Compound loss of GSDMD and GSDME function is necessary to achieve maximal therapeutic effect in colitis

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Abbreviations: AIM2, absent in melanoma 2; ASC, apoptosis-associated speck-like protein containing a CARD; CD, Crohn disease; cGAS, cyclic guanosine monophosphate-adenosine monophosphate (GMP-AMP) synthase; CuET, bis(diethyldithiocarbamate)-copper; DSS, dextran sodium sulfate; GREM1, gremlin 1; GSDMD, gasdermin D; GSDME, gasdermin E; IBD, inflammatory bowel disease; IL-1β, interleukin-1β; IL-1R1, IL-1 receptor 1; NLRP3, NLR family, pyrin domain containing 3 (NLRP3), absent in melanoma 2 (AIM2), and caspase-11 upon detection of microbial or sterile danger molecules and subsequent inflammation in the gastrointestinal tract. IBD can be experimentally induced in animals by means of genetic manipulation (e.g., upon deletion of IL-10, TLR5, or T-bet) or upon exposure to chemicals (e.g., DSS, 2,4,6-trinitro-benzene sulfonic acid (TNBS), and ozaanolone) [6–11]. Despite shortcomings such as the inability of each model to fully recapitulate the complexity of human conditions, these experimental models are amenable to mechanistic studies. For example, the DSS model provides insight into the contribution of innate immune networks in colitis pathogenesis, since the acute inflammatory response induced by this irritant is independent of T and B cells [12–14].

IBD pathogenesis is associated with dysregulated functions of inflammasomes, intracellular multiprotein complexes that are assembled by pathogen recognition receptors such as NLR family, pyrin domain containing 3 (NLRP3), absent in melanoma 2 (AIM2), and caspase-11 upon detection of microbial or sterile danger molecules

1. Introduction

Genetic predispositions and environmental factors contribute to the pathogenesis of chronic inflammatory bowel disease (IBD), of which ulcerative colitis (UC) and Crohn disease (CD) are the most common manifestations [1,2]. UC mainly affects the mucosal lining of the colon and rectum whereas CD may affect any part of the gastrointestinal tract. These chronic relapsing-remitting disorders are associated with life-threatening complications, including considerable morbidity or risk of developing colorectal cancers [3,4]. Despite the encouraging data on clinical efficacy and mucosal healing, TNF-α antagonists are ineffective in up one-third of patients [5]. Thus, a better understanding of this disease is essential for developing efficacious and safe therapeutics.

The collapse of the gut epithelial barrier triggers unwanted interactions between the mucosal immune cells and colonic microflora and subsequent inflammation in the gastrointestinal tract. IBD can be experimentally induced in animals by means of genetic manipulation (e.g., upon deletion of IL-10, TLR5, or T-bet) or upon exposure to chemicals (e.g., DSS, 2,4,6-trinitro-benzene sulfonic acid (TNBS), and ozaanolone) [6–11]. Despite shortcomings such as the inability of each model to fully recapitulate the complexity of human conditions, these experimental models are amenable to mechanistic studies. For example, the DSS model provides insight into the contribution of innate immune networks in colitis pathogenesis, since the acute inflammatory response induced by this irritant is independent of T and B cells [12–14].

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2.1. Mice

FDA-approved drug for the treatment of alcohol addiction, our findings lay ground for exploring the efficacy of this drug in IBD patients.

Accordingly, a recent study reports that signaling downstream of IL-1 receptor 1 (IL-1R1) by R-spondin 3 (RSPO3) and IL-22 is important for epithelial recovery after Citrobacter rodentium infection whereas IL-1R1-dependent production of RSPO3 by gremlin 1 (GREM1)-positive mesenchymal cells alone is sufficient for recovery after DSS-induced colitis [28]. Yet, blockade of IL-18 or IL-1 signaling is claimed to alleviate DSS-induced colitis [3,20,29]. Those conflicting results underscore the complexity of inflammasome actions in IBD pathogenesis.

To elucidate the role of GSDMD and GSDME in colitis, we administered DSS to mice with single or compound loss of these proteins or WT mice exposed to bis(diethyldithiocarbamate)-copper (CuET), an inhibitor of GSDMD and GSDME [36]. We found that genetic inactivation of CBDC37/Hsp90 and the E3 ligase, NEDD4, which catalyzes IL-1β ubiquitination [38] but is inconsistent with the severe colitis phenotype of another mouse strain lacking GSDMD [39]. In the latter report, GSDMD presumably preserves gut homeostasis by dampening cyclic guanosine monophosphate-adenosine monophosphate (GMP-AMP) synthase (cGAS) inflammatory actions in macrophages but not epithelial cells [39]. However, GSDMD can also promote caspase-8-dependent IL-1β secretion in intestinal epithelial cells (IECs) through pore formation-independent mechanisms involving the recruitment of Cdc37/Hsp90 and the E3 ligase, NEDD4, which catalyzes IL-1β polyubiquitination [38]. Evidence also implicates GSDME expressed by intestinal epithelial cells (IECs) in TNBS-induced colitis [40]. However, the interplay between GSDMD and GSDME during the pathogenesis of colitis has yet to be investigated.

2. Materials and methods

2.1. Mouse

Gsdmd knockout (Gsdmd−/−) mice were kindly provided by Dr. V.M. Dixit and Dr. N. Kayagki (Genentech, South San Francisco, CA). Gsdme−/− mice were purchased from Jackson Laboratory. All mice were on the C57BL/6 background, and mouse genotyping was performed by PCR. All procedures were approved by the Institutional Animal Care and Use Committee (IACUC) of Washington University School of Medicine in St. Louis. All experiments were performed in accordance with the relevant guidelines and regulations described in the IACUC-approved protocol#19–0971.
3. Results

3.1. Inactivation of Gsdmd or Gsdme attenuated DSS-induced colitis

Proteolytic cleavage of GSDMD and GSDME generates amino-terminal fragments (GSDMD-NT and GSDME-NT, respectively), which are endowed with pore-forming activity [32–37]. To determine the fate of GSDMD and GSDME in colitis-associated acute inflammation, we fed mice with DSS polymers in the drinking water and analyzed the processing of these proteins in colon lysates. Immunoblotting analysis revealed that GSDMD full-length (GSDMD-FL) and GSDME-FL were readily detected in samples from wild-type (WT) but not the corresponding null mice, as expected (Fig. 1A). Loss of GSDMD resulted in slightly decreased GSDME-FL levels, and vice-versa. Unlike GSDME-NT, GSDMD-NT was readily detected in samples from DSS-treated WT mice, and barely in samples from Gsdme knockout (Gsdme−/−) mice treated with this irritant (Fig. 1A). Pro-IL-1β levels were markedly decreased in samples from knockout mice compared to WT counterparts (Fig. 1B).
a result, mature IL-1β p17 was detected only in WT samples (Fig. 1B). Thus, the maturation of GSDMD and IL-1β, but not GSDME, is readily noticeable in the colon lysates from DSS-treated WT mice.

To determine the impact of GSDMD and/or GSDME deficiency on DSS-induced colitis, we assessed a battery of reliable surrogate marker of morbidity associated with this disease in WT and mutant mice. Oral administration of the sulfated polysaccharide DSS to WT mice caused body weight loss noticeable by day 5, reaching up to 25% by day 9 post-treatment (Fig. 1C). DSS-exposed Gsdmd<sup>−/−</sup> and Gsdme<sup>−/−</sup> mice also lost body weight equally but to a significantly lesser extent compared to WT

![DSS-treated mice](image)

**Fig. 2.** Loss of GSDMD or GSDME attenuated DSS-induced colon damage and cytokine secretion. Mice were administrated with 2.5% DSS in drink water for 9 days. Colons were collected for histology or tissue culture. (A) Representative of histology pictures for each mouse. (B) Histology score for each mouse group. (C) IL-1β concentrations in tissue culture medium. (D) IL-18 concentrations in tissue culture medium. Data are mean ± SEM. N = 5 mice/group. *p < 0.05; **p < 0.005; ****p < 0.0001. One-Way ANOVA. NS, non-significant; WT, wild-type.
cohorts (Fig. 1C). Remarkably, compound knockout mice barely lost body weight during the evaluation period of this study (Fig. 1C). Accordingly, disease activity index (DAI) score, which was similarly lower in \textit{Gsdmd} \textsuperscript{-/-} and \textit{Gsdme} \textsuperscript{-/-} mice compared to WT littermates was further decreased in \textit{Gsdmd} \textsuperscript{-/-};\textit{Gsdme} \textsuperscript{-/-} mice (Fig. 1D). We also measured colon length, the parameter with the lowest variability in the model of DSS-induced colitis [14]. The colons were longer in \textit{Gsdmd} \textsuperscript{-/-} and \textit{Gsdme} \textsuperscript{-/-} mice compared to WT controls, but shorter relative to \textit{Gsdmd} \textsuperscript{-/-};\textit{Gsdme} \textsuperscript{-/-} mice (Fig. 1E and F).

Histopathological analysis of hematoxylin and eosin (H&E)-stained colonic sections from DSS-treated WT mice showed severely compromised integrity of the mucosal barrier, loss of epithelial cells, and massive neutrophil infiltrations (Fig. 2A and B). These outcomes were significantly attenuated in \textit{Gsdmd} \textsuperscript{-/-} or \textit{Gsdme} \textsuperscript{-/-} mice, though to a lesser extent in the latter cohort. Remarkably, double knockout mice appeared protected from DSS-induced tissue damage (Fig. 2A and B). Consistent with histopathological findings, IL-1\textbeta and IL-18 levels were lower in cultured colon explants from \textit{Gsdmd} \textsuperscript{-/-} and \textit{Gsdme} \textsuperscript{-/-} mice compared to WT controls, but further decreased or undetectable in those from \textit{Gsdmd} \textsuperscript{-/-};\textit{Gsdme} \textsuperscript{-/-} mice (Fig. 2C and D). Collectively, these results suggest that GSDMD and GSDME play an important role in DSS-induced inflammation in the colon and the ensuing tissue damage.

3.2. CuET inhibited DSS-induced colitis

Since GSDMD and GSDME are implicated in colitis [38–40], recent data indicating that CuET inhibits the maturation and pore-forming activity of these proteins provided a strong rationale for translational
studies aimed at testing the efficacy of this drug in colitis, as outlined in Fig. 3A. Immunoblotting analysis revealed that CuET administration did not affect baseline GSDMD and GSDMD-NT levels in colon lysates from naïve WT mice (Fig. 3B). DSS treatment increased the levels of GSDMD-FL and GSDMD-NT, but failed to induce this response in mice pre-treated with CuET. DSS slightly increased GSDME-FL levels, but GSDME-NT was not detected in any of these conditions (Fig. 3B), findings that are consistent with those shown in Fig. 1A. Consistent with the result described above (Fig. 1C), administration of DSS to WT mice caused time-dependent body weight loss starting on day 2 and progressing linearly until day 9 post-treatment (Fig. 3C). CuET did not affect body weight of naïve mice throughout the duration of this study, suggesting that it was well tolerated. Importantly, treatment with CuET delayed DSS-induced body weight as it was not different from untreated mice until day 6 post-treatment (Fig. 3C). CuET also attenuated DAI score (Fig. 3D) and disease-associated colon shortening (Fig. 3E and F) compared to WT controls. H&E-based histopathological analysis revealed that colonic architecture of naïve mice was unperturbed by CuET treatment (Fig. 4A). DSS-induced toxicity, which included epithelial defects, crypt atrophy, and massive neutrophil infiltrations, was reduced in CuET-treated mice (Fig. 4A and B). Thus, the severe gut pathology caused by DSS in mice is attenuated upon treatment with CuET.

4. Discussion

We found that amino-terminal pore-forming fragments from GSDMD but not GSDME were readily detected in colon extracts from mice exposed to DSS. Our inability to detect GSDME-NT fragments in DSS-treated mice was unexpected given the comparable colitogenic phenotype of mice lacking GSDMD or GSDME. Although secretory conduits assembled by amino-terminal fragments and ultimately cell lysis are the main mechanism of GSDM actions, a recent study reported the lytic activity-independent function of GSDMD in colitis [38]. Therefore, it is tempting to speculate that GSDME may promote colitis independently of its processing and pore-forming activity. Alternatively, GSDME amino-terminal fragments may have been undetectable simply because they were lost from pyroptotic cells as immunoblotting analyses were carried out using sample extracts from mainly non-pyroptotic cell lysates. Our results underscore the complexity of evaluating GSDME fate in vivo. This view is supported by a recent report indicating that cleaved GSDMD fragments were readily detected in myeloid cells but barely in IECs of mice exposed to DSS even with comparable expression levels of GSDMD in both cell compartments [39]. Despite apparent differences in the fate of these GSDMs, as noted above, we found that inactivation of
Gasmd or Gsdme attenuates DSS-induced colitis, an outcome further reduced in double knockout mice. These results are consistent with recent reports indicating that GSDMD or GSDME deficiency reduced the severity of experimental colitis [38,40], but they conflict with others’ findings implicating GSDMD in the pathogenesis of colitis [39]. Biological variables that underlie these discrepancies are unclear but may include the age, sex, strains, and microbiota composition of mice.

We discovered that CuET inhibits DSS-induced colitis, an outcome that correlated with inhibition of GSDMD cleavage and decreased levels of GSDMF-L. Residual inflammatory responses in CuET-treated mice may be due to suboptimal dosing regimens, as serum concentrations of the drug were not monitored to ensure that appropriate exposure levels were achieved. CuET inactivates GSDMD presumably by modifying Cys191, but the mechanisms of its inhibition of GSDMD remain unclear. Despite shortcomings in the mechanisms of action of CuET, the results reported here are consistent with its efficacy in autoimmune and auto-inflammatory disease models [36,43,44].

Our findings demonstrate that genetic inactivation of GSDMD and GSDME or functional blockade of these proteins by CuET inhibits the pathogenesis of experimental colitis. They provide a rationale for evaluating the utility of this drug for the treatment of IBD in human patients.

Data availability

This study includes no data deposited in external repositories.

Author contributions

Study conception and design: JX, GM. Acquisition of data and methodology: JX, KS, CW. Analysis and interpretation of data: JX, KS, CW, YA, GM. *Editing: JX, YA. Writing: JX, GM.

Declaration of competing interest

Dr. Gabriel Mbalaviele is consultant for Aclaris Therapeutics, Inc. All other authors declare no conflict of interest.

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