Adelmidrol, a Palmitoylethanolamide Analogue, as a New Pharmacological Treatment for the Management of Inflammatory Bowel Disease

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ABSTRACT

Leukocyte infiltration, improved levels of intercellular adhesion molecule 1 (ICAM-1), and oxidative stress in the colon are the principal factors in inflammatory bowel disease. The goal of the current study was to explore the effects of adelmidrol, an analog of the anti-inflammatory fatty acid amide signaling molecule palmitoylethanolamide, in mice subjected to experimental colitis. Additionally, to clarify whether the protective action of adelmidrol is dependent on the activation of peroxisome proliferator-activated receptors (PPARs), we investigated the effects of a PPARγ antagonist, GW9662, on adelmidrol action. Adelmidrol (10 mg/kg daily, o.s.) was tested in a murine experimental model of colitis induced by intracolonic administration of dinitrobenzene sulfonic acid. Nuclear factor-κB translocation, cyclooxygenase-2, and phosphoextracellular signal-regulated kinase, as well as tumour necrosis factor-α and interleukin-1β, were significantly increased in colon tissues after dinitrobenzene sulfonic acid administration. Immunohistochemical staining for ICAM-1, P-selectin, nitrotyrosine, and poly(ADP)ribose showed a positive staining in the inflamed colon. Treatment with adelmidrol decreased diarrhea, body weight loss, and myeloperoxidase activity. Adelmidrol treatment, moreover, reduced nuclear factor-κB translocation, cyclooxygenase-2, and phosphoextracellular signal-regulated kinase expression; proinflammatory cytokine release; and the incidence of nitrotyrosine and poly(ADP)ribose in the colon. It also decreased the upregulation of ICAM-1 and P-selectin. Adelmidrol treatment produced a reduction of Bax and an intensification of Bcl-2 expression. This study clearly demonstrates that adelmidrol exerts important anti-inflammatory effects that are partly dependent on PPARγ, suggesting that this molecule may represent a new pharmacologic approach for inflammatory bowel disease treatment.

Introduction

Ulcerative colitis (UC) and Crohn disease (CD) are the foremost categories of inflammatory bowel disease (IBD), a class of autoimmune diseases in which the body’s own immune system assaults elements of the digestive apparatus (Reddy et al., 1991). In UC, the inflammatory process involves the mucosa and extends by continuity, beginning from the rectum. Two of the key characteristic symptoms of UC are bloody diarrhea and abdominal discomfort associated with fever (Ordás et al., 2012). In CD, the inflammatory event involves the entire wall of the gastrointestinal area and is propagated segmentally, not by continuity, from the oral cavity to the rectum (Baumgart and Sandborn, 2012). The most representative symptoms of CD are abdominal pain, loss of body mass, anemia, and diarrhea associated with fever (Riordan et al., 1998). Chronic intestinal inflammation is linked with nitrosative and oxidative stress, which have been linked in numerous human diseases, including IBD (Wendland et al., 2001). Substantial evidence proposes that IBD is accompanied by an imbalance among reactive oxygen species (ROS) and antioxidant activity, which generates oxidative stress as the result of ROS overproduction such as decreased antioxidant activity (Halliwell, 1997).

Macrophages play a focal role in the improvement of noncaseous epithelioid granuloma in the intestinal mucosa, which is typical of Crohn’s disease; they are involved also in the mucosal immune response. Activated macrophages produce cytokines, for example, tumour necrosis factor (TNF-α) and interleukin (IL)-1β, among others. Additionally, recruitment of inflammatory cells from circulation is a main process in amplifying the inflammatory response (Sandborn and Hanauer, 1999). TNF-α and IL-1β increase the levels of adhesion molecules in the vascular endothelium, leading to penetration

ABBREVIATIONS: CD, Crohn disease; COX-2, cyclooxygenase-2; DNBS, dinitrobenzene sulfonic acid; IBD, inflammatory bowel disease; ICAM-1, intercellular adhesion molecule 1; IL, interleukin; KO, knockout; MDA, 1,1,3,3-tetramethoxypropan/99% malondialdehyde bis (dymethylacetal)/99%; MPO, myeloperoxidase; NAE, N-acelethanolamine; NF-κB, nuclear factor-κB; PBS, phosphate-buffered saline; PEA, palmitoylethanolamide; p-ERK, phosphoextracellular signal-regulated kinases; PPAR, peroxisome proliferator-activated receptors; ROS, reactive oxygen species; TNF, tumor necrosis factor; UC, ulcerative colitis; WT, wild type.

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of inflammatory cells into the mucosal layer. Critical performers in this process are the selectins, vascular cell adhesion molecule-1, and intercellular adhesion molecule 1 (ICAM-1), which are expressed on the vascular endothelial surface (Koizumi et al., 1992).

Several animal models of IBD have been established that show similarities to human CD, although most do not predict what happens in human immunology. Amid these models, colonic inflammation provoked by the intrarectal administration of dinitrobenzene sulfonic acid (DNBS) in mice is considered a well-documented model for identification of new pharmacologic targets to treat human CD (Impellizzeri et al., 2015a). Such approaches include anti-TNF-antibodies, whose main aim is to induce clinical remission on a long-term basis and thereby effect improved patient quality of life.

Different studies have determined that N-acyl ethanolamines (NAEs), which are widely expressed in mammals, are involved in a range of physiologic functions, including inflammation, neurotransmission, analgesia, reproduction, appetite, and cytoprotection (Schmid and Berdyhev, 2002). Like other NAEs, palmitoylethanolamide (PEA) has been extensively studied for its anti-inflammatory and neuroprotective effects (Hansen et al., 2002; Scuderi et al., 2012). PEA inhibits mast cell activation, stabilizes mitochondrial function, and inhibits degradation of the endocannabinoid anandamide, which also has neuroprotective effects. Further, PEA may activate peroxisome proliferator-activated receptor α (PPARα) and/or potentiate microglial cell motility in a cannabinoid receptor-independent manner (Skaper et al., 1996; Nagayama et al., 1999; Franklin et al., 2003; Impellizzeri et al., 2015b). Interestingly, as previously demonstrated, in addition to the PPARα receptor activation, the PPARβ and PPARγ receptors also contribute to the anti-inflammatory activity of PEA (D’Agostino et al., 2007; Paterniti et al., 2013).

Moreover, PEA reportedly improved outcome in a murine model of experimental colitis, the effect being mediated by cannabinoid CB2 receptors GPR55 and PPARα and modulated by transient receptor potential cation channel subfamily V member 1, all of which are involved in the control of intestinal inflammation (Borrelli et al., 2015). The anti-inflammatory ethanoidamide derivative ademidrol (international nonproprietary name) is a naturally occurring saturated dicarboxylic acid found in trace amounts in the human body and in some whole grains. Ademidrol (N,N′-bis(2-hydroxyethyl)nonanedicarboxamide) possesses both hydrophilic and hydrophobic properties that favor its solubility both in aqueous and organic media (De Filippis et al., 2009). Topical treatment with ademidrol is reported to increase mast cell granular density, suggesting a decrease in their degranulation (De Filippis et al., 2009). In addition, ademidrol displayed some benefit in a pilot study on mild atopic dermatitis (Pulvirenti et al., 2007).

Our study was designed to evaluate the effects of ademidrol in an animal model of IBD. To investigate whether the mechanism of action of ademidrol treatment was similar to one previously studied for PEA, we have investigated the role of the PPARα and PPARγ and CB2 receptors on the ademidrol anti-inflammatory property.

Materials and Methods

Animals. Male adult CD1 mice (25–30 g, Envigo, Italy) and male mice (2027 g, Envigo, Italy) with a targeted disruption of the PPARα gene (PPARα knockout [KO]) and littermate wild-type controls [PPARα wild-type (WT)] were placed in a controlled environment and maintained on a 12-hour light/dark cycle with food and water available ad libitum. The study was permitted by the University of Messina Review Board for the care of animals. (D.M.116192 and O.J. of E.C. L 358/1 12/18/1986).

Induction of Experimental Colitis. Colitis was made as previously described (Impellizzeri et al., 2015a). After colitis, the animals were observed for 4 days. After this period, the animals were weighed and anesthetized with chloral hydrate and the abdomen opened by a midline cut. The colon was removed, freed from surrounding tissues, opened along the antimesenteric border, washed, weighed and processed for histologic and biochemical studies.

Experimental Groups. Mice were casually divided into the following groups (10 in each group):

1. Sham + vehicle group: Vehicle solution (saline) was given by oral administration for 4 days.
2. Sham + ademidrol (10 mg/kg): Administered o.s. for 4 days.
3. DNBS + vehicle: Mice were injected by DNBS as described, and vehicle (saline) was given o.s. each day for 4 days, starting 60 minutes after the injection of DNBS.
4. DNBS + ademidrol (10 mg/kg): Mice were injected by DNBS as described, and ademidrol (10 mg/kg) was given o.s. each day, starting 60 minutes after administration of DNBS.

To better determine whether the mechanism of action of ademidrol is related to the activation of PPARα and PPARγ or CB2 receptors, we performed our studies in the following experimental groups:

1. Sham + vehicle group: Vehicle solution (saline) was given o.s. for 4 days.
2. Sham + ademidrol (10 mg/kg): Administered o.s. for 4 days.
3. Sham + SR144528 (1 mg/kg): Administered o.s. for 4 days.
4. Sham PPARα WT + vehicle group: Vehicle solution (saline) was given orally for 4 days.
5. Sham PPARα KO mice + vehicle: Vehicle solution (saline) was given o.s. for 4 days.
6. Sham PPARα WT + ademidrol (10 mg/kg): Administered o.s. for 4 days.
7. Sham PPARα KO mice + ademidrol (10 mg/kg): Administered o.s. for 4 days.
8. DNBS + vehicle: Mice were injected by DNBS as described, and vehicle (saline) was given o.s. daily for 4 days, starting 60 minutes after the injection of DNBS.
9. DNBS + vehicle: PPARα WT mice were injected by DNBS as described.
10. DNBS + vehicle: PPARα KO mice were injected by DNBS as described.
11. DNBS + ademidrol (10 mg/kg): PPARα WT mice were injected by DNBS as described, and ademidrol (10 mg/kg) was given o.s. daily for 4 days, starting 60 minutes after administration of DNBS.
12. DNBS + ademidrol (10 mg/kg): PPARα KO mice were injected by DNBS as described, and ademidrol (10 mg/kg) was given o.s. daily for 4 days, starting 60 minutes after administration of DNBS.
13. DNBS + GW96662 (1 mg/kg): Mice were injected by DNBS as described, but GW96662 (1 mg/kg) was given o.s. daily for 4 days, starting 60 minutes after injection of DNBS.
14. DNBS + GW96662 (1 mg/kg) + ademidrol (10 mg/kg): Mice were injected by DNBS as described, but GW96662 (1 mg/kg) was given orally 30 minutes before ademidrol administration.
15. DNBS + SR144528 (1 mg/kg): Mice were injected by DNBS as described, but SR144528 (1 mg/kg) was given orally 30 minutes before ademidrol administration.
16. DNBS + SR144528 (1 mg/kg) + ademidrol (10 mg/kg): Mice were injected by DNBS as described, but SR144528 (1 mg/kg) was given orally 30 minutes before ademidrol administration.
Evaluation of Colon Damage. After removal, the entire colon was gently rinsed with saline solution, opened by a longitudinal cut, and immediately observed under a microscope. Colon injury (macroscopic damage score) was evaluated and scored by two independent observers as previously described: 0, no damage; 1, restricted hyperemia without ulcers; 2, linear ulcers with no important inflammation; 3, linear ulcers with inflammation at one site; 4, two or more major sites of inflammation and ulceration extending >1 cm along the length of the colon; and 5–8, one point is added for each centimeter of ulceration beyond an initial 2 cm (Zingarelli et al., 1993; Cuzzocrea et al., 2003).

Tissue Processing and Histology. Concisely, paraffin tissue slices (thickness, 7 μm) were deparaffinized with xylene, stained with H&E and observed by light microscopy (AxioVision, Zeiss, Milan, Italy) by a qualified histopathologist. The degree of inflammation on microscopic cross-sections of the colon was graded semiquantitatively from 0 to 4 as previously described by Impellizzeri et al. (2015a), in particular, the following morphologic criteria were considered: score 0, no damage; score 1 (mild), focal epithelial edema and necrosis; score 2 (moderate), diffuse swelling and necrosis of the villi; score 3 (severe), necrosis with the presence of neutrophil infiltrate in the submucosa; score 4 (highly severe), widespread necrosis with massive neutrophil infiltrate and hemorrhage (Cuzzocrea et al., 2004). The scores from all sections of each colon were averaged to give a final score for each mouse. All histologic analyses were performed in a blinded fashion.

Myeloperoxidase Assay. Neutrophil infiltration in the colon was examined by determining tissue myeloperoxidase (MPO) activity using a spectrophotometric assay with tetramethylbenzidine as substrate, according to a previously published method (Mullane et al., 1985). After DNBS injection, colon tissues were collected and weighed. Every piece of tissue was homogenized in a mixture containing 0.5% hexadecyltrimethyl ammonium bromide dissolved in 10 mM potassium phosphate buffer, pH 7, and centrifuged for 30 minutes at 20,000g at 4°C. An aliquot of the supernatant was then allowed to react with a solution of 1.6 mM tetramethylbenzidine and 0.1 mM H₂O₂. The degree of change in absorbance was measured spectrophotometrically at 650 nm. MPO activity was described as the quantity of enzyme degrading 1 mmol of peroxide per minute at 37°C and expressed in U/g wet tissue.

Thiobarbituric Acid–Reactant Substances Measurement. Thiobarbituric acid–reactant substances measurement was determined in colon tissue 4 days after DNBS administration as a marker of lipid peroxidation. Thiobarbituric acid–reactant substances were calculated by comparison the OD₅₃₂ to a standard mixture of 1,1,3,3-tetramethoxypropan/99% malondialdehyde bis (dymethylacetal)/99% (MDA) (Sigma, Milan, Italy). The absorbance of the supernatant was measured spectrophotometrically at 532 nm.

Immunohistochemical Localization of TNF-α, IL-1β, ICAM-1, P-Selectin, Poly(ADP-ribose) (PAR), and Nitrotyrosine. Seven
days after DNBS administration, colon tissues were collected and fixed for 24 hours in paraformaldehyde (4% in 0.1M phosphate-buffered saline (PBS)) at room temperature, dehydrated through a graded series of ethanol and xylene, and embedded in BioPlast Plus (Bio Optica, Milan, Italy). Thereafter, 7 μm sections were cut from the paraffin-embedded tissue. After deparaffinization with xylene and graded ethanol as described herein, endogenous peroxidase was quenched with 0.3% (v/v) hydrogen peroxide in 60% (v/v) methanol for 30 minutes. Slices were permeabilized with 0.1% (w/v) Triton X-100 in PBS for 20 minutes. Nonspecific adsorption was diminished by incubating the section in 2% (v/v) normal goat serum in PBS for 20 minutes. Endogenous biotin and avidin binding sites were blocked by progressive incubation for 15 minutes with biotin and avidin (Vector Laboratories, Burlingame, CA), respectively. Subsequently, slices were incubated overnight with anti-TNF-α murine polyclonal antibody (1/100 in PBS, v/v; Santa Cruz Biotechnology, Dallas, Texas) or anti-IL-1β murine polyclonal antibody (1/100 in PBS; v/v, Santa Cruz Biotechnology), anti-ICAM-1 murine polyclonal antibody (1/100 in PBS; v/v, Santa Cruz Biotechnology), anti-P-selectin murine polyclonal antibody (1/100 in PBS; v/v, Santa Cruz Biotechnology), anti-PAR murine polyclonal antibody (1/100 in PBS; v/v, Santa Cruz Biotechnology), and anti-nitrotyrosine rabbit polyclonal antibody (1/200 in PBS, v/v; Millipore, Billerica, MA). Sections were rinsed with PBS and incubated with peroxidase-conjugated bovine anti-mouse IgG secondary antibody or peroxidase-conjugated goat anti-rabbit IgG (1:2,000; Jackson Immuno Research, West Grove, PA). Specific labeling was detected with a biotin-conjugated goat anti-rabbit IgG or biotin-conjugated goat anti-mouse IgG and avidin-biotin peroxidase complex (Vector Laboratories, Burlingame, CA). To verify the binding specificity for TNF-α, IL-1β, ICAM-1, P-selectin, PAR, and nitrotyrosine, control slices were incubated with only primary antibody or secondary antibody. In these controls, no positive staining was detected. Immunohistochemical images were collected using a Zeiss microscope and AxioVision software (Zeiss). For graphic display of densitometric analyses, the intensity of positive staining (brown staining) was measured by computer-assisted color image analysis (Leica QWin V3, UK). The percentage area of immunoreactivity (determined by the number of positive pixels) was expressed as percentage of total tissue area (red staining). Replicates for every experimental condition and histochemical staining were acquired from each mouse in all experimental groups. In sham-operated mice, the central areas of equivalent tissue sections were taken as reference points, and a comparable number of optical fields were counted (Shea, 1994). All histologic analyses were carried out by an observer without knowledge of the treatments.

Western Blot Analysis for Ikb-α, Nuclear Factor-κB, Cyclooxygenase-2, Phosphoextracellular Signal-Regulated Kinase, Bel-2, Bax, Lamin a/c, and β-Actin. The levels of Ikb-α, nuclear factor-κB (NF-κB), cyclooxygenase-2 (COX-2), phosphoextracellular signal-regulated kinase (p-ERK), Bel-2, Bax, lamin a/c, and β-actin were calculated, as previously described, in cytosolic and

Fig. 2. Effects of adelmidrol on histologic damage and MPO activity in DNBS-induced colitis. Histologic alteration was absent in colon tissue from sham-treated mice (A,A'); histologic score (D). Four days after intracolonic administration of DNBS, the colon showed transmural necrosis and edema with a diffuse leukocyte cellular infiltrate in the submucosa (B,B'); histologic score (D). Adelmidrol (10 mg/kg, o.s.) reduced significantly the histologic signs of colon injury (C,C'); histologic score (D). Myeloperoxidase (MPO) activity was increased in DNBS-injected mice in comparison with sham-treated mice (C), and treatment with adelmidrol (10 mg/kg, o.s.) reduced the extent of PMN infiltration (determined as decrease in MPO activity) in inflamed colon (2E).

*P < 0.05 versus sham group; #P < 0.05 versus DNBS group; ***P < 0.001 versus sham group; ###P < 0.001 versus DNBS group.
nuclear fractions from colon tissue collected at the end of the experiment with minor modifications (Bethea et al., 1998). Colon tissue from each mouse was suspended in extraction buffer A containing 0.2 mM phenylmethylsulfonyl fluoride, 0.15 mM pepstatin A, 20 mM leupeptin, 1 mM sodium orthovanadate, homogenized at the maximum setting for 2 minutes, and centrifuged at 12,000g × rpm for 4 minutes at 4°C. Supernatants represented the cytosolic fraction. The pellets, containing enriched nuclei, were resuspended in buffer B containing 1% Triton X-100, 150 mM NaCl, 10 mM Tris–HCl pH 7.4, 1 mM EGTA, 1 mM EDTA, 0.2 mM phenylmethylsulfonyl fluoride, 20 mM leupeptin, 0.2 mM sodium orthovanadate. After centrifugation 10 minutes at 12,000 rpm at 4°C, the supernatants containing the nuclear protein were stored at −80°C for further analysis. The filters were blocked with 1× PBS, 5% (w/v) nonfat dried milk for 40 minutes at room temperature, and successively probed with anti-IkB-α (1/500 in PBS, v/v, Santa Cruz Biotechnology), anti-NF-κB (1/500 in PBS, v/v, Santa Cruz Biotechnology), anti-COX-2 (1/500 in PBS, v/v, Cayman), anti-p-ERK (1/500 in PBS, v/v, Santa Cruz Biotechnology), anti-Bax (Santa Cruz Biotechnology), anti-Bcl-2 (1/500 in PBS, v/v, Santa Cruz Biotechnology), and anti-lamin a/c (1/500 in PBS, v/v, Santa Cruz Biotechnology) in 1× PBS, 5% (w/v) nonfat dried milk, 0.1% Tween-20 (PMT) at 4°C overnight. Membranes were incubated with peroxidase-conjugated bovine anti-mouse IgG secondary antibody or peroxidase-conjugated goat anti-rabbit IgG (1:2000, Jackson Immuno Research, West Grove, PA) for 1 hour at room temperature. To establish that blots were loaded with equivalent amounts of protein lysates, they were similarly incubated with antibody against β-actin (1/1000 in PBS, v/v, Santa Cruz Biotechnology v). Relative expression of the protein bands for IkB-α (37 kDa), NF-κB (65 kDa), COX-2 (72 kDa), p-ERK (46 kDa), Bcl-2 (29 kDa), Bax (23 kDa), lamin a/c (65 kDa), and β-actin (42 kDa) were detected with the enhanced chemiluminescence detection system according to the manufacturer's instructions (SuperSignal West Pico Chemiluminescent Substrate, Thermo Fisher Scientific, Waltham, MA). Expression of protein bands was calculated by densitometry with Bio-Rad ChemiDoc XRS software (Hercules, CA) and standardized to β-actin levels. Images of blot signals (8-bit/600-dpi resolution) were imported to an analysis program (Image Quant TL, v2003). Commercially available molecular weight markers (10–250 kDa) were used to establish molecular weight positions.

Fig. 3. Effects of adelmidrol treatment on NF-κB pathway, COX-2, and p-ERK expression in DNBS-induced colitis. Basal expression of IkB-α was detected in colon samples from sham-treated animals were substantially reduced in colon tissues from vehicle-treated animals 4 days after DNBS injection (A); densitometric examination (A’). Adelmidrol treatment prevented DNBS-induced IkB-α degradation (A); densitometric examination (A’). NF-kB p65 levels in the colon nuclear fractions were substantially increased 4 days after DNBS injection compared with sham-treated mice (B); see densitometric examination (B’). Treatment with adelmidrol (10 mg/kg, o.s.) reduced the levels of NF-kB p65 (B); see densitometric examination (B’). Moreover, COX-2 levels were significantly increased in the colon tissue of DNBS-injected mice compared with sham mice. Treatment with adelmidrol (10 mg/kg, o.s.) significantly reduced DNBS-mediated COX-2 expression (C); see densitometric examination (C’). In addition, pERK1/2 levels were significantly increased in the colon tissues of DNBS-injected mice (D); see densitometric examination (D’) compared with sham-treated mice. Adelmidrol significantly reduced the level of pERK1/2 activation (D); see densitometric examination (D’). The densitometric expression of protein bands was normalized to β-actin and lamin a/c levels. *P < 0.05 versus sham; #P < 0.05 versus DNBS.
Materials. Adelmidrol was obtained from Epitech Group Spa (Saccolongo, Italy). All compounds were purchased from Sigma Aldrich (Milan, Italy). All chemicals were of the maximum commercial grade available. All stock mixes were made in non-pyrogenic saline (0.9% NaCl; Baxter, UK).

Statistical Evaluation. All values in the images and text are expressed as mean ± S.E.M. of n observations. For in vivo studies, n represents the number of animals. In experiments involving histology and immunohistochemistry, the pictures shown are demonstrative of at least three independent experiments. Moreover, Western blot images are representative of three different gels obtained by dividing the number of samples from 10 animals for each experimental group on different days. A P value of less than 0.05 was appraised as significant. The results were analyzed by one-way analysis of variance, followed by a Bonferroni post hoc test for multiple comparisons.

Results

Effects of Adelmidrol Treatment on the Degree of Colitis in DNBS-Challenged Mice. Histologic analysis of colonic mucosa of sham-treated mice showed an intact epithelium (Fig. 1A, see macroscopic score, Fig. 1D; Fig. 2A, A'; view histologic score, Fig. 2D). Four days after intracolonic administration of DNBS, the colon appeared flaccid and filled with liquid stool. Macroscopic examination of cecum, colon, and rectum showed mucosal congestion, erosion, and hemorrhagic ulcerations (Fig. 1B; see macroscopic score, Fig. 1D). The histopathological features included transmural necrosis and edema and a diffuse leukocyte cellular infiltrate in the submucosa of colon sections from DNBS-injected mice (Fig. 2B, B'; view histologic score Fig. 2D). Adelmidrol (10 mg/kg, o.s.) reduced significantly the degree and severity of the macroscopic (Fig. 1C; see macroscopic score, Fig. 1D) and histologic signs of colon injury (Fig. 2C, C'; view histologic score, Fig. 2D). Moreover, 4 days after colitis induced by DNBS treatment, all mice had diarrhea and a reduction in body weight (compared with the sham groups) (Fig. 1E). Adelmidrol (10 mg/kg, o.s.) treatment significantly reduced the loss of body weight (Fig. 1E). The IBD induced by DNBS intrarectally administered was also characterized by an augmentation in MPO activity, an indicator of neutrophil accumulating in the colon (Fig. 2E). This was consistent with light microscopic observations showing the colon of vehicle-treated DNBS mice to contain a large number of neutrophils. In contrast, adelmidrol (10 mg/kg, o.s.) significantly reduced the degree of polymorphonuclear cell infiltration (determined as reduction in MPO activity) in inflamed colon (Fig. 2E).

Fig. 4. Adelmidrol treatment reduces cytokine production in DNBS-induced colitis. The substantial increase in TNF-α and IL-1β formation observed in colon samples collected from DNBS-injected mice compared with sham mice (B,E); see densitometric examination (G) was significantly attenuated in mice treated with adelmidrol (10 mg/kg, o.s.) (C,F); see densitometric examination (G'). TNF-α and IL-1β immunostaining was not detected in colon from sham mice (A and D); see densitometric examination (G). ***P < 0.001 versus sham group; ###P < 0.001 versus DNBS group.
Effects of Adelmidrol Treatment on NF-κB Pathway, COX-2, and p-ERK Expression in DNBS-Challenged Mice. To explore the cellular mechanism(s) underlying adelmidrol mitigation of the development of DNBS-induced colitis, we used Western blot analysis to evaluate IκB-α degradation and nuclear NF-κB p65 translocation. NF-κB p65 levels in the colon nuclear fractions were substantially improved 4 days after DNBS injection compared with sham mice (Fig. 3B; see densitometric examination, Fig. 3B'). Treatment with adelmidrol (10 mg/kg, o.s.) reduced the colon levels of NF-kB p65 (Fig. 3B; see densitometric examination Fig. 3B'). Basal expression of IκB-α detected in colon samples from sham-treated animals were significantly reduced in colon tissues from vehicle-treated animals 4 days after DNBS injection (Fig. 3A; see densitometric examination, Fig. 3A'). Adelmidrol treatment prevented DNBS-induced IκB-α degradation (Fig. 3A; see densitometric examination, Fig. 3A'). In addition, phosphorylation of ERK1/2 plays a role in the control of gene expression, for example, COX-2, mediating the inflammatory responses. Basal levels of COX-2 in homogenates from colon tissues of sham-operated animals (Fig. 3C; see densitometric examination, Fig. 3C') were significantly increased in colon tissue of DNBS-injected mice. Treatment of mice with adelmidrol (10 mg/kg, o.s.) reduced DNBS-mediated COX-2 expression (Fig. 3C; see densitometric examination, Fig. 3C'). This increase in COX-2 expression appeared to correspond to an activation of signal transduction pathways involved in its regulation, as pERK1/2 levels were significantly increased in the colon tissues of DNBS-injected mice (Fig. 3D; see densitometric examination, Fig. 3D'). Likewise, treatment with adelmidrol significantly reduced pERK1/2 activation (Fig. 3D; see densitometric examination, Fig. 3D').

Adelmidrol Treatment Reduces Cytokine Production in DNBS-Challenged Mice. Immunohistological analysis of colon tissue was carried out to determine whether adelmidrol might modulate the secondary inflammatory reaction also by regulating secretion of cytokines, such as TNF-α and IL-1β. A substantial increase of TNF-α and IL-1β production was found in colon samples collected from DNBS-injected mice compared with sham-operated mice (Fig. 4, B and E; see densitometric examination 4G). Colon levels of TNF-α and IL-1β were significantly attenuated in mice treated with adelmidrol (10 mg/kg, o.s.) (Fig. 4, C and F; see densitometric examination, Fig. 4G). There was no...
staining for TNF-α and IL-1β in colon obtained from sham groups of mice (Fig. 4, A and D; see densitometric examination, Fig. 4G).

**Adelmidrol Treatment Reduces ICAM-1 and P-Selectin Expression in DNBS-Challenged Mice.** The potential contribution of intestinal expression of ICAM-1 and P-selectin to cell recruitment throughout colon inflammation was next examined. Positive staining for ICAM-1 and P-selectin (Fig. 5, B and E; see densitometric examination, Fig. 5G) was significantly increased in vessels of the lamina propria and submucosa as well as in epithelial cells of injured colon and in infiltrating inflammatory cells in damaged tissues from DNBS-injected mice. Treatment with adelmidrol (10 mg/kg, o.s.) reduced staining for ICAM-I and P-selectin (Fig. 5, C and F; see densitometric examination, Fig. 5G) in colon tissues of DNBS-injected mice. No positive staining for ICAM-I and P-selectin was observed in colon tissues of sham-treated mice (Fig. 5, A and D; see densitometric examination, Fig. 5G).

**Effects of Adelmidrol Treatment on Nitrotyrosine and PAR Formation and Lipid Peroxidation in DNBS-Challenged Mice.** Immunohistochemistry for PAR revealed positive staining localized in the nuclei of inflammatory cells in colon tissues from DNBS-injected mice (Fig. 6B; see densitometric examination, Fig. 6G). Adelmidrol (10 mg/kg, o.s.) significantly reduced the extent of PAR immunoreactivity in the colon (Fig. 6C; see densitometric examination, Fig. 6G). Four days after DNBS administration, nitrotyrosine, an indicator of nitrosative stress, was assessed by immunohistochemical analysis in terminal colon sections to identify “peroxynitrite formation” and/or other nitrogen derivatives formed during experimental colitis. Colon sections from sham-treated mice did not stain for nitrotyrosine (Fig. 6D; see densitometric examination, Fig. 6G), but sections from DNBS-injected mice displayed positive nitrotyrosine immunostaining, mainly in inflammatory cells and around vessels (Fig. 6E; see densitometric examination, Fig. 6G). Treatment with adelmidrol (10 mg/kg, o.s.) reduced the degree of positive immunostaining for nitrotyrosine (Fig. 6F; see densitometric examination, Fig. 6G) in the colon. In addition, plasma levels of thiobarbituric acid-reactant substances (an indicator of lipid peroxidation) were significantly increased (H) in plasma collected from mice subjected to DNBS compared with sham-treated animals. Treatment with adelmidrol (10 mg/kg, o.s.) markedly attenuated the DNBS-induced rise in thiobarbituric acid-reactant substances (H). ***P < 0.001 versus sham group; ###P < 0.001 versus DNBS group.

![Fig. 6. Effects of adelmidrol treatment on nitrotyrosine and PAR formation and lipid peroxidation in DNBS-induced colitis.](molpharm.aspetjournals.org) PAR immunoreactivity was visible in the nuclei of inflammatory cells in colon tissues from DNBS-injected mice compared with sham-treated animals (B); see densitometric examination (G). Adelmidrol (10 mg/kg, o.s.) significantly reduced the extent of immunostaining for PAR in the colon (C); see densitometric examination (G). Whereas colon sections from sham-treated mice did not stain for nitrotyrosine (D); see densitometric examination (G), sections from DNBS-injected mice exhibited positive immunostaining for nitrotyrosine (E); see densitometric examination (G). Treatment with adelmidrol (10 mg/kg, o.s.) reduced the degree of positive immunostaining for nitrotyrosine (F); see densitometric examination (G) in the colon. In addition, plasma levels of thiobarbituric acid-reactant substances (an indicator of lipid peroxidation) were significantly increased (H) in plasma collected from mice subjected to DNBS compared with sham-treated animals. Treatment with adelmidrol (10 mg/kg, o.s.) markedly attenuated the DNBS-induced rise in thiobarbituric acid-reactant substances (H). ***P < 0.001 versus sham group; ###P < 0.001 versus DNBS group.
immunoreactivity in the colon (Fig. 6F; see densitometric examination, Fig. 6G). In addition, plasma levels of thiobarbituric acid–reactant substances, as an indicator of lipid peroxidation, increased significantly in mice subjected to DNBS compared with sham-operated mice (Fig. 6H). Thiobarbituric acid–reactant substance levels were significantly attenuated in DNBS treated with adelmidrol (10 mg/kg, o.s.) (Fig. 6H).

Effects of Adelmidrol Treatment on the Apoptotic Pathway in DNBS-Challenged Mice. To test whether colon damage was connected with apoptosis, 4 days after DNBS, the presence of proteic effectors of canonical mitochondrial apoptosis, such as Bax and Bcl-2, was investigated by Western blot analysis. Bax levels were appreciably increased in the colon of mice subjected to DNBS (Fig. 7B; see densitometric examination, Fig. 7B’). In contrast, adelmidrol treatment (10 mg/kg, o.s.) prevented DNBS-induced Bax expression (Fig. 7B; see densitometric examination, Fig. 7B’). On the other hand, adelmidrol administration (10 mg/kg, o.s.) increased Bcl-2 expression in DNBS-injected mice (Fig. 7A; see densitometric examination, Fig. 7A’), essentially reaching the basal level of Bcl-2 (Fig. 7A; see densitometric examination, Fig. 7A’).

Role of PPARγ Receptors in the Systemic Anti-inflammatory Effects of Adelmidrol in DNBS-Induced Colitis. To investigate the mechanism of adelmidrol action, we used the potent PPARγ antagonist GW9662 in the model of DNBS-induced colitis. Histologic evaluation by H&E staining revealed that mice that received GW9662 after DNBS injection showed an intensification of the damage as well as an increase in MPO levels, similar to the DNBS group (Fig. 8, B and C; see macroscopic score, Fig. 8F; Fig. 9, B and C; view histologic score, Fig. 9F). Moreover, DNBS-injected mice pretreated with GW9662 displayed limited protection by adelmidrol, suggesting a possible antagonist effect of GW9662 pretreatment on adelmidrol action (Fig. 8, D and E; see macroscopic score, Fig. 8F; Fig. 9, D and E; view histologic score, Fig. 9F). Additionally, 4 days after colitis induced by DNBS treatment, mice pretreated with GW9662 showed a major loss in body weight (Fig. 8G) and intensification of MPO activity (Fig. 9G) compared with adelmidrol-treated mice.

Role of PPARα and CB2 Receptors in the Systemic Anti-inflammatory Effects of Adelmidrol in DNBS-Induced Colitis. Histologic evaluation by H&E staining showed a transmural necrosis and edema and a diffuse leukocyte cellular infiltrate in the submucosa of colon sections from DNBS groups (data not shown). The histologic alteration was also found in PPARα WT and KO mice and in DNBS-injected mice that have received SR144528 (Fig. 10, A, A’, C, C’, E, and E’; view histologic score, Fig. 10, G and H) compared with sham groups (data not shown). Moreover, adelmidrol treatment was able to decrease the histologic alteration in all experimental groups, suggesting that the absence of PPARα receptor or pretreatment with SR144528 did not modify the action of adelmidrol (Fig. 10, B, B’, D, D’, F, and F’; view histologic score, Fig. 10, G and H).

Discussion

IBD is a chronic, relapsing, inflammatory condition of the gastrointestinal tract and includes UC and CD, which show differences in pathology and clinical characteristics. Presently, the causes and pathogenesis of IBD are poorly understood. It is widely accepted that the pathogenesis of IBD involves genetic and environmental factors (Pierik et al., 2005; Ye et al., 2015). Until recently, the main goal of IBD therapy was to achieve and preserve clinical remission, whereas today’s therapeutic aim is that of a prolonged remission characterized by sustained clinical remission, complete mucosal healing, and normalization of serologic markers of inflammation. The most frequently applied biologic agents in CD and UC are TNF-α-targeted therapies, a class of medication that has modernized the treatment of these conditions.

Fig. 7. Effects of adelmidrol treatment on apoptotic pathway in DNBS-induced colitis. Basal Bcl-2 levels in sham mice were markedly diminished after DNBS injection (A; densitometric examination (A’), an effect overcome with adelmidrol administration (10 mg/kg, o.s.) (A); see densitometric examination (A’). Bax levels appreciably increased in colon tissue from mice subjected to DNBS and were prevented from doing so in adelmidrol-treated mice (10 mg/kg, o.s.) (B); see densitometric examination (B’). Densitometric analysis of protein bands was normalized to the level of β-actin. *P < 0.05 versus sham; #P < 0.05 versus DNBS; **P < 0.01 versus sham; ##P < 0.01 versus DNBS.
disorders and the quality of life for patients; however, they also pose risks of developing various side effects, including infections, exacerbation of some neurologic manifestations, cutaneous lesion, or antibody production (Casili et al., 2016). Adelmidrol, a diethanolamide derivative of azelaic acid, is effective in the treatment of human inflammatory disorders, and its mechanism of action has been extensively investigated (Mastrofrancesco et al., 2010). Adelmidrol belongs to the aliamide family, with anti-inflammatory and antinociceptive proprieties similar to those of PEA and able to control mast cell hyper-reactivity in several pathophysiological conditions (Aloe et al., 1993; Costa et al., 2008; Genovese et al., 2008; De Filippis et al., 2011; Esposito et al., 2011).

Here, we investigated the beneficial effects of adelmidrol in an experimental model of IBD. In particular, adelmidrol attenuated DNBS-induced colitis in mice. At the macroscopic and histologic levels, epithelial disruption was significantly reduced in mice treated with adelmidrol. Further, mice treated with adelmidrol were more resistant to DNBS-induced colitis, showing a marked resolution of the macroscopic and histologic markers of the inflammatory process. This was also reflected in a decreased weight loss as well as a reduction of MPO activity in mice treated with adelmidrol compared with the DNBS-injected group.

NF-κB is an important mediator of inflammation. In response to a wide range of stimuli, including oxidative stress, infection, hypoxia, extracellular signals, and inflammation, IκBα is phosphorylated by IκB kinase (Bowie and O'Neill, 2000). This result is the release of the NF-κB dimer, which then translocates to the nucleus. DNBS induced a significant degradation of IκBα and a consequent increase in the nuclear translocation of the subunit p65, whereas adelmidrol treatment significantly reduced NF-κB translocation and inhibited IκBα degradation. Moreover, intestinal epithelial cells express COX-2 when stimulated by proinflammatory factors, such as lipopolysaccharide and oxidative stress (Longo et al., 1998). Adelmidrol reduced COX-2 and p-ERK DNBS-induced expression.
TNF-α and IL-1β are the most important cytokines present in colon tissues during the evolution of colitis (Kapsoritakis et al., 2001). The present study confirmed expression of TNF-α and IL-1β in colon tissues from DNBS-injected mice. Importantly, treatment with adelmidrol reduced these inflammatory cytokine levels. It has been suggested that during acute and chronic colitis, the continuous production of proinflammatory cytokines plays a key role in the adherence and infiltration of leukocytes to endothelial cells, thus maintaining chronic inflammation within the cecal and colonic interstitium (Kawachi et al., 2000). Here, we confirmed that DNBS injection induced the manifestation of P-selectin on the endothelial vascular wall and upregulated surface expression of ICAM-1 on endothelial cells. Treatment with adelmidrol halted expression of P-selectin and ICAM-1 upregulation without affecting constitutive levels of ICAM-1 on endothelial cells. Activated neutrophils produce ROS and reactive nitrogen species within intestinal mucosa, which provoke oxidative stress, leading to DNA single-strand damage, PAR synthetase activation, and cell death (Szabó and Dawson, 1998; Mandalari et al., 2011). In accord with this process, we detected an increased staining for nitrotyrosine and PAR in DNBS-injected mice, which was blunted by adelmidrol treatment. One form of epithelial cell damage in the inflamed colonic mucosa has been described to involve apoptosis (Araki et al., 2010). Interestingly, proapoptotic transcriptional changes, including upregulation of proapoptotic Bax and downregulation of antiapoptotic Bel-2, were observed by Western blot. Treatment with adelmidrol lowered the signal for Bax compared with DNBS injected mice, whereas the signal for Bcl-2 in DNBS mice treated with adelmidrol was significantly greater than in the DNBS group.

As described herein, adelmidrol shares similar pharmacologic properties with PEA; this can be related to activation of nuclear receptor of PPAR family (Farquhar-Smith et al., 2002; Paterniti et al., 2013). Our previous studies, in fact, have proven that the deletion of PPAR genes reduced the protective effect of PEA; additionally, we found that PPARα, PPARγ, and PPARδ agonists exerted positive effects in several experimental models, such as kidney ischemia/reperfusion and spinal cord trauma (Di Paola et al., 2012; Paterniti et al., 2013). Therefore, we have demonstrated that the anti-inflammatory effect of adelmidrol appeared to be related to PPARγ.

**Fig. 9.** Role of PPARγ receptors on histologic damage and MPO activity compared with adelmidrol. Four days after intracolonic administration of DNBS, the colon presented a transmural necrosis and edema with a diffuse leukocyte cellular infiltrate in the submucosa (B, B’; histologic score (F) compared with sham (A, A’; histologic score F). No significant difference was appreciate between DNBS and DNBS + GW9662 group (C, C’; view histologic score (F). Adelmidrol (10 mg/kg, o.s.) reduced significantly the histologic signs of colon injury (D, D’; histologic score (F). The protective effects of adelmidrol (10 mg/kg, o.s.) were inhibited in mice injected with DNBS and pretreated with the PPARγ antagonist GW9662, in terms of both histologic damage (E, E’); histologic score (F) and MPO activity (G). *P < 0.05 versus sham group; **P < 0.001 versus sham group; #P < 0.05 versus DNBS group; ###P < 0.001 versus DNBS group.
activation because the PPARγ antagonist GW9662 efficiently neutralized the protective actions of adelmidrol against DNBS-induced colitis. On the contrary, use of PPARα KO mice has clearly shown that the adelmidrol protective effect is not associated with PPARα activation. Our results are also in agreement with a previous study in which the administration of GW6471, a PPARα antagonist, did not reverse the anti-inflammatory effect of adelmidrol (De Filippis et al., 2009). Finally, we have also showed, using the CB2 antagonist SR144528, that the adelmidrol protective effect is not related to the activation of the CB2 receptor pathways.

Our study clearly has established that the use of adelmidrol, compared with PEA, presents some important differences that may clearly justify its use in chronic inflammatory disease. In particular, it has been demonstrated that adelmidrol, unlike than PEA, which is very lipophilic, presents both hydrophilic and lipophilic features; moreover, adelmidrol increases PEA intracellular concentrations, modulating the availability of endogenous anti-inflammatory lipids (Petrosino et al., 2016). In addition, our study clearly demonstrates in this experimental model that adelmidrol, in contrast with PEA, exerts its anti-inflammatory properties by actions only on the PPARγ receptor, without involvement of the PPARα or CB2 receptor related pathways (Borrelli et al., 2015; Impellizzeri et al., 2015b). This evidence clearly represents a specific molecular mechanism that differentiates adelmidrol treatment from PEA. In conclusion, adelmidrol could represent a novel therapeutic intervention in autoimmune/inflammatory disorders such as IBD.

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Participated in research design: Esposito, Cuzzocrea.
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