Rat Strain Effects of AT₁ Receptor Activation on D₁ Dopamine Receptors in Immortalized Renal Proximal Tubule Cells

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Abstract—The dopaminergic and renin-angiotensin systems regulate blood pressure, in part, by affecting sodium transport in renal proximal tubules (RPTs). We have reported that activation of a D₁-like receptor decreases AT₁ receptor expression in the mouse kidney and in immortalized RPT cells from Wistar-Kyoto (WKY) rats. The current studies were designed to test the hypothesis that activation of the AT₁ receptor can also regulate the D₁ receptor in RPT cells, and this regulation is aberrant in spontaneously hypertensive rats (SHRs). Long-term (24 hours) stimulation of RPT cells with angiotensin II, via AT₁ receptors increased total cellular D₁ receptor protein in a time- and concentration-dependent manner in WKY but not in SHR cells. Short-term stimulation (15 minutes) with angiotensin II did not affect total cellular D₁ receptor protein in either rat strain. However, in the short-term experiments, angiotensin II decreased cell surface membrane D₁ receptor protein in WKY but not in SHR cells. D₁ and AT₁ receptors colocalized (confocal microscopy) and their coimmunoprecipitation was greater in WKY than in SHRs. However, AT₁/D₁ receptor coimmunoprecipitation was decreased by angiotensin II (10⁻⁸M/24 hours) to a similar extent in WKY (−22±8%) and SHRs (−22±12%). In summary, these studies show that AT₁ and D₁ receptors interact differently in RPT cells from WKY and SHRs. It is possible that an angiotensin II-mediated increase in D₁ receptors and dissociation of AT₁ from D₁ receptors serve to counter regulate the long-term action of angiotensin II in WKY rats; different effects are seen in SHRs. (Hypertension. 2005;46:799-805.)

Key Words: dopamine • kidney • receptors, angiotensin II • rats, spontaneously hypertensive

Angiotensin II and dopamine are important regulators of sodium and water transport across the renal proximal tubule (RPT). Angiotensin II receptor subtypes (AT₁, AT₂, and AT₄) are expressed in brush border and basolateral membranes of RPTs. The activation of AT₁ receptors by low concentrations of angiotensin II (picomolar) causes an increase in sodium reabsorption in RPTs. All the dopamine receptor subtypes, D₁-like (D₁ and D₅) and D₂-like (D₂, D₃, and D₄) are also expressed in brush border and basolateral membranes of RPTs. In contrast to the stimulatory effect of AT₁ receptors on renal sodium transport, activation of D₁ and D₅ receptors decreases renal sodium reabsorption.

Several reports have shown an interaction between the dopamine and renin-angiotensin system. Intrarenally produced angiotensin II opposes the natriuretic action of the D₁-like dopamine receptor agonist, fenoldopam, in rats. D₁-like receptor agonists also antagonize the stimulatory effect of angiotensin II, acting via AT₁ receptors, on renal proximal tubular luminal sodium transport. When angiotensin II generation is inhibited or AT₁ receptors are blocked, the natriuretic effect of dopaminergic drugs is enhanced.

The AT₁ receptor mediates the anti-natriuretic effect of angiotensin II, whereas the D₁ dopamine receptor is responsible for ~80% of D₁-like receptor activity in RPTs. We have reported that in RPT cells of Wistar-Kyoto (WKY) rats, the D₁-like agonist, fenoldopam, increased D₁ receptor but decreased AT₁ receptor protein expression. In contrast, in RPT cells of spontaneously hypertensive rats (SHRs), fenoldopam also decreased AT₁ receptor expression but no longer stimulated D₁ receptor expression. We also reported that AT₁ and D₁ receptors coimmunoprecipitate in RPT cells; fenoldopam increased this communoprecipitation in WKY RPT cells but decreased it in SHR RPT cells. We hypothesize that the AT₁ receptor may also regulate the D₁ receptor, including its expression. Therefore, we studied the effect of angiotensin II on D₁ receptor expression and AT₁ and D₁...
receptor interaction in immortalized rat RPT cells. We have previously shown that the D₁ receptor effects on signal transduction and sodium transporters in immortalized RPT cells are similar to those obtained in freshly obtained renal proximal tubules.20–22 Parenti et al have also reported that the AT₁ receptor behaves similarly in freshly obtained renal tubules and immortalized RPT cells.23

We now report that AT₁ and D₁ receptors colocalize in RPT cells. D₁ and AT₁ receptor coimmunoprecipitation was greater in WKY than in SHRs, in agreement with our previous report.19 In this earlier study, long-term fenoldopam stimulation (24 hours) increased the coimmunoprecipitation of D₁ and AT₁ receptors in WKY but decreased it in SHRs.19 We now show that angiotensin II decreases D₁ and AT₁, coimmunoprecipitation similarly in WKY and SHRs. However, D₁ receptor expression is increased by angiotensin II in WKY but not in SHRs. In contrast, short-term angiotensin II, via AT₁ receptors (15 minutes), decreases cell surface membrane expression of D₁ receptors in WKY but not in SHRs. These studies show that angiotensin II differentially affects total cellular and surface membrane D₁ receptor expression in RPT cells from WKY and SHRs.

Methods

Cell Culture

Immortalized RPT cells from 4- to 8-week-old WKY and SHRs were cultured at 37°C in 95% air/5% CO₂ atmosphere in DMEM/F-12 culture media, as previously described.21–26 The cells (80% confluence) were extracted in ice-cold lysis buffer (phosphate-buffered saline with 1% NP40, 0.5% sodium deoxycholate, 0.1% SDS, 1 mmol/L EDTA, 1 mmol/L EGTA, 1 mmol/L PMSF, 10 µg/mL aprotinin, and 10 µg/mL leupeptin), sonicated, kept on ice for 1 hour, and centrifuged at 16 000 g for 30 minutes. The supernatants were stored at −70°C until use for immunoblotting and/or immunoprecipitation.

Immunoblotting

The antibodies are polyclonal purified antipeptides. The amino acid sequence for the immunogenic peptide (rabbit anti-human AT₁ receptor antibody) is QDDCPKAGRHC, amino acids 15 to 24 of the AT₁ receptor. The specificity of this antibody to the AT₁ receptor is indicated as previously reported.21–26 The amino acid sequence for rat D₁ receptor antibody corresponds to positions 299 to 307 (GSEETQPFC) on D₁ receptor (Research Genetics). The specificity of this D₁ receptor antibody has also been reported.19–20 Rat RPT cells were treated with vehicle (dH₂O), angiotensin II or an AT₁ receptor antagonist (losartan) at the indicated concentrations and times. Immunoblotting was performed as previously reported,22–26 except that the transblots were probed with the D₁ (1:800) or the AT₁ receptor antibody (1:400). The amount of protein transferred onto the membranes was determined by Ponceau-S staining and immunoblotting for α-actin.19

Immunofluorescence Confocal Microscopy of Double-Stained RPT Cells

RPT cells, grown on coverslips, were fixed with 3% paraformaldehyde (30 minutes) and permeabilized with 0.1% Triton X-100 in phosphate-buffered saline (15 minutes). Reactions with antibodies were performed as described previously.22,30 The D₁ and AT₁ receptors were visualized by using a rabbit antipeptide polyclonal IgG affinity-purified rat D₁ receptor antibody followed by fluorescein isothiocyanate-conjugated anti-rabbit secondary antibody (Molecular Probes) or by a mouse anti-human AT₁ receptor monoclonal antibody followed by the secondary goat anti-mouse antibody labeled with Alexa 568 (Molecular Probes).22 Cells on coverslips were mounted with the ProLong Antifade Kit (Molecular Probes). The immunofluorescence densities and images were acquired (Olympus AX70) at an excitation wavelength of 488 nm and 568 nm; emission was detected at 535 and 645 nm.22–30

Immunoprecipitation

RPT cells were incubated with vehicle or angiotensin II (10⁻⁸ M) for 24 hours, as described. The cells were lysed with ice-cold lysis buffer (1 hour) and centrifuged at 16 000g for 30 minutes. The supernatants were pelleted and washed 4 times with lysis buffer. The pellets were suspended in sample buffer, boiled for 10 minutes, and subjected to immunoblotting with the AT₁ receptor antibody. To determine the specificity of the bands, preimmune serum of D₁ receptor antibody (negative control) and AT₁ receptor antibody (positive control) were used as immunoprecipitants, instead of the D₁ receptor antibody. The densities of the bands were quantified by densitometry using Quantiscan (Ferguson, Mo) as previously reported.19,22,26

Cell Surface D₁ Receptor Expression

Cultured RPT cells were starved in serum-free medium for 2 hours, and then treated with angiotensin II (10⁻⁸ M) for 15 minutes. Surface membrane proteins were biotinylated by adding sulfo-NHS-LC-biotin (final concentration 250 µg/mL) into the medium 5 minutes before adding angiotensin II. The cells were washed 3 times with wash buffer. Then, the cells were lysed with lysis buffer, sonicated and placed on ice for 1 hour. The supernatant from the cell lysate was immunoprecipitated with the anti-rat D₁ receptor antibody, followed by immunoblotting. The membrane sheets were blocked with 5% milk overnight and after washing (3 times), the sheets were incubated with peroxidase-conjugated streptavidin (Jackson ImmunoResearch Laboratory, Inc, in wash buffer at 1/5000 dilution for 30 minutes. The biotinylated protein bands were visualized by enhanced chemiluminescence (Western Blotting Detection Kit; Amersham, Arlington Heights, Ill).31

Materials

Rabbit anti-human AT₁ receptor antibodies were purchased from Santa Cruz Biotechnology, Inc (Santa Cruz, Calif). Rabbit anti-rat D₁ receptor antibody was produced against a synthetic oligopeptide from the amino acid sequence of rat D₁ receptor (amino acids 299 to 307) (Research Genetics). Monoclonal mouse anti-human AT₁ receptor antibody was purchased from Abcam Limited (Cambridge, UK). Angiotensin II was purchased from Peninsula Laboratory, Inc (St Louis, Mo). Losartan was a gift from Merck & Co (Philadelphia, Pa). Peroxidase-conjugated streptavidin was purchased from Jackson ImmunoResearch Laboratory, Inc (West Grove, Pa). Sulfo-NHS-LC-biotin was purchased from PIERCE (Rockford, Ill). Other chemicals for various buffers were of the highest purity available and purchased either from Sigma or Gibco.

Statistical Analysis

The data are expressed as mean ± SEM. Comparison within groups was made by ANOVA for repeated measures, and comparison among groups was made by factorial ANOVA with Duncan’s test. P<0.05 was considered significant.

Results

Activation of AT₁ Receptors Increases D₁ Receptor Expression in RPT Cells From WKY Rats, But Not From SHRs

In RPT cells from WKY rats, angiotensin II increased D₁ receptor expression in a concentration- and time-dependent...
manner. The stimulatory effect was evident at 10^{-9} M (Figure 1A) as early as 16 hours and maintained for at least 30 hours (Figure 1B). Consistent with the stimulatory effect of angiotensin II on D_{1} receptor expression (Figure 1A and 1B), a 24 hour-incubation with angiotensin II (10^{-8} M) increased D_{1} receptors in RPT cells from WKY rats. In contrast, this effect was not observed in RPT cells from SHRs (WKY: control = 0.77 ± 0.15, angiotensin II = 1.33 ± 0.19; SHR: control = 0.87 ± 0.13, angiotensin II = 1.04 ± 0.17; n = 7) (Figure 1C).

To determine the specificity of angiotensin II action on AT_{1} receptors, we studied the effect of the AT_{1} receptor antagonist, losartan. Consistent with the results in WKY rats in Figure 1A, 1B, and 1C, angiotensin II (10^{-8} M/24 hours) increased D_{1} receptor expression (control = 0.83 ± 0.15, angiotensin II = 1.48 ± 0.15; n = 8). The AT_{1} receptor antagonist, losartan (10^{-8} M), by itself, had no effect on D_{1} receptor expression (0.8 ± 0.13) but reversed the stimulatory effect of angiotensin II on D_{1} receptor expression (0.7 ± 0.08) (Figure 1D).

To investigate whether there is a right-shift of the concentration-response curve in SHRs, their RPT cells were incubated with varying concentrations of angiotensin II (10^{-9} M to 10^{-5} M) for 24 hours. Consistent with the results in Figure 1C, angiotensin II had no effect on D_{1} receptor expression in SHRs (Figure 1E).

Figure 1. Effect of angiotensin II on D_{1} receptor protein in RPT cells from WKY and SHRs. A, Concentration-response of D_{1} receptor protein in RPT cells from WKY rats treated with angiotensin II. Immunoreactive D_{1} receptor protein was determined after 24 hour incubation with the indicated concentrations of angiotensin II. Results are expressed as relative density units (DU) (n = 8, *P < 0.05 vs control (C), ANOVA, Duncan’s test). B, Time-course of D_{1} receptor protein in RPT cells from WKY rats treated with angiotensin II. The cells were incubated for the indicated times with 10^{-8} M angiotensin II. Results are expressed as relative density units (DU) (n = 8, *P < 0.05 vs control [0 time], ANOVA, Duncan’s test). C, Effect of angiotensin II (10^{-8} M/24 hours) on D_{1} receptor protein in RPT cells from WKY and SHRs. Results are expressed as the ratio of D_{1} receptor to β-actin densities (n = 7, *P < 0.05 vs control, ANOVA, Duncan’s test). D, Effect of angiotensin II (Ang) and an AT_{1} receptor antagonist (losartan) on D_{1} receptor protein in WKY rat RPT cells. The cells were incubated with the indicated reagents (angiotensin II, 10^{-8} M; losartan, 10^{-8} M) for 24 hours. Results are expressed as the ratio of D_{1} receptor to β-actin densities (n = 8, *P < 0.05 vs others, ANOVA, Duncan’s test). E, Concentration-response of D_{1} receptor protein in SHR RPT cells treated with angiotensin II. Immunoreactive D_{1} receptor protein was determined after a 24 hour-incubation with the indicated concentrations of angiotensin II. Results are expressed as relative density units (DU) (n = 6, P = NS vs control (C), ANOVA, Duncan’s test).

AT_{1} Receptor Colocalizes With the D_{1} Receptor in Rat RPT Cells

Immunofluorescence laser confocal microscopy revealed a colocalization of D_{1} and AT_{1} receptors in WKY rat RPT cells (Figure 2). To determine whether there is a physical interaction between the D_{1} and the AT_{1} receptor, additional experiments were performed. As shown in Figure 3, in the basal state, the band of 45 kDa, representing the coimmunoprecipitated D_{1} and AT_{1} receptors in RPT cells from WKY and SHRs. Results are expressed as relative density units (DU) (n = 6, P = NS vs control (C), ANOVA, Duncan’s test).

Zeng et al AT_{1} Receptor Regulation of D_{1} Receptors in Kidney

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Activation of AT₁ Receptors Decreases the D₁ Receptor Expression in Surface Membranes of RPT Cells From WKY Rats But Not From SHRs

The effect of short-term stimulation with angiotensin II on cell surface D₁ receptors is shown in Figure 4. Angiotensin II (10⁻⁸ M) decreased the quantity of D₁ receptors on the cell surface membranes in WKY RPT cells, but not in SHR RPT cells (WKY: control = 45±9 DU, angiotensin II = 17±5 DU; SHR: control = 19±3 DU, angiotensin II = 19±5 DU, n = 6).

Discussion

Polygenic essential hypertension is associated with increased sodium transport in renal proximal tubules.32,33 As mentioned, dopamine and angiotensin II are important regulators of sodium and water reabsorption in the kidney, serving contrasting functions in the proximal tubule.1,5,17,34,35 Both dopamine and renin-angiotensin systems exist in the RPT, and the components of the renin-angiotensin system, including angiotensinogen mRNA, renin, and angiotensin-converting enzyme, have been localized to the proximal tubule.1,6,36,37 The proximal tubule is also the site of local dopamine production.38–40 Urinary dopamine and angiotensin II concentrations exceed circulating levels, suggesting both systems may have autocrine and/or paracrine effects in RPTs.1,6,38,41 Angiotensin II stimulates sodium reabsorption via activation of sodium transporting proteins that are inhibited by dopamine (NHE3, Cl/HCO₃ exchanger, Na/HCO₃ cotransporter, and Na/K⁺-ATPase).34,35 Dopamine and D₁-like and D₂-like receptor agonists have been reported to antagonize the actions of angiotensin II on NHE3 and Na/K⁺-ATPase activities in brush border and basolateral membranes of renal proximal tubules.15,16 Dopamine, via D₁-like receptors, has also been reported to decrease the AT₁ receptor mRNA and protein, as well as angiotensin II binding sites in renal proximal tubules.19,42 The effect of angiotensin II on D₁-like receptors has not been reported.

In WKY RPT cells, stimulation of the AT₁ receptor with angiotensin II for 2 different periods (short-term or long-term) yields opposite results; short-term stimulation decreases cell surface D₁ receptor expression, whereas long-term stimulation increases whole cell D₁ receptor expression. It is unlikely that the change in the short-term could account for the long-term result. A decrease of cell surface D₁ receptor expression would remove a restraint allowing AT₁ receptor activation to increase sodium reabsorption to a greater extent. However, the increase in D₁ receptor expression would tend to counterbalance the prolonged angiotensin II effect.

Cell surface membrane localization of G protein-coupled receptors is decreased by phosphorylation of the receptor.8,43 We have reported that G protein-coupled receptor kinases (GRKs), GRK2 and GRK4, are involved in D₁ receptor phosphorylation.44 Among the GRKs, GRK2 is most impor-
tant in promoting AT$_1$ receptor phosphorylation.\textsuperscript{4,5} It is possible that the GRK2 activation subsequent to AT$_1$ receptor stimulation also results in the alteration of the phosphorylation and membrane localization of the D$_1$ receptor. Such a scenario can explain the ability of AT$_1$ receptors to decrease the membrane localization of the D$_1$ receptor in WKY. This does not occur in SHRs because the D$_1$ receptor is already hyperphosphorylated and fewer D$_1$ receptors are found on renal cell surface membranes in SHR.\textsuperscript{46} Although GRK4 is the major GRK regulating D$_1$ receptor function,\textsuperscript{43,44} GRK4 is not involved in the desensitization of the AT$_1$ receptor.\textsuperscript{45} The possibility exists that the AT$_1$ receptor can cause heterologous desensitization of the D$_1$ receptor via stimulation of effector enzymes, but it is not clear which one.\textsuperscript{48}

The dephosphorylation of D$_1$ receptors in renal proximal tubules is also different in WKY and SHRs. We have reported that short-term D$_1$-like receptor stimulation increases protein phosphatase 2A activity in renal proximal tubules in WKY but not in SHRs.\textsuperscript{49} It is possible that in the WKY, the AT$_1$ receptor inhibits protein phosphatase 2A activity and thus prevents dephosphorylation and recycling of the D$_1$ receptor to the cell surface membrane. Although there is no report to support this mechanism, AT$_1$ receptor has been reported to stimulate protein phosphatase 2A activity.\textsuperscript{50,51}

Long-term stimulation of AT$_1$ receptors increases total cellular D$_1$ receptor expression in WKY. This finding in vitro was also found in vivo; chronic angiotensin II infusion in mice also caused an increase in D$_1$ receptor expression (unpublished data). Presumably, cell surface D$_1$ receptor expression is also increased. Although the mechanism by which AT$_1$ receptor stimulation increases D$_1$ receptor expression remains to be determined, such an effect could serve as a physiological negative feedback under normal circumstances (in WKY). However, in SHR cells, this upregulation of D$_1$ receptors by stimulation of AT$_1$ receptors is lost because of decreased responsiveness of the hyperphosphorylated D$_1$ receptor.\textsuperscript{46,52,53} We have reported that the renal D$_1$ receptor is hyperphosphorylated in SHRs as a consequence of increased activity of GRK4\textsuperscript{54} and decreased protein phosphatase 2A activity.\textsuperscript{49}

Long-term incubation with angiotensin II decreases D$_1$/AT$_1$ receptor commonprecipitation to the same degree in cells from SHR and WKY rats. Our previous study showed that long-term exposure to angiotensin II decreases AT$_1$ receptor protein expression in RPT cells from WKY rats but increases it in SHRs.\textsuperscript{26} The decreased interaction between D$_1$ and AT$_1$ receptors in renal proximal tubules in WKY rats is, therefore, not the result of decreased AT$_1$ receptor expression, per se, because a similar response is seen in SHRs where AT$_1$ expression is increased by angiotensin II. Thus, angiotensin II, via the AT$_1$ receptor, probably causes a decrease in the physical interaction of AT$_1$ and D$_1$ receptors in both WKY and SHR cells. Further studies are needed to determine whether the decreased interaction between these 2 receptors is direct or indirect, possibly by the alteration of an adaptor gene or adaptor proteins.

In both SHR and Dahl salt-sensitive rats, dopamine and D$_1$-like receptor agonist-mediated natriuresis and diuretic responses are impaired.\textsuperscript{8,43} The impaired D$_1$-like receptor function in hypertension is not caused by abnormalities in G proteins, effectors, or ion transporting proteins, such as adenylyl cyclase, NHE3 or Na$^+$/K$^+$ ATPase. Rather, the renal D$_1$-like receptor is uncoupled from G protein subunits, leading to decreased D$_1$-like receptor interaction with G protein subunits, and resulting in decreased production of second messengers and decreased interaction between G protein subunits, effector enzymes, and ion transporters.\textsuperscript{3,43,53} To determine whether the impaired D$_1$ receptor function occurs at the receptor level, we investigated the expression of D$_1$ receptor in cell surface membranes and whole cells. We found that cell surface membrane expression of D$_1$ receptors is lower and D$_1$ receptor phosphorylation is higher in SHRs than in WKY cells, although total and D$_1$ receptor expression are not different in the 2 cell lines.\textsuperscript{46,54} Renal D$_1$ receptor phosphorylation and GRK4 activity impact on the regulation of blood pressure. Inhibition of renal GRK4 activity by antisense oligonucleotides attenuates the increase in blood pressure with age in SHRs without affecting blood pressure in WKY rats.\textsuperscript{55}

In summary, we have demonstrated that long-term stimulation of AT$_1$ receptors positively regulates the expression of D$_1$ receptors in RPT cells from WKY but not from SHRs. AT$_1$ and D$_1$ receptors colocalize in RPT cells from both rat strains, but the basal level of cell surface membrane D$_1$ receptor expression is higher in WKY than in SHR RPT cells. It appears that a greater proportion of D$_1$ receptors are located on the cell surface membrane in WKY cells than in SHR cells. Short-term AT$_1$ receptor stimulation decreases cell surface membrane D$_1$ receptor expression in WKY rats but not in SHRs. It is possible that differences in AT$_1$ receptor regulation of D$_1$ receptor expression and cell surface expression may participate in the abnormal regulation of renal proximal sodium transport in genetic hypertension.

**Perspectives**

The dopaminergic and renin-angiotensin system are 2 important systems that regulate blood pressure.\textsuperscript{1–8} Dopamine promotes natriuresis, whereas angiotensin II decreases sodium excretion.\textsuperscript{1–8} The major D$_1$-like receptor subtype mediating the increase in sodium excretion is probably the D$_1$ receptor, whereas the major angiotensin II receptor mediating the decrease in renal sodium excretion is the AT$_1$ receptor.\textsuperscript{1–8} In SHRs, renal proximal tubular D$_1$ receptor function is impaired.\textsuperscript{7,8} Regardless of the mechanism involved in the interaction between D$_1$ and AT$_1$ receptors, the dissociation of D$_1$ from AT$_1$ receptors after angiotensin II stimulation may allow the AT$_1$ and D$_1$ receptor to exert their functions separately. Renal proximal tubular D$_1$ receptors are functional in WKY but not in SHRs. In contrast, AT$_1$ receptor function is enhanced in SHRs.\textsuperscript{32} The inability of AT$_1$ receptors to increase D$_1$ receptor expression in renal proximal tubules in SHRs and a decreased D$_1$ and AT$_1$ receptor interaction could lead to enhanced AT$_1$ receptor function.

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