Enhanced passive Ca\textsuperscript{2+} reabsorption and reduced Mg\textsuperscript{2+} channel abundance explains thiazide-induced hypocalciuria and hypomagnesemia

Tom Nijenhuis, …, Joost G.J. Hoenderop, René J.M. Bindels


Thiazide diuretics enhance renal Na\textsuperscript{+} excretion by blocking the Na\textsuperscript{+}-Cl\textsuperscript{–} cotransporter (NCC), and mutations in NCC result in Gitelman syndrome. The mechanisms underlying the accompanying hypocalciuria and hypomagnesemia remain debated. Here, we show that enhanced passive Ca\textsuperscript{2+} transport in the proximal tubule rather than active Ca\textsuperscript{2+} transport in distal convolution explains thiazide-induced hypocalciuria. First, micropuncture experiments in mice demonstrated increased reabsorption of Na\textsuperscript{+} and Ca\textsuperscript{2+} in the proximal tubule during chronic hydrochlorothiazide (HCTZ) treatment, whereas Ca\textsuperscript{2+} reabsorption in distal convolution appeared unaffected. Second, HCTZ administration still induced hypocalciuria in transient receptor potential channel subfamily V, member 5–knockout (Trpv5-knockout) mice, in which active distal Ca\textsuperscript{2+} reabsorption is abolished due to inactivation of the epithelial Ca\textsuperscript{2+} channel Trpv5. Third, HCTZ upregulated the Na\textsuperscript{+}/H\textsuperscript{+} exchanger, responsible for the majority of Na\textsuperscript{+} and, consequently, Ca\textsuperscript{2+} reabsorption in the proximal tubule, while the expression of proteins involved in active Ca\textsuperscript{2+} transport was unaltered. Fourth, experiments addressing the time-dependent effect of a single dose of HCTZ showed that the development of hypocalciuria parallels a compensatory increase in Na\textsuperscript{+} reabsorption secondary to an initial natriuresis. Hypomagnesemia developed during chronic HCTZ administration and in NCC-knockout mice, an animal model of Gitelman syndrome, accompanied by downregulation of the epithelial Mo\textsuperscript{2+} channel transient receptor potential

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Tom Nijenhuis, Volker Vallon, Annemietje W.C.M. van der Kemp, Johannes Loffing, Joost G.J. Hoenderop, and René J.M. Bindels

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Thiazide diuretics enhance renal Na\textsuperscript{+} excretion by blocking the Na\textsuperscript{+}-Cl\textsuperscript{−} cotransporter (NCC), and mutations in NCC result in Gitelman syndrome. The mechanisms underlying the accompanying hypocalciuria and hypomagnesemia remain debated. Here, we show that enhanced passive Ca\textsuperscript{2+} transport in the proximal tubule rather than active Ca\textsuperscript{2+} transport in distal convolution explains thiazide-induced hypocalciuria. First, micropuncture experiments in mice demonstrated increased reabsorption of Na\textsuperscript{+} and Ca\textsuperscript{2+} in the proximal tubule during chronic hydrochlorothiazide (HCTZ) treatment, whereas Ca\textsuperscript{2+} reabsorption in distal convolution appeared unaffected. Second, HCTZ administration still induced hypocalciuria in transient receptor potential channel subfamily V, member 5–knockout (Trpv5-knockout) mice, in which active distal Ca\textsuperscript{2+} reabsorption is abolished due to inactivation of the epithelial Ca\textsuperscript{2+} channel Trpv5. Third, HCTZ upregulated the Na\textsuperscript{+}/H\textsuperscript{+} exchanger, responsible for the majority of Na\textsuperscript{+} and, consequently, Ca\textsuperscript{2+} reabsorption in the proximal tubule, while the expression of proteins involved in active Ca\textsuperscript{2+} transport was unaltered. Fourth, experiments addressing the time-dependent effect of a single dose of HCTZ showed that the development of hypocalciuria parallels a compensatory increase in Na\textsuperscript{+} reabsorption secondary to an initial natriuresis. Hypomagnesemia developed during chronic HCTZ administration and in NCC-knockout mice, an animal model of Gitelman syndrome, accompanied by downregulation of the epithelial Mg\textsuperscript{2+} channel transient receptor potential channel subfamily M, member 6 (Trpm6). Thus, Trpm6 downregulation may represent a general mechanism involved in the pathogenesis of hypomagnesemia accompanying NCC inhibition or inactivation.

Introduction
Thiazide diuretics are among the most commonly prescribed drugs, particularly in the treatment of arterial hypertension. These diuretics enhance renal Na\textsuperscript{+} excretion through inhibition of the Na\textsuperscript{+}-Cl\textsuperscript{−} cotransporter (NCC) present in the apical membrane of distal convoluted tubule (DCT) cells (1). In addition, these drugs are known to affect the Ca\textsuperscript{2+} and Mg\textsuperscript{2+} balance, inducing hypocalciuria and hypomagnesemia, respectively (2–7). Consequently, thiazides are frequently used in the treatment of idiopathic hypercalciuria and hypomagnesemia, disorders with a high incidence and socioeconomic burden in Western society (8–10). Furthermore, mutations in the gene encoding NCC have been shown to cause Gitelman syndrome, a recessive disorder with a phenotype that resembles the effects of chronic thiazide administration characterized by hypocalciuria, renal Mg\textsuperscript{2+} wasting, and hypomagnesemia (4, 6, 11, 12). Intriguingly, the molecular mechanisms responsible for the hypocalciuria and hypomagnesemia during thiazide administration and Gitelman syndrome remain elusive.

Two hypotheses prevail with respect to the Ca\textsuperscript{2+}-sparing effect of thiazides (2, 4, 5, 13). First, renal salt and water loss due to thiazide treatment result in contraction of the extracellular volume (ECV), which triggers a compensatory increase in proximal Na\textsuperscript{+} reabsorption. This would in turn enhance the electrochemical gradient, driving passive Ca\textsuperscript{2+} transport in the proximal tubule (1, 14). According to this line of reasoning, thiazide-induced hypocalciuria results from enhancement of passive paracellular Ca\textsuperscript{2+} reabsorption secondary to ECV contraction (2, 4, 7, 15). Second, microperfusion experiments suggested that acute administration of thiazides in the tubular lumen stimulates Ca\textsuperscript{2+} reabsorption in the distal convolution accessible to micropuncture (3). These accessible segments primarily consist of distal aspects of NCC–expressing DCT (DCT2) as well as low- or non-NCC–expressing connecting tubule (CNT). Subsequently, several molecular mechanisms were postulated to explain this latter stimulatory effect (2, 4, 5, 16). These include hyperpolarization of the luminal plasma membrane and/or enhanced basolateral Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange due to a decreased intracellular Na\textsuperscript{+} concentration, both of which may increase apical Ca\textsuperscript{2+} entry through the epithelial Ca\textsuperscript{2+} channel transient receptor potential channel subfamily V, member 5 (Trpv5),
the expression of which is restricted to DCT2 and the CNT (15–19). Similar mechanisms were proposed to explain the hypo-
calciuria in Gitelman syndrome (4, 5).

Hypomagnesemia has been suggested to result from K+ defi-
ciency, increased passive Mg2+ secretion, or decreased active Mg2+
transport in the DCT (5, 6, 20). However, experimental evidence for
either hypothesis is lacking. Studies have been seriously hampered
by the fact that the exact mechanism responsible for active Mg2+
reabsorption has not been identified. Transient receptor potential
channel subfamily M, member 6 (Trpm6) was recently identified as
a Mg2+-permeable channel predominantly expressed along the
apical membrane of the DCT (21–23). Mutations in Trpm6 were
shown to cause autosomal recessive hypomagnesemia, character-
ized by inappropriately high fractional Mg2+ excretion rates and
disturbed intestinal Mg2+ absorption (21, 22). This clearly sug-
gested that Trpm6 constitutes the apical entry step in active Mg2+
(re)absorption and provides an important new tool for studying
this process on a molecular level.

Recently, transgenic mouse models were developed that might
offer new insights into the pathogenesis of hypocaliuria and hypo-
magnesemia during thiazide treatment and in Gitelman syndrome.
We generated Trpv5-knockout (Trpv5–/–) mice by ablation of the
Trpv5 gene (24). These mice showed robust renal Ca2+ wasting, and
micropuncture experiments illustrated that active Ca2+
reabsorption in distal convolution is effectively abolished.
Thus, Trpv5–/– mice constitute a unique mouse model that can be used to unravel the relative contribution of passive and active Ca2+
reabsorption in thiazide-induced hypocaliuria. Furthermore, Schultheis et al. generated NCC-knockout (NCC–/–) mice exhibiting both hypo-
caliuria and hypomagnesemia, which represent a valuable
animal model that mimics Gitelman syndrome (25).

The aim of the present study was to elucidate the molecular mechanisms responsible for hypocaliuria and hypomagnesemia accompanying NCC inactivation. The effect of chronic hydrochlorothiazide (HCTZ) treat-
ment and the time-dependent effect of a single dose of
HCTZ on urinary Ca2+ and Mg2+ excretion was evaluated in wild-type and Trpv5–/– mice. Tubular Na+ and Ca2+
handling was assessed by in vivo free-flow micropunc-
ture experiments in control and HCTZ-treated wild-type
mice. In addition, an extensive evaluation of the renal expression level of Na+, Ca2+, and Mg2+ trans-
port proteins was performed in vehicle and HCTZ-
treated wild-type and Trpv5–/– mice. Moreover, the renal expression of the epithelial Mg2+ channel
Trpm6 was assessed in NCC–/– mice.

Results
Metabolic studies in HCTZ-treated Trpv5+/+ and Trpv5–/– mice. The metabolic data obtained during chronic
administration of HCTZ (25 mg/kg/d during 6
days) in Trpv5+/+ and Trpv5–/– mice are shown in
Table 1 and 2. Genetic ablation of Trpv5 in mice
resulted in a calcification that was about 6-fold higher
than in Trpv5+/+ mice (Table 1) (24). Important-
ly, HCTZ treatment significantly decreased urinary Ca2+
excretion in Trpv5–/– as well as Trpv5+/+ mice. Serum Ca2+ levels were not affected by HCTZ in
Trpv5–/– mice but significantly increased in Trpv5+/+
mice. In addition, HCTZ treatment significantly enhanced urinary Mg2+ excretion in Trpv5–/– mice. Serum Mg2+ levels were signifi-
cantly reduced in HCTZ-treated wild-type mice. Urine volume was
increased by HCTZ treatment in the Trpv5–/– mice, whereas diure-
sis in HCTZ-treated Trpv5+/+ mice did not differ from that in non-
treated controls. Furthermore, overall Na+ excretion was unaltered
by chronic HCTZ treatment in wild-type as well as Trpv5–/– mice, and GFR was not affected, as shown by the creatinine clearance
(CCr). HCTZ treatment significantly decreased endogenous lithi-
um clearance (Ci), an inverse measure of proximal tubular Na+
reabsorption and, thereby, passive paracellular Ca2+ transport in
the proximal tubule. Urinary pH was not affected by HCTZ treat-
ment in wild-type mice, whereas HCTZ neutralized the acidic uri-
inary pH in Trpv5–/– mice. HCTZ significantly increased hematocrit in
Trpv5+/+ and Trpv5–/– mice, and body weight was reduced com-
pared with their respective controls (Table 2). Serum Na+, K+, and
creatinine levels were not influenced by HCTZ treatment.

Renal mRNA and protein expression of Ca2+, Mg2+, and Na+ transport-
ers. Ca2+, Mg2+, and Na+ transport protein mRNA expression levels were determined by real-time quantitative PCR analysis, and protein
abundance was determined by immunohistochemistry (Figures 1 and
2). HCTZ did not affect the mRNA expression levels of the api-
cally localized epithelial Ca2+ channel Trpv5 in wild-type mice (Figure

<table>
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<th>HCTZ</th>
<th>Trpv5–/– Controls</th>
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<td>Urine volume (ml/24 h)</td>
<td>5.2 ± 0.9</td>
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<td>Ca2+ excretion (μmol/24 h)</td>
<td>41 ± 2</td>
<td>34 ± 2A</td>
<td>273 ± 10</td>
<td>169 ± 13A</td>
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<td>Ca2+/creatinine</td>
<td>0.29 ± 0.02</td>
<td>0.15 ± 0.02A</td>
<td>1.96 ± 0.06</td>
<td>1.17 ± 0.14A</td>
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<td>Mg2+ excretion (μmol/24 h)</td>
<td>26 ± 14</td>
<td>85 ± 8B</td>
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<td>Mg2+/creatinine</td>
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<td>Na+ excretion (μmol/24 h)</td>
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<td>Urinary pH</td>
<td>7.1 ± 0.1</td>
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<td>C0 (μl/min)</td>
<td>0.24 ± 0.04</td>
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<td>0.27 ± 0.01</td>
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<td>C1 (μl/min)</td>
<td>13.5 ± 0.6</td>
<td>9.8 ± 0.2A</td>
<td>13.9 ± 0.7</td>
<td>10.1 ± 0.5A</td>
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Controls, animals receiving vehicle only; HCTZ, animals receiving 25 mg/kg/d HCTZ; nd, not determined. Data are presented as mean ± SEM. A < 0.05 versus vehicle-treated Trpv5+/+. The Journal of Clinical Investigation

<table>
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<td><strong>Serum analysis and body weight of vehicle and HCTZ-treated Trpv5+/+ and Trpv5–/– mice</strong></td>
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<th>HCTZ</th>
<th>Trpv5–/– Controls</th>
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<td>[Ca+] (mmol/l)</td>
<td>2.47 ± 0.01</td>
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<td>[Mg+] (mmol/l)</td>
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<td>[Na+] (mmol/l)</td>
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<td>104 ± 3</td>
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<td>[K+] (mmol/l)</td>
<td>34 ± 1</td>
<td>36 ± 1</td>
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<td>[Creatinine] (μmol/l)</td>
<td>52 ± 1</td>
<td>57 ± 1A</td>
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<td>Hematocrit (%)</td>
<td>1.0 ± 0.1</td>
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<td>0.7 ± 0.2A</td>
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Data are presented as mean ± SEM. A < 0.05 versus vehicle-treated Trpv5+/+.
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1A), nor did it affect Trpv5 protein levels in the DCT and CNT (Figure 2A). Renal mRNA and protein levels of the cytosolic Ca\(^{2+}\)-binding protein calbindin-D\(_{28K}\) were significantly decreased in Trpv5\(^{-/-}\) mice compared with their wild-type littermates (Figure 1B and Figure 2B). Likewise, mRNA expression of the basolateral Na\(^{+}/Ca^{2+}\) exchanger 1 (NCX1) was reduced in these mice. However, HCTZ administration did not significantly alter calbindin-D\(_{28K}\) and NCX1 expression in both Trpv5\(^{+/+}\) and Trpv5\(^{-/-}\) mice (Figure 1, B and C, and Figure 2B). This unaffected calbindin-D\(_{28K}\) protein expression was confirmed by semiquantitative immunoblotting (89% ± 11% and 106% ± 11% of nontreated Trpv5\(^{+/+}\) and Trpv5\(^{-/-}\) controls, respectively).

In general, passive Ca\(^{2+}\) reabsorption is driven by the electrochemical gradient generated by transcellular Na\(^{+}\) transport. Therefore, we determined Na\(^{+}/H^{+}\) exchanger (NHE3) and Na\(^{+}-K^{+}-2Cl^{-}\) cotransporter (NKCC2) expression as indirect measures of passive paracellular Ca\(^{2+}\) transport in the proximal tubule and thick ascending limb of Henle (TAL), respectively. In accordance with the decreased CL\(_{i}\), proximal tubular NHE3 protein expression was significantly increased in HCTZ-treated Trpv5\(^{+/+}\) and Trpv5\(^{-/-}\) mice (Figure 2D). In contrast, the level of renal NKCC2 mRNA expression, which is exclusively expressed in TAL, was not affected by HCTZ treatment (Figure 1D).

**Figure 1**
Effect of chronic HCTZ treatment on renal mRNA expression levels of Ca\(^{2+}\) and Na\(^{+}\) transport proteins in Trpv5\(^{+/+}\) and Trpv5\(^{-/-}\) mice. Renal mRNA expression levels of the epithelial Ca\(^{2+}\) channel Trpv5 (A), calbindin-D\(_{28K}\) (B), NCX1 (C), and NKCC2 (D) were determined by real-time quantitative PCR analysis and are depicted as the ratio to hypoxanthine-guanine phosphoribosyl transferase (HPRT). Black bars, vehicle-treated; white bars, HCTZ-treated, 25 mg/kg/d during 6 days. n = 9 animals per treatment group. Data are presented as mean ± SEM. \(*P < 0.05 \) versus vehicle-treated Trpv5\(^{+/+}\).

**Figure 2**
Effect of chronic HCTZ treatment on renal protein abundance of Ca\(^{2+}\) and Na\(^{+}\) transport proteins in Trpv5\(^{+/+}\) and Trpv5\(^{-/-}\) mice. Protein abundance was determined by computerized analysis of immunohistochemical images and is presented as integrated optical density (IOD; AU) for the epithelial Ca\(^{2+}\) channel Trpv5 (A), calbindin-D\(_{28K}\) (B), NCC (C), and NHE3 (D). Black bars, vehicle-treated (CTR); white bars, HCTZ-treated, 25 mg/kg/d during 6 days; \(+/-\) CTR and \(+/-\) HCTZ, vehicle- and HCTZ-treated Trpv5\(^{+/+}\) mice, respectively; \(-/-\) CTR and \(-/-\) HCTZ, vehicle- and HCTZ-treated Trpv5\(^{-/-}\) mice, respectively. n = 9 animals per treatment group. Data are presented as mean ± SEM. \(*P < 0.05 \) versus respective vehicle-treated controls; \(#P < 0.05 \) versus vehicle-treated Trpv5\(^{+/+}\).
Interestingly, HCTZ treatment significantly reduced mRNA expression and protein abundance of the epithelial Mg$^{2+}$ channel Trpm6 in wild-type mice (Figure 3, A and B). To confirm the viability of the DCT and thereby the specificity of the Trpm6 downregulation, we determined NCC protein expression by immunohistochemical analysis (Figure 2C). NCC protein abundance was significantly increased in HCTZ-treated Trpv5$^{-/-}$ and Trpv5$^{+/-}$ mice. This was confirmed by semiquantitative immunoblotting (153% ± 20% and 143% ± 11% of nontreated Trpv5$^{-/-}$ and Trpv5$^{+/-}$ controls, respectively). Of note, deleterious effects or apoptotic alterations in the DCT were not detected by immunohistochemical or light microscopical analysis of HCTZ-treated mice as reported previously (7, 26).

Renal expression of the epithelial Mg$^{2+}$ channel Trpm6 in NCC$^{-/-}$ mice. Mice lacking NCC display a phenotype similar to the effects of chronic thiazide administration, including hypocaliuria and hypomagnesemia (25). Therefore, the renal expression of Trpm6 was determined in NCC$^{+/-}$ and NCC$^{-/-}$ mice. Renal Trpm6 mRNA expression was significantly reduced in NCC$^{-/-}$ mice (Figure 4A). Furthermore, immunohistochemical analysis revealed that Trpm6 protein abundance along the apical membrane of the DCT is profoundly decreased in these mice (Figure 4B).

Time-dependent effect of a single dose of HCTZ in wild-type and Trpv5$^{-/-}$ mice. To further evaluate the time-dependent effect of thiazides on Na$^{+}$, Ca$^{2+}$, and Mg$^{2+}$ excretion and their interdependency, additional metabolic cage experiments were performed. Figure 5 summarizes the effect of a single dose of HCTZ on Na$^{+}$ and Ca$^{2+}$ excretion 6, 12, and 24 hours after administration. During the first 6 hours after HCTZ administration, Na$^{+}$ excretion was significantly increased in Trpv5$^{+/-}$ and Trpv5$^{-/-}$ mice (433% ± 16% and 414% ± 17%, respectively). In contrast, the urinary excretion of Ca$^{2+}$ was unaffected (109% ± 11% and 95% ± 3%, respectively). However, during the next 6 hours, Na$^{+}$ excretion was significantly decreased in both HCTZ-treated Trpv5$^{+/-}$ and Trpv5$^{-/-}$ mice compared with their corresponding controls (54% ± 11% and 55% ± 3%, respectively). Importantly, within this latter time period a significant hypocalciuria developed in HCTZ-treated Trpv5$^{+/-}$ as well as Trpv5$^{-/-}$ mice (44% ± 3% and 46% ± 6%, respectively). Thus, the Ca$^{2+}$-sparing effect resulting from a single dose of HCTZ coincides with a period of increased renal Na$^{+}$ reabsorption. Furthermore, while absolute Ca$^{2+}$ excretion differed between Trpv5$^{+/-}$ and Trpv5$^{-/-}$ mice, the overall effect of HCTZ administration was identical in Trpv5$^{+/-}$ and Trpv5$^{-/-}$ mice. Mg$^{2+}$ excretion was unaffected by a single dose of HCTZ during the 24 hours after its administration (data not shown).

In vivo free-flow micropuncture studies in HCTZ-treated mice. We performed micropuncture experiments in control and HCTZ-treated (25 mg/kg/d during 6 days) wild-type mice in order to directly evaluate tubular Na$^{+}$ and Ca$^{2+}$ handling in response to chronic thiazide treatment. No significant differences were observed between HCTZ-treated mice and control mice with regard to mean arterial blood pressure (93 ± 4 vs. 87 ± 3 mmHg; n = 5–6 mice), single nephron GFR from distal (7.3 ± 0.8 vs. 6.9 ± 0.5 nl/min; n = 10 nephrons per group) or proximal tubular collections (6.8 ± 0.3 vs. 6.9 ± 0.3 nl/min; n = 17–21 nephrons per group). Similarly, the amounts of Na$^{+}$ and Ca$^{2+}$ filtered per nephron were not different between HCTZ-treated and control mice (1,146 ± 44 vs. 1,181 ± 50 pmol/min and 15.2 ± 0.5 vs. 15.9 ± 0.7 pmol/min, respectively). Reabsorption of Na$^{+}$, fluid, and Ca$^{2+}$ up to the last surface loop of the proximal tubule, however, was significantly greater in HCTZ-treated than in control mice (Figure 6A). As a consequence, the absolute delivery of Ca$^{2+}$ to the late proximal tubule was significantly lower in HCTZ-treated mice (5.4 ± 0.4 vs. 6.9 ± 0.4 pmol/min). Absolute and fractional delivery of Ca$^{2+}$ to the distal convolution accessible to micropuncture was likewise significantly lower in HCTZ-treated versus control mice (0.21 ± 0.03 vs. 0.71 ± 0.18 pmol/min and 0.26 ± 0.03 vs. 0.74 ± 0.2 pmol/min, respectively). Ca$^{2+}$ delivery to the last loop of the proximal tubule was significantly lower in HCTZ-treated mice (0.11 ± 0.02 vs. 0.21 ± 0.03 pmol/min, respectively).
1.6% ± 0.3% vs. 4.4% ± 1.0%). Since K⁺ secretion occurs along the distal part of the nephron accessible to micropuncture (together with water reabsorption in the CNT and cortical collecting duct [CCD]), the distal luminal concentration of K⁺ was used as an indicator of the distal collection site. Consistent with intact Ca²⁺ reabsorption along the distal convolution and confirming previous experiments which related fractional Ca²⁺ delivery to the early distal convolution (24), both HCTZ-treated and control mice showed a rapid fall in fractional Ca²⁺ delivery with increasing luminal concentrations of K⁺ (Figure 6B). The fractional delivery of Ca²⁺ to the early distal convolution, identified by low tubular fluid K⁺ concentrations, however, appeared reduced in HCTZ-treated versus control mice (about 4% vs. 10%). This indicates that the Ca²⁺-sparing effect of chronic HCTZ administration localizes upstream to the distal convolution accessible to micropuncture, i.e. proximal to the site of Trpv5-mediated active Ca²⁺ reabsorption (24).

Discussion

The present study demonstrates that enhanced passive Ca²⁺ transport in the proximal tubule due to ECV contraction explains the hypocalciuria that develops during chronic thiazide treatment. Of crucial importance is that micropuncture experiments in HCTZ-treated mice demonstrated increased reabsorption of Na⁺ and Ca²⁺ in the proximal tubule, whereas Ca²⁺ reabsorption in the distal convolution accessible to micropuncture, which includes the site of Trpv5-mediated active Ca²⁺ reabsorption, was unaffected. Furthermore, we showed that thiazide-induced hypocalciuria can be elicited in Trpv5−/− mice, in which active Ca²⁺ reabsorption is abolished. In line with these data, we showed that the hypocalciuric response to thiazides parallels a compensatory increase in renal Na⁺ reabsorption secondary to an initial natriuresis. Chronic thiazide administration enhanced Mg²⁺ excretion and specifically reduced renal expression levels of the epithelial Mg²⁺ channel Trpm6. In addition, Trpm6 expression was severely decreased in NCC−/− mice. Therefore, the pathogenesis of hypomagnesemia in chronic thiazide treatment as well as Gitelman syndrome appears to involve Trpm6 downregulation.

ECV contraction is a known stimulus for paracellular Ca²⁺ reabsorption in the proximal tubule (2, 14). Hypovolemia triggers a compensatory increase of proximal Na⁺ reabsorption, which in turn enhances the electrochemical gradient driving passive Ca²⁺ transport in proximal tubular segments (1, 2, 14). HCTZ-treated mice exhibited a significant increase in hematocrit and concomitant decrease in body weight compared with nontreated controls, which confirms that ECV contraction occurred. Importantly, micropuncture experiments showed that HCTZ increases Ca²⁺ reabsorption in the proximal tubule, which results in decreased Ca²⁺ delivery to the last surface loop of the proximal tubule and to the first surface loop of the distal convolution. This was associated with an increased fractional Na⁺ reabsorption rate in the proximal tubule, as further substantiated by the reduced Ccr in HCTZ-treated mice. In line with these data, chronic HCTZ treatment upregulated expression of NHE3, which is responsible for the majority of Na⁺ reabsorption in proximal tubules and thus provides the main driving force for passive Ca²⁺ reabsorption. Alternatively, thiazide-induced hypocalciuria has been previously attributed to increased active Ca²⁺ reabsorption. However, the in vivo micropuncture experiments indicated similar or even reduced absolute Ca²⁺ reabsorption along the accessible distal convolution of HCTZ-treated versus control mice, whereas Ca²⁺ delivery to the early accessible distal convolution was decreased by HCTZ treatment. Previous micropuncture studies in distal convolutions of mice lacking Trpv5 revealed that Ca²⁺ reabsorption...
is normal up to the early accessible sites but becomes abolished along the downstream accessible segments of distal convolution (24). This indicated that no Trpv5-mediated Ca²⁺ reabsorption occurs upstream to the early sites accessible to micropuncture, which is consistent with the localization of Trpv5 in DCT2 and the CNT (17, 24). Thus, the reduced delivery of Ca²⁺ to the early accessible distal convolution in HCTZ-treated mice cannot be the result of Trpv5-mediated active Ca²⁺ reabsorption. In accordance with these findings, chronic HCTZ administration still decreased urinary Ca²⁺ excretion in mice lacking Trpv5, in which active Ca²⁺ transport in the distal convolution is effectively abolished (24). This is further exemplified by the severe downregulation of the remaining Ca²⁺ transport proteins in Trpv5–/– mice, which was unaffected by HCTZ treatment. Together with the micropuncture data, these results indicate that the Ca²⁺-sparing effect of thiazides can be explained neither by increased Ca²⁺ entry through Trpv5 nor by enhanced active Ca²⁺ transport in general. Additional experiments investigating the time dependency of these HCTZ effects demonstrated that Ca²⁺ excretion is unaltered during the natriuretic response following HCTZ administration, again indicating that direct stimulation of active Ca²⁺ reabsorption by inhibition of NCC does not occur. In contrast, a profound decrease in urinary Ca²⁺ excretion followed the initial natriuresis and, importantly, paralleled a reduced net Na⁺ excretion. In line with the present data, we previously demonstrated that volume contraction mimics thiazide-induced hypocalciuria and volume repletion completely reverses this hypocalciuria in rats (7). In conclusion, these data demonstrate that enhanced proximal tubular Na⁺ transport, as a consequence of ECV contraction, stimulates paracellular Ca²⁺ transport and constitutes the molecular mechanism underlying thiazide-induced hypocalciuria.

Gitelman syndrome is an autosomal recessive disorder caused by loss-of-function mutations in the gene encoding NCC, with a phenotype resembling chronic thiazide administration (4, 11). Loffing et al. recently demonstrated that renal Trpv5 and NCX1 expression are unaffected in NCC–/– mice, which display hypocalciuria (25, 27). Accordingly, micropuncture experiments in NCC–/– mice showed that active Ca²⁺ reabsorption is unaltered in distal convolution but that fractional absorption of both Na⁺ and Ca²⁺ in the proximal tubule is increased (27). The latter observation is in line with the enhancement of passive Ca²⁺ reabsorption through increased Na⁺ reabsorption in the proximal tubule, with results similar to the micropuncture data obtained during chronic HCTZ treatment in the present study. Taken together, our studies demonstrate that increased passive Ca²⁺ reabsorption in the proximal tubule explains the Ca²⁺-sparing effect of both NCC inhibition and inactivation.

Previously, we showed that thiazide-induced hypocalciuria occurs in spite of reduced renal expression of Ca²⁺ transport proteins in the rat (7). In these experiments a significantly higher dose of HCTZ was administered compared with that in the present study. Loffing et al. previously showed structural damage to and loss of DCT cells during thiazide administration with equivalently high doses, and, therefore, we hypothesized that apoptosis explains the reduced expression levels (7, 26). However, this was never observed in thiazide-treated mice. In the past, we have tried to reproduce the observed apoptotic changes in mice using several mouse strains, both sexes of mice, and different thiazide diuretics and application protocols but were never able to produce any DCT cell apoptosis in mice (J. Loffing, unpublished observations). Accordingly, deleterious effects were not detected in the present study, and the increased NCC expression in HCTZ-treated animals points to the viability of the DCT (28, 29). However, both studies consistently show that thiazide-induced hypocalciuria persists despite the absence or reduced abundance of proteins essentially responsible for active Ca²⁺ transport.

Interestingly, Trpv5–/– mice displayed significant polyuria and acidic urinary pH, which facilitate the excretion of large quantities of Ca²⁺ by reducing the risk of Ca²⁺ precipitations (24, 30–32). HCTZ administration increased diuresis in wild-type animals but did not alter urine volume in Trpv5–/– mice. Furthermore, HCTZ normalized the acidic urinary pH in Trpv5–/– mice. It has been demonstrated that a high luminal Ca²⁺ concentration, by activating the Ca²⁺-sensing receptor in the apical membrane of the collecting duct, blunts water permeability through aquaporin-2 (33, 34). Therefore, the Ca²⁺-sparing effect of HCTZ might counteract the hypercalciuria-induced polyuria and remove the necessity for urine acidification in Trpv5–/– mice, which would suggest that the distal Ca²⁺ load directly influences urine volume and acidification in an effort to prevent kidney stone formation.

Hypomagnesemia, as a side-effect of chronic thiazide administration and a defining feature of Gitelman syndrome, remains unexplained. Chronic HCTZ administration increased urinary Mg²⁺ excretion in the presence of reduced serum Mg²⁺ levels while GFR remained unaffected, which confirms that the hypomagnesemia is due to renal Mg²⁺ wasting. Importantly, renal Trpm6 expression was reduced in HCTZ-treated animals, while NCC expression was enhanced, which illustrates that Trpm6 downregulation is a specific nondeleterious effect. Trpm6 constitutes a Mg²⁺-permeable channel localized along the apical membrane of the DCT to which active Mg²⁺ reabsorption is restricted (21–23). Mutations in Trpm6 were shown to be associated with renal Mg²⁺ wasting (21, 22). Furthermore, we previously demonstrated a similarly reduced Trpm6 expression in tacrolimus-induced hypomagnesemia (35). Thus, the present data suggested that chronic thiazide treatment results in a similar defect in active Mg²⁺ reabsorption. As Trpm6 and NCC exactly colocalize in the DCT, a direct inhibitory effect of decreased NaCl influx on active Mg²⁺ transport could in principle be involved (23). However, whereas Ca²⁺ reabsorption was diminished upon a single dose of HCTZ, urinary Mg²⁺ excretion remained unaltered within 24 hours after HCTZ administration, which contradicts the hypothesis that Mg²⁺ reabsorption is directly inhibited. This dissociation of Ca²⁺ and Mg²⁺ excretion can be explained when the relative contribution of the proximal tubule and the TAL in the passive reabsorption of these divalents is taken into account. The majority of Mg²⁺ is reabsorbed in the TAL due to the driving force generated by NKCC2-mediated NaCl reabsorption, while micropuncture studies have shown that thiazides particularly enhance proximal tubule Na⁺ transport (14, 36). Accordingly, we showed that HCTZ increases proximal tubular NHE3 expression without affecting the NKCC2 expression. Hypothetically, an additional defect of Mg²⁺ reabsorption in TAL could explain the increased Mg²⁺ excretion in HCTZ treatment. However, inborn as well as acquired defects in TAL Mg²⁺ reabsorption are consistently accompanied by hypercalciuria, which renders this hypothesis unfeasible when the Ca²⁺-sparing effect of thiazides is taken into account (37–40). In line with the data obtained during HCTZ administration, NCC–/– mice were also shown to display hypomagnesemia in the absence of hypokalemia (4, 25). In the present study we report that, similar to what occurs during chronic thiazide administration, renal Trpm6 abundance in the
DCT is significantly reduced in NCC−/− mice. Therefore, Trpm6 downregulation may represent a general mechanism involved in the pathogenesis of hypomagnesemia in both Gitelman syndrome and chronic thiazide administration.

NCC−/− mice were previously shown to display widespread atrophy of DCT cells (27). This marked reduction in DCT plasma membrane area and, thereby, apical expression of Mg2+ channels could explain the observed renal Mg2+ wasting. As discussed above, deleterious effects of chronic thiazide administration particularly on DCT1 were previously suggested but did not occur in the present study (7, 26). Thus, at present it is unknown which mechanism is responsible for the observed Trpm6 downregulation. In this respect, it is interesting to note that aldosterone excess has been shown to be associated with renal Mg2+ wasting, whereas hypermagnesemia may accompany aldosterone deficiency (4, 41). In addition, it has been shown that the mineralocorticoid receptor antagonist spironolactone reduces urinary Mg2+ excretion in patients with Gitelman syndrome (42, 43). During thiazide-induced ECV contraction as well as in NCC−/− mice, aldosterone levels are increased (25). Therefore, hyperaldosteronism might hypothetically downregulate Trpm6 expression and, thereby, result in renal Mg2+ wasting.

In conclusion, this study addressing the mechanism underlying thiazide-induced hypocalciuria answers a long-standing question in physiology and medicine. Furthermore, it offers new insights concerning the hypomagnesemia accompanying chronic thiazide treatment and Gitelman syndrome.

Methods

Animal studies in Trpv5−/− and NCC−/− mice

Experiment 1. Trpv5−/− mice were recently generated by targeted ablation of the Trpv5 gene (24). In short, the Trpv5 gene was cloned from a 129/Sv mouse genomic library and subcloned in a modified neomycin-kan–targeting vector. Eventually, a recombinant ES cell line was used to generate chimeras, which allowed germline transmission of the mutant allele (Trpv5loxneo). Heterozygous (Trpv5+/−) mice, harboring 1 null allele, were obtained by breeding Trpv5loxneo mice with a germline Ella-cre-deletor strain (44). The offspring of Trpv5loxneo mice were genotyped by PCR as described previously (44). Eight-week old male Trpv5+/− and Trpv5−/− littermates were kept in a light- and temperature-controlled room with ad libitum access to deionized drinking water and standard pelleted chow (0.25% [wt/vol] NaCl; 1% [wt/vol] Ca; 0.2% [wt/vol] Mg); after animals were sacrificed, kidneys were sampled for determination of renal Trpm6 mRNA expression and protein abundance. The animal ethics board of the Radboud University Nijme genen Medical Centre approved the animal studies.

Analytical procedures

We determined serum and urine Ca2+ and Mg2+ concentrations using a colorimetric assay as described previously (45). We measured serum and/or urine Na+, Cl−, K+, and creatinine concentrations using a Hitachi autoanalyzer (Hitachi Corp.). A flame spectrophotometer (FCM 6343; Eppendorf) was used to measure serum and urine Li+ concentrations. We determined hematocrit using a standard centrifugation protocol (46).

Real-time quantitative PCR

Total RNA was extracted from kidney and duodenum and reverse transcribed as described previously (7, 47). The obtained cDNA was used to determine Trpv5, calbindin-D28K, NCCX1, Trpm6, NKCC2, and hypoxanthine-guanine phosphoribosyl transferase mRNA levels in kidney by real-time quantitative PCR, as described previously (48). NKCC2 forward and reverse primer sequences, respectively, were 5′-CTATGGATGGTCTGTGAGGTCTC-3′ and 5′-GCCCTCTCCACAGAGGCTC-3′, and the sequence for the fluorescent probe (5′FAM-3′TAMRA) was 5′-CACATTGTGTCCTCACTGTGTGGTT-3′. In the case of Trpv5, these were 5′-CTCTGGTGTGAGGTATGTTTCTCTAAGCC-3′, 5′-AAAGGACTTGCGAGTGTAT CAGC-3′, and 5′-CTCTGACATGAAAACCTTGCC-3′.

Immunohistochemistry and immunoblotting

Staining of kidney sections for Trpv5, calbindin-D28K, NCCX, and NHE3 was performed on 7-μm cryosections of peritubular-lysine-paraformaldehyde–fixed kidney samples. Sections were stained with guinea pig anti-Trpv5 (17), mouse anti–calbindin-D28K, affinity-purified guinea pig anti-Trpm6 (23), rabbit anti-Ncc (7), and rabbit anti-NHE3 (49), as described previously (24, 35). Images were made using a Zeiss fluorescence microscope equipped with a digital photo camera (DMX1200, Nikon). For semiquantitative determination of protein levels, images were analyzed with the Image-Pro Plus 4.1 image analysis software (MediaCybernetics), and protein levels were quantified as the mean of integrated optical density. Of note, in the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents the mean of integrated optical density. In the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents the mean of integrated optical density. Of note, in the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents the mean of integrated optical density. Of note, in the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents the mean of integrated optical density. Of note, in the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents the mean of integrated optical density. Of note, in the case of NHE3 specifically, the immunopositive signal in kidney cortex was quantified, which represents
Statistical analysis

Data are expressed as mean ± SEM. Statistical comparisons were analyzed by 1-way ANOVA and Fisher multiple comparison. P < 0.05 was considered statistically significant. All analyses were performed using the StatView Statistical Package software (Power PC version 4.51; Abacus Concepts Inc.) on an iMac computer (Apple Computer Inc.).

Acknowledgments

The work presented in this article was financially supported by the Dutch Kidney Foundation (C10.1881, C03.6017) and the Dutch Organization of Scientific Research (Zon-Mw 016.006.001). The authors wish to thank O.W. Moe (University of Texas Southwestern Medical Center, Dallas, Texas, USA) for generously providing the NHE3 antibody and K. Richter (University of California and Veterans Affairs Medical Center) and the Central Animal Facility (Radboud University Nijmegen Medical Centre) for expert technical assistance. Received for publication December 9, 2004, and accepted in revised form April 12, 2005.

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