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Prednisolone-induced Ca\(^{2+}\) malabsorption is caused by diminished expression of the epithelial Ca\(^{2+}\) channel TRPV6

Sylvie Huybers,1 Ton H. J. Naber,2 René J. M. Bindels,1 and Joost G. J. Hoenderop1

1Department of Physiology, Nijmegen Centre for Molecular Life Sciences, Radboud University Nijmegen Medical Centre; and 2Departments of Gastroenterology, Radboud University Nijmegen Medical Centre and Internal Medicine, Hilversum Hospital, Nijmegen, The Netherlands

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Huybers S, Naber TH, Bindels RJ, Hoenderop JG. Prednisolone-induced Ca\(^{2+}\) malabsorption is caused by diminished expression of the epithelial Ca\(^{2+}\) channel TRPV6. Am J Physiol Gastrointest Liver Physiol 292: G92–G97, 2007. First published August 10, 2006; doi:10.1152/ajpgi.00317.2006.—Glucocorticoids, such as prednisolone, are often used in clinic because of their anti-inflammatory and immunosuppressive properties. However, glucocorticoids reduce bone mineral density (BMD) as a side effect. Malabsorption of Ca\(^{2+}\) in the intestine is supposed to play an important role in the etiology of low BMD. To elucidate the mechanism of glucocorticoid-induced Ca\(^{2+}\) malabsorption, the present study investigated the effect of prednisolone on the expression and activity of proteins responsible for active intestinal Ca\(^{2+}\) absorption including the epithelial Ca\(^{2+}\) channel TRPV6, calbindin-D\(_{9K}\), and the plasma membrane ATPase PMCA1b. Therefore, C57BL/6 mice received 10 mg/kg body wt prednisolone daily by oral gavage for 7 days and were compared with control mice receiving vehicle only. An in vivo \(^{45}\text{Ca}^{2+}\) absorption assay indicated that intestinal Ca\(^{2+}\) absorption was diminished after prednisolone treatment. We showed decreased duodenal TRPV6 and calbindin-D\(_{9K}\) mRNA and protein abundance in prednisolone-treated compared with control mice, whereas PMCA1b mRNA levels were not altered. Importantly, detailed expression studies demonstrated that in mice these Ca\(^{2+}\) transport proteins are predominantly localized in the first 2 cm of the duodenum. Furthermore, serum Ca\(^{2+}\) and 1,25-dihydroxyvitamin D\(_3\) [1,25(OH)\(_2\)D\(_3\)] concentrations remained unchanged by prednisolone treatment. In conclusion, these data suggest that prednisolone reduces the intestinal Ca\(^{2+}\) absorption capacity through diminished duodenal expression of the active Ca\(^{2+}\) transporters TRPV6 and calbindin-D\(_{9K}\) independent of systemic 1,25(OH)\(_2\)D\(_3\).

Reduced bone mineral density (BMD) is particularly present in the elderly and women, which implies that age and gender are important risk factors for developing low BMD. However, in clinical practice low BMD is frequently observed in several patient groups, including inflammatory bowel disease (IBD) patients. Estimates of osteopenia in IBD range from 31 to 59% and osteoporosis from 5 to 41%. Various studies exploring the cause of low BMD in IBD found a significant correlation between glucocorticoid treatment and decreased BMD (3, 5, 17, 28, 29). Glucocorticoids, such as prednisolone, are well-known drugs for their potent anti-inflammatory and immunosuppressive properties. As a consequence, glucocorticoids are widely used in clinic as drugs to treat inflammatory conditions such as IBD. To date, glucocorticoids are generally accepted to reduce BMD, despite the fact that in a number of studies an effect on bone mass could not be observed (5, 11) or could be observed only in male glucocorticoid users (31). This effect of glucocorticoids on BMD is caused by the combined activity of increased bone resorption and malabsorption of vitamin D and Ca\(^{2+}\) from the intestine. Reduced vitamin D levels, as observed in IBD patients, are associated with impaired Ca\(^{2+}\) absorption and a compensatory increase in serum parathormone levels that, in turn, stimulates bone resorption (31). Furthermore, in most studies high glucocorticoid dosage and long-term treatment are positively associated with low BMD. Glucocorticoids are generally prescribed in high doses for a short period in acute exacerbations and are subsequently given in low maintenance doses for a prolonged time. Given these facts, prevention of low BMD in glucocorticoid-treated patients deserves serious attention and treatment.

Disturbance of the intestinal Ca\(^{2+}\) absorption likely plays an important role in glucocorticoid-induced bone problems. Ca\(^{2+}\) is absorbed by two distinct mechanisms including passive (paracellular) and active (transcellular) transport, and the relative importance of each pathway is set by the dietary Ca\(^{2+}\) content (20). Active Ca\(^{2+}\) absorption is mainly localized in the duodenum and tightly regulated, enabling the organism to adapt to changes in Ca\(^{2+}\) demands. Transcellular Ca\(^{2+}\) transport can be described in three sequential cellular steps including transfer of luminal Ca\(^{2+}\) into the enterocyte by the epithelial Ca\(^{2+}\) channel TRPV6, translocation of cytosolic Ca\(^{2+}\) toward the basolateral membrane by calbindin-D\(_{9K}\), and finally active extrusion into the circulatory system by the plasma membrane ATPase 1b (PMCA1b) (20, 34). Active Ca\(^{2+}\) absorption is predominantly regulated by 1,25-dihydroxyvitamin D\(_3\) [1,25(OH)\(_2\)D\(_3\)], the active form of vitamin D in the body. This is exemplified in 1,25(OH)\(_2\)D\(_3\)-deficient 1\(_{a}\)-hydroxylase knockout mice. This strain has a deletion in the enzyme 25-hydroxyvitamin D\(_3\)-1\(_{a}\)-hydroxylase responsible for the biosynthesis of active 1,25(OH)\(_2\)D\(_3\) in the kidney. As a consequence, these mice show impaired intestinal Ca\(^{2+}\) absorption, decreased serum Ca\(^{2+}\) concentration, and a compensatory increase in serum parathormone levels (10, 21).

Glucocorticoids diminish active Ca\(^{2+}\) absorption; however, the responsible molecular mechanism has not been elucidated. Hypothetically, glucocorticoid-induced Ca\(^{2+}\) malabsorption is exerted through reduced levels of intestinal proteins involved in active Ca\(^{2+}\) transport. The aim of the present study was, therefore, to investigate the effect of prednisolone on the...
expression level of the Ca\(^{2+}\) transport proteins TRPV6, calbindin-D\(_{9K}\), and PMCA1b in mouse duodenum. To this end, mice were treated with prednisolone for 7 days and characterized by in vivo \(^{45}\)Ca\(^{2+}\) absorption assays. Expression levels of the intestinal Ca\(^{2+}\) transporters were measured by real-time PCR analysis and immunoblotting.

**MATERIALS AND METHODS**

**Animal protocol.** Twelve-week-old C57BL/6 mice were kept in a light- and temperature-controlled room with ad libitum access to standard pelleted diet and water. For studying the localization of duodenal Ca\(^{2+}\) transporters in mice (\(N = 4\)), the first 6 cm of the small intestine were sampled and divided in three parts of 2 cm each. In the prednisolone experiment, mice were randomly assigned to either the control group receiving vehicle only (\(N = 8\)) or the treatment group (\(N = 8\)), receiving 10 mg/kg body wt prednisolone-hemisuccinate solution. Mice were housed individually in metabolic cages for 24 h to collect urine samples. Subsequently, blood samples were taken and the mice were killed. The first 2 cm of the duodenum (whole segment) were sampled and immediately frozen in liquid nitrogen. Samples were stored at \(-80^\circ\)C until further processing. The animal ethics board of the Radboud University Nijmegen approved all experimental procedures.

**Serum and urine biochemistry.** Serum and urine Ca\(^{2+}\) concentrations were determined by a colorimetric assay as described previously (19). Serum 1,25(OH)\(_2\)D\(_3\) concentrations were analyzed by immunextraction followed by 125I-RIA (IDS, Boldon, UK) (9).

**Quantitative real-time PCR analysis.** Total RNA was extracted from the duodenum by use of Trizol total RNA isolation reagent (Life Technologies BRL, Breda, The Netherlands). The obtained RNA was subjected to DNAse treatment to prevent genomic DNA contamination. Thereafter, 1.5 \(\mu\)g of RNA was reverse transcribed by Moloney-murine leukemia virus reverse transcriptase (Life Technologies BRL, as described previously (33). The obtained duodenal cDNA was used to determine TRPV6, calbindin-D\(_{9K}\), and PMCA1b mRNA levels, as well as mRNA levels of the housekeeping gene hypoxanthine-guanine phosphoribosyl transferase as an endogenous control. PCR primers and fluorescent probes were designed using the computer program Primer Express (Applied Biosystems, Foster City, CA) and purchased from Biolegio (Malden, The Netherlands). The primer and probe sequences are described previously (32, 33). Expression levels were quantified by real-time PCR on an ABI Prism 7700 sequence detection system (PE Biosystems, Rotkreuz, Switzerland).

**Immunoblotting.** For protein analysis, frozen duodenal tissues were homogenized in ice-cold solubilization buffer as previously described (35). Protein concentration of the homogenates was determined (Bio-Rad protein assay; Bio-Rad München, Munich, Germany) and samples were normalized accordingly. Subsequently, total duodenal protein fractions (10 \(\mu\)g) were separated on a 16.5% (wt/vol) SDS-PAGE gel and blotted to polyvinylidene difluoride-nitrocellulose membranes (Immobilon-P, Millipore, Bedford, MA). Blots were incubated overnight at 4°C with calbindin-D\(_{9K}\) antibody (Swant, Bellizona, Switzerland) (1:5,000) or \(\beta\)-actin antibody (1:25,000). Thereafter, blots were incubated with a goat anti-rabbit (calbindin-D\(_{9K}\) or goat anti-mouse (\(\beta\)-actin) peroxidase-coupled secondary antibody (Sigma, St. Louis, MO) (1:10,000). Immunoactive protein was detected by the chemiluminescence (ECL) method as described by the manufacturer (Amersham, Buckinghamshire, UK). Immunopositive bands were scanned by using an imaging densitometer (Bio-Rad GS-690) to determine pixel density (Molecular Analyst Software; Bio-Rad Laboratories, Hercules, CA).

\(^{45}\)Ca\(^{2+}\) in vivo absorption assay. In vivo Ca\(^{2+}\) absorption was assessed by measuring serum \(^{45}\)Ca\(^{2+}\) at early time points after oral gavage of a \(^{45}\)Ca\(^{2+}\) buffer. Mice were fasted overnight (12 h) before the test. Animals were hemodynamically stable under anesthesia (urethane, 1.4 mg/g body wt) during the experiment. The solution used to measure Ca\(^{2+}\) absorption contained 0.1 mM CaCl\(_2\), 125 mM NaCl, 17 mM Tris, and 1.8 g/l fructose and was enriched with 20 \(\mu\)Ci \(^{45}\)CaCl\(_2\) ml (18 Ci/g; New England Nuclear, Newton, MA). For the oral tests, 15 \(\mu\)l/g body wt of this solution were administrated by gavage as described previously (36). Blood samples were obtained at 1, 2, 3, 4, and 7 min after oral gavage, and serum (10 \(\mu\)l) was analyzed by liquid scintillation counting. The change in the serum Ca\(^{2+}\) concentration (\(\mu\)M) was calculated from the \(^{45}\)Ca\(^{2+}\) content of the serum samples and the specific activity of the administrated \(^{45}\)Ca\(^{2+}\) solution.

**Statistical analyses.** Data are expressed as means ± SE. Statistical comparisons were analyzed by ANOVA for the in vivo \(^{45}\)Ca\(^{2+}\) absorption study and by unpaired Student’s \(t\)-test for the other experiments. \(P < 0.05\) was considered statistically significant. All analyses were performed using the Instat Statistical Software on an Apple iMac computer.

**RESULTS**

**Body weight, urine, and serum analysis.** Mice were placed in metabolic cages to collect 24-h urine samples. Prednisolone-treated mice showed equal amounts of urinary Ca\(^{2+}\) loss compared with controls (Table 1). Likewise, no effect of prednisolone was observed on serum Ca\(^{2+}\) and 1,25(OH)\(_2\)D\(_3\) levels. To investigate the effect of prednisolone on body weight, mice were weighed before and after 7 days of oral treatment. Body weight significantly reduced after prednisolone treatment compared with controls (Table 1).

**Effect of prednisolone on in vivo intestinal Ca\(^{2+}\) absorption.** In addition, we used an in vivo \(^{45}\)Ca\(^{2+}\) absorption assay to evaluate the effect of prednisolone on intestinal Ca\(^{2+}\) absorption. At several time points after oral \(^{45}\)Ca\(^{2+}\) intake, the amount of \(^{45}\)Ca\(^{2+}\) in the blood was measured in controls and prednisolone-treated mice. Figure 1 shows that prednisolone resulted in a diminished uptake of Ca\(^{2+}\) from the intestinal lumen. Two minutes after oral gavage, the Ca\(^{2+}\) absorption in prednisolone-treated mice was 47 ± 8% compared with controls. After 4 min an equilibrium for Ca\(^{2+}\) uptake was reached.

**Localization of active Ca\(^{2+}\) transporters in the duodenum.** Subsequently, the molecular mechanism of prednisolone-induced Ca\(^{2+}\) malabsorption in the intestine was investigated. First, the main localization of active intestinal Ca\(^{2+}\) uptake was determined. Therefore, the first 6 cm of the duodenum was divided in three equal parts in which the expression level of active Ca\(^{2+}\) transporters was quantified by real-time PCR and immunoblotting (Fig. 2). All Ca\(^{2+}\) transporters displayed a robust mRNA expression gradient, which was highest near the stomach and decreased toward the jejunum. Intriguingly, more than 90% of TRPV6 and calbindin-D\(_{9K}\) mRNA was localized in the first 2 cm directly after the stomach. This was less evident for PMCA1b, where 61% of PMCA1b mRNA

<table>
<thead>
<tr>
<th>Wild-Type Mice</th>
<th>Controls</th>
<th>Prednisolone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serum Ca(^{2+}), mM</td>
<td>2.42 ± 0.04</td>
<td>2.43 ± 0.03</td>
</tr>
<tr>
<td>Urine Ca(^{2+}), (\mu)mol/24 h</td>
<td>4.9 ± 0.7</td>
<td>3.7 ± 0.5</td>
</tr>
<tr>
<td>Diuresis, ml/24 h</td>
<td>0.8 ± 0.1</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>Serum 1,25(OH)(_2)D(_3), pmol/l</td>
<td>91.8 ± 15.8</td>
<td>86.4 ± 16.6</td>
</tr>
<tr>
<td>Change body weight, g</td>
<td>−0.9 ± 0.3</td>
<td>−2.7 ± 0.4*</td>
</tr>
</tbody>
</table>

Values are means ± SE (\(N = 8\)). *\(P < 0.01\) vs. control.
was expressed in the first 2 cm. Similar results were obtained when analyzing duodenal calbindin-D$_{9K}$ protein abundance (Fig. 2).

**Effect of prednisolone on duodenal expression of active Ca$^{2+}$ transporters.** To study the effect of prednisolone on duodenal expression of the Ca$^{2+}$ transport proteins TRPV6, calbindin-D$_{9K}$, and PMCA1b, mRNA levels were measured in the first 2 cm by quantitative real-time PCR (Fig. 3A). Prednisolone treatment induced a twofold decrease in TRPV6 mRNA expression compared with controls, and also calbindin-D$_{9K}$ expression was slightly but significantly reduced. However, no significant effect of prednisolone was observed on PMCA1b mRNA levels and, therefore, we did not perform immunoblot analysis. Unfortunately, there is no appropriate antibody available to measure duodenal TRPV6 expression by immunoblot analysis. Subsequently, immunoblot analysis of duodenal samples consistently demonstrated a reduction in calbindin-D$_{9K}$ protein abundance in the prednisolone-treated group (Fig. 4A). Densitometric analysis of the intensity of the immunocomplexes confirmed this reduction and showed a significant decrease in calbindin-D$_{9K}$ protein expression after prednisolone treatment (Fig. 4B).

Fig. 1. Effect of prednisolone on in vivo intestinal $^{45}$Ca$^{2+}$ absorption. At $t = 0$, $^{45}$Ca$^{2+}$ is loaded in the stomach of the mouse by oral gavage. After the indicated time points blood was collected by orbita punctation and subsequently analyzed for the amount of $^{45}$Ca$^{2+}$ in serum. The control group (●) received vehicle only; the treatment group (○) received 10 mg/kg body wt prednisolone daily by oral gavage. Data are means ± SE ($N = 8$). *$P < 0.05$ vs. control.

Fig. 2. Localization of Ca$^{2+}$ transporters in the duodenum. The first 6 cm of the duodenum were sampled and divided into 3 parts of 2 cm each. By using quantitative real-time PCR, duodenal mRNA expression of the Ca$^{2+}$ transporters TRPV6 (solid bars), calbindin-D$_{9K}$ (shaded bars), and PMCA1b (open bars) were measured in each of the 3 parts, corrected for the housekeeping gene hypoxanthine-guanine phosphoribosyl transferase (HPRT), and presented as % of total expression. Calbindin-D$_{9K}$ protein abundance was analyzed by immunoblot analysis. Data are means ± SE ($N = 4$).

Fig. 3. Effect of prednisolone on duodenal and renal mRNA levels of genes encoding Ca$^{2+}$ transport proteins. Using quantitative real-time PCR, duodenal mRNA expression of TRPV6, calbindin-D$_{9K}$, and PMCA1b (A) and renal mRNA expression of TRPV5, calbindin-D$_{28K}$, and Na$^+$/Ca$^{2+}$ exchanger (NCX1) (B) were measured, corrected for HPRT, and presented as % of the control group. The control group (solid bars) received vehicle only; the treatment group (open bars) received 10 mg/kg body wt prednisolone daily by oral gavage. Data are means ± SE ($N = 8$). $#P < 0.01$ vs. control; *$P < 0.05$ vs. control.

Fig. 4. Immunoblot analysis of calbindin-D$_{9K}$ protein abundance. A, Western blot of calbindin-D$_{9K}$ and β-actin protein expression in the duodenum. B, Southern blot analysis of calbindin-D$_{9K}$ and β-actin protein expression in the duodenum.
**PREDNISOLONE REDUCES TRPV6 EXPRESSION IN DUODENUM**

**DISCUSSION**

The present study demonstrated that prednisolone impairs Ca\(^{2+}\) absorption, which is accompanied by diminished TRPV6 and calbindin-D\(_{9K}\) expression in the early part of the duodenum. These findings strongly suggest that inhibition of active Ca\(^{2+}\) transport is at least in part responsible for the Ca\(^{2+}\) malabsorption during glucocorticoid treatment. This defect likely contributes to the markedly decreased BMD after prolonged glucocorticoid usage.

Prednisolone could exert a direct inhibitory action on Ca\(^{2+}\) transport proteins, which can, however, also be due to a secondary response to decreased 1,25(OH)\(_2\)D\(_3\) serum levels. Importantly, we have previously shown that the expression of intestinal Ca\(^{2+}\) transport proteins is under the tight control of 1,25(OH)\(_2\)D\(_3\) (34, 36, 37). Available data about the effect of glucocorticoids on vitamin D metabolism are, however, inconclusive. Serum levels of 25-hydroxyvitamin D were low in a number of studies (7) and normal in others (39). Serum 1,25(OH)\(_2\)D\(_3\) levels also varied between studies (1, 7, 32). In addition, increased mRNA levels of the vitamin D receptor were measured in both intestine and kidney after dexamethasone treatment (1, 22). Our finding demonstrating a decline in expression of the duodenal Ca\(^{2+}\) transporters TRPV6 and calbindin-D\(_{9K}\) in combination with constant serum 1,25(OH)\(_2\)D\(_3\) levels indeed implies a 1,25(OH)\(_2\)D\(_3\)-independent effect of glucocorticoids on Ca\(^{2+}\) absorption. These data are in line with a previous study of Hahn et al. (18), who demonstrated that 20 mg of prednisone per day for 14 days had a minor effect on serum 1,25(OH)\(_2\)D\(_3\) levels in 12 patients, whereas intestinal Ca\(^{2+}\) absorption fell by 30%, suggesting that the glucocorticoid-related impairment in Ca\(^{2+}\) absorption may be independent of vitamin D. Moreover, renal 1α-hydroxylase mRNA abundance and enzyme activity were not altered (1), and glucocorticoids did not alter the vitamin D binding protein expression (6). The 1,25(OH)\(_2\)D\(_3\)-independent effect of glucocorticoids on Ca\(^{2+}\) absorption, in turn, could implicate a direct effect of prednisolone. Lee et al. (23) examined the effect of mifepristone, a glucocorticoid receptor antagonist. They observed that the decline of calbindin-D\(_{9K}\) caused by dexamethasone was completely abolished by mifepristone. Altogether this implicates that the decline of intestinal Ca\(^{2+}\) uptake is 1,25(OH)\(_2\)D\(_3\) independent and might be caused by a direct effect on the glucocorticoid receptor.

The duodenum is generally implicated as the main site of active Ca\(^{2+}\) absorption; however, the precise localization of active Ca\(^{2+}\) transporters in the intestine has not been evaluated to date. Interestingly, the Ca\(^{2+}\) transporter expression did not gradually decrease toward jejunum, but Ca\(^{2+}\) transporters were almost exclusively localized in the first part (2 cm) of mouse duodenum. This holds true for TRPV6 and calbindin-D\(_{9K}\) and to a lesser extent for PMCA1b. Because the expression level of the Ca\(^{2+}\) transporters was measured in duodenal segments instead of isolated mucosa preparations the presence of PMCA1b in duodenal muscle layers could theoretically contribute to the determined mRNA levels. However, Walters and coworkers (16) demonstrated significant higher levels of the PMCA1b transcript in duodenal mucosa compared with duodenal muscle layers. Thus it is unlikely that PMCA1b contamination from another layer (e.g., muscle cells) does significantly contribute to the PMCA1b expression in duodenal mucosa. Our study suggests that active Ca\(^{2+}\) transport is restricted to the duodenal part directly after the stomach. In addition, previous data indicated that TRPV6 is abundantly expressed in stomach (26, 27), where Ca\(^{2+}\) is ionized by gastric acid enabling absorption in the duodenum. Possibly the stomach plays a role in active dietary Ca\(^{2+}\) absorption next to the duodenum. Overall, the strong duodenal gradient of the Ca\(^{2+}\) transport proteins is a unique finding and suggests that active intestinal Ca\(^{2+}\) absorption occurs only in the first part of the duodenum.

In the etiology of low BMD, it is emphasized that there is interplay between Ca\(^{2+}\) waste from bone, increased renal Ca\(^{2+}\) wasting, and diminished Ca\(^{2+}\) absorption from the duodenum. The involvement of this last pathway is supported by previous studies. With the in situ intestinal loop technique it was evaluated that the net active Ca\(^{2+}\) flow over the duodenal membrane is inhibited by prednisolone (2, 38). A study in children on dexamethasone treatment observed a 61 to 42% fall in Ca\(^{2+}\) absorption (30). Moreover, in rats injected with other glucocorticoid drugs including dexamethasone or methylprednisolone, a decline of duodenal calbindin-D\(_{9K}\) mRNA was observed (13, 22). Furthermore, Li and Christakos (25) demonstrated a dose-dependent decrease of duodenal calbindin-D\(_{9K}\) after dexamethasone treatment in mice. Recently, Lee et al. (23) showed that dexamethasone reduces duodenal cal-

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**Fig. 4. Effect of prednisolone on calbindin-D\(_{9K}\) protein abundance in mouse duodenum.** Immuno blot from mouse duodenal homogenates labeled with antibodies against calbindin-D\(_{9K}\) (A). Expression of calbindin-D\(_{9K}\) protein was quantified by computer-assisted densitometry analysis and expressed as % of controls (B). The control group (solid bars) received vehicle only; the treatment group (open bars) received 10 mg/kg body wt prednisolone daily by oral gavage. Data are means ± SE (N = 8). *P < 0.05 vs. control.
bindin-D9K expression in mice when exposed for more than 3 days, whereas an exposure time shorter than 3 days did not affect calbindin-D9K expression. This finding implies a time-dependent effect of glucocorticoids on intestinal Ca\(^{2+}\) uptake. These studies together with our observation that prednisolone reduces duodenal TRPV6, conclusively demonstrates that disabled active Ca\(^{2+}\) uptake is involved in glucocorticoid-induced Ca\(^{2+}\) malabsorption. Our findings indicated that the abundance of the renal Ca\(^{2+}\) transporters including TRPV5, calbindin-D\(_{28K}\), and NCX1 is not affected by prednisolone treatment. These results could explain the normal Ca\(^{2+}\) excretion in mice administered with prednisolone.

Although glucocorticoids are not likely to affect 1,25(OH)\(_2\)D\(_3\) levels, 1,25(OH)\(_2\)D\(_3\) supplementation may still be an important treatment to prevent glucocorticoid-induced Ca\(^{2+}\) malabsorption, because of its stimulatory effect on active Ca\(^{2+}\) uptake. This can protect patients against the negative side effects of glucocorticoids on BMD (24). Furthermore, glucocorticoid treatment can only partly explain reduced BMD. For example, IBD patients who did not receive a glucocorticoid treatment also showed a reduction in BMD (4). Besides Ca\(^{2+}\) malabsorption, inflammatory cytokines, which are released during IBD, can directly stimulate osteoclast activity and decrease osteoblast function. Dresner-Pollak et al. (12), using an IL-10 knockout IBD mouse model, measured enhanced serum TNF-\(\alpha\), IL-1\(\beta\), and IL-6 levels and showed an increased incidence of osteopenia (8, 12). It is evident that the occurrence of reduced BMD has multifactorial causes and cannot be explained by just one mechanism.

In conclusion, this study shows that prednisolone decreases intestinal Ca\(^{2+}\) absorption via impaired active duodenal Ca\(^{2+}\) absorption, mainly through diminished duodenal TRPV6 expression. This process takes place independently of blood 1,25(OH)\(_2\)D\(_3\) levels. The described decline in active Ca\(^{2+}\) absorption may explain the Ca\(^{2+}\) malabsorption observed in patients using glucocorticoids and may in the long-term contribute to the development of osteoporosis.

GRANTS

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