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Clcn5 Knockout Mice Exhibit Novel Immunomodulatory Effects and Are More Susceptible to Dextran Sulfate Sodium-Induced Colitis

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Although the intracellular Cl⁻/H⁺ exchanger Clc-5 is expressed in apical intestinal endocytic compartments, its pathophysiological role in the gastrointestinal tract is unknown. In light of recent findings that CLC-5 is downregulated in active ulcerative colitis (UC), we tested the hypothesis that loss of CLC-5 modulates the immune response, thereby inducing susceptibility to UC. Acute dextran sulfate sodium (DSS) colitis was induced in Clcn5 knockout (KO) and wild-type (WT) mice. Colitis, monitored by disease activity index, histological activity index, and myeloperoxidase activity were significantly elevated in DSS-induced Clcn5 KO mice compared with those in WT mice. Comprehensive serum multiplex cytokine profiling demonstrated a heightened Th1–Th17 profile (increased TNF-α, IL-6, and IL-17) in DSS-induced Clcn5 KO mice compared with that in WT DSS colitis mice. Interestingly, Clcn5 KO mice maintained on a high vitamin D diet attenuated DSS-induced colitis. Immunofluorescence and Western blot analyses of colonic mucosa validated the systemic cytokine patterns and further revealed enhanced activation of the NF-κB pathway in DSS-induced Clcn5 KO mice compared with those in WT mice. Intriguingly, high baseline levels of IL-6 and phospho-IκB were observed in Clcn5 KO mice, suggesting a novel immunopathogenic role for the functional defects that result from the loss of Clc-5. Our studies demonstrate that the loss of Clc-5 1) exhibits IL-6–mediated immunopathogenesis, 2) significantly exacerbated DSS-induced colitis, which is influenced by dietary factors, including vitamin D, and 3) portrays distinct NF-κB–modulated Th1–Th17 immune dysregulation, implying a role for Clc-5 in the immunopathogenesis of UC. The Journal of Immunology, 2010, 184: 3988–3996.

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protein CLC-5, encoded by the CLCN5 gene is a voltage-depen-
dent Cl-/H+ exchanger (20, 26). Mutations in the CLCN5 gene
are associated with X-linked renal tubulopathy of Dent dis-
ease, with functional defects in both patients and mouse that are
characterized by low-m.w. proteinuria, aminoaciduria, glycosuria,
phosphaturia, hypercalcarnia, nephrolithiasis, and progressive re-
nal failure (27–35). In general, CLC channels have been demon-
strated to contribute to a host of biological and cellular processes,
including cell migration, proliferation, and apoptosis (36). Only
CLC-3 has been shown to play a critical role in TGF-β-induced
apoptosis of human airway epithelial cells and has recently been
shown to be involved in the recruitment and activation of immune
cells in the respiratory tract (36, 37). However, the specific role of
CLC-5 and/or cellular mediators that modulate important immune
functions to trigger downstream signaling pathways has not yet
been defined.

Identifying changes of CLC-5 and associated modulators in IBD
may lead to a better understanding of the molecular causes for IBD-
associated diarrhea. Because IFN-γ inhibits intestinal transport by
downregulating Na+/K+ ATPase and Na+/K+2Cl−, we and others
previously suggested that IBD-associated inflammatory cytokines
may play a role (6, 13). In experimental colitis models, we have
demonstrated that diarrhea was associated with significant eleva-
tion of various cytokines in colonic mucosa (6). In the acute
dextran sulfate sodium (DSS) colitis model, Th1–Th2 cytokines
(IL-6, IFN-γ, and IL-17) were increased, whereas in chronic col-
itis models IL-6 and IFN-γ (but not IL-12 p40/70 and IL-17) were
reversed. Our studies also suggested that, although there are clear
differences in the production of specific cytokines between DSS
and trinitrobenzen sulfonic acid models of experimental colitis,
these cytokine differences result in a similar clinical consequence:
diarrhea (6). The cytokine network in IBD is a complex and dy-
namic system in which cellular and humoral cytokines, chemo-
kines, and growth factors regulate the initiation and perpetuation of
inflammation (4, 6). Given the significance of CLC-5 and that
CLC-5 is downregulated in sigmoid mucosal biopsies of most
patients with active UC (19), we tested the hypothesis that the loss
of CLC-5 modulates the immune response, thereby inducing
susceptibility to UC. Herein, we demonstrate that the loss of Clc-5
1 significantly exacerbates DSS-induced colitis, 2 is associated
with elevated baseline levels of IL-6 and phospho-IκB, and 3) is
influenced by dietary factors, such as vitamin D and NF-κB–
mediated distinct Th1–Th17 immune dysregulation, implying the
role of downregulated CLC-5 in the immunopathogenesis of UC.

Materials and Methods

Animals and diet

C57BL/6 Clcn5 knockout (KO) mice, created by deletion of exon VI of
Clcn5 (35), and wild-type (WT) C57BL/6 age-matched adult male mice
(6–8 wk old) were group-housed at Johns Hopkins Animal Facility under
controlled temperature (25°C) and photoperiods (12:12 h light–dark cycle).
Care and experimentation of mice were performed in accordance with
institutional guidelines under protocols approved by the Institutional An-
imal Care and Use Committee. Mice were fed on Harlan Teklad Diet (H-
diet; Harlan Laboratories, Madison, WI). In studies of dietary effects on
DSS-induced colitis, subgroups of mice were also fed with NIH-31
modified open formula diet (Z-diet; Zeigler Brothers, Gardners, PA) or
a vitamin D (4.18 IU/g)-supplemented H-diet (Vit D-enriched H-diet).

Abs

Abs used include: IL-6 mAb (Transduction Laboratories, Lexington, KY),
IL-7 and NF-κB polyclonal Abs (pAbs) (Santa Cruz Biotechnology, Santa
Cruz, CA), IL-12 p40/70 pAb (BioSource International, Camarillo,
CA), phospho-IκB pAb (Abcam, Cambridge, MA), and actin pAb
(Sigma-Aldrich, St. Louis, MO). Clc-5 pAb was obtained as previously
described (35).

Induction of colitis

Acute colitis of C57BL/6 mice was induced by feeding mice (n ≥ 7 mice in
each group) with 2.5% (w/v) DSS (molecular mass 40 kDa; ICN Bio-
chemicals, Aurora, OH) as described previously (6).

Evaluation of colitis

Animals were observed twice daily for weight, water/food consumption,
morbidity, stool consistency, piloerection, and the presence of gross blood
in feces and at the anus. Disease activity index (DAI) was calculated as de-
scribed previously (6). At day 7 following induction with DSS, animals were
sacrificed by CO2 inhalation, rapidly dissected, and the entire colon was
quickly excised, photographed, and gently cleared of feces with 4°C saline.
Small segments of the colon taken for histopathology and immunohisto-
chemistry were fixed in 10% normal buffered formalin as described pre-
viously (6). Sections (4 μm) were stained with H&E (Richard Allen
Scientific, Kalamazoo, MI), histological scores were blindly determined
with minor modifications from Obermeier et al. (36), and histological ac-
tivity index (HAI) was calculated as described previously (6). The activity
of the enzyme myeloperoxidase (MPO), a marker of polymorphonuclear neu-
trophil primary granules, was also determined in colonic mucosa as de-
scribed previously (6, 39).

Isolation of colonic mucosa and extraction of proteins for
SDS-PAGE and Western blot analysis

At 4°C, the mucosa was scraped from the muscle layer of the colon,
and samples were snap frozen and stored at −80°C for the remaining ex-
periments. Frozen tissue samples were homogenized in homogenization
buffer (50 mM Tris-HCl [pH 7.2]) containing Na2VO4 and a protease-
inhibitor mixture (Sigma-Aldrich) using an Omni TH homogenizer
(OMNI Healthcare, Marietta, GA). Following sonication, the homo-
genate was centrifuged at 2000 × g for 10 min. Supernatants were col-
cated as total mucosal proteins, and protein concentrations were measured
using the Bio-Rad Protein Assay (Bio-Rad, Hercules, CA). Protein ex-
traction, SDS-PAGE, and Western blots were performed as described previously (6, 19, 40).

Serum collection and biometric multiplex cytokine profiling

Blood was collected by cardiac puncture in endotoxin-free, silicon-coated
containers with no additive. Blood samples were allowed to clot at room tem-
perature for 30 min before centrifugation (2200 × g, 4°C, 10 min), and the
serum was collected and stored at −80°C until analyzed. A multiplex
sandwich immunoassay from the Bio-Plex Protein Array System (Bio-
Rad), which contains fluorescently labeled microspheres conjugated with
mAbs specific for 16 target cytokines, was used as described previously (6, 41).

Serum cytokine levels were measured in 20–22 μl of serum. Blood samples
for cytokine measurement were collected on ice and centrifuged at
1500 rpm for 10 min. Serum samples were stored at −80°C before analy-
sis. Analyses were performed in duplicate with the Bio-Plex Pro-
tein Array System (Bio-Rad) and evaluated using Luminex xMAP
Technology (GE Healthcare, Pittsburgh, PA).

Isolation of peritoneal macrophages and PBMCs

Peritoneal macrophages were prepared as previously described (42). Briefly,
2 ml thioglycollate broth was injected into the peritoneal cavities of mice to
elicit macrophages. After 3 d, peritoneal cells were recovered by washing
the peritoneal cavity with 10 ml DMEM. Peritoneal macrophages were then
purified by adherence to tissue culture plastic (4 d after initial culture). Mouse
PBMCs were isolated from whole blood by Ficoll gradient. Briefly, whole
blood from three mice (~2–3 ml) was mixed with an equal volume of HBSS
and then overlaid onto 9 ml Ficoll. After centrifugation (with brake off) at
2500 rpm for 30 min, the PMBC fraction (buffy coat layer) was collected
and diluted two times with HBSS. PMBCs were recovered by centrifugation
at 1500 rpm for 10 min.

Immunocytochemistry

Immunocytochemical detection was determined in 4-μm paraffin-embed-
ded colonic sections as described previously (6) using Alexa Fluor 488
(Invitrogen) goat anti-mouse IgG (MCP-1 and IL-17) or Alexa Fluor 568
(Invitrogen) goat anti-mouse IgG (IL-6).

Statistical analysis

Statistical analysis (for all of the data with the exception of cytokine
experiments) within and between each groups was done using a Student t
test, and descriptive results are presented as mean ± SD. p values <0.05
were considered statistically significant.
Statistical analysis of cytokine profiles
Analyte concentrations were quantified by fitting using a calibration or standard curve. A five-parameter logistic regression analysis was performed to derive an equation that allowed concentrations of unknown samples to be predicted. Statistical differences in measured values were assessed by a Mann-Whitney U test. Data are presented with mean, median, upper, and lower quartile values. p values <0.05 were considered statistically significant.

Multidimensional scaling
Multidimensional scaling (MDS) is an iterative process to detect meaningful underlying dimensions to explain observed similarities or dissimilarities between the groups studied (43). This analysis uses correlational matrices to construct configurations of the data in a lower-dimensional matrix, such that the relative distances between the groups are similar to those in the higher-dimensional matrix. The degree of correspondence between the distances and the matrix input by the user is measured (inversely) by a stress function defined by 

\[ \text{Stress} = \sqrt{\sum (d_{ij} - f(d_{ij}))^2} \]

where \(d_{ij}\) is the Euclidean distance and \(f(d_{ij})\) is the observed distance. The proximities and distances are then represented on a two-dimensional Shepard diagram scatter plot, which facilitates visualization and the interpretation of patterns. All of the statistical analyses for MDS were performed with R software, version 2.8 (44).

Results
Clcn5 KO mice exhibit increased susceptibility to DSS-induced colitis
We recently demonstrated the coordinated downregulation of several transporter proteins, including CLC-5, in the sigmoid colon of patients with active IBD, suggesting its potential contribution to IBD-associated diarrhea (19). To investigate whether the loss of Clc-5 would induce susceptibility to colitis, we subjected Clcn5 KO mice to the well-established DSS chemical model of mucosal inflammation. Oral DSS administration for 7 d induced more significant acute colitis in Clcn5 KO mice when compared with that in WT mice (n=7 mice per group) (Fig. 1). This was characterized by a significant increase in DAI scores (p = 0.034), as demonstrated by greater weight loss, earlier appearance of diarrhea/loose feces, and fecal blood in DSS-induced Clcn5 KO mice when compared with those in DSS-induced WT mice, as early as 5 d following induction with DSS (Fig. 1A). Morphological examination at day 5 and day 7 of induction revealed significant reduction in colon length and increased loose bloody stools in DSS-induced Clcn5 KO mice when compared with those in DSS-induced WT mice (Fig. 1B). Histological examination of acute DSS colitis in Clcn5 KO mice was characterized by greater loss of architecture, fewer goblet cells, and increased inflammatory cell infiltration at the areas of lesions when compared with those in DSS-induced WT mice (Fig. 1C). This was also demonstrated by the significant increase in HAI colitis scores for DSS-induced Clcn5 KO mice relative to those for DSS-induced WT mice (p = 0.039) (Fig. 1D). Neutrophil infiltration, as demonstrated by increased MPO activity, was also significantly elevated in Clcn5 KO mice induced with DSS colitis when compared with that in DSS-induced WT mice, indicative of an increased susceptibility to DSS-induced colitis (p = 0.028). The colons of Clcn5 KO mice uninduced with DSS colitis appeared normal and not different from those of control WT mice (Fig. 1). Our data therefore demonstrate that the loss of Clc-5 significantly exacerbates DSS-induced colitis.

Unique systemic immune profiles in Clcn5 KO mice at both basal conditions and when induced with DSS colitis
It is not known whether Clc-5 modulates the immune response to trigger distinct signaling inflammatory pathways. To analyze the influence of the cytokine patterns in the increased susceptibility of Clcn5 KO mice to DSS, we performed systemic multiplex serum cytokine profiling in DSS-induced Clcn5 KO and WT mice. The levels of 16 systemic cytokines covering a broad spectrum of immune and inflammatory mechanisms were measured in parallel following induction of colitis. Acute DSS-induced Clcn5 KO mice demonstrated a cellular, cytotoxic, and chemotactic profile with significant elevated levels of IL-12 and IL-17 (p <0.05), as well as IFN-γ, KC, MIP-1α, and MCP-1 (p <0.001), when compared with those in DSS-induced WT mice (Fig. 2A, 2B). This predominantly chemotactic cellular immune profile is distinct and is unlike any of our prior observations from several autoimmune conditions (6, 41, 45–47), suggesting the unique immunomodulatory role of Clc-5 in DSS colitis. Interestingly, the baseline levels of IL-6 were significantly elevated in Clcn5 KO mice when compared with those in WT mice (Fig. 2C), suggesting the likelihood that IL-6 may function as a proinflammatory mediator in Clcn5 KO mice.

MDS analyses reveal unique categorical cytokine networks in Clcn5 KO mice
Complementary multivariate analytical methods provide a vivid picture of the biological significance of the immune profile network. MDS provides a means of identifying correlational configurations of statistically significant cytokines and allows for a visual representation of the pattern of proximities within the groups studied (43). As depicted in Fig. 3, MDS analysis of the cytokine patterns in DSS-induced Clcn5 KO mice identified a strong positive cluster between IL-12 and IL-17 (r = 0.742, p = 0.041), whereas those clusters were weaker in DSS-induced WT mice (r = 0.558, p = 0.057) (Fig. 3A). DSS-induced Clcn5 KO mice also showed a significantly tight positive cluster among KC, MIP-1α, and MCP-1 (r = 0.713, p = 0.027), whereas those clusters were absent in DSS-induced WT mice (Fig. 3A). However, DSS-induced WT mice showed a strong positive correlation between IL-12 and IFN-γ (r = 0.758, p = 0.03), one that was not present in DSS-induced Clcn5 KO mice (Fig. 3B). Interestingly, even at basal conditions (uninduced) Clcn5 KO mice showed a strong positive correlation between IL-6 and IL-10 (r = 0.722, p = 0.039), which was absent among all other groups studied (Fig. 3C). These unique representations provide a visual inspection of similarities and differences between cytokine changes among the group, indicating the intricate but distinct immune network associated with Clc-5 expression.

Alteration of cytokine profiles in colon validate and correlate with that of systemic cytokines
To determine whether the observed systemic cytokine profiles in acute experimental colitis of Clcn5 KO mice correlated with that of local levels seen within the colonic mucosa, immunoblots and immunofluorescence analysis of colons from DSS mice were performed. Proteins were extracted from mucosa scraped from freshly excised colons, and samples were analyzed by SDS-PAGE Western blots using primary Abs for IL-6, IL-12 p40/70, and IL-17. As shown in Fig. 4A, acute DSS-induced Clcn5 KO colitis had significantly higher IL-6, IL-12 p40/70, and IL-17 protein expression in the colon than that in WT DSS-induced colitis, suggesting similar patterns of changes to those observed in the systemic levels, thereby validating the correlation of the systemic immune response to that observed in local tissue.

Acute experimental colitis of Clcn5 KO mice is characterized by an NF-κB–mediated immunomodulatory profile. DSS-induced Clcn5 KO colitis had significantly higher NF-κB and phospho-IκB protein expression in the colon than that in WT DSS-induced colitis, suggesting the role of the NF-κB proinflammatory pathway in the distinct immune regulation associated with Clc-5 expression (Fig. 4B). Intriguingly, the baseline levels of phospho-IκB (no DSS treatment) were also significantly elevated in Clcn5 KO mice.
compared with those in WT mice, suggesting the likelihood that phospho-IκB, along with IL-6, may function as a proinflammatory mediator in Clcn5 KO mice.

Changes in mucosal cytokine levels are consistent with systemic levels as observed by immunofluorescence. As shown in Fig. 4C, IL-6 and MCP-1 were elevated in Clcn5 KO mice with DSS-induced colitis, predominantly associated with lamina propria infiltrating mononuclear cells, demonstrating the immune modulatory potential of inflammatory infiltrates and further validating the observed systemic cytokine profiles with that of local levels seen within tissue.

*Elevated levels of IL-6 protein expression identified in the kidney, but not the colon, of Clcn5 KO mice*

Although Clcn5 KO mice had significantly high systemic IL-6 levels relative to those of WT controls, the colonic mucosa from Clcn5 KO mice did not exhibit elevated levels of IL-6 protein expression in Western blots compared with those of WT controls (Supplemental

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**FIGURE 1.** Administration of DSS demonstrated increased susceptibility to experimental colitis in Clcn5 KO mice. Results presented are representative of seven mice from each group. A, DAI was scored from WT and Clcn5 KO mice for weight loss, stool consistency, and bleeding. B, Clinical assessment of acute DSS colitis in WT and Clcn5 KO mice. C, Histological analysis of acute DSS colitis in WT and Clcn5 KO mice by H&E-stained colonic sections (original magnification ×20). D, For detailed histological analysis, colonic sections of WT and Clcn5 KO mice were scored in a blinded fashion as described in Materials and Methods. E, MPO activities in colon from WT and Clcn5 KO mice were determined as described in Materials and Methods. Clcn5 KO mice induced with colitis demonstrated statistically significant elevations in DAI, HAI, and MPO relative to those of WT mice, demonstrating increased susceptibility to acute experimental colitis. e, epithelial disruption; i, inflammatory infiltrate; m, lamina muscularis mucosae; s, submucosal edema.

**FIGURE 2.** Distinct cellular cytotoxic and chemotactic patterns identified in Clcn5 KO mice induced with acute experimental colitis. Levels of 16 cytokines were measured simultaneously using a biometric multiplex assay from serum of WT and Clcn5 KO mice with and without acute DSS colitis. Data is presented with mean (+), median (−), and upper and lower quartile values. *p < 0.05; **p < 0.001. A and C, Cytokine pattern in acute colitis of Clcn5 KO mice is represented by a Th1–Th17-polarized (IL-17, IL-12, and IFN-γ) and a strong chemotactic pattern (MIP-1α, KC, and MCP-1) when compared with that of acute colitis in WT mice. B, No significant differences were observed in levels of humoral cytokines and other cellular cytokines and chemokines between WT and Clcn5 KO mice. Of particular significance are the statistically increased levels of IL-6 in untreated Clcn5 KO mice. At least seven mice were used in each group.
Because mutations in the CLCN5 gene are associated with functional defects characterized by nephrolithiasis and progressive renal failure (27, 29, 31–33, 48–50), we investigated the protein expression of IL-6 in the kidney cortex of Clcn5 KO mice and WT mice. SDS-PAGE and Western blot studies demonstrated a significant increase in IL-6 protein expression in the kidney cortex of Clcn5 KO mice compared to WT mice.

**FIGURE 3.** Unique categorical cytokine networks identified in Clcn5 KO mice induced with acute experimental DSS colitis. MDS analysis was used to generate dimensions that can interpret statistically significant differences between cytokine networks in DSS-induced WT and Clcn5 KO mice. A, Two strong positive clusters, 1) between IL-12 and IL-17 and 2) among MPO, KC, MIP-1β, and MCP-1, were identified in DSS-induced Clcn5 KO mice, when compared with those in DSS-induced WT mice (marked by circles). B, DSS-induced WT mice showed a strong positive correlation between IL-12 and IFN-γ when compared with those in DSS-induced Clcn5 KO mice. C, Interestingly, uninduced Clcn5 KO mice showed a strong positive correlation between IL-6 and IL-10 ($r = 0.722$, $p = 0.039$), which was absent among all of the other groups studied. These unique representations provide a visual inspection of similarities and differences between cytokine changes among the group, indicating the intricate but distinct immune network in Clcn5 KO mice.

**FIGURE 4.** Correlation of cytokine profiles in colon with that of systemic levels in Clcn5 KO mice. Western blot and immunofluorescence analyses of cytokines from mucosal scrapings and tissue of colon in DSS-induced and uninduced WT and Clcn5 KO mice. A, WB show significantly higher IL-6, IL-12 p40/70, and IL-17 protein expression in acute DSS-induced Clcn5 KO colon when compared with that in WT DSS-induced colon. B, WB show significantly higher levels of colonic NF-κB and phospho-IκB protein expression in acute DSS-induced Clcn5 KO colitis when compared with those in WT DSS-induced colitis. C, IF shows higher IL-6 and MCP-1 protein in lamina propria of acute DSS-induced Clcn5 KO colitis when compared with those in WT DSS-induced colitis. These data validate the observed systemic cytokine profiles with those of local levels seen within tissue. Representatives of at least three independent experiments are shown in A and B.
Cln5 KO mice relative to that in WT mice, suggesting the novel finding that IL-6 may contribute to an immunopathogenic role (Supplemental Fig. 1A). To further define the expression and localization of renal IL-6 expression in Cln5 KO mice, we performed immunofluorescence analyses on frozen sections of kidney cortex of WT and Cln5 KO mice. Immunofluorescence analyses showed that IL-6 was significantly elevated in the kidney cortex of Cln5 KO mice compared with that in WT mice (Supplemental Fig. 1B). In WT kidney, a low level of IL-6 expression was localized to the tubular basement membrane. However, in the Cln5 KO kidney, there was increased expression of IL-6 in the basement membrane and upregulation in the interstitium, surrounding renal tubules, as well as epithelial cells of the proximal tubules, which was not observed in WT kidney sections. Our data demonstrate, for the first time, the involvement of novel immunomodulatory effects in a mouse model of Dent disease.

Clt-5 is highly expressed in the macrophages and weakly expressed in the colonic mucosa of WT mice but not in PBMcs

Because the immune profiles of Cln5 KO mice are distinctly different from those of WT mice both under the basal condition (baseline level) and in DSS-induced colitis, we speculate that Clt-5 may be expressed in the immune cells, where it could directly affect the function of these cells. Peritoneal macrophages and PBMcs, including lymphocytes and monocytes, were isolated from both WT and Cln5 KO mice. Surprisingly, Clt-5 was highly expressed in the macrophages (comparable to that in kidney), but not in PBMcs (Supplemental Fig. 2). Low levels of Clt-5 expression were also observed in the colonic mucosa of WT mice. These data provide the first evidence that Clt-5 is expressed in immune cells.

Protective effect of diet and vitamin D on Cln5 KO DSS-induced colitis

A case-control study to evaluate the etiological role of dietary factors in UC identified dietary patterns that were associated with an increased risk to develop UC (51). To evaluate the influence of diet on the development of experiment colitis in Cln5 KO mice, we subjected a group of mice (n = 5 per group) to a separate diet: Z-diet (Supplemental Fig. 3). The diet was initiated from birth (in both mother and F1 generation used in these experiments) and contains greater amounts of vitamin D, vitamin B12, selenium, and choline (all >1.5-fold) and lower amounts of iodine, vitamin K3, inositol, pantothenic acid, vitamin B2, vitamin B6, vitamin B7, and vitamin E (all <1.5-fold) when compared with the H-diet, which is the regular diet used at our mouse facility (Supplemental Fig. 3). Interestingly, a significant increase in colitis, as demonstrated by DAI scores, was observed in DSS-induced Cln5 KO mice maintained on H-diet, when compared with that of Cln5 KO DSS-induced mice on the Z-diet (p = 0.047) (Fig. 5A). Among the differences in dietary components between H-diet and Z-diet, vitamin D has been reported to play a role in preventing or ameliorating the IBD in the colitis model of IL-10 KO mice (52). Because Z-diet contains 2-fold higher level of vitamin D than that in the H-diet (Supplemental Fig. 1), we hypothesized that the high level of vitamin D in the Z-diet might be an important reason why Z-diet exhibited protective effect on colitis of Cln5 KO mice. Because we did not observe the beneficial effect of Z-diet on DSS colitis of WT mice, we decided to test the effect of vitamin D supplement on DSS colitis in Cln5 KO mice by giving the mice Vit D-enriched H-diet, which was specially formulated H-diet containing a higher level of vitamin D (4.18 IU/g), which is the same as that found in the Z-diet. As shown in Fig. 5B and 5C, DSS-treated Cln5 KO mice on Vit D-enriched H-diet for 4 wk exhibited a more significant reduction of disease activity than those on regular H-diet. Interestingly, this effect depends on the duration of the diet change: Cln5 KO mice on Vit D-enriched H-diet for 1 wk exhibited only marginal improvement of DSS colitis compared with that of the mice on the same diet for 4 wk (Fig. 5B). There was no significant difference in colitis DAI (and MPO scores, data not shown) of DSS-induced WT mice between the mice fed with the H-diet and the mice fed the Z-diet (Fig. 5A). This suggests that the loss of Clt-5 significantly exacerbates DSS-induced colitis and is influenced by the dietary factors, such as vitamin D. Further quantitative studies are warranted to more fully investigate whether the loss of Clt-5 is a true risk factor in the development of UC.

Discussion

Diarrhea continues to be a frequent symptom in UC patients, the underlying mechanisms of which depend on various factors, including, but not limited to, the location, extent, and severity of the inflammation, altered motility, associated infections, and iatrogenic factors (10, 53). Furthermore, diarrhea in UC is associated with fluid and electrolyte imbalance, indicative of impaired gastrointestinal epithelial ion transport (54). Recently, we demonstrated the coordinated downregulation of CLC-5 among several Na+ transporters in sigmoid mucosal biopsies of patients with active IBD and mice with experimental colitis (19). However, the specific role of CLC-5 in UC has not yet been defined.

Previous studies have demonstrated that the Guggino Cln5 KO mice develop classical signs of Dent disease with fluid and electrolyte imbalance manifested by polyuria, low-m.w. proteinuria, aminoaciduria, glycosuria, and hypercalciuria (28–30, 35). Although fluid, sodium, and chloride measurements have not yet been performed on the stool from these mice, Cln5 KO mice afford an ideal model to investigate whether the loss of CLC-5 would induce susceptibility to UC. In so doing, we present here the first evidence that the loss of Clt-5 significantly exacerbates both clinical and histopathological signs of DSS-induced UC-like colitis. It is important to infer the mechanisms of the phenotypic abnormalities in intestinal mucosa as a result of the lack of Clt-5 function. Clt-5 is an intracellularly localized Cl-/H+ exchanger that has been suggested to play an important role in regulation of protein trafficking in epithelial cells (54). Our recent studies have shown that, in mouse mucosa, both Nhe3 and Clc-5 comigrated in the same endosomal pool isolated by OptiPrep gradient fractionation (data not shown). Because trafficking of Nhe3 between plasma membrane and endosomal compartments is a major regulatory mechanism of Nhe3 (55), our data suggest that Clt-5 may be involved in Nhe3 trafficking. Lack of Clt-5 causes alkalization of the early and perhaps recycling endosomes (56) but not late endosomes. Because Clt-5 acts to provide the neutralizing negative charge for the proton moved by the H-ATPase that acidifies this compartment, the lack of Clt-5 increases the pH in the endosomal compartment. The lack of Clt-5, and consequent alkaline endosomal pH, causes trafficking defects in the apical membrane proteins Na+/phosphate cotransporter 2a (Npt2a), Nhe3, and megalin (55). In proximal tubules devoid of Clt-5, a significantly reduced apical membrane expression of megalin (57) results in low-m.w. proteinuria. Furthermore, both Npt2a and Nhe3 are mislocalized to a subapical compartment in the proximal tubule of Cln5 KO mice. The reduced apical membrane localization of Npt2a and Nhe3 decreases transport activity and thus results in hyperphosphaturia and sodium loss, respectively. By analogy, we expect that the same physiological outcome would be present in the intestine where Nhe3 is well known to traffic on and off of the plasma membrane (58). The idea of less surface Nhe3 caused by defective Nhe3 trafficking in the Cln5 KO mice would be compatible with other mouse KO studies that have shown the lack of colonic Nhe3 or its regulatory factor Na+/H+ exchanger regulatory factor 1 (data not shown) causes diarrhea
and susceptibility to IBD (59). Given these considerations and the studies reported herein, our data further substantiate the hypothesis that IBD-associated diarrhea manifests as a result of the coordinated downregulation of multiple Na\(^{+}\) transporters and related regulatory proteins, including NHE3 and CLC-5.

Our studies herein also ascertained that the exacerbated colitis from the loss of Clc-5 was influenced by specific immune-mediated dysregulation, implying the immunopathogenic role of downregulated CLC-5 in UC. The activation of the innate immune system has been shown to provide the source of cytokines, which includes IL-12, that then trigger the adaptive CD4\(^{+}\) T cellular and humoral immune response in IBD (2). Costimulated and activated T cells then secrete a distinct set of cytokines that perpetuate the disease process. In UC, there are specific mucosal-damage pathways characterized by dysregulated cytokine profiles at different stages of the disease process (2). We have previously shown that acute experimental DSS-induced colitis was represented by a distinct set of Th1–Th17 cytokine profiles that involved altered expression of IL-6, IL-1β, IL-12, that then trigger the adaptive CD4\(^{+}\) T cellular and humoral immune response in IBD (2). Costimulated and activated T cells then secrete a distinct set of cytokines that perpetuate the disease process. In UC, there are specific mucosal-damage pathways characterized by dysregulated cytokine profiles at different stages of the disease process (2). We have previously shown that acute experimental DSS-induced colitis was represented by a distinct set of Th1–Th17 cytokine profiles that involved altered expression of TNF-α, IL-6, IL-17, and KC (6). Our current studies of experimental colitis using Clcn5 KO mice demonstrated a further exacerbation of the Th1–Th17 immune response, characterized by elevated levels of TNF-α, IL-6, and IL-17, suggesting the immune-mediated pathophysiological role of downregulated CLC-5 in UC.

The inflammatory response to an antigenic stimulus in UC is primarily manifested by the recruitment of distinct chemokines characteristic for the activation that function as critical players in the regulation of the immune response (6, 60). Our profiles identified a significant positive cluster among KC, MIP-1β, and MCP-1 as active chemokines in the signaling network of the acute experimental colitis in Clcn5 KO mice. It is likely that these distinct chemokines drive the initial acute innate immune response, which is consistent with the finding that MPO levels, a marker of innate neutrophil activity, were significantly elevated in the colonic tissues of acute experimental colitis in Clcn5 KO mice. Chemokines involved in the recruitment of CD4\(^{+}\) T cells are also expressed in colonic epithelial cells, and it has been shown that in patients with UC colonic enterocytes are the major source for neutrophil-directing chemokines, such as MCP-1 (61, 62), which is in agreement with our observations.

The mechanisms of the innate–adaptive interface in IBD have been well-demonstrated to primarily involve the TLR pathway, which generates inflammatory factors modulated by the NF-κB pathway (63). This is initiated by the stimulation of intermediate kinases, leading to phosphorylation of the inhibitor of B kinase and subsequent release of NF-κB, which then translocates to the nucleus, where it activates transcription of proinflammatory genes (63). Our studies in experimental colitis using Clcn5 KO mice also show increased activation of phospho-IκB and increased dissociation of NF-κB, suggesting the role of the TLR–NF-κB pathway mediated inflammatory mechanisms in the acute experimental colitis of Clcn5 KO mice.

IL-6 plays an important role in differentiation and growth of hematopoietic progenitor cells and lymphocytes and in the generation of the Th17 immune population (64). IL-6 contributes to increased T cell survival, which then accumulates in the lamina propria, leading to perpetuation of inflammation (65). Elevated proinflammatory levels of IL-6 have been identified in several chronic inflammatory conditions, including UC (1, 64), which is consistent with the increased systemic levels of IL-6 in acute experimental colitis of Clcn5 KO mice. Interestingly, we identified elevated baseline systemic levels of IL-6 in Clcn5 KO mice when compared with those in WT mice. We also demonstrated that Clcn5 KO mice exhibit elevated basal activation of IκB in colon, indicating the possibility that increased IκB and IL-6 activation at basal conditions may sensitize the Clcn5 KO mice to DSS-induced colitis. Further examination also identified elevated levels of IL-6 in proximal tubules, suggesting the likelihood that IL-6 may function as a proinflammatory mediator in Clcn5 KO mice. IL-6 has been previously demonstrated to enhance osteoclastogenesis by the induction of the NF-κB ligand in osteoblastic cells (66) and has also shown to be the central pathogenic player in arthritis. Given the multifaceted role of IL-6, our findings therefore suggest that the increased production of IL-6 under basal conditions in the kidney may explain the development of both hypercalcemia and nephrolithiasis in Clcn5 KO mice, although a direct correlation has not been established (67, 68). Moreover, elevated IL-6 is involved in defective bone mineralization, which may also explain the sporadic presentation of rickets/osteomalacia in patients with Dent disease (27, 51, 69–71).

Why does the lack of Clc-5 expression lead to alteration of both basal and DSS-induced immunological responses? Our preliminary study demonstrates that Clc-5, a Cl\(^{-}/\)H\(^{+}\) exchanger previously known to be expressed only in renal and intestinal epithelial cells (20, 28–30),
is highly expressed in macrophages. This finding implicates an interesting possibility that Clc-5 may play an important and previously unrecognized role in regulating innate immunity. It is therefore necessary to further study this potentially novel function of Clc-5 in macrophages.

Diet is also suspected to influence the severity of IBD symptoms by influencing the microbial flora and directly modulating the mucosal immune response of the host (72, 73). We observed attenuation of DSS colitis in Clcn5 KO mice maintained on a separate diet (Z-diet) containing high vitamin D, vitamin B₁₂, and selenium (and low iodine) (76). With the Z-diet, our data suggest that genetic predisposition appears to provide the substrate for such effects, implying the potential of a double-hit mechanism in the immunopathogenesis of UC, a disease contributed by both genetic and environmental factors. This therefore implies that diet can impact the severity of UC symptoms, particularly in patients genetically predisposed to either mutations or down-regulation of CLC5. Among the dietary factors that may be involved in modulation of DSS colitis, we identified vitamin D as a key factor contributing to the protective effect of DSS-induced colitis on Clcn5 KO mice. Vitamin D, recognized for a long time to play a significant immunomodulatory role, exerts a marked inhibitory effect on both adaptive and innate immune systems (74). Vitamin D has been reported to play a role in preventing or ameliorating IBD in the colitis model of IL-10 KO mice (53, 75). Furthermore, it was demonstrated that diet plays a role in preventing or ameliorating IBD in the colitis model of IL-10 KO mice. As a result, diet may play a role in the modulation of DSS-induced colitis, implicating a beneficial effect of dietary vitamin D in the therapy of colitis (76). Our present data provide additional strong evidence that dietary vitamin D is highly expressed in macrophages. This finding implicates an interesting possibility that Clc-5 may play an important and previously unrecognized role in regulating innate immunity. It is therefore necessary to further study this potentially novel function of Clc-5 in macrophages.

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