The gut lactic acid bacteria metabolite, 10-oxo-*cis*-6,*trans*-11-octadecadienoic acid, suppresses inflammatory bowel disease in mice by modulating the NRF2 pathway and GPCR-signaling

Short title: γKetoC ameliorates DSS-induced colitis

Miki Ando[1†], Kazuki Nagata[1†], Naoto Ito[1†], Sakura Noguchi[1], Asuka Yamamoto[1], Naoki Kodama[1], Takuya Yashiro[1], Masakazu Hachisu[1], Gaku Ichihara[2], Shigenobu Kishino[3], Masayuki Yamamoto[4], Jun Ogawa[3], and Chiharu Nishiyama[1]

[1] Department of Biological Science and Technology, Faculty of Advanced Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan

[2] Department of Occupational and Environmental Health, Faculty of Pharmaceutical Science, Tokyo University of Science, 2641 Yamazaki, Noda, Chiba 278-8510, Japan

[3] Division of Applied Life Sciences, Graduate School of Agriculture, Kyoto University, Kitashirakawa-oiwakecho, Sakyo-ku, Kyoto 606-8502, Japan

[4] Department of Medical Biochemistry, Tohoku University Graduate School of Medicine, Sendai, Japan

[†] These authors contributed equally to this work and share first authorship.

Correspondence should be addressed to: Chiharu Nishiyama, Ph.D.
Department of Biological Science and Technology, Faculty of Advanced Engineering, Tokyo University of Science, 6-3-1 Niijuku, Katsushika-ku, Tokyo 125-8585, Japan
Phone: +81-3-5876-1468; Email: chinishi@rs.tus.ac.jp

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Abstract

Various gut bacteria, including *Lactobacillus plantarum*, possess several enzymes that produce hydroxy fatty acids (FAs), oxo FAs, conjugated FAs, and partially saturated FAs from polyunsaturated FAs as secondary metabolites. Among these derivatives, we identified 10-oxo-*cis*-6,*trans*-11-octadecadienoic acid (γKetoC), a γ-linolenic acid-derived enon FA, as the most effective immunomodulator, which inhibited the antigen-induced immunoactivation and the LPS-induced production of inflammatory cytokines. The treatment with γKetoC markedly increased the protein level of NRF2, a master transcription factor for antioxidant responses, and the mRNA level of *Hmox1*, a target gene of NRF2, in bone marrow-derived dendritic cells (BMDCs). Although γKetoC significantly suppressed the LPS-induced activation of control BMDCs, particularly the secretion of IL-12/23p40, the suppressive effects of γKetoC were reduced in *Nrf2*$^{-/-}$ BMDCs. GW9508, an agonist of GPR40/GPR120, inhibited the release of cytokines from LPS-stimulated BMDCs without activating the NRF2 pathway. We evaluated the role of NRF2 in the anti-inflammatory effects of γKetoC in a dextran sodium sulfate-induced colitis model. The oral administration of γKetoC significantly reduced body weight loss, improved stool scores, and attenuated atrophy of the colon, in wild-type C57BL/6J and *Nrf2*$^{+/-}$ (C57BL/6N) mice with colitis. In contrast, the pathology of colitis was deteriorated in *Nrf2*$^{-/-}$ mice even with the administration of γKetoC.

Collectively, the present results demonstrated the involvement of the NRF2 pathway in γKetoC-mediated anti-inflammatory responses.

Keywords:

colitis, dendritic cell, inflammatory cytokine, NRF2, polyunsaturated fatty acid

Abbreviations: Ab; antibody, Ag; antigen, αHYA; 10-hydroxy-*cis*-12,*cis*-15-octadecadienoic acid, αKetoA; 10-oxo-*cis*-12,*cis*-15-octadecadienoic acid, αKetoC; 10-oxo-*trans*-11,*cis*-15-octadecadienoic acid, APCs; antigen-presenting cells, BMDCs; bone marrow-derived dendritic cells, DCs; dendritic cells, γHYA; 10-hydroxy-*cis*-6,*cis*-12-octadecadienoic acid, γKetoA; 10-oxo-*cis*-6,*cis*-12-octadecadienoic acid, γKetoC; 10-oxo-*cis*-6,*trans*-11-octadecadienoic acid, LA; linoleic acid, ALA; α-linolenic acid, GLA; γ-linolenic acid, HYA; 10-hydroxy-*cis*-12-octadecenoic acid, KetoA; 10-oxo-*cis*-12-octadecenoic acid, KetoC; 10-oxo-*trans*-11-octadecenoic acid, NRF2; NF-E2-related factor 2, OVA; ovalbumin, p.o.; per os

Introduction

In the intestines, various secondary metabolites are produced by intestinal bacteria using food ingredient-derived materials as substrates. Several bacteria metabolites exert beneficial effects on the host body, such as short-chain fatty acids (FAs) produced from dietary fibers by *Clostridium*, which are involved in the maintenance of homeostasis and prevention of immune-related inflammatory diseases by modulating the function of both hematopoietic cells and non-hematopoietic cells. Although polyunsaturated FAs (PUFAs) are catalyzed by enzymes in host cells to achieve various bioactivities and their relationships with inflammatory diseases have been vigorously studied with a focus on the ω3/ω6 balance (1), a recent study revealed that PUFAs are also converted to derivatives, including hydroxy FAs, oxo FAs, conjugated FAs, and partially saturated FAs, through the catalysis of enzymes identified in the gut lactic acid bacterium, *Lactobacillus plantarum* (2). The PUFA metabolite 10-hydroxy-*cis*-12-octadecenoic acid (HYA), a hydroxy FA derived from linoleic acid (LA), regulates glucose homeostasis by activating GPR40 and GPR120, and increases resistance to obesity (3). The HYA-mediated activation of GPR40 has also been shown to accelerate the recovery of an impaired intestinal epithelial barrier (4) and disrupted gingival epithelial barrier (5). The metabolite 10-oxo-*cis*-12-octadecenoic acid (KetoA), an oxo FA derived from LA, enhances energy metabolism by activating TRPV1 in adipose tissue and exerts anti-obesity effects on the host body (6). KetoA is also involved in the regulation of host energy metabolism by accelerating adipocyte differentiation, adiponectin production, and glucose uptake through the activation of PPARγ (7). Another LA derivative 10-oxo-*trans*-11-octadecenoic acid (KetoC), an enon FA, was found to regulate the function of monocytes (8) and epithelial cells (9) via GPR120 signaling. Although

accumulating evidence has demonstrated the beneficial effects of the bacteria metabolites of PUFAs on the host body, the roles of these metabolites in immune-related events remain unclear.

In the present study, we examined the effects of the bacteria-generated FAs on antigen (Ag)-induced immunoresponses and revealed that enon FAs suppressed the proliferation of T cells and the activation of dendritic cells (DCs). Detailed analyses focusing on 10-oxo-*cis*-6,*trans*-11-octadecadienoic acid (γKetoC), an enon FA derived from γ-linolenic acid (GLA), demonstrated that the expression of inflammatory cytokines in LPS-stimulated DCs was inhibited by γKetoC. This was partly dependent on the NF-E2-related factor 2 (NRF2) pathway, which modulated GPCR signaling, but was not activated by the stimulation of GPR40/120 signaling.

Methods

Mice

C57BL/6 mice were purchased from Japan SLC (Hamamatsu, Japan). OT-II mice purchased from The Jackson Laboratory (USA) and previously generated *Nrf2*$^{-/-}$ mice (10) were maintained on the C57BL/6J and C57BL/6N backgrounds, respectively. Mice were housed in a specific pathogen-free facility, and all animal experiments were performed in accordance with the guidelines of the Institutional Review Board of Tokyo University of Science. The present study was approved by the Animal Care and Use Committees of Tokyo University of Science: K22005, K21004, K20005, K19006, K18006, K17009, and K17012.

Cells

Bone marrow-derived DCs (BMDCs) generated as previously described (11), were stimulated with 100 ng/mL LPS (#L3024, Fujifilm Wako Chemicals Co., Ltd., Japan). GW9508 (#10008907, Cayman Chemical, Ann Arbor, MI, USA) was used as an agonist of GPR40 and GPR120. Ovalbumin (OVA) peptide 323-339 (POV-3636-PI, Peptide Institute Inc., Osaka, Japan) was added to the culture medium of whole spleen cells prepared from OT-II mice to induce the antigen-presenting cell (APC)-dependent activation of CD4^{+} T cells. The MojoSort Mouse Naïve CD4^{+} T cell Isolation Kit (#480040, BioLegend), anti-CD3ε antibody (Ab) (clone 145-2C11, BioLegend), and anti-CD28 Ab (clone 37.51, BioLegend) were used for the isolation and stimulation of CD4^{+} T cells, respectively, as previously described (12).

Preparation of PUFA metabolites

Hydroxy, oxo, and enon FAs were prepared from LA, α-linolenic acid (ALA), and GLA, using the conversion enzymes isolated from *L. plantarum* AKU1009 (2). LA (#126-06571), and ALA (#122-05831) were purchased from Fujifilm Wako Chemicals and GLA (#L0152) from Tokyo Chemical Industry Co., Ltd. (Tokyo, Japan).

Enzyme-linked immunosorbent assay (ELISA)

The concentrations of mouse cytokines were measured using ELISA kits purchased from BioLegend (#431004 for IL-2, #431315 for IL-6, #430915 for TNF-α, and #431604 for IL-12p40, respectively).

Flow cytometry

CFSE (eBioscience Inc., San Diego, CA, USA) was used to monitor the proliferation of T cells. Surface MHC class II and CD86 on BMDCs were stained with anti-I-A/I-E-PerCP (clone M5/114.15.2, BioLegend) and anti-CD86-PE (clone GL-1, BioLegend), respectively. Fluorescence was detected by a MACS Quant Analyzer (Miltenyi Biotech) and analyzed with FlowJo (Tomy Digital Biology Co., Ltd., Tokyo, Japan).

Quantification of mRNA

The extraction of total RNA, synthesis of cDNA, and quantitative PCR were performed as previously described (13).

Western blot analysis

A Western blot analysis was performed with anti-NRF2 Ab (clone D1Z9C, Cell

Signaling) and anti-β-actin Ab (clone AC-15, Sigma-Aldrich) as previously described (14).

Dextran sodium sulfate (DSS)-induced colitis

To induce colitis, mice were administered 2.5% (w/v) DSS (#160110, MP Biomedicals, Santa Ana, USA) in their drinking water. γKetoC (15 mg/kg/day) or vehicle (100 μl soybean oil) was orally administered using a sonde (#5202K, Fuchigami, Kyoto, Japan).

Statistical analysis

A two-tailed Student's t-test was used for comparisons of two samples. To compare more than three samples, a one-way ANOVA-followed by the Tukey-Kramer multiple comparison test or Dunnett's multiple comparison test was used. P values <0.05 were considered to be significant.

Results

Effects of bacteria metabolites of PUFAs on Ag-dependent responses in vitro

To examine the effects of bacteria metabolites of PUFAs on Ag-induced immunoresponses, we incubated OVA-stimulated OT-II spleen cells in the presence or absence of 50 μM of each metabolite for 48 h. The treatments with KetoC, αKetoC, γKetoA, and γKetoC markedly reduced the concentration of IL-2 in culture media, whereas those with HYA, αHYA, and γHYA did not (Fig. 1A). We then compared the suppressive effects of enon FAs on IL-2 production with those of the original PUFAs without conversion, and found that KetoC, αKetoC, and γKetoC significantly and dose-dependently suppressed IL-2 production, whereas apparent effects were not observed in LA, ALA, and GLA (Fig. 1B).

These results indicate that converted FAs carrying the enon structure acquired immunosuppressive effects, which were not observed in hydroxy FAs and were moderately induced in oxo FAs.

Suppressive effects of enon FAs on T cell proliferation and DC activation

To identify the cells in splenocytes that were regulated by the enon FAs, we examined the proliferation of T cells and the activation of DCs in the presence of enon FAs. The proliferation of naïve $CD4^+$ T cells, which was induced by the treatment with plate-coated anti-CD3 and anti-CD28 Abs independent of APC, was suppressed by all three FAs at 50 μM (Fig. 1C). The pretreatment with 50 μM enon FAs also inhibited the up-regulation of MHC class II and CD86 on DCs (Fig. 1D) and the release of IL-6 and TNF-α from DCs (Fig. 1E) 24 h after the LPS stimulation.

These results demonstrate that enon FAs inhibited the activation of both of DCs and T

cells, resulting in the suppression of Ag-induced IL-2 production in OT-II splenocytes.

Involvement of the NRF2 pathway in the γKetoC-mediated suppression of DCs

To elucidate the mechanisms underlying the immunosuppressive effects of enon FAs, we performed further analyses with a focus on γKetoC as the strongest suppressor among the three enon FAs. We confirmed that γKetoC significantly suppressed the LPS-induced production of IL-6 in whole leukocytes isolated from the spleen and peritoneal cells (Fig. 2A). Measurements of the mRNA levels of cytokines in LPS-stimulated BMDCs revealed that the inhibitory effects of γKetoC on transactivation was marked in the *Il12b*, and significant in *Il6* and *Tnf*, but not significant in *Il1b* (Fig. 2B). Previous studies reported that KetoC induced the expression of the antioxidant-related genes through the activation of NRF2, a master transcription factor of antioxidant responses, in the hepatic cell line HepG2 (15), and epithelial cell line Epi4 (9). In addition, a NRF2 deficiency enhanced the expression of IL-12p40 in stimulated DCs (16). Therefore, to confirm whether γKetoC induced an antioxidant response via the activation of NRF2 in DCs, we examined NRF2 protein levels in γKetoC-treated DCs using Western blotting. As shown in Fig. 2C, the expression of NRF2 in BMDCs peaked at 1 h after the addition of γKetoC. The mRNA levels of *Hmox1*, a target gene of NRF2, were also increased in γKetoC-treated DCs (Fig. 2D). Furthermore, the release of IL-12p40 and TNF-α in the presence of γKetoC from *Nrf2*$^{-/-}$ DCs stimulated by LPS was significantly and moderately greater, respectively, than that from control DCs (Fig. 2E).

Roles of Gq-GPCRs in DC activation

Previous studies demonstrated that KetoC inhibited the LPS-induced activation of the monocyte cell line RAW264.7 with binding to GPR120 (8), and KetoC-induced NRF2 signaling was mediated by GPR120 in epithelial cells (9). GPR120 is expressed in adipocytes, macrophages, and DCs (17), and GPR120 mRNA, but not GPR40 mRNA, was detected in the BMDCs generated under our experimental conditions (data not shown). To examine the involvement of GPR120 in the γKetoC-mediated suppression of DCs, we treated BMDCs with GW9508, an agonist common to GPR40/GPR120, and revealed that GW9508 inhibited the LPS-induced release of IL-12p40 in a dose-dependent manner (Fig. 3A), suggesting that the stimulation of GPR120 suppressed the LPS-induced activation of DCs. To elucidate the relationship between GPR120 signaling and the NRF2 pathway in DCs, we then treated *Nrf2*$^{-/-}$ DCs with GW9508. As shown in Fig. 3B, GW9508 suppressed the release of cytokines from LPS-stimulated control DCs, whereas the inhibitory effects of GW9508 were reduced in *Nrf2*$^{-/-}$ DCs. In contrast to γKetoC, which induced the expression of *Hmox1* in DCs, GW9508 did not increase *Hmox1* mRNA levels in control DCs (Fig. 3C).

These results indicate that the NRF2 pathway modulated GPR120 signaling, while the stimulation of GPR120 did not activate NRF2 in DCs.

Oral administration of γKetoC ameliorates DSS-induced colitis

We utilized a DSS-induced colitis model to examine the protective effects of γKetoC on inflammatory responses *in vivo*. In the first colitis experiment, wild-type C57BL/6J mice were orally administered γKetoC (Fig. 4A). We found that the pathology of colitis, reflected by the loss of body weight and increases in the disease activity index (DAI) score, was alleviated by the intake of γKetoC (Fig. 4B). Fibrosis-mediated atrophy of

the colon in mice with colitis was significantly reduced in γKetoC-treated mice (Fig. 4C). In the next experiment, we investigated the roles of NRF2 in the γKetoC-mediated amelioration of colitis by using *Nrf2*$^{-/-}$ mice (Fig. 4D). The administration of γKetoC was initiated 4 days earlier than that in the first experiment and the results obtained revealed that the loss of body weight and increases in the DAI score were significantly suppressed by γKetoC in *Nrf2*$^{+/-}$ mice, but not in *Nrf2*$^{-/-}$ mice (Fig. 4E). Atrophy of the colon in *Nrf2*$^{+/-}$ mice was significantly restored by the intake of γKetoC, with the length of the colon being similar with and without the administration of γKetoC in *Nrf2*$^{-/-}$ mice (Fig. 4F).

Discussion

The gut microbiota metabolizes food ingredients, and the resulting compounds exert beneficial effects on homeostasis in the host body. PUFAs, which are positively associated with inflammatory diseases depending on the amount consumed and the ω3/ω6 ratio, were recently shown to be modified by the enzymes of gut bacteria (2). Although previous studies demonstrated the useful effects of the bacteria metabolites of PUFAs on host health, particularly the attenuation of metabolic disorders (3, 6, 7), their effects on immunoresponses remain unclear.

The present results revealed that enon FAs suppressed Ag-mediated immunoresponses, which were not observed for their precursors, namely, LA, ALA, and GLA, or hydroxy FAs. Further analyses with a focus on γKetoC indicated that γKetoC suppressed the release of inflammatory cytokines from LPS-stimulated DCs, whole splenocytes, and peritoneal cells. KetoC has been shown to inhibit the expression of inflammatory cytokines in LPS-stimulated RAW264.3 cells, and this was mitigated by a GPR120 antagonist, but not a GPR40 antagonist (8). In contrast to GPR40, which is a receptor for long-chain FAs as well as GPR120, but is highly expressed in the pancreas and liver and is involved in metabolism, GPR120 has an anti-inflammatory role as an receptor for ω3 FAs (17). Since HYA, which activates GPR40 (3-5), did not suppress the production of IL-2 by OVA-stimulated OT-II splenocytes in the present study, GPR40 might not play a prominent role in the regulation of inflammatory responses by immune-related cells. Based on the result showing that GW9508, a common agonist of GPR40 and GPR120, also reduced cytokine production by DCs, we speculate that GPR120 is involved in the anti-inflammatory effects of γKetoC as its receptor; however, we need to confirm this hypothesis in further experiments using a specific antagonist, siRNA, or

knockout (KO) mice. γKetoC, KetoC, and αKetoC are categorized as ω7, ω7, and ω3, respectively. The structure of a FA required for ligand activity against GPR120 may not be the location of the unsaturated bond, but rather other factors, which were increased in enon FAs. If the enon structure is essential for binding to GPR120, metabolism by bacteria confers anti-inflammatory effects on dietary PUFAs.

In a SV40-T-transformed human gingival epithelial cell line, KetoC induced ERK phosphorylation and the subsequent activation of the NRF2 pathway via GPR120 (9). Under our experimental conditions, the GPR120 agonist did not induce *Hmox1* transactivation in DCs, whereas the suppressive effects of the GPR120 agonist on cytokine production in DCs were reduced by a NRF2 deficiency. These results suggest that γKetoC activated both the NRF2 pathway and GPR120 in DCs and also that the NRF2 pathway modulated GPR120 activity, whereas the stimulation of GPR120 did not induce an antioxidant response in DCs.

γKetoC increased NRF2 protein and *Hmox1* mRNA levels in DCs, and NRF2 deficiency reduced the anti-inflammatory effects of γKetoC both *in vitro* and *in vivo*. NRF2 is a ubiquitous transcription factor, and *Nrf2* KO mice exhibit severe inflammation in various immune-related diseases, including contact hypersensitivity, autoimmune disease, colitis, and psoriasis (18-23). Therefore, γKetoC and other enon FAs have the potential to prevent and/or treat immune-related diseases. In addition, since we recently demonstrated that γKetoC suppressed osteoclast development and macrophage activation (24), it may also attenuate rheumatoid arthritis.

The present study showed that several bacteria metabolites of PUFAs, particularly enon FAs, were involved in the regulation of immunoresponses, which were not observed for their precursors. The NRF2 pathway and GPR120, both of which play important roles in

anti-inflammatory responses, appear to be involved in the effects of γKetoC. The intake of γKetoC ameliorated colitis in mice in a NRF2-dependent manner. Based on these results, we conclude that gut bacteria and their metabolites of PUFAs exert beneficial effects on immune homeostasis in the host body.

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Legends

Figure 1. Effects of bacteria metabolites of PUFAs on the activation of T cells and DCs *in vitro*

A. and **B.** IL-2 concentrations in the culture media of splenocytes incubated in the presence or absence of OVA and FAs. In total, 1.0 x 10^5/200 μL of OT-II spleen-derived single cell-suspended cells were stimulated by 2.5 μg/mL OVA with or without 50 μM bacteria metabolites of PUFAs or vehicle (ethanol) for 48 h (**A**). The indicated concentrations of enon FAs or their starting PUFAs were added to the culture media of OT-II spleen-derived cells with OVA during a 48-h incubation (**B**).

C. The proliferation of $CD4^+$ T cells stimulated with plate-coated anti-CD3 and anti-CD28 Abs. $CD4^+$ T cells, which were isolated from the C57BL/6 spleen and were stained with CFSE, were incubated in Abs-coated dishes in the presence of 50 μM enon FAs for 72 h.

D. Cell surface expression levels of MHC class II and CD86 in LPS-stimulated DCs. In total, 5.0 x 10^6/2 mL of BMDCs were stimulated by 100 ng/mL LPS for 24 h in the presence or absence of 50 μM enon FAs. MFIs were shown as a ratio to that of LPS-stimulated BMDCs without FAs.

E. Concentrations of cytokines in the culture media of LPS-stimulated DCs. In total, 5.0 x 10^6/2 mL of BMDCs were stimulated by 100 ng/mL LPS for 24 h in the presence or absence of 50 μM enon FAs.

Data represent the mean ± SEM of three independent experiments performed in triplicate (**A**-**E**). The Dunnett's test (**A**, **B**) and the Tukey-Kramer test (**C**-**E**) were used. $*p < 0.05$, $**p < 0.01$.

Figure 2. Involvement of the NRF2 pathway in the suppressive effects of γKetoC on DCs

A. IL-6 release from LPS-stimulated spleen cells and peritoneal cells was reduced by a treatment with γKetoC. Spleen cells (5.0 x 10^6/mL) and peritoneal cells (4.0 x 10^5/mL) were stimulated with 100 ng/mL LPS for 24 h with or without 50 μM γKetoC.

B. mRNA levels of cytokine genes in LPS-stimulated DCs. 1.0 x 10^6/mL of BMDCs were stimulated by 100 ng/mL LPS for 4 h in the presence or absence of 50 μM enon FAs.

C. NRF2 protein levels in γKetoC-treated DCs. BMDCs were cultured in the presence of 50 μM γKetoC for the indicated times, and aliquots of the whole cell lysate containing 10 μg of protein were applied to each lane of SDS-PAGE for Western blotting. Representative results were obtained in three independent experiments and a typical result is shown in this figure.

D. mRNA levels of *Hmox1* in BMDCs derived from NRF2 deficient mice and its control.

E. The amounts of cytokines released from NRF2-deficient DCs and their control DCs.

BMDCs derived from *Nrf2*$^{+/+}$, *Nrf2*$^{+/-}$, or *Nrf2*$^{-/-}$ mice, which were pretreated with or without γKetoC for 24 h, were cultured in the presence or absence of LPS for an additional 24 h (**D** and **E**).

Data represent the mean ± SEM of three independent experiments performed in triplicate (**A**, **B**, **D**, **E**). The Tukey-Kramer test was used. *$p < 0.05$, **$p < 0.01$

Figure 3. Roles of Gq-GPCR-signaling in the effects on DCs

A. IL-12 release from LPS-stimulated DCs in the presence of the indicated

concentrations of a Gq agonist. BMDCs (C57BL/6J) pretreated in the presence or absence of the indicated concentrations of γKetoC or GW9508 for 24 h, were cultured with or without LPS for an additional 24 h.

B. Effects of a Gq agonist on the release of cytokines from NRF2-deficient DCs. BMDCs derived from *Nrf2*$^{+/-}$ or *Nrf2*$^{-/-}$ mice, which were pretreated in the presence or absence of the indicated concentrations of γKetoC or GW9508 for 24 h, were stimulated with LPS for 24 h.

C. mRNA levels of *Hmox1* in Gq-agonist treated DCs. *Nrf2*$^{+/-}$ BMDCs and *Nrf2*$^{-/-}$ BMDCs were incubated in the presence or absence of γKetoC or GW9508 for 3 h.

Data represent the mean ± SEM of three independent experiments performed in triplicate (**A**-**C**). The Dunnett's test (**A**) and the Tukey-Kramer test (**B**, **C**) were used. *$p < 0.05$, **$p < 0.01$.

Figure 4. Effects of γKetoC on colitis in mice

A. Schematic of the oral administration schedule of γKetoC in the DSS-induced colitis model. C57BL/6J mice were orally administered 15 mg/kg/day of γKetoC in 100 μl soybean oil or vehicle.

B. Percent body weight change from that measured on day 0 (left), and disease activity index (DAI) scores (right).

C. Images (left) and length (right) of the large intestine.

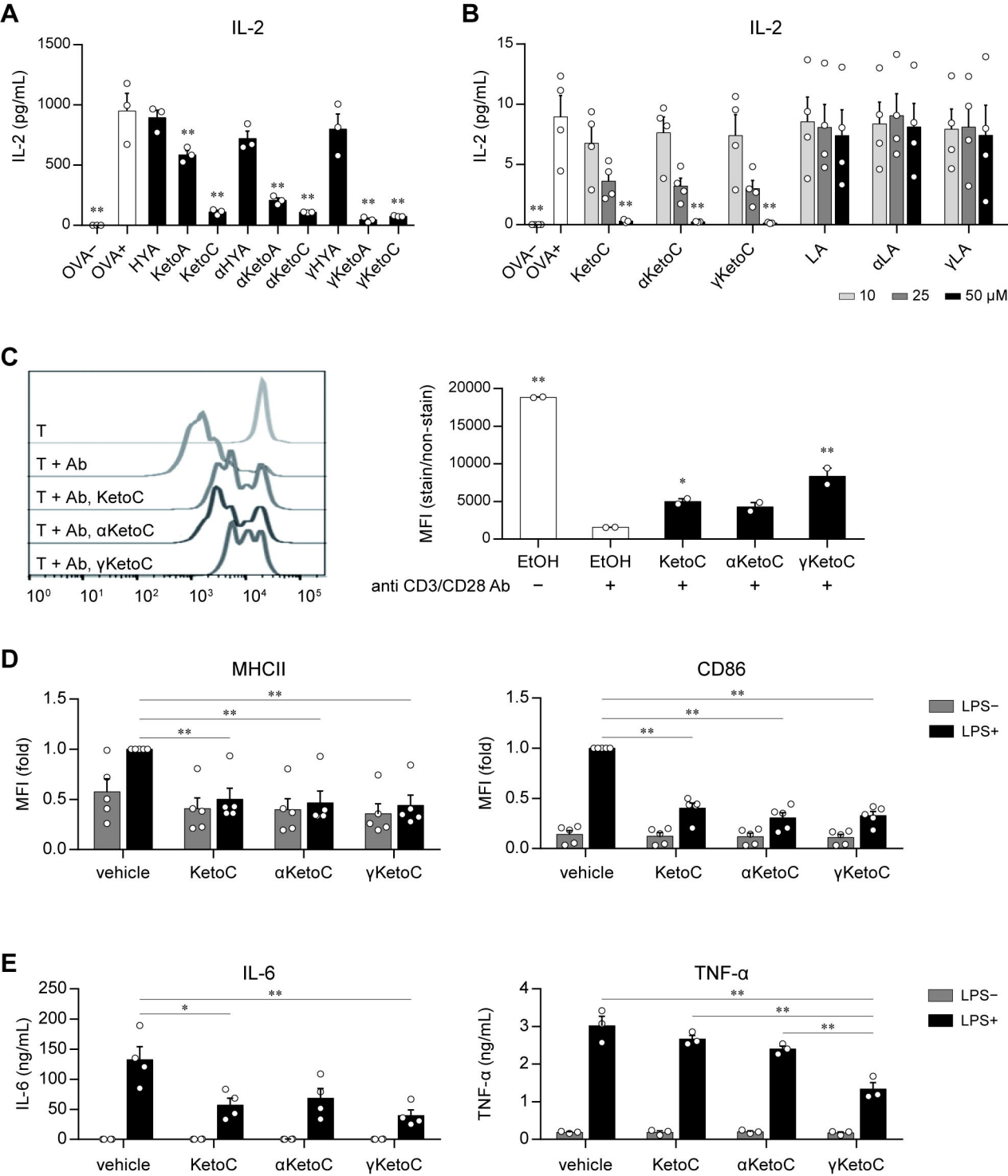
DSS-; without the DSS treatment (n=6), DSS+; with the DSS treatment (n=15), DSS+γKetoC; administration of γKetoC with the DSS treatment (n=15) (**B** and **C**).

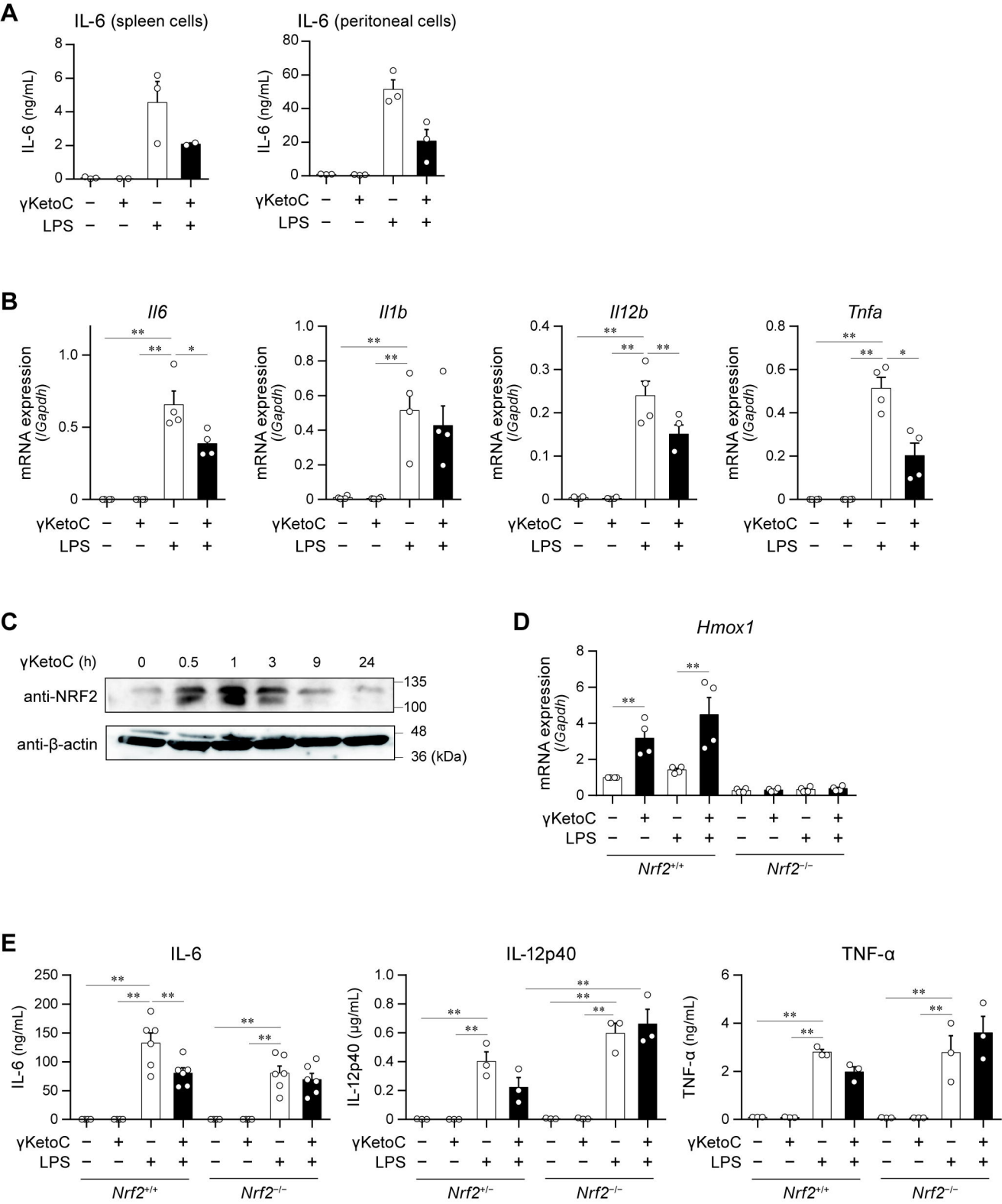
D. Schematic of the schedule of administration of γKetoC (15 mg/kg/day) to colitis induced-*Nrf2* gene targeted mice.

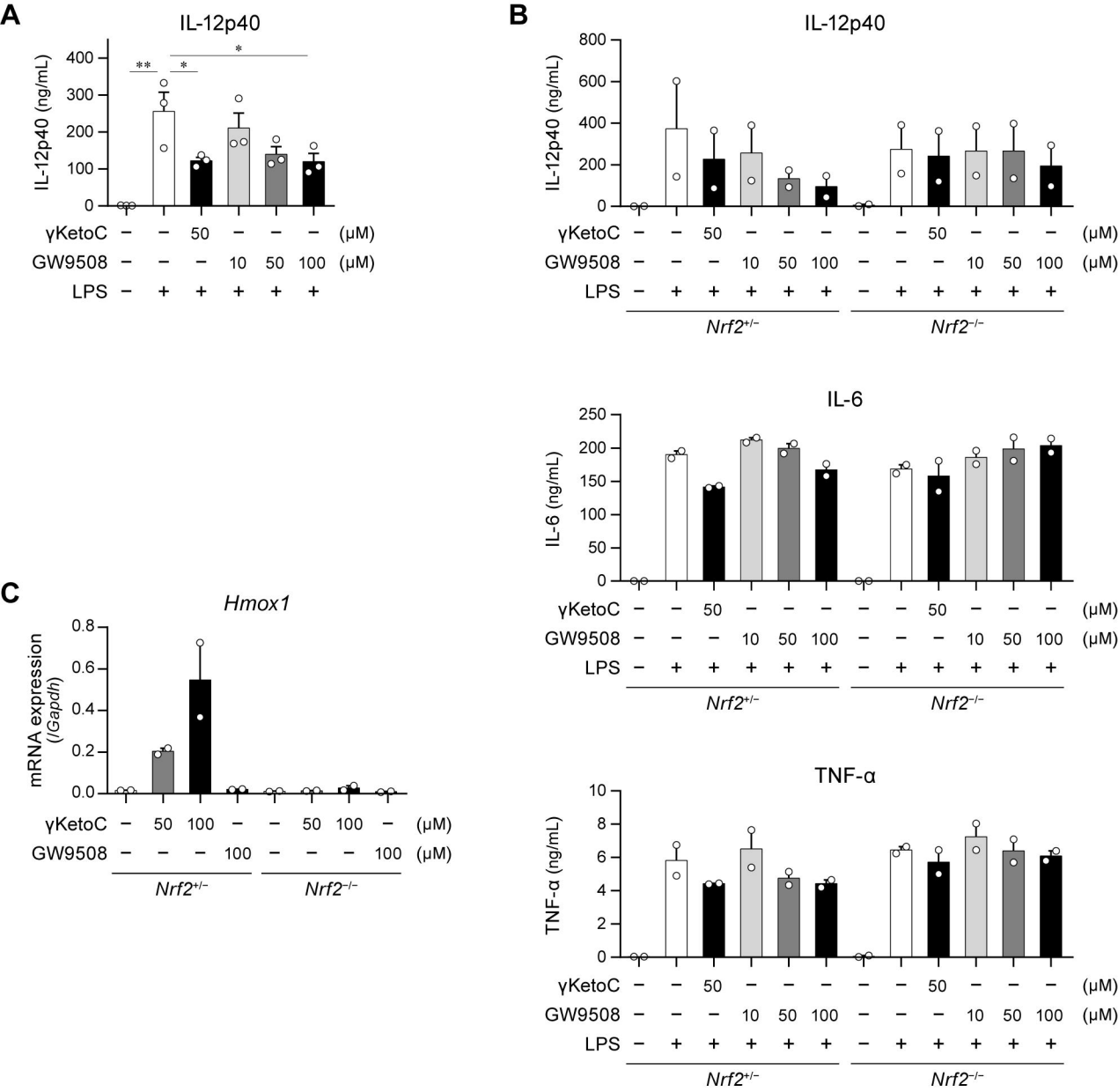
E. Body weight changes (left) and DAI scores (right).

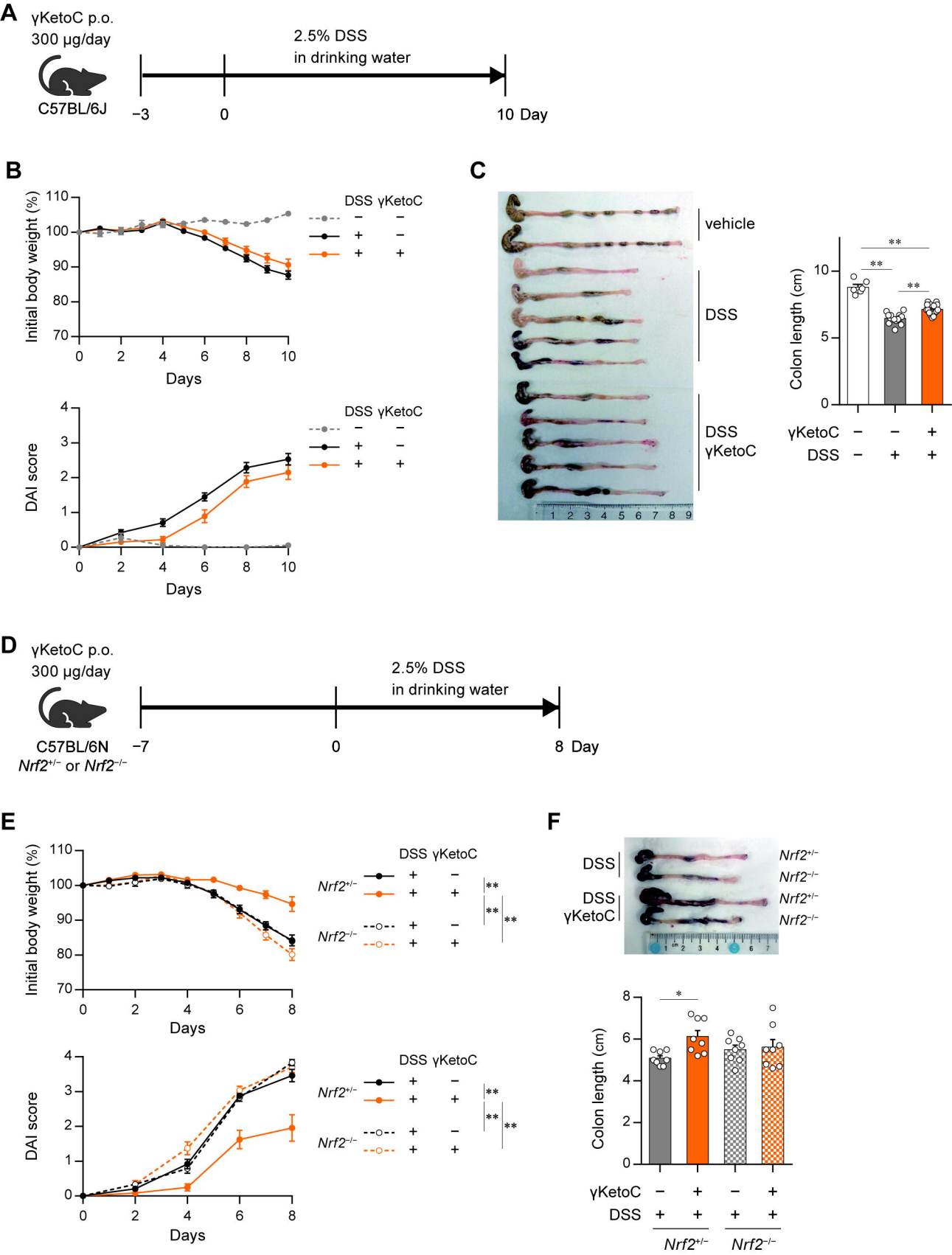
F. Atrophy levels of the colon.

Nrf2$^{+/-}$ DSS+; colitis-induced *Nrf2*$^{+/-}$ mice (n=8), *Nrf2*$^{+/-}$ DSS+γKetoC; γKetoC-treated colitis-induced *Nrf2*$^{+/-}$ mice (n=8), *Nrf2*$^{-/-}$ DSS+; colitis-induced *Nrf2*$^{-/-}$ mice (n=8), *Nrf2*$^{-/-}$ DSS+γKetoC; γKetoC-treated colitis-induced *Nrf2*$^{-/-}$ mice (n=8) (**E** and **F**). Data are shown as the mean ± SEM. *$p < 0.05$, **$p < 0.01$ The Tukey-Kramer test was used.


A
IL-2
IL-2 (pg/mL)
1500
1000
500
0
OVA−
OVA+
HYA
KetoA
KetoC
αHYA
αKetoA
αKetoC
γHYA
γKetoA
γKetoC
B
IL-2
IL-2 (pg/mL)
15
10
5
0
OVA−
OVA+
KetoC
αKetoC
γKetoC
LA
αLA
γLA
10
25
50 μM
C
T
T + Ab
T + Ab, KetoC
T + Ab, αKetoC
T + Ab, γKetoC
MFI (stain/non-stain)
20000
15000
10000
5000
0
EtOH
EtOH
KetoC
αKetoC
γKetoC
anti CD3/CD28 Ab
−
+
+
+
+
D
MHCII
CD86
MFI (fold)
1.5
1.0
0.5
0.0
vehicle
KetoC
αKetoC
γKetoC
LPS−
LPS+
E
IL-6
IL-6 (ng/mL)
250
200
150
100
50
0
TNF-α
TNF-α (ng/mL)
4
3
2
1
0
vehicle
KetoC
αKetoC
γKetoC
LPS−
LPS+


A
IL-6 (spleen cells)
IL-6 (peritoneal cells)
IL-6 (ng/mL)
γKetoC
LPS
B
Il6
Il1b
Il12b
Tnfa
mRNA expression (/Gapdh)
C
γKetoC (h)
0
0.5
1
3
9
24
anti-NRF2
anti-β-actin
135
100
48
36 (kDa)
D
Hmox1
mRNA expression (/Gapdh)
Nrf2+/+
Nrf2−/−
E
IL-6
IL-12p40
TNF-α
IL-6 (ng/mL)
IL-12p40 (μg/mL)
TNF-α (ng/mL)
Nrf2+/+
Nrf2+/−
Nrf2−/−


A
IL-12p40
IL-12p40 (ng/mL)
400
300
200
100
0
**
*
*
γKetoC – – 50 – – – (μM)
GW9508 – – – 10 50 100 (μM)
LPS – + + + + +
B
IL-12p40
IL-12p40 (ng/mL)
800
600
400
200
0
γKetoC – – 50 – – – – – 50 – – – (μM)
GW9508 – – – 10 50 100 – – – 10 50 100 (μM)
LPS – + + + + + – + + + + +
Nrf2+/–
Nrf2–/–
IL-6
IL-6 (ng/mL)
250
200
150
100
50
0
γKetoC – – 50 – – – – – 50 – – – (μM)
GW9508 – – – 10 50 100 – – – 10 50 100 (μM)
LPS – + + + + + – + + + + +
Nrf2+/–
Nrf2–/–
C
Hmox1
mRNA expression (/Gapdh)
0.8
0.6
0.4
0.2
0.0
γKetoC – 50 100 – – 50 100 – (μM)
GW9508 – – – 100 – – – 100 (μM)
Nrf2+/–
Nrf2–/–
TNF-α
TNF-α (ng/mL)
10
8
6
4
2
0
γKetoC – – 50 – – – – – 50 – – – (μM)
GW9508 – – – 10 50 100 – – – 10 50 100 (μM)
LPS – + + + + + – + + + + +
Nrf2+/–
Nrf2–/–


A
γKetoC p.o.
300 μg/day
C57BL/6J
2.5% DSS
in drinking water
−3
0
10 Day
B
Initial body weight (%)
Days
DSS γKetoC
DAI score
C
vehicle
DSS
DSS
γKetoC
Colon length (cm)
γKetoC
DSS
D
γKetoC p.o.
300 μg/day
C57BL/6N
Nrf2+/− or Nrf2−/−
2.5% DSS
in drinking water
−7
0
8 Day
E
Nrf2+/−
Nrf2−/−
F
DSS
DSS
γKetoC
Nrf2+/−
Nrf2−/−
Nrf2+/−
Nrf2−/−
Colon length (cm)
γKetoC
DSS
Nrf2+/−
Nrf2−/−