Kidney

Gastrin and D₁ Dopamine Receptor Interact to Induce Natriuresis and Diuresis

Yue Chen,* Laureano D. Asico,* Shuo Zheng,* Van Anthony M. Villar, Duofen He, Lin Zhou, Chunyu Zeng, Pedro A. Jose

See Editorial Commentary, pp 834–835

Abstract—Oral NaCl produces a greater natriuresis and diuresis than the intravenous infusion of the same amount of NaCl. Gastrin is the major gastrointestinal hormone taken up by renal proximal tubule (RPT) cells. We hypothesized that renal gastrin and dopamine receptors interact to synergistically increase sodium excretion, an impaired interaction of which may be involved in the pathogenesis of hypertension. In Wistar-Kyoto rats, infusion of gastrin induced natriuresis and diuresis, which was abrogated in the presence of a gastrin (cholecystokinin B receptor [CCKBR]; CI-988) or a D₁-like receptor antagonist (SCH23390). Similarly, the natriuretic and diuretic effects of fenoldopam, a D₁-like receptor agonist, were blocked by SCH23390, as well as by CI-988. However, the natriuretic effects of gastrin and fenoldopam were not observed in spontaneously hypertensive rats. The gastrin/D₁-like receptor interaction was also confirmed in RPT cells. In RPT cells from Wistar-Kyoto but not spontaneously hypertensive rats, stimulation of either D₁-like receptor or gastrin receptor inhibited Na⁺-K⁺-ATPase activity, an effect that was blocked in the presence of SCH23390 or CI-988. In RPT cells from Wistar-Kyoto and spontaneously hypertensive rats, CCKBR and D₁ receptor coimmunoprecipitated, which was increased after stimulation of either D₁ receptor or CCKBR in RPT cells from Wistar-Kyoto rats; stimulation of one receptor increased the RPT cell membrane expression of the other receptor, effects that were not observed in spontaneously hypertensive rats. These data suggest that there is a synergism between CCKBR and D₁-like receptors to increase sodium excretion. An aberrant interaction between the renal CCKBR and D₁-like receptors (eg, D₁ receptor) may play a role in the pathogenesis of hypertension. (Hypertension. 2013;62:927-933.) • Online Data Supplement

Key Words: hypertension • kidney • kidney tubules, proximal • receptor, cholecystokinin B receptors, dopamine D₁

Hypertension with its complications is a paramount problem imperiling human health, which is caused by the combined effects of environmental and genetic factors.¹ There is general agreement that salt (NaCl) intake is one such environmental factor,²,³ and epidemiological studies have shown a positive correlation between sodium intake and blood pressure.⁴ Thus, limiting salt intake and promoting sodium excretion are effective in the treatment of sodium-induced hypertension, keeping in mind that there may be a J-shaped relationship between sodium intake and mortality.⁵ Indeed, in some individuals, blood pressure may actually increase with a low sodium intake.⁶

The kidney, especially the renal proximal tubule (RPT), which is responsible for ≈60% of total renal sodium reabsorption, is critical in the regulation of sodium balance.⁷,⁸ We and others have reported that renal dopamine, via D₁-like (composed of D₁ receptor [D₁R] and D₁ receptor subtypes) and D₂-like receptors (composed of D₁ receptor, D₃ receptor, and D₄ receptor subtypes), plays an important role in preventing volume expansion by increasing sodium excretion secondary to a decrease in renal sodium reabsorption in several nephron segments, including the RPT.⁹,¹⁰ At least 50% of basal sodium excretion in moderately volume-expanded states is mediated by the paracrine action of renal dopamine exerted on D₁Rs.⁹,¹⁰ Dopamine, via D₁R, inhibits the activity of Na⁺-K⁺-ATPase in the basolateral membrane and the Na⁺/H⁺ exchanger, isof orm 3 in the apical membrane of RPT cells.⁵,¹⁰ A dysfunction of the D₁R is involved in the pathogenesis of hypertension.⁸,¹⁰ Depending on the state of sodium balance, an oral NaCl load has been reported to produce stronger natriuresis and diuresis than an intravenous infusion of the same amount of NaCl, indicating the existence of a gastro-renal axis.¹⁵,¹⁶ Several hormones secreted by the stomach and duodenum have been suggested.

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to be effectors of the gastro-renal axis. An effector of the gastro-renal axis may be gastrin, produced by the G cells of stomach antrum and duodenum. Food intake increases circulating gastrin levels 10-20-fold more than those of stomach antrum and duodenum. Food intake increases circulating gastrin, produced by the G cells of the stomach antrum and duodenum. Furthermore, the gastrin receptor, also called cholecystokinin B receptor (CCKBR), is expressed in the kidney, including glomerular mesangial cells, collecting duct cells, and proximal convoluted tubule cells. In addition, stimulation of CCKBR promotes natriuresis. However, as aforementioned, we and others have suggested that the renal dopaminergic system is important for the excretion of an oral or an intravenous sodium load. Therefore, we tested the hypothesis that gastrin interacts with dopamine receptors in the kidney to synergistically increase sodium excretion. We hypothesized, further, that this interaction is impaired in hypertension. To verify the hypotheses, we studied the natriuretic effect of intrarenal arterial infusion of gastrin with or without coinfusion of a D1-like receptor agonist, fenoldopam, in the normotensive Wistar-Kyoto (WKY) rat and the spontaneously hypertensive rat (SHR). We also studied the colocalization and functional and physical interactions between CCKBR and D1R in rat RPT cells.

Materials and Methods

Materials and Methods are available in the online-only Data Supplement.

Results

In Vivo Study

Intrarenal Infusion of Gastrin Induces Natriuresis and Diuresis in WKY Rats But Not SHRs

To determine the effect of renal CCKBR on sodium excretion and urine flow, varying doses of gastrin (0, 0.1, 0.5, 1.0, 5.0 μg/kg per minute for 40 minutes in each period; n=6) were infused into the right kidney (via the right suprarenal artery) in WKY rats. The intrarenal arterial infusion of fenoldopam increased V and UNaV. An increase in V was first observed at a dose of 0.5 μg/kg per minute, whereas an increase in UNaV was first observed at a dose of 1.0 μg/kg per minute (Figure 1A and 1B, respectively). In contrast, gastrin had no effect on V and UNaV in SHRs (Figure 1A and 1B). The right intrarenal infusion of gastrin had no effect on blood pressure in WKY rat (Table S1) and SHR (not shown).

To determine the specificity of the gastrin effect on urine flow and sodium excretion, a gastrin receptor (CCKBR) antagonist, CI-988, was used. CI-988, infused at 1.0 mg/kg per minute, did not affect V and UNaV in WKY rats (Table S2); in the presence of CI-988, the diuretic and natriuretic effects of gastrin (1.0 μg/kg per minute) were blocked (Table S3).

Stimulation of Renal D1-Like Receptors Induces Natriuresis and Diuresis in WKY Rats

To determine the effect of D1-like receptors on natriuresis and diuresis, varying doses of fenoldopam (0, 0.1, 0.5, 1.0, 5.0 μg/kg per minute for 40 minutes in each period; n=6) were infused into the right kidney (via the right suprarenal artery) in WKY rats. The intrarenal arterial infusion of fenoldopam increased V and UNaV. An increase in V was first observed at a dose of 0.5 μg/kg per minute, whereas an increase in UNaV was first observed at a dose of 1.0 μg/kg per minute (Figure 2A and 2B). The impaired natriuretic and diuretic effects of dopamine and D1-like receptor agonists, including fenoldopam, in SHRs have been reported; therefore, this experiment was not performed in the current study.

A D1-like receptor antagonist, SCH23390, was used to determine the specificity of the D1-like receptors agonist (fenoldopam) on renal function. SCH23390, infused at a low dose of 0.4 μg/kg per minute, did not affect V and UNaV in WKY rats (Table S4). In the presence of SCH23390, the natriuretic and diuretic effects of fenoldopam were blocked in WKY rats (Table S5).

Blockade of 1 Receptor (D1-Like or Gastrin [CCKBR] Receptor) Abolishes the Natriuresis and Diuresis Caused by Gastrin or Fenoldopam, Respectively, in WKY Rats

To determine whether there is an interaction between D1-like and gastrin receptors, we investigated the diuretic and natriuretic effects of gastrin in the presence of the D1-like

![Figure 1](http://hyper.ahajournals.org/)

**Figure 1.** Effect of the renal infusion of gastrin on urine flow and sodium excretion in Wistar-Kyoto (WKY) and spontaneously hypertensive rats (SHRs). **A,** Urine flow (V); **B** absolute sodium excretion (UNaV). Varying doses of gastrin (0.1–5.0 μg/kg per minute) were infused into the right suprarenal artery of anesthetized rats. *P*<0.05 vs control (repeated-measures ANOVA, Holm–Sidak test). *P*<0.05 vs SHR, n=6 (t test).
receptor antagonist, SCH 23390, and the diuretic and natriuretic effects of fenoldopam in the presence of the CCK_BR antagonist, CI-988. In the presence of D_1-like receptor antagonist, SCH23390 (0.4 μg/kg per minute), the diuretic and natriuretic effects of gastrin were blocked (Figure 3A and 3B). Similarly, in the presence of gastrin receptor (CCK_BR) antagonist, CI-988, the diuretic and natriuretic effects of fenoldopam (1.0 μg/kg per minute) were also blocked (Figure 3C and 3D).

In Vitro Study

**Inhibitory Effect of Gastrin or Fenoldopam on Na^+-K^+-ATPase Activity Is Impaired in RPT Cells From SHRs**

The effect of gastrin on the activity of Na^+-K^+-ATPase, the primary active sodium transporter located at the basolateral membrane, was studied in RPT cells. We found that gastrin inhibited Na^+-K^+-ATPase activity in WKY RPT cells in a concentration-dependent (10^{-11} to 10^{-8} mol/L) and time-dependent manner (Figure S1A and S1B). In contrast, the inhibitory
effect of gastrin (10^{-9} \text{ mol/L}) on Na^+-K^+-ATPase activity was not observed in SHR RPT cells (Figure S1C).

The receptor specificity of the inhibitory effect of gastrin on Na^+-K^+-ATPase activity was also studied. CI-988 (10^{-3} \text{ mol/L} for 15 minutes), by itself, had no effect on the basal Na^+-K^+-ATPase activity, but in the presence of CI-988, the inhibitory effect of gastrin (10^{-9} \text{ mol/L} for 15 minutes) on Na^+-K^+-ATPase activity was blocked (basal=0.44±0.05; gastrin=0.31±0.05 [P<0.05 versus others]; CI-988=0.38±0.03; gastrin+CI-988=0.38±0.03 \text{ μmol Pi/mg protein per minute}).

Previous studies 29–32 have shown that the inhibitory effect of D_{1}-like receptor agonists on renal or RPT Na^+-K^+-ATPase activity is impaired in the SHR. We also studied the effect of fenoldopam on Na^+-K^+-ATPase activity in WKY RPT cells. We found that SCH23390 (10^{-6} \text{ mol/L} for 15 minutes), by itself, had no effect on the basal Na^+-K^+-ATPase activity but blocked the inhibitory effect of fenoldopam (10^{-7} \text{ mol/L} for 15 minutes) on Na^+-K^+-ATPase activity in WKY RPT cells (basal=0.42±0.04; fenoldopam=0.27±0.08 [P<0.05 versus others]; SCH23390=0.41±0.07; fenoldopam+SCH23390=0.37±0.01 \text{ μmol Pi/mg protein per minute}).

**Gastrin (CCKBR) and D_{1}-Like Receptors Interact to Inhibit Na^+-K^+-ATPase Activity in WKY RPT Cells**

Gastrin receptor (CCKBR) and D_{1}-like receptor interact to inhibit Na^+-K^+-ATPase activity in WKY RPT cells because in the presence of gastrin receptor (CCKBR) antagonist, CI-988 (10^{-3} \text{ mol/L} for 15 minutes), the inhibitory effect of fenoldopam (10^{-7} \text{ mol/L} for 15 minutes) on Na^+-K^+-ATPase activity was blocked (Figure S2A). Similarly, in the presence of a D_{1}-like receptor antagonist, SCH23390 (10^{-4} \text{ mol/L} for 15 minutes), the inhibitory effect of gastrin (10^{-9} \text{ mol/L} for 15 minutes) on Na^+-K^+-ATPase activity was blocked (Figure S2B).

**Augmented Plasma Membrane Expression Is Involved in the Synergistic Interaction Between D_{1}-Like and Gastrin Receptors in WKY RPT Cells**

To determine whether gastrin affects the cellular localization of D_{1}R, the effect of short-term stimulation with gastrin on cell-surface D_{1}Rs was studied. Gastrin (10^{-9} \text{ mol/L} for 15 minutes) caused a 44.5% increase in cell-surface D_{1}R expression (Figures S3A and S3B) in WKY RPT cells but not in SHR RPT cells (WKY: control=24.28±6.92; gastrin=34.52±4.91 [P<0.05]; SHRs: control=19.22±4.58, gastrin=21.98±5.40 density units; n=4/group; Figure S3C). Similarly, we also found that the stimulation of D_{1}-like receptors with fenoldopam increased gastrin receptor (CCKBR) expression in cellular membranes of WKY RPT cells (Figure S4A) but not in SHR RPT cells (Figure S4A). Cell-surface D_{1}R but not CCKBR expression was also lesser in SHRs than in WKY rats. The ability of fenoldopam to increase cell-surface D_{1}R expression was blocked by both CCKBR and D_{1}R antagonists, which by themselves had no effect (Figure S4B).

**Gastrin Receptors (CCKBRs) Colocalize With D_{1}Rs in RPT Cells**

To confirm the potential for a direct or indirect interaction between gastrin (CCKBR) and D_{1}Rs, we studied the colocalization of gastrin (CCKBR) and D_{1}Rs in RPT cells from WKY rats. Immunofluorescence laser confocal microscopy showed that gastrin (CCKBR) and D_{1}Rs were found throughout the cell and, with evidence of colocalization, especially in the plasma membrane (Figure 4). To demonstrate the specificity of the antibodies for CCKBR and D_{1}Rs, these antibodies were preincubated with their corresponding immunizing peptides (1:10 wt/wt incubation for 12 hours). The staining for TRITC (tetramethyl rhodamine isothiocyanate)-tagged CCKBR (red) and fluorescein isothiocyanate–tagged D_{1}R (green) was no longer visible when the CCKBR antibody was incubated with the CCKBR immunizing peptide and the D_{1}R antibody was incubated with the D_{1}R immunizing peptide (Figure S5).

To determine whether there is a physical interaction between gastrin (CCKBR) and D_{1}Rs, a coimmunoprecipitation study was performed; gastrin receptors were first immunoprecipitated with anti-gastrin (CCKBR) receptor antibodies, and the immunoprecipitates were immunoblotted with anti-D_{1}R antibodies. The CCKBR/D_{1}R coimmunoprecipitation was increased with gastrin (10^{-9} \text{ mol/L} for 15 minutes) treatment in WKY RPT cells but not in SHR RPT cells; similar results were obtained after treatment with fenoldopam (Figure 5A and 5B).

**Discussion**

As indicated earlier, depending on the state of sodium balance, an oral NaCl load produces a stronger diuresis and natriuresis than an intravenous infusion of the same amount of NaCl.15,16 In addition to neural mechanisms, several gut hormones (eg, CCK, uroguanylin) have been proposed to mediate the natriuresis of an oral NaCl load.16–21 Although a high NaCl intake increases renal uroguanylin expression, it may not always increase circulating uroguanylin levels.16,17,33,34 Guca2b−/− mice have an impaired natriuretic response to an acute oral NaCl load, but blood pressure is only slightly increased and salt sensitivity is similar to that of Guca2b−/− mice.18 CCK is natriuretic,16,19 but circulating CCK levels are not increased by an oral NaCl load15 and CCK is not taken up by renal tubules.23

Food intake increases circulating gastrin levels 10-to 20-fold more than those of CCK,22 and all of the gut hormones tested, gastrin is taken up the most by RPTs;22 therefore, gastrin is a good candidate for the gastro-renal reflex. Furthermore, the oral intake of NaCl, without food, increases circulating gastrin levels (P.A. Jose PA et al, unpublished data, 2012). The gastrin receptor, CCKBR, is expressed in specific nephron segments, including the proximal tubule.16,21,24,25 Furthermore, gastrin is important for the excretion of an

Figure 4. Colocalization of cholecystokinin B receptor (CCKBR) and D_{1} receptor (D_{1}R) in Wistar-Kyoto renal proximal tubule cells. Colocalization appears as yellow after merging the images of fluorescein isothiocyanate–tagged D_{1}R (green) and TRITC (tetramethyl rhodamine isothiocyanate)-tagged CCKBR (red). No staining is seen without the antibodies (differential interference contrast [DIC]).
Consistent with previous reports, we found that renal D1-like receptors in the SHR are due, in part, to hyper- and SHRs. The impaired diuretic and natriuretic effects of gastrin in WKY rats and SHRs. However, in SHRs, the diuretic and natriuretic effects of gastrin, as well as its inhibitory effect on Na⁺-K⁺-ATPase activity, are lost. These results may, at first glance, be taken as contradictory to our previous report that the intrarenal infusion of sulfated CCK octapeptide produced a similar natriuretic and diuretic effect in WKY and SHRs. However, sulfated CCK octapeptide has a much greater affinity to CCKR than CCKR, whereas gastrin has a much greater affinity to CCKR than CCKR. Indeed, the natriuretic and diuretic effects of gastrin were blocked by the selective CCKR antagonist, CI-98826. Although CCKBR is expressed in the renal proximal tubule, CCKR is not.

In addition to gastrin, dopamine, a catecholamine produced endogenously by the renal proximal tubule, plays an important role in the regulation of sodium excretion and blood pressure. Several studies have shown that the natriuretic effect of dopamine is mainly exerted via D₁-like receptors. However, in SHRs, the diuretic and natriuretic effects of dopamine have been reported to positively interact with the D₁R, including aldosterone, insulin, and renin. Although several GPCRs and other hormones/humoral factors have been reported to positively interact with the D₁R in the regulation of sodium excretion, including atrial natriuretic peptide/ANP (atrial natriuretic peptide A), nitric oxide, and prolactin, the role of such interactions in hypertension has not been reported. Our present study found that CCKR is another GPCR that positively interacts with the D₁R in the regulation of sodium excretion. As indicated above, both gastrin and fenoldopam induced diuresis and natriuresis in WKY rats. However, in the presence of a CCKR antagonist, the fenoldopam-mediated diuresis and natriuresis are blocked and vice versa, that is, a D₁-like receptor antagonist blocks the diuretic and natriuretic effects of gastrin. However, whether Na⁺ balance and blood pressure regulation are the results of a net positive and negative interactions among D₁R, other dopamine receptor, and other GPCRs remain to be determined.

We also sought to elucidate the underlying mechanism regulating the interaction between renal CCKR and D₁-like receptors, specifically D₁R. We found that CCKR and D₁R colocalize and physically interact, proved by the coimmunoprecipitation study. Stimulation of one receptor increases the cellular distribution of the receptor into the cell membrane, that is, gastrin treatment increases D₁-like receptor expression in the cell membrane; fenoldopam increases CCKR in the cell membrane in WKY RPT cells. The RPT cell membrane targeting of D₁R and CCKR is physiologically relevant because blockade of D₁-like receptors or CCKR prevents the fenoldopam-mediated increase in RPT cell membrane D₁R and the gastrin-mediated inhibition of Na⁺-K⁺-ATPase activity and vice versa; blockade of CCKR blocks the inhibitory effect of fenoldopam on Na⁺-K⁺-ATPase activity. In SHR RPT cells, both the inhibitory effects of gastrin and fenoldopam on Na⁺-K⁺-ATPase activity are lost, and their synergism is no longer evident. Whether the synergistic inhibitory effect of CCKR and D₁R on sodium transport involves signaling mechanisms, in addition to direct protein/protein interaction, will be determined in the future.

In conclusion, we have demonstrated that gastrin, via CCKR, interacts with D₁-like receptors, specifically D₁R in the kidney, synergistically increasing water and sodium excretions, effects that are not observed in SHRs. An impaired interaction among GPCRs, CCKR, and D₁R, for instance, in the regulation of renal sodium excretion may be important for the pathogenesis of hypertension.

**Perspectives**

The intrarenal infusion of gastrin or fenoldopam induces diuresis and natriuresis; CCKR and D₁-like receptors synergistically increase sodium excretion in WKY rats. However, in SHRs, both the diuresis and natriuresis mediated by CCKR or D₁-like receptors are no longer observed. Previous studies
have shown that the D1R dysfunction in hypertensive states is because of the hyperphosphorylation and uncoupling of D1R from its G protein–effector complex, caused by increased constitutive activity of GPCR kinases 2 and 4.10,30,40–42 Whether GPCR kinases regulate CCK2R is not known. We hypothesize that GPCR kinases impair CCK2R receptor function, including the interaction between CCK2R and D1R, in SHRs, which need to be confirmed in the future.

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Disclosures

None.

References


### Novelty and Significance

**What Is New?**

- Cholecystokinin B receptor (CCKBR) and D_1_ receptor synergistically increase sodium excretion in Wistar-Kyoto rats. The natriuresis and diuresis mediated by CCKBR and its synergism with D_1_ receptors to increase sodium excretion are not observed in spontaneously hypertensive rats.

**What Is Relevant?**

- The impaired CCKBR and D_1_ receptor-mediated natriuretic and diuretic effects in the spontaneously hypertensive rat could be involved in the pathogenesis of hypertension.

### Summary

CCKBR and D_1_–like receptors synergistically increase sodium excretion. Aberrant interaction between the renal CCKBR and D_1_–like receptors (eg, D_1_ receptor) may play a role in the pathogenesis of hypertension.
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Gastrin and D₁ Dopamine Receptor Interact to Induce Natriuresis and Diuresis

Running title: Interaction of gastrin and dopamine receptors in kidney

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Expanded Materials and Methods

1. Animal Surgery

Male WKY and SHRs (SLRC Laboratory Animals, Shanghai, China), ranging in age from 9 to 16 weeks, fed a regular and normal sodium (0.4% NaCl) rat chow were used. Food but not water was withheld 24hrs before the study. Prior to the performance of the experiments, the rats were anesthetized with pentobarbital (50 mg/kg body wt, intraperitoneally), placed on a heated table to maintain rectal temperature between 36 and 37°, and tracheotomized (PE-240). Anesthesia was maintained by the infusion of pentobarbital sodium at 0.8 mg/100 g body wt per hr. Catheters (PE-50) were placed into the external jugular and femoral veins, for fluid replacement, and carotid artery, for monitoring systemic arterial pressure (Cardiomax II; Columbus Instruments, Columbus, OH, USA). A laparotomy was performed and both the right and left ureters were catheterized (PE-10). The right renal artery was exposed, and the right suprarenal artery, which originates from the right renal artery, was catheterized (PE-10 heat stretched to 180 um) for vehicle (saline) or drug infusion at a rate of 40 ul/h. The total duration of the surgical procedures was about 60 min. Fluid losses during surgery were replaced with 5% albumin in normal saline at 1% body weight over 30 min. After an equilibration period of 120 min, urine was collected every 40 min, five times, for clearance measurements. All studies were approved by the Daping Hospital Animal Care and Use Committee.

2. Studies on Renal Function In Vivo

2.1. Dose-response infusion: After a baseline period, the WKY and SHRs were infused, through the right suprarenal artery, with gastrin and fenoldopam at a dose of 0.1, 0.5, 1.0, and 10.0 mg/kg/min. Thereafter, the infusate was changed to the vehicle for the recovery period; each period lasted 40 min.

2.2. Single-dose infusion: The WKY rats were divided into 8 groups.

- Control Group. Normal saline (vehicle) was infused into the right suprarenal artery.
- Gastrin/Fenoldopam Group. Two baseline periods were obtained. Thereafter, gastrin and/or fenoldopam was infused (1.0 mg/kg/min) for two time periods, followed by one recovery period in which the drug infusion was stopped but the vehicle infusion was continued for another 40 min.
- CI-988/SCH23390 Group. CI-988 (1.0 mg/kg/min) or SCH223390 (0.4 mg/kg/min) was infused during the second period after one baseline period and continued for two periods followed by recovery in order to determine the effect of blockade of gastrin or D1-like receptors on basal renal function.
- Gastrin+CI-988/Fenoldopam+SCH23390 Group. To determine the specificity of the gastrin and fenoldopam effects, a CCKBR antagonist, CI-988, or D1-like receptor antagonist, SCH23390, was infused during the second baseline period, and then co-infused with gastrin or fenoldopam separately for two periods, followed by recovery.
- Gastrin+SCH23390/ Fenoldopam+CI-988 Group. To explore the interaction between D1-like and gastrin receptors, SCH23390 or CI-988 was infused during the second baseline period, and then co-infused with gastrin or fenoldopam separately for two periods, followed by recovery.

The rats were sacrificed by an overdose of pentobarbital (100 mg/kg body wt). Sodium and potassium concentrations in serum and urine samples were analyzed.
Urine flow, absolute and fractional sodium (U_{NaV}, FENa) and potassium (U_{K}V, FEK) excretions were calculated. 

3. Cell Culture

Immortalized RPT cells from microdissected S₁ segments of proximal tubules of 4- to 8-week old WKY and SHRs were cultured at 37 °C in 95% air/ 5% CO₂ atmosphere in DMEM/F-12 with transferrin (5 μg/ml), insulin (5 μg/ml), epidermal growth factor (10 ng/ml), dexamethasone (4 μg/ml), and FBS 5% in a 25 cm cell culture flask. For subculturing, cells were dissociated with 0.25% trypsin, split in 6-well plates or Petri dishes. Cells were made quiescent by incubation for 2 hrs in medium without FBS before the addition of drugs.

4. Na⁺-K⁺-ATPase Activity

Na⁺-K⁺-ATPase activity was determined as the rate of inorganic phosphate (Pi) released to the reaction medium by the hydrolysis of the ATP in the presence or absence of ouabain according to the method proposed by Atkinson et al. To prepare membranes for Na⁺-K⁺-ATPase activity assay, RPT cells, cultured in 6 well plates or 35 cm² petri-dishes, were washed twice with 5ml chilled phosphate-free buffer (physiological saline, 0.9% NaCl) and centrifuged at 3000 g for 5 min. The pellet (membrane fraction) was washed twice and then suspended in 500 μl 110mM Tris-HCl and 1μM EDTA (pH 7.5) on ice. Protein concentrations were determined by the Bradford assay (Bio-Rad Laboratories, Hercules, CA, USA) or the BCA assay (Pierce Protein Biology, Rockford, IL, USA), using bovine serum albumin (BSA) as standard. Aliquots of membrane fractions (100 μl each) were suspended in 1ml of reaction mixture A (pH 7.0) (0.75 M imidazole, 1 M NaCl, 0.1 M KCl, 0.1 M MgCl₂·6H₂O, 0.12 M sodium azide, 0.02 M Na₄EGTA and 1 M Tris-HCl) for total ATPase activity and reaction mixture B (pH 7.0) (0.75 M imidazole, 0.1 M MgCl₂·6H₂O, 0.12 M sodium azide, 0.02 M Na₄EGTA and 1 M Tris-HCl) with ouabain 10 mM (final volume=1ml) for ouabain-sensitive ATPase activity. Then they were preincubated for 5 min in water bath at 37 °C. The reaction was initiated by the addition of 160 μM ATP and terminated after 20 min of incubation at 37 °C by adding 50 μl of ice-cold 50% trichloroacetic acid solution. The tubes were transferred onto ice and kept for 5 min. To quantify the amount of phosphate produced, 1ml of coloring reagent (5% Fe₂SO₄ in 10% ammonium molybdate in 10 N H₂SO₄) was added and then centrifuged at 3000 g for 3 min after thorough mixing. The liberated inorganic phosphate (Pi) was determined by measuring the absorbance at 740 nm against a standard curve prepared from K₂HPO₄. Na⁺-K⁺-ATPase activity was measured as a function of liberated Pi. The total ATPase activity minus the ATPase activity in presence of ouabain (nonspecific) represents the specific Na⁺-K⁺-ATPase activity.

5. Cell Surface Protein Expression

Cultured RPT cells were starved in serum-free medium for 2 hr, and then treated with reagents at the indicated concentrations and durations of incubation. Surface membrane proteins were biotinylated by adding sulfo-NHS-LC-biotin (final concentration 250 μg/ml) into the medium 30 min before the end of the reagent treatment. The cells were washed 3 times with ice-cold phosphate-buffered saline (PBS), lysed with an ice-cold lysis buffer (PBS with 1% NP40, 0.5% sodium deoxycholate, 0.1% SDS, 1 mM EDTA, 1 mM EGTA, 1 mM PMSF, 10 μg/ml aprotinin, and 10 μg/ml leupeptin), sonicated, placed on ice for about 1 hr, and centrifuged at 16000 g for 30-45 min. The supernatant from the cell lysate was
immunoprecipitated with the polyclonal goat anti-rat D\textsubscript{1}R antibody (SC-31478, Santa Cruz Biotechnology, USA) or rabbit anti-rat CCK\textsubscript{B}R antibody (AP01421PU-N, Acris Antibodies, Germany), followed by immunoblotting. The membrane sheets were blocked with 5% milk overnight, washed with TBST buffer (1 M pH 7.4 Tris-HCl, 0.9 g NaCl and 100% Tween-20) for 3 times, and incubated with peroxidase-conjugated streptavidin (1:4000-1:5000 dilution, 30 min; Jackson ImmunoResearch Laboratory). The biotinylated protein bands were visualized by enhanced chemiluminescence (Western Blotting Detection Kit; Thermo Scientific, USA).

6. Immunofluorescence Confocal Microscopy of Double-Stained RPT Cells

RPT cells, grown on coverslips, were fixed with 4% paraformaldehyde (30 min), permeabilized with 0.05% Triton-100 in phosphate-buffered saline (20 min) and blocked with normal goat serum (1 hr). Reactions with antibodies were performed as described previously\textsuperscript{8,10}. The D\textsubscript{1}R was visualized using the goat anti-D\textsubscript{1}R antibody (1:25-1:50) followed by a fluorescein isothiocyanate (FITC); conjugated CCK\textsubscript{B}R (gastrin receptor) was visualized using the rabbit anti-CCK\textsubscript{B}R antibody (1:50-1:100), followed by a rhodamine (TRITC)-conjugated affinity-purified goat anti-rabbit secondary antibody (red; Molecular Probes). Cells on coverslips were mounted with the ProLong Antifade Kit (Molecular Probes). Immunofluorescence densities and images were acquired (Olympus AX70 laser confocal microscopy) at an excitation wavelength of 488 and 547 nm; emission was detected at 535 and 572 nm.

7. Immunoprecipitation

Immortalized RPT cells were incubated with vehicle, gastrin (10\textsuperscript{-9} M) or fenoldopam (10\textsuperscript{-7} M) for 15 min. The cells were lysed with ice-cold lysis buffer for 1 hr and centrifuged at 16000 g for 30-45 min. Equal amounts of lysates (5 ug protein/1 supernatant for RPT cells from both WKY and SHRs) were incubated with affinity-purified anti-CCK\textsubscript{B}R antibody (5 ug/ml) for 1 hr and protein G plus-agarose at 4 °C for overnight. The immunoprecipitates were pelleted and washed 3 times with PBS. The pellets were suspended in sample buffer, boiled for 10 min, and subjected to immunoblotting with the D\textsubscript{1}R antibody. The densities of the bands were quantified by densitometry using Quantiscan (Ferguson, MO, USA), as previously reported\textsuperscript{8,10}.

8. Materials

Rabbit anti-rat gastrin and goat anti-rat D\textsubscript{1}R antibodies were both purchased from Santa Cruz Biotechnology Inc. Gastrin (Gastrin I rat) was purchased from Sigma and fenoldopam (Fenoldopam hydrochloride; 1659) was purchased from Tocris Bioscience. Peroxidase-conjugated streptavidin was purchased from Jackson ImmunoResearch Laboratory, Inc (West Grove, PA, USA). Sulfo-NHS-LC-biotin was purchased from Thermo Scientific Inc. Other chemicals for various buffers were of the highest purity available and purchased either from Sigma or Gibco.
References


Supplemental Tables

Table S1. Effect of vehicle on blood pressure and renal function in the infused right kidney of WKY rats

<table>
<thead>
<tr>
<th>Group</th>
<th>Systolic BP (mmHg)</th>
<th>MAP (mmHg)</th>
<th>Diastolic BP (mmHg)</th>
<th>V (µl/min)</th>
<th>UNaV (nEq/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>132.80 ±4.09</td>
<td>106.13 ±3.31</td>
<td>92.80 ±2.95</td>
<td>4.82 ±0.15</td>
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<td>w/P</td>
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<td>92.80 ±3.90</td>
<td>5.12 ±0.52</td>
<td>398.27 ±74.56</td>
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<td>w/P</td>
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<td>105.13 ±5.00</td>
<td>91.80 ±4.82</td>
<td>5.36 ±0.65</td>
<td>387.47 ±73.28</td>
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<td>5.26 ±0.99</td>
<td>388.40 ±82.75</td>
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<td>134.80 ±4.09</td>
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<td>94.20 ±2.86</td>
<td>5.56 ±0.59</td>
<td>384.13 ±65.53</td>
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</tbody>
</table>

BP, blood pressure; MAP, mean arterial pressure; V, urine flow; UNaV, urine Na excretion; CTRL is the baseline period (vehicle [normal saline] infusion); periods w/P are the vehicle (normal saline) infusion periods, and recovery is the recovery period (vehicle [normal saline] infusion); WKY rat: Wistar–Kyoto rat (body wt 229 ± 10g, n=5).
Table S2. Effect of CI-988, a CCK$_{BR}$ antagonist, on blood pressure and renal function in the infused right kidney of WKY rats

<table>
<thead>
<tr>
<th>Group</th>
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<th>Systolic BP (mmHg)</th>
<th>MAP (mmHg)</th>
<th>Diastolic BP (mmHg)</th>
<th>V (µl/min)</th>
<th>UNaV (nEq/min)</th>
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</thead>
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<td>5.11±0.51</td>
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<td>95.40±3.65</td>
<td>4.90±0.37</td>
<td>216.20±18.74</td>
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<tr>
<td>1.0 CI</td>
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<td>137.00±6.52</td>
<td>109.13±4.29</td>
<td>95.20±3.63</td>
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<td>108.20±5.82</td>
<td>94.20±5.26</td>
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</table>

BP, blood pressure; MAP, mean arterial pressure; V, urine flow; UNaV, urine Na excretion; CTRL is the baseline period (vehicle infusion); the next three periods (1.0 CI) were infused with CI-988 (1.0mg/kg/min) only; recovery is the recovery period (vehicle [normal saline] infusion); WKY rat: Wistar–Kyoto rat (body wt 228 ± 6g, n=5). P =NS, repeated measures ANOVA, Holm-Sidak test.
Table S3. Effect of gastrin on blood pressure and renal function in the presence of CI-988 (CCK8R antagonist) in the infused right kidney of WKY rats

<table>
<thead>
<tr>
<th>Group</th>
<th>Index</th>
<th>Systolic BP (mmHg)</th>
<th>MAP (mmHg)</th>
<th>Diastolic BP (mmHg)</th>
<th>V (µl/min)</th>
<th>UNaV (nEq/min)</th>
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<td>123.80±9.65</td>
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<td>CI-988</td>
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<td>3.97±0.46</td>
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<td>127.40±12.66</td>
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<td>377.20±21.90</td>
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BP, blood pressure; MAP, mean arterial pressure; V, urine flow; UNaV, urine Na excretion; CTRL is the baseline period (vehicle [normal saline] infusion); the second period is CI-988 (1.0mg/kg/min) infusion only; the third and fourth periods (CI+G) are infused with the combination of CI-988 (1.0mg/kg/min) and gastrin (1.0 g/kg/min); recovery is the recovery period (vehicle [normal saline] infusion); WKY rat: Wistar–Kyoto rat (body wt 238 ± 8g, n=6). P = NS, repeated measures ANOVA, Holm-Sidak test.
Table S4. Effect of SCH23390, a D₁-like receptor antagonist, on blood pressure and renal function in the infused right kidney of WKY rats

<table>
<thead>
<tr>
<th>Group</th>
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<th>Systolic BP (mmHg)</th>
<th>MAP (mmHg)</th>
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<th>V (µl/min)</th>
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<td>Recovery</td>
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<td>124.80±2.28</td>
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BP, blood pressure; MAP, mean arterial pressure; V, urine flow; UNaV, urine Na excretion; CTRL is the baseline period (vehicle [normal saline] infusion); the next three periods were infused with SCH23390 (SCH, 0.4 g/kg/min) only; recovery is the recovery period (vehicle [normal saline] infusion); WKY rat: Wistar-Kyoto rat (body wt 288 ± 11g, n=5).  P=NS, repeated measures ANOVA, Holm-Sidak test.
Table S5. Effect of fenoldopam on blood pressure and renal function in the presence of SCH23390 in the infused right kidney of WKY rats

<table>
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<tr>
<th>Index Group</th>
<th>Systolic BP (mmHg)</th>
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<th>UNaV (nEq/min)</th>
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<tr>
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<td>3.18±0.22</td>
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BP, blood pressure; MAP, mean arterial pressure; V, urine flow; UNaV, urine Na excretion; CTRL is the baseline period (vehicle infusion); the second period is SCH23390 (SCH, 0.4 g/kg/min) infusion only; the next two periods are with the combination of SCH23390 (0.4 g/kg/min) and fenoldopam (F, 1.0 g/kg/min); recovery is the recovery period (vehicle [normal saline] infusion); WKY rat: Wistar–Kyoto rat (body wt 227 ± 12g, n=5). P=NS, repeated measures ANOVA, Holm-Sidak test.
Supplemental Figure Legends

Fig. S1A

Fig. S1B
Figure S1. Effect of gastrin on Na\(^+\)-K\(^+\)-ATPase activity in WKY rat RPT cells. (A) Concentration–response of Na\(^+\)-K\(^+\)-ATPase activity in WKY RPT cells incubated with gastrin (10\(^{-11}\)-10\(^{-8}\)M) for 15min (n = 4-6, *P<0.05 vs. control). (B) Time-course of gastrin (10\(^{-9}\)M)-mediated inhibition of Na\(^+\)-K\(^+\)-ATPase activity in WKY RPT cells (n=5, *P<0.05 vs. control (0 min)). (C) Differential effect of gastrin on Na\(^+\)-K\(^+\)-ATPase activity in WKY and SHR RPT cells. The cells were incubated with gastrin (10\(^{-9}\)M) or vehicle (dH\(_2\)O) for 15min (n=3, *P<0.05 vs. control, #P<0.05 vs. WKY rats). Results are expressed as mol inorganic phosphate released per mg protein per min (Factorial ANOVA, Holm-Sidak test).
**Figure S2.** Interaction between gastrin and D₁-like receptors on Na⁺-K⁺-ATPase activity in WKY rat RPT cells.

**A:** Effect of the fenoldopam (10⁻⁷M/15min) on Na⁺-K⁺-ATPase activity in the presence of D₁-like receptor antagonist (SCH23390, 10⁻⁶M/15min) or gastrin receptor (CCK₉R) antagonist (CI-988, 10⁻⁵M/15min) in RPT cells (n= 5-8, *P<0.05 vs. others). Results are expressed as mol inorganic phosphate released per mg protein per min (Factorial ANOVA, Holm-Sidak test).

**B:** Effect of the gastrin (gastrin, 10⁻⁹M/15min) on Na⁺-K⁺-ATPase activity in the presence of D₁-like receptor antagonist (SCH23390, 10⁻⁶M/15min) or gastrin receptor (CCK₉R) antagonist (CI-988, 10⁻⁵M/15min) in RPT cells (n= 4-7, *P<0.05 vs. others). Results are expressed as mol inorganic phosphate released per mg protein per min (Factorial ANOVA, Holm-Sidak test).
Figure S3. Effect of gastrin on cell surface membrane D₁R expression in RPT cells from WKY and SHRs.

A: Effect of gastrin on cell surface membrane D₁R expression in WKY RPT cells. RPT cells were incubated with gastrin (10⁻⁹M) for 15 or 30 min. Results are expressed as relative density units (DU) (n=3, *P<0.05 vs. others, factorial ANOVA, Holm-Sidak test).

B: Effect of gastrin on cell surface membrane D₁R expression in WKY RPT cells in the presence of CCKₐR or D₁-like receptor antagonist. RPT cells were incubated with gastrin (10⁻⁹M/15min) in the presence of CCKₐR antagonist, CI-988 (10⁻⁵M/15min) or D₁-like receptor antagonist, SCH23390 (10⁻⁶ M/15 min). Results are expressed as relative DU (n=4, *P<0.05 vs. others, factorial ANOVA, Holm-Sidak test).

C: Effect of gastrin (10⁻⁹M/15min) on cell surface membrane D₁R expression in RPT cells from WKY and SHRs. Results are expressed as relative DU (n=4, *P<0.05 vs. control, #P<0.05 vs. WKY, factorial ANOVA, Holm-Sidak test).
Fig. S4A

CCK<sub>8</sub>

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Fig. S4B

CCK<sub>8</sub>

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<th>Fenoldopam</th>
<th>SHR</th>
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</tbody>
</table>

![Graph showing relative density against KDa for different conditions](image)

**Relative Density % Area**

- **Control**
- **Fenoldopam**
**Figure S4.** Effect of fenoldopam on cell surface membrane CCK_{b}R expression in RPT cells from WKY and SHRs.

**A.** Effect of fenoldopam on cell surface membrane CCK_{b}R expression in WKY RPT cells in the presence of CCK_{b}R or D_{1}-like receptor antagonist. TRPT cells were treated with fenoldopam (10^{-7}M/15min) in the presence of CCK_{b}R antagonist, CI-988 (10^{-5}M/15min) or D_{1}-like receptor antagonist, SCH23390 (10^{-6}M/15 min). Results are expressed as relative DU (n=6, *P<0.05 vs. others, factorial ANOVA, Holm-Sidak test).

**B:** Effect of fenoldopam (10^{-7}M/15min) on cell surface membrane CCK_{b}R expression in RPT cells from WKY and SHRs. Results are expressed as relative DU (n=5, *P<0.05 vs. control, factorial ANOVA, Holm-Sidak test).
Figure S5. Specificity of CCKβR and D1R antibodies. After pre-absorption with their respective immunizing control peptides (1:10 w/w incubation for 12 hrs), the staining for TRITC-tagged CCKβR (red) and FITC-tagged D1R (green) were no longer visible in WKY RPT cells.