insulin levels in obese rats were about eight times higher compared with lean rats, whereas plasma glucose was ~50% higher in obese rats than in lean rats. These data confirm that obese Zucker rats are hyperinsulinemic with moderate hyperglycemia. Also, the blood TG levels in obese rats were 10 times higher than in lean rats, suggesting defective lipid metabolism, a hallmark of obesity and insulin resistance. Rosiglitazone completely normalized the plasma glucose levels, as there was no significant difference in plasma glucose levels in lean or RTO rats. Furthermore, treatment of obese rats with rosiglitazone reduced plasma insulin and TG levels by 73% and 72%, respectively (Table 1).

**Characterization of D1 receptor function in PTECs from lean and obese Zucker rats.** At ~80–85% confluency, lean and obese Zucker rat PTECs cultured in 10% FCS were serum starved for 24 h and studied for D1 receptor expression and function.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lean</th>
<th>Obese</th>
<th>RTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight, g</td>
<td>265.0±7.0</td>
<td>488.0±18.0</td>
<td></td>
</tr>
<tr>
<td>Blood glucose, mmol/l</td>
<td>5.5±0.3</td>
<td>8.3±1.8</td>
<td></td>
</tr>
<tr>
<td>Insulin, mmol/l</td>
<td>0.62±0.1</td>
<td>1.3±0.2±</td>
<td></td>
</tr>
<tr>
<td>Triglycerides, mg/dl</td>
<td>≤50.0</td>
<td>145.0±30.0</td>
<td></td>
</tr>
</tbody>
</table>
As shown in Fig. 1A, the specific binding of the D<sub>1</sub>-receptor antagonist [3H]SCH-23390 was similar in lean and obese PTEC membranes, suggesting an equal number of D<sub>1</sub>-like receptors on the cell membrane. D<sub>1A</sub> receptor protein was measured by Western blotting using D<sub>1A</sub>-specific antibody. This antibody labeled a D<sub>1A</sub>-specific band with a molecular mass of ~50 kDa (Fig. 1C). Similar to ligand binding, densitometric analysis of bands revealed that basal expression of the D<sub>1A</sub> receptor is similar in PTECs from lean and obese Zucker rats (Fig. 1B).

The functional responsiveness of the D<sub>1</sub> receptor was performed by measuring D<sub>1</sub> receptor ligand-induced stimulation of G proteins and DA-induced inhibition of NKA activity. Incubation of membranes with 10 nM SKF-38393, a D<sub>1</sub>-receptor agonist, elicited an equal stimulation of [35S]GTPγS binding, suggesting intact receptor-G protein coupling (Fig. 1D). Furthermore, DA (10 nM-1 μM) produced a concentration-dependent inhibition of NKA activity in both groups of PTECs (Fig. 2). These results along with light microscopy (data not shown) suggest that D<sub>1</sub> receptors are functional in both lean and obese PTECs and also confirm that culture conditions are conducive to normal cell growth (2).

**Effect of DA on NKA activity in PTECs cultured in rat serum.** Because we did not observe any morphological (light microscopy; data not shown) or D<sub>1</sub> receptor functional difference in lean or obese Zucker rat PTECs cultured in 10% FCS, further experiments were performed to study the effect of serum from obese rats on D<sub>1</sub> receptor function in PTECs from lean and obese Zucker rats. PTECs (from the same animal) cultured in 20% serum from lean or RTO rats served as the control. The three cultures from the same animal grown in different sera were studied in parallel. As shown in Table 2, DA (1 μM) significantly inhibited the activity of NKA in obese rat PTECs cultured in serum from lean and RTO rats. However, DA-induced inhibition of NKA activity was completely...
absent in PTECs cultured in serum from obese Zucker rats. When PTECs from lean rats were cultured in 20% serum from lean or RTO animals, DA (1 μM) caused a 28% inhibition in NKA activity (lean rat serum, control vs. DA: 14.0 ± 0.8 vs. 10.0 ± 0.3; RTO rat serum, control vs. DA: 13.5 ± 0.8 vs. 10.5 ± 0.5 nM 86Rb·mg protein⁻¹·h⁻¹, P < 0.05 control vs. DA). However, DA (1 μM)-induced inhibition of NKA was attenuated when these PTECs were grown in serum from obese rats (control vs. DA: 13.03 ± 0.5 vs. 11.8 ± 0.4 nM 86Rb·mg protein⁻¹·min⁻¹).

Effect of rat serum on D₁ receptor expression and G protein coupling in PTEC membranes. Obese rat cells cultured in obese rat serum showed a 43% decrease in [3H]SCH-23390 binding compared with cells grown in serum from lean or RTO rats. There was no difference in [3H]SCH-23390 membrane binding between cells cultured in lean or RTO rat serum (Table 2). Similar to ligand binding, densitometric analysis of Western blotting revealed a 30% decrease in membrane receptor protein abundance in cells cultured in obese rat serum compared with lean or RTO rat serum (Table 2). A similar decrease in D₁ receptor number was observed when cells were harvested from lean rats and cultured in obese rat serum ([3H]SCH-23390 binding, lean rat serum: 89.0 ± 7.0, obese rat serum: 46.0 ± 3.0 and RTO rat serum: 87.0 ± 5.0 fmol/mg protein; Western blot densitometry, lean rat serum: 99 ± 4, obese rat serum: 65 ± 3 and RTO rat serum: 95.6 ± 3.9 arbitrary units, P < 0.05 obese rat serum vs. lean or RTO rat serum).

As shown in Table 2, SKF-38393 elicited equal stimulation of [35S]GTPγS binding in obese rat PTEC membranes cultured in lean or RTO rat serum. Similar stimulation of [35S]GTPγS binding was observed when cells harvested from lean rats were cultured in lean (control vs. SKF-38393: 102.7 ± 5.0 vs. 129.4 ± 7.0, P < 0.05) or RTO rat serum (control vs. SKF-38393: 98.9 ± 5.0 vs. 121.60 ± 6.0 fmol/mg protein, P < 0.05). However, SKF-38393 was unable to stimulate [35S]GTPγS binding in PTEC membranes from obese rats (Table 2) as well as those from lean rats (control vs. SKF-38393: 95.8 ± 3.0 vs. 101.0 ± 6.0 fmol/mg protein) cultured in obese rat serum.

In separate experiments, serum from obese rats was also able to attenuate D₁ receptor function in PTECs harvested from RTO rats and SD rats (results not shown).

Influence of insulin on the effect of DA on NKA activity in PTECs from lean and obese Zucker rats. The basal characterization of lean and obese PTECs revealed no difference in their morphological and D₁ receptor functional parameters. Furthermore, serum from obese Zucker rats diminished D₁ receptor function to a similar extent in PTECs from both lean and obese rats. Because obese Zucker rats are associated with hyperinsulinemia and mild hyperglycemia, we sought to determine the effect of chronic insulin (100 nM) exposure in PTECs from lean and obese rats on D₁ receptor function. As shown in Table 3, DA (1 μM) caused significant inhibition of NKA activity in control cells, but not in insulin-pretreated cells from lean and obese rats. It should be noted that the NKA activity in this protocol was measured after 3 h of stabilization of cells in insulin-free medium, and we observed no difference in basal NKA activity between control and insulin-treated cells. Also, basal NKA activity in control or insulin-treated cells is similar to basal activity observed (see Fig. 2).

Effect of insulin on D₁ receptor expression and G protein coupling in PTEC membranes from lean and obese Zucker rats. The specific binding of [3H]SCH-23390, a D₁ receptor ligand, was reduced by 42% in membranes from 100 nM insulin-pretreated cells

Table 2. Effect of lean, obese, and RTO serum on Na-K-ATPase activity, [3H]SCH-23390-specific binding, D₁A receptor protein abundance, and [35S]GTPγS binding in PTECs

<table>
<thead>
<tr>
<th>Na-K-ATPase Activity, nmol 86Rb·mg protein⁻¹·h⁻¹</th>
<th>[3H]SCH-23390 Bound, fmol/mg protein</th>
<th>Western Blot Densitometry, arbitrary units</th>
<th>[35S]GTPγS Bound, fmol/mg protein</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean serum Control</td>
<td>14.0±0.8</td>
<td>99.0±4.0</td>
<td>99.66±5.5</td>
</tr>
<tr>
<td>Lean serum Dopamine</td>
<td>10.0±0.3*</td>
<td>33.8±3.4†</td>
<td>97.0±5.0</td>
</tr>
<tr>
<td>Obese serum Control</td>
<td>13.0±0.5</td>
<td>11.8±0.4</td>
<td>46.0±3.0†</td>
</tr>
<tr>
<td>Obese serum Dopamine</td>
<td>10.5±0.5*</td>
<td>56.0±3.0†</td>
<td>95.66±5.9</td>
</tr>
<tr>
<td>RTO serum Control</td>
<td>13.5±0.8</td>
<td>10.5±0.5*</td>
<td>121.60±6.0</td>
</tr>
<tr>
<td>RTO serum Dopamine</td>
<td>11.8±0.4</td>
<td>68.0±3.4†</td>
<td>101±6</td>
</tr>
</tbody>
</table>

Values are means ± SE of 5 experiments (animals) performed in triplicate. PTECs were incubated with 100 nM insulin-DMEM for 24 h. Cells incubated with DMEM alone served as the control. *Significantly different from DMEM; †significantly different from respective control (1-way ANOVA-Newman-Keuls, P < 0.05).

Table 3. Effect of insulin on [3H]SCH-23390 specific binding, D₁A receptor protein abundance, [35S]GTPγS binding, and Na-K-ATPase activity in PTECs

<table>
<thead>
<tr>
<th>PTECs from Lean Rats</th>
<th>PTECs from Obese Rats</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMEM</td>
<td>Insulin</td>
</tr>
<tr>
<td>Na-K-ATPase, nmol 86Rb·mg protein⁻¹·min⁻¹</td>
<td>Control</td>
</tr>
<tr>
<td>[3H]SCH-23390, fmol/mg protein</td>
<td>17.1±0.6</td>
</tr>
<tr>
<td>Western blot densitometry, arbitrary units</td>
<td>102.0±5.0</td>
</tr>
<tr>
<td>[35S]GTPγS bound, fmol/mg protein</td>
<td>118±0.7±3</td>
</tr>
</tbody>
</table>

Values are means ± SE of 5 experiments (animals) performed in triplicate. PTECs were incubated with 100 nM insulin-DMEM for 24 h. Cells incubated with DMEM alone served as the control. *Significantly different from DMEM; †significantly different from respective control (1-way ANOVA-Newman-Keuls, P < 0.05).
insulin-treated cells compared with control (Table 3). The densitometry of the bands revealed that D1A receptor protein was decreased by 25% in the membranes of insulin-treated compared with control cells (Table 3). A similar decrease in D1A receptor protein was observed in whole cell lysate of insulin-treated cells (data not shown).

As shown in Table 3, SKF-38393 (10 μM) elicited a 23% stimulation of [35S]GTPγS binding in the membranes of control cells. However, the stimulatory effect of SKF-38393 was absent in membranes of insulin-treated cells. There was no significant difference in basal [35S]GTPγS binding in membranes of control and treated cells.

Effect of varying concentrations of chronic insulin treatment on DA-induced inhibition of NKA activity. After confirmation that PTECs from SD or lean and obese Zucker rats show similar functional response to DA and that this response is attenuated to a similar extent by chronic exposure to 100 nM insulin, treatment of PTECs with varying concentrations of insulin was performed in cells harvested from SD rats only. The aim of these experiments was to examine the effects of different insulin concentrations on D1 receptor function that are comparable to those observed in lean and obese Zucker rats as well as to PTECs cultured in rat serum. As shown in Fig. 3, insulin is able to attenuate DA-induced NKA inhibition at both higher and lower concentrations. Although a concentration-dependent effect of insulin was not observed, at a lower concentration (1 nM) the effect of insulin on D1 receptor function was not so striking, as DA was still able to induce an ~15% inhibition in NKA activity.

Effect of fatty acids on D1 receptor function and expression. To address the question of whether elevated levels of free fatty acids can perturb renal D1 receptor function, experiments were performed to examine the effect of saturated and unsaturated fatty acids on D1 receptor expression and function in PTECs harvested from SD, lean, or obese rats. Palmitic acid (50 μM), steric acid, and oleic acid showed no effect on D1 receptor number or function, whereas at higher concentrations palmitic acid and steric acid caused cell rounding and detachment. Oleic acid (100 μM), an unsaturated fatty acid, showed no detrimental effect on cell morphology and was therefore used in subsequent studies. Similar to insulin treatment, oleic acid treatment also blunted the DA-induced inhibition of NKA, reduced D1 receptor expression, and caused D1 receptor-G protein uncoupling (data not shown). However, unlike insulin, oleic acid exposure reduced basal pump activity as well as membrane [35S]GTPγS binding. Thus these studies do not explain whether the reduction of D1 receptor expression and function is a specific effect or a direct toxic effect of free fatty acids on the Na pump and/or other membrane proteins. Regardless, it appears that free fatty acids will contribute to some extent to D1 receptor function.

DISCUSSION

Our results show that impaired D1 receptor function in proximal tubules of obese Zucker rats is caused by circulating factors. We found that PTECs from both lean and obese Zucker rats expressed functional D1 receptors. Further experiments revealed that culturing of PTECs from lean or obese animals in obese rat serum blunted the DA-induced inhibition of NKA, whereas cells cultured in lean or rosiglitazone-treated rat serum exhibited no defect in D1 receptor function. Furthermore, consistent with our recent report in PTECs from SD rats, the present findings demonstrate that chronic insulin exposure of PTECs from lean or obese rats attenuated DA-induced inhibition of NKA.

Obese Zucker rats (fa/fa) are homozygous for a mutation in the leptin receptor gene and develop pronounced hyperinsulinemia and severe obesity with relatively mild hyperglycemia (7, 11, 35, 45). In addition to secondary endocrine abnormalities, these rats also exhibit mild hypertension (1, 8). The mechanisms responsible for altered renal function and hypertension in obese Zucker rats are not clear. However, as has been reported with other forms of hypertension, the increased blood
pressure in obese Zucker rats is accompanied by impaired pressure-natriuresis (1, 16). In these animals, impaired pressure-natriuresis is mainly due to increased renal sodium reabsorption because the glomerular filtration rate and renal blood flow are increased by ~50% (1). The increased sodium reabsorption may be attributable, at least in part, to reduced DA-induced inhibition of sodium transporters and, subsequently, decreased sodium excretion (22, 23, 25).

Various authors have also reported a close relationship between sodium retention and hypertension in human essential hypertension and SHR (14, 50) and suggested that the failure in D1 receptor-mediated inhibition of sodium transporters in renal proximal tubules leads to a diminished natriuretic response to endogenously produced or exogenously administered DA (9, 15, 24). These defects in D1 receptor function were reproduced in cultured proximal tubules from essential hypertensive patients and SHR for several passages (14, 38, 50). To test whether this phenomenon is observed in obese Zucker rats, the present studies were conducted in PTECs from lean and obese animals. Our results show that DA caused a concentration-dependent inhibition of NKA in PTECs from lean and obese Zucker rats. Basal NKA activity was also similar in both groups of PTECs. Furthermore, there was no change in D1 receptor number, receptor protein abundance, or ligand-induced stimulation of G proteins in PTECs from lean compared with obese rats. These results show that renal proximal tubule cells from obese Zucker rats with impaired D1 receptor function do not retain the specific D1 receptor defect once are they are cultured. Also, the PTECs from obese rats show similar D1 receptor expression and function as observed in PTECs from their lean Zucker rat littermates. The possible confounding effect of dedifferentiation is unlikely because Sanada et al. (38) have shown the preservation of the response to forskolin and parathyroid hormone-related peptide in human proximal tubule cells studied after several passages. Also, there are other reports suggesting that the genetic defect is retained under in vitro culture conditions (50). Felder et al. (14) reported the hyperphosphorylation of the D1 receptor due to a ligand-independent increase in GRK activity in proximal tubular cell cultures obtained from patients with essential hypertension. In our study, the D1 receptor-G protein uncoupling observed in proximal tubules from obese Zucker rats was not present when we prepared primary cultures of these tubules. This suggests that the D1 receptor defect observed in proximal tubules of obese Zucker rats is probably induced by either paracrine factors or circulating factors associated with obesity. Our results support the latter notion because we found that culturing of PTECs from obese or lean rats in serum from obese rats blunted the DA-induced NKA inhibition, reduced D1 receptor expression, and caused D1 receptor-G protein uncoupling. When PTECs from both groups were cultured in serum from lean or rosiglitazone-treated rats, there was no difference in D1 receptor number and in the ability of DA to inhibit NKA activity. We have earlier reported that DA failed to inhibit NKA and NHE3 activity in proximal tubules of obese Zucker rats compared with their lean Zucker rat littermates (22, 23, 47). The inability of DA to inhibit NKA activity may have resulted from decreased D1 receptor number and D1 receptor-G protein uncoupling (22, 23, 47). Treatment of obese Zucker rats with rosiglitazone normalized blood glucose and caused a significant decrease in plasma insulin, TG, and free fatty acid levels (29, 33, 47). Rosiglitazone, while reducing the levels of these elevated factors, also effectively restored renal responsiveness to DA and normalized membrane D1 receptors to the levels seen in lean rats (47).

Our results in obese Zucker rats demonstrate that the D1 receptor defect in these animals is not intrinsic to renal proximal tubules, as is the case with human essential hypertension. A plausible explanation for these differences could be that obese Zucker rats mimic human syndrome X, often exhibiting hyperglycemia, hyperphagia, hyperlipidemia, hyperinsulinemia, insulin resistance, and hypertension (30). Multiple mechanisms have been proposed to explain the relationship between obesity and hypertension, including increased sympathetic activity, increased activity of the renin-angiotensin-aldosterone system, increased cardiac output, increased mechanical pressure from intestinal fat around organs, hyperinsulinemia, insulin resistance, changes in vascular reactivity, activated function of voltage-dependent Ca2+ channels in vascular smooth muscle, impaired endothelial function, and/or altered pressure-natriuresis (8, 16, 32, 49, 51). It is possible that some of these factors are altering the D1 receptor function in obese rats and thus contributing to sodium retention and hypertension. It should be noted that the blood pressure difference between hypertensive and normotensive controls has been attributed to two to six genetic loci (21, 31, 52). In human essential hypertension, a single nucleotide polymorphism of G protein-coupled receptor kinase GRK4γ increases GRK activity and causes the serine phosphorylation and uncoupling of the D1 receptor from its G protein effector enzyme in renal proximal tubules. Moreover, expressing GRK4γ gene in transgenic mice produces hypertension and reduces the diuretic and natriuretic effects of a D1-like agonist (14).

The mechanism underlying the development of hypertension in type 2 diabetes has begun to be elucidated through the use of several animal models including obese Zucker rats. A growing body of evidence has been accumulated demonstrating that insulin resistance is an important risk factor in the genesis of hypertension. It is obviously difficult to single out unequivocally which of the factors is responsible for hypertension as well as the D1 receptor impairment observed in ex vivo studies or in vivo obese models. However, there are reports suggesting a negative correlation between renal D1 receptor function and plasma insulin levels (39, 40). Recently, we were able to show that chronic insulin exposure of PTECs from SD rats causes a reduction in D1 receptor number and receptor-G protein uncoupling with the subsequent failure of SKF-38393, a D1-like agonist, to inhibit NKA activity (2). In the present studies, we also found that chronic insulin exposure of PTECs from lean and obese Zucker rats blunts the DA-induced NKA inhibition. This inability of DA to inhibit NKA may be attributable to reduced receptor number and receptor-G protein uncoupling. These studies suggest that hyperinsulinemia, commonly associated with obesity, could be an important contributing factor for D1 receptor dysfunction and subsequent hypertension. Furthermore, in support of our findings in obese Zucker rats, it has been shown that in type 2 diabetic patients the infusion of low doses of dopamine elicited a suppressed natriuretic response compared with normal volunteers and that this reduced natriuretic response was further exaggerated when patients were pretreated with insulin (39, 40). These studies suggest that impairment of the renal dopaminergic system and
subsequent blunted response to dopamine in type 2 diabetic patients may be due to hyperinsulinemia.

Insulin may play a role in the development of hypertension associated with syndrome X, or risk factor clustering, a common age-related syndrome that is expressed as hyperinsulinemia and lipid abnormalities (28, 41). Insulin is one the hormones that positively regulate NKA and epithelial Na\(^+\) channel (ENaC) activity. Although the role of NKA in the development of hypertension is still under debate, as of now ENaC is the only sodium transport protein for which genetic evidence exists for involvement in the genesis of both hypertension (Liddle’s syndrome) and hypertension (pseudohypaldosteronism type 1) (6, 27, 41–43, 46). The regulation of ENaC involves a variety of hormonal signals including insulin, but the molecular mechanisms behind this regulation are mostly unknown. Recently, Blazer-Yost and others (5, 36) reported that insulin-induced trafficking of ENaC in renal cells is mediated by phosphatidylinositol 3-kinase. Despite the elevated levels of circulating insulin and increased abundance of β-ENaC in obese Zucker rats, the role of ENaCs in the genesis of hypertension in these animals is yet to be determined (4).

Both obese rat serum and insulin (≥1 nM) led to the complete loss of DA-induced NKA inhibition. We speculate that in addition to reduction in D\(_1\) receptor number, insulin or obese rat serum may also alter the cell signaling downstream of the D\(_1\) receptor. This may be explained, in part, by the absence of G protein stimulation in PTECs cultured in obese rat serum or treated with insulin. Thus the reduction in receptor number and D\(_1\) receptor-G protein uncoupling may act synergistically to blunt D\(_1\) receptor function in obese Zucker rats.

In conclusion, our results demonstrate that D\(_1\) receptor dysfunction in obese Zucker rats is not intrinsic but is induced by elevated plasma levels of circulating factors. The observation that PTECs grown in serum from RTO rats, with reduced function, would show the same response is consistent with the idea that changes in this receptor are not intrinsic but are induced by elevated levels of circulating factors. Furthermore, chronic exposure of PTECs to insulin caused decreased D\(_1\) receptor expression and receptor-G protein uncoupling with subsequent D\(_1\) receptor dysfunction. Thus these results provide substantial evidence that hyperinsulinemia may be a contributing factor for impaired renal D\(_1\) receptor function in obese Zucker rats.

GRANTS

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