Aldosterone Requires Vasopressin V1a Receptors on Intercalated Cells to Mediate Acid-Base Homeostasis

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ABSTRACT

Both aldosterone and luminal vasopressin may contribute to the maintenance of acid-base homeostasis, but the functional relationship between these hormones is not well understood. The effects of luminal vasopressin likely result from its interaction with V1a receptors on the luminal membranes of intercalated cells in the collecting duct. Here, we found that mice lacking the V1a receptor exhibit type 4 renal tubular acidosis. The administration of the mineralocorticoid agonist fludrocortisone ameliorated the acidosis by restoring excretion of urinary ammonium via increased expression of Rhcg and H-K-ATPase and decreased expression of H-ATPase. In a cell line of intercalated cells established from transgenic rats expressing the mineralocorticoid and V1a receptors, but not V2 receptors, knockdown of the V1a receptor gene abrogated the effects of aldosterone on H-K-ATPase, Rhcg, and H-ATPase expression. These data suggest that defects in the vasopressin V1a receptor in intercalated cells can cause type 4 renal tubular acidosis and that the tubular effects of aldosterone depend on a functional V1a receptor in the intercalated cells.


Aldosterone and vasopressin regulates the acid-base balance by proton secretion through reabsorption of bicarbonate and the excretion of ammonium and titratable acid mainly in the collecting ducts.1–4 Principal and intercalated cells are present in the collecting ducts.1,2 Vasopressin regulates sodium and water transport via the V2 receptor (V2R) in the basolateral membrane of the principal cells and subsequent activation of aquaporin 2 and amiloride-sensitive epithelial sodium channel (ENaC), which is also regulated by aldosterone.3 Although vasopressin is known to act as an anti-diuretic hormone, findings regarding the effects of luminal (urinary) vasopressin have shown that luminal vasopressin acts as an intrinsic diuretic and regulates the anti-diuretic effects of basolateral vasopressin.6 The effect of luminal vasopressin has been thought to be caused via V1a receptor (V1aR), probably in the luminal membrane of the intercalated cells, given that V2R is not present in the luminal membrane of the collecting ducts.6–9 Al-
Table 1. Blood and urine parameters obtained under the basal, acid-load, and fludrocortisone-treated conditions

<table>
<thead>
<tr>
<th></th>
<th>Basal Condition</th>
<th>NH₄Cl Loading</th>
<th>Fludrocortisone</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>WT</td>
<td>V1aR⁻/⁻</td>
<td>WT</td>
</tr>
<tr>
<td>Blood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7.26 ± 0.01</td>
<td>7.28 ± 0.01</td>
<td>7.27 ± 0.05</td>
</tr>
<tr>
<td>Pco₂ (mmHg)</td>
<td>45.8 ± 1.0</td>
<td>39.6 ± 1.5b</td>
<td>39.8 ± 3.7</td>
</tr>
<tr>
<td>Po₂ (mmHg)</td>
<td>83.7 ± 2.6</td>
<td>98.2 ± 3.0b</td>
<td>84.0 ± 1.4</td>
</tr>
<tr>
<td>HCO₃⁻ (mmol/L)</td>
<td>20.4 ± 0.5</td>
<td>18.6 ± 0.6</td>
<td>18.5 ± 1.9</td>
</tr>
<tr>
<td>Na (mmol/L)</td>
<td>149.6 ± 0.6</td>
<td>150.6 ± 0.7</td>
<td>155.0 ± 0.6d</td>
</tr>
<tr>
<td>K (mmol/L)</td>
<td>3.79 ± 0.14</td>
<td>4.26 ± 0.14</td>
<td>3.57 ± 0.15</td>
</tr>
<tr>
<td>Cl (mmol/L)</td>
<td>111.3 ± 0.7</td>
<td>113.7 ± 1.1</td>
<td>120.7 ± 1.3a</td>
</tr>
<tr>
<td>Acid-base balance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>titratable acid (µEq/µg Cr)</td>
<td>0.11 ± 0.01</td>
<td>0.15 ± 0.01b</td>
<td>0.21 ± 0.01*</td>
</tr>
<tr>
<td>ammonium (µEq/µg Cr)</td>
<td>0.16 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>1.79 ± 0.13*</td>
</tr>
<tr>
<td>net acid excretion (µEq/µg Cr)</td>
<td>0.27 ± 0.01</td>
<td>0.28 ± 0.01</td>
<td>2.01 ± 0.14a</td>
</tr>
</tbody>
</table>

V1aR⁻/⁻ mice showed low plasma bicarbonate and Pco₂ levels in addition to an increased plasma potassium concentration, indicating the presence of type 4 renal tubular acidosis. The NH₄Cl load showed that V1aR⁻/⁻ mice have decreased ability to excrete urinary ammonium. Fludrocortisone ameliorated metabolic acidosis and hyperkalemia mainly by increasing the urinary excretion of ammonium in V1aR⁻/⁻ mice. Mean ± SEM. n = 6.

aP < 0.01 and bP < 0.05 versus wild-type or V1aR⁻/⁻ in the basal condition.
bP < 0.01 and P < 0.05 versus wild-type orV1aR⁻/⁻ in each condition.

Results

Type 4 Renal Tubular Acidosis in V1aR⁻/⁻ Mice

V1aR⁻/⁻ mice have been generated as previously reported.19–21 Analysis of arterial blood gases and urinary parameters in wild-type (WT) and V1aR⁻/⁻ mice under basal conditions showed no significant differences in the arterial pH values between WT and V1aR⁻/⁻ mice (Table 1). However, the blood HCO₃⁻ concentration and PCO₂ in V1aR⁻/⁻ mice were significantly lower than those in WT mice, indicating that V1aR⁻/⁻ mice undergo metabolic acidosis with respiratory compensation. Plasma K concentration was higher in V1aR⁻/⁻ mice, whereas the urinary pH in the basal condition was lower in V1aR⁻/⁻ mice than that observed in WT mice. Interestingly, the titratable acid excretion level was significantly larger and the amount of ammonium excretion was lower in V1aR⁻/⁻ mice compared with the WT mice. Thus, net acid excretion was not significantly different between WT and V1aR⁻/⁻ mice.

Stimulation of urinary acidification by the drinking of NH₄Cl showed a decrease in the urinary pH both in WT and V1aR⁻/⁻ mice, with lower urinary pH levels observed in V1aR⁻/⁻ mice (Figure 1). The increase in net acid excretion was significantly smaller in V1aR⁻/⁻ mice because of insufficient ammonium excretion. Interestingly, the blood HCO₃⁻ levels were remarkably lower in V1aR⁻/⁻ mice. These data, which were gleaned under basal and acid-loading conditions, show that V1aR⁻/⁻ mice are characterized by metabolic acidosis and hyperkalemia mainly as a consequence of low ammonium excretion, which is compatible with type 4 RTA. It is surprising that V1aR⁻/⁻ mice are susceptible to metabolic acidosis even with a superior ability to acidify its urine, suggesting a significant defect of urinary ammonium excretion.

Effects of Fludrocortisone on Acid-Base Balance in V1aR⁻/⁻ Mice

V1aR⁻/⁻ mice with type 4 RTA were treated with fludrocortisone. Although the urinary pH values in both WT and V1aR⁻/⁻ mice were increased, the increase in urinary pH in the V1aR⁻/⁻ mice was remarkably larger than the increase

though V1aR has been thought to perform an important role in acid excretion in the collecting ducts, the mechanisms and its interactions with aldosterone have not been elucidated.

Aldosterone regulates acid excretion by the intercalated cells where vacuolar H-ATPase, H-K-ATPase, Rhesus blood group C glycoprotein (Rhcg), anion exchanger 1 (AE1), and pendrin exist.1,2,10,11 Thus far, many functional defects of these transporters have been hypothesized to cause distal type or type 4 renal tubular acidosis. The NH₄Cl load showed that V1aR⁻/⁻ mice have decreased ability to excrete urinary ammonium. Fludrocortisone ameliorated metabolic acidosis and hyperkalemia mainly by increasing the urinary excretion of ammonium in V1aR⁻/⁻ mice.
observed in the WT mice (Table 1; Figure 1). The higher levels of excreted titratable acid in V1aR<sup>−/−</sup> mice under the basal condition became significantly lower after the treatment with fludrocortisone. Urinary ammonium excretion was significantly increased in the V1aR<sup>−/−</sup> mice. The net acid excretion of V1aR<sup>−/−</sup> mice was significantly higher than that of WT mice. Although the plasma HCO<sub>3</sub> concentration in V1aR<sup>−/−</sup> mice remained lower than that of WT mice, there were no significant differences in the blood pH, PCO<sub>2</sub>, PO<sub>2</sub>, and plasma K concentration between the WT and V1aR<sup>−/−</sup> mice. These data suggest that the effects of fludrocortisone on the acid-base balance are more pronounced in V1aR<sup>−/−</sup> mice than in WT mice, suggesting that aldosterone-induced acid excretion could be modulated by V1aR.

**Changes in Acid-Base–Related Transporters of V1aR<sup>−/−</sup> Mice after Administration of Fludrocortisone**

To examine the key transporters for the induction of type 4 RTA in V1aR<sup>−/−</sup> mice, Western blot analyses were performed. Notably, the expression of H-K-ATPase and Rhcg was significantly higher in V1aR<sup>−/−</sup> mice than in WT mice. Fludrocortisone decreased H-ATPase expression, whereas it increased H-K-ATPase, Rhcg, and AE1 expression in WT mice. The effects of fludrocortisone were smaller in V1aR<sup>−/−</sup> mice. (A) H-ATPase (116 kD), (B) H-K-ATPase (67 kD), (C) Rhcg (58 kD), (D) AE1 (96 kD), (E) pendrin (100 kD), and (F) β actin (42 kD). Expression of each transporter in sham of WT was considered as 1. *P < 0.05 and **P < 0.01 versus sham of the WT or V1aR<sup>−/−</sup>; ††P < 0.05 versus sham of the WT. Means ± SEM. n = 4 to 7.

**Figure 1.** The different effects of acid-load (A–D) and fludrocortisone (E–H) on urinary acid excretion in WT and V1aR<sup>−/−</sup> mice.

**Figure 2.** Smaller physiologic effects of fludrocortisone (flud) on acid-base–related transporters in the kidney of V1aR<sup>−/−</sup> mice. V1aR<sup>−/−</sup> mice showed higher expression levels of H-ATPase and lower expression levels of H-K-ATPase and Rhcg than WT mice. Fludrocortisone decreased H-ATPase expression, whereas it increased H-K-ATPase, Rhcg, and AE1 expression in WT mice. Effects of fludrocortisone were smaller in V1aR<sup>−/−</sup> mice. (A) H-ATPase (116 kD), (B) H-K-ATPase (67 kD), (C) Rhcg (58 kD), (D) AE1 (96 kD), (E) pendrin (100 kD), and (F) β actin (42 kD). Expression of each transporter in sham of WT was considered as 1. *P < 0.05 and **P < 0.01 versus sham of the WT or V1aR<sup>−/−</sup>; ††P < 0.05 versus sham of the WT. Means ± SEM. n = 4 to 7.
V1aR−/− mice; however, this decrease was less pronounced in V1aR−/− mice than in WT mice. These data suggest that the lower urine pH in V1aR−/− mice is dependent on the upregulation of H-ATPase, given that urinary acidification by intercalated cells is dependent on H-ATPase and H-K-ATPase. AE1 expression was increased by treatment with fludrocortisone larger in WT than V1aR KO mice. The expression levels of pendrin were not significantly different between WT and V1aR−/− mice.

Knockdown of V1aR by RNA Interference (RNAi) in an Intercalated Cell Line

To further examine the role of V1aR in acid secretion by the intercalated cells, a cell line of intercalated cells (IN-IC cells) was established from transgenic rats expressing a temperature-sensitive SV40 large T antigen. RT-PCR and real-time PCR analysis showed the presence of mineralocorticoid receptor, 11β hydroxysteroid dehydrogenase type 2, V1aR, H-ATPase H-K-ATPase, Rhcg, AE1, and pendrin, although the presence of V2R, aquaporin 2, and ENaC was not identified, which is compatible with the characteristics of intercalated cells (Figure 3). Knockdown of V1aR by siRNA caused a reduction in the level of V1aR mRNA by 70 and 80% after 2 and 6 days, respectively (Supplemental Figure 1). To examine the relationship between aldosterone and vasopressin, effects of aldosterone and vasopressin on V1aR mRNA expression was examined. Aldosterone and vasopressin decreased V1aR mRNA expression (Figure 3). To confirm the participation of V1aR in the regulation of these transporters, the IN-IC cells were incubated for 24 hours with vasopressin (10−9 and 10−7 M) at 48 hours after the induction of V1aR knockdown. Interestingly, vasopressin did not cause any change in the expression of AE1 and pendrin (Figure 4). In contrast, vasopressin increased the expression of H-ATPase, H-K-ATPase, and Rhcg (Figure 4). Although changes in the expression by vasopressin were small, our data showed that H-ATPase, H-K-ATPase, and Rhcg are all V1aR-sensitive and that AE1 and pendrin are V1aR insensitive.
Finally, to examine the effects of aldosterone on acid-base–related transporters, IN-IC cells were incubated with aldosterone (10^{-10}, 10^{-8}, and 10^{-6} M) for 24 hours after the knockdown of V1aR. Notably, the administration of aldosterone significantly increased the expression of Rhcg and H-K-ATPase and largely decreased the abundance of H-ATPase in intact IN-IC cells (Figure 5). Knockdown of the V1aR gene almost inhibited the effects of aldosterone on H-ATPase, H-K-ATPase, and Rhcg. Although aldosterone slightly increased AE1 expression, knockdown of V1aR resulted in no changes in AE1 expression (Figure 5). Pendrin expression was not altered with aldosterone. These data confirm that, among the aldosterone-related transporters, H-ATPase, H-K-ATPase, and Rhcg are vasopressin-sensitive transporters and AE1 and pendrin are vasopressin-insensitive transporters.

**DISCUSSION**

Our findings indicate that deficiency of V1aR causes type 4 RTA. Many potential mechanisms have been proposed to be
responsible for distal and type 4 RTA. However, no previous reports have focused on the role of V1aR as a causative factor in type 4 RTA. Previously, we showed that the stimulation of V1aR in the macula densa is the first step of renin production and the deficient of V1aR in macula densa causes hyporeninemic hypoaldosteronism. This study shows that the defect in urinary acid excretion in V1aR mice is associated with functional defects in the vasopressin V1aR and subsequent changes in Rhcg, H-K-ATPase, and H-ATPase in the intercalated cells of the collecting ducts. Therefore, V1aR is essential not only for aldosterone production but also for tubular effects of aldosterone. It is interesting that H-K-ATPase is localized to the macula densa and the collecting ducts.

An important characteristic of type 4 RTA is low urinary pH. According to the theory of nonionic diffusion of ammonia in the collecting ducts, low urinary pH should stimulate ammonia secretion. This theory has been accepted for many years, but it has been questioned by findings related to Rhcg. Urinary ammonium excretion has been shown to be mainly mediated by Rhcg as ammonia and not as ammonium. We found that low urinary pH in type 4 RTA is associated with the activation of H-ATPase and that low urinary ammonium excretion is caused by the decreased levels of Rhcg. Both changes are caused by the functional defect in V1aR, which mediates tubular effects of aldosterone. We classified aldosterone-related transporters into vasopressin-sensitive and -insensitive ones. H-ATPase, H-K-ATPase, and Rhcg are vasopressin-sensitive transporters and AE1 and pendrin are vasopressin-insensitive ones. Such a classification will be very useful for further studies of aldosterone.

Our study is the first to assess stimulation of V1aR specifically in intercalated cells. The direct effect of vasopressin on H-ATPase, H-K-ATPase, and Rhcg confirmed the participation of V1aR in the regulation of these acid-base-related transporters given that IN-IC cells do not express V2R. The mineralocorticoid receptor is thought to be localized in the principal cells and non-type A intercalated cells but not in type A intercalated cells in rabbit cortical collecting ducts, suggesting that aldosterone stimulates the mineralocorticoid receptor in the principal cells and indirectly affects transporters in the intercalated cells. Our findings of the presence of the mineralocorticoid receptor and 11beta-hydroxysteroid dehydrogenase type 2 in the intercalated cells clearly suggest that aldosterone directly stimulates expression of the mineralocorticoid receptor in the intercalated cells. Vasopressin and aldosterone are thought to regulate the transporters from different sides of the cell (Figure 6). Accumulated and current evidence suggests that V1aR regulates both the osmo-regulatory V2R–aquaporin 2 system and the volume-regulatory renin–angiotensin–aldosterone system (RAS). The mechanisms for the regulation of the acid-base–related transporters by V1aR require further examination.

Our findings have many clinical implications. Thus far, type 4 RTA is frequently seen in patients with diabetic nephropathy and has been treated by administering sodium bicarbonate or fludrocortisone. V1aR agonists may promote aldosterone modulation of intercalated cells and can serve as a candidate for alternative therapy, if V1aR in only the intercalated cells but not in the blood vessels can be stimulated in future. RAS blockers have been used for the treatment of patients with chronic renal and heart failure. Because V1aR antagonists can block both the RAS and the V2R-aquaporin 2 system, V1aR antagonists may become a new type of RAS inhibitor.

These data showed that the lack of V1aR in the intercalated cells blocks the effects of aldosterone on urinary acid excretion, finally resulting in type 4 RTA. In conclusion, aldosterone requires V1aR for its tubular effects in the intercalated cells.

CONCISE METHODS

Animal Experiments
All experiments were approved by the Committee for Animal Experimentation at the Kumamoto University Graduate School of Medical Sciences (19-063 and 20-219) and Hyogo College of Medicine (28036).
Arterial blood gases were taken from the abdominal aorta of mice anesthetized with sodium pentobarbital (65 mg/kg, intraperitoneally). Blood pH, Pco2, Po2, and HCO3− were analyzed using an i-STAT Portable Clinical Analyzer 200 (i-STAT). Plasma Na, K, and Cl concentrations were measured at the SRL Laboratory (Tokyo, Japan).

Urinary pH was measured using a HORIBA pH Meter F-21 (HORIBA, Kyoto, Japan). The ammonia concentration in the urine was examined using an Ammonia Assay Kit (Sigma-Aldrich, St. Louis, MO). The amount of titratable acid was determined by the addition of 1 N NaOH to the urine. The amount of 1 N NaOH required to titrate the urine to pH 7.4 was recorded. The net acid excretion was calculated as a sum of ammonia and titratable acid and was corrected by the ratio to urinary creatinine concentration.

To estimate the level of urinary acidification, WT and V1aR mice maintained in metabolic cages were given free access to 0.28 M NH4Cl for 3 days or intraperitoneal injection of fludrocortisone (25 mg/kg per day; Sigma-Aldrich) for 3 days.

Cell Line Experiments

The new rat intercalated cell line was established from the outer medulla of the kidney of a tsA58 transgenic rat that ubiquitously expressed the temperature-sensitive large T-antigen gene of Simian Virus 40 (SV40; FACT, Sendai, Japan). The slice of the outer medulla was incubated in DMEM/F12 medium (Life Technologies), 10% FBS, 10 µg/ml transferin, 1 µg/ml insulin, 10 ng/ml EGF, 0.5 µg/ml hydrocortisone, 6.5 ng/ml Triiodo-Tyronine, and 1% penicillin/streptomycin. The proliferated cell population was cloned using a cloning cylinder as described in the Supplemental Methods.

The characteristics of the new cell line were examined by RT-PCR using the following primers (29,30, and via Primer Blast); GAPDH, 5′-CCCTGAGTACG-3′ and 5′-AGACATCGCGAAACGCCGCA-3′, 540 bp in length; H-K-ATPase and 5′-AGGGATGGATCTCCAGGACT-3′, 380 bp in length; 11β-hydroxysteroid dehydrogenase type 2, 5′-GCAGTTCCAGCTAGGACCG-3′ and 5′-TTGGTCTCGTGGGCT-3′, 361 bp in length; (sense and antisense primer, and the size of PCR product, respectively). For the control of RT-PCR, renal medulla from Sprague-Dawley rats was prepared. The expression levels of V1aR and 18S (internal control) were examined by real-time PCR using primers supplied by Applied Biosystems (Rn00583910-m1 and Hs99999901-s1, respectively).

The knockdown of the V1aR gene was performed in the same buffer containing 10% FBS, 80 nM oligofectamine, and 10 nM siRNA or a negative control siRNA (S128995–7 and 4390843, respectively; Applied Biosystems). To examine the effects of aldosterone or vasopressin, aldosterone or vasopressin was added, and the cells were incubated for an additional 24 hours.

Statistical Analysis

Statistical analysis was performed using paired and unpaired t tests, Wilcoxon signed-rank tests, or ANOVA with multiple comparison of Dunnet or Scheffe. Dr-SPSS-II (SPSS) was used for the analysis.

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