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Title

Inhibition of mite-induced dermatitis, pruritus, and nerve sprouting in mice by the endothelin receptor antagonist bosentan

Short title: Bosentan application inhibits AD-like dermatitis

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Abstract

Background: Endothelin-1 (EDN1) can evoke histamine-independent pruritus in mammals and is upregulated in the lesional epidermis of atopic dermatitis (AD). EDN1 increases the production of interleukin 25 (IL-25) from keratinocytes to accelerate T helper type 2 immune deviation. Plasma EDN1 levels are positively correlated with the clinical severity and itch intensity of AD. Therefore, we hypothesized that the inhibition of EDN1 might be useful for treating atopic inflammation and itch and investigated the effects of the topical application of the EDN1 receptor antagonist bosentan on the skin inflammation and itch in a murine AD model.

Methods: We analyzed the mite-induced AD-like NC/Nga murine model, which was topically applied with bosentan or ethanol control every day for 3 weeks. We also subjected in vitro primary sensory neuron culture systems to nerve elongation and branching assays after EDN1 stimulation.

Results: Topical application of bosentan significantly attenuated the development of mite-induced AD-like skin inflammation, dermatitis scores, ear thickness, scratching bouts, and serum level of thymus and activation-regulated chemokine in NC/Nga mice. Bosentan application also significantly reduced the gene expression of *Il13*, *Il17*, and *Ifng* in the treated lesions. Histologically, the number of infiltrated dermal cells, the epidermal EDN1 expression, and the number of intraepidermal nerve fibers were significantly inhibited upon bosentan application. While EDN1 significantly elongated the neurites of dorsal root ganglion cells in a dose- and time-dependent manner, bosentan treatment attenuated this.

Conclusions: EDN1 plays a significant role in mite-induced inflammation and itch. Topical bosentan is a potential protective candidate for AD.

Keywords

Atopic dermatitis, endothelin-1, endothelin receptor, nerve elongation, pruritus

Abbreviations

AD: atopic dermatitis

DRG: dorsal root ganglion

EDN1: endothelin-1

EDNR: endothelin receptor

ERK: extracellular signal-regulated kinase

ILC2: group 2 innate lymphoid cell

IL: interleukin

JNK: c-Jun N-terminal kinase

MAPK: mitogen-activated protein kinase

MEK: mitogen-activated protein kinase kinase

NHEK: normal human epidermal keratinocyte

PGP9.5: protein gene product 9.5

qRT-PCR: quantitative real-time polymerase chain reaction

SDS: sodium dodecyl sulfate

TARC: thymus and activation-regulated chemokine

Th2 cell: T helper 2 cell

Introduction

Atopic dermatitis (AD) is a common, chronic, severely pruritic, eczematous skin disease, which markedly deteriorates the quality of life of those afflicted by it.[1,2] Besides intense itch, AD is characterized by skin inflammation and barrier dysfunctions.[1,3] Severe and chronic pruritus induces inevitable scratching and the vicious itch/scratch cycle exacerbates and sustains the atopic inflammation and skin barrier dysfunction.[4] The acute skin lesions of AD exhibit a T helper type 2 (Th2)-deviated reaction, but at the chronic stage, Th1- and Th17-related cytokines and chemokines also intermingle and perpetuate the skin inflammation. The skin microbiome and the autoallergic inflammation are also related to the pathological condition of AD.[5,6] Moreover, many peptides and proteases have been shown to play important roles in the pathophysiology of AD.[2,7]

Endothelin-1 (EDN1) is a 21-amino-acid peptide that is expressed by a variety of cell types, including endothelial cells, immune cells such as dendritic cells, monocytes, and macrophages, neurons, and keratinocytes.[8–13] In addition to its potent vasoconstricting activity, EDN1 is also involved in keratinocyte proliferation, neo-angiogenesis, and leukocyte chemotaxis.[14–16] Increased EDN1 expression is closely associated with pathogenetic mechanisms of several diseases such as scleroderma and asthma.[17,18] EDN1 also acts as a potent pruritogen in mice[19,20] and humans,[21] and induces itch by directly activating sensory neurons.[22] Moreover, plasma EDN1 levels have been shown to be elevated and positively correlated with clinical severity, itch intensity, and serum IgE level in AD.[23] We also demonstrated that EDN1 amplified epidermal inflammation via mutual positive feedback between EDN1 and IL-25,[24] which is one of the main activators of group 2 innate lymphoid cells (ILC2),[25] and that EDN1 polarized the dendritic-cell–T-cell response toward Th17/1 differentiation.[26] Therefore, EDN1 could be suggested to induce the promotion of both type 1/17 inflammation (at the immune synapsis level) and type 2 inflammation (via ILC2). Thus, we hypothesize that EDN1 may accelerate the chronicity of AD lesions. However, its role in atopic inflammation remains elusive.

EDN1 works via G-protein-coupled EDN receptor (EDNR) types A and B.[27] The binding of EDN1 to EDNR types A and B activates various signaling pathways including adenylyl cyclase signaling, phosphoinositide signaling, oxidative stress, growth factor receptor transactivation, and the mitogen-activated protein kinase (MAPK) pathway.[28] Bosentan is known as a potent antagonist that inhibits EDNR of both types A and B.[29] Bosentan tablets are used to treat pulmonary arterial hypertension in the United States, the European Union, Japan, and other countries. In addition to vasodilation, bosentan has been reported to have anti-inflammatory effects.[30,31] In this study, we examined the effects of bosentan on mite-antigen-induced AD-like model mice. We found that topical bosentan significantly reduced the clinical and histological inflammatory response as well as *Il13*, *Il17a*, and *Ifng* expression in AD mice. Bosentan also inhibited the itching/scratching behavior, the epidermal EDN1 expression, and the number of intraepidermal nerve fibers. Notably, EDN1 appeared to accelerate neurite elongation and branch formation of dorsal root ganglion (DRG) cells, which was inhibited by bosentan.

Methods

For several sections, additional details are provided in Supplementary Data S1.

Mice

Female NC/Nga mice aged 9–11 weeks old were used for the experiments on an AD-like murine model. Female C57BL/6 mice aged 6 weeks old were used for the experiment of DRG neuron elongation in vitro. The maintenance and experimental procedures of the mice were approved by the Animal Care and Use Committee of Kyushu University School of Medicine.

Induction of mite-induced AD-like murine model

It is known that repeated epicutaneous application of mite antigen induces AD-like dermatitis in NC/Nga mice.[32] In this study, the hair on their upper back was shaved with a clipper and removed with depilatory. The shaved dorsal back and ear skin was treated with 200 ml of 4% sodium dodecyl sulfate (SDS). These mice were topically treated with 200 ml of 5% bosentan (AD-bosentan group, n=7) or vehicle (AD-ethanol group, n=7; and control-ethanol group, n=7) every day for 3 weeks-on the same dorsal back and ear skin. After 1 or 2 h, 100 mg of mite antigen (*Dermatophagoides farinae* extract; Biostir AD) was epicutaneously applied to the same site where SDS and bosentan had been applied, twice a week for 3 weeks (AD-ethanol group and AD-bosentan group). On day 22, these mice were sacrificed (Fig. 1A).

Evaluation of skin lesions

The clinical severity of dermatitis was evaluated at every timepoint of mite antigen application. The development of 1) erythema/hemorrhage, 2) scaling/dryness, 3) edema, and 4) excoriation/erosion was scored as 0 (none), 1 (mild), 2 (moderate), or 3 (severe). The sum of the individual scores was taken as the dermatitis score.

Evaluation of scratching behavior

Scratching behavior of the mice was measured for 4 h immediately after the last stimulation of mite antigen using the Microact1 system.

ELISA

Serum obtained from the whole blood of NC/Nga mice was kept at −80℃ until further use. Quantikine ELISA Kit, eotaxin mouse SimpleStep ELISA Kit, and mouse Anti-HDM IgG Antibody Assay Kit were used for determining thymus and activation-regulated chemokine (TARC), eotaxin, and house dust mite IgG concentrations, respectively, in mouse serum, in accordance with the manufacturer's protocol.

Primary DRG neuron culture

DRGs of C57BL/6 mice were dissociated from the lumbar, thoracic, and cervical regions after removing blood, and then treated with papain–cysteine solution containing 0.67 mg/ml L-cysteine, 2 mg/mL papain, and 0.2% (v/v) saturated $NaHCO_3$ in HBSS without Ca^{2+} or Mg^{2+}, and collagenase solution containing 3 mg/mL collagenase in HBSS without Ca^{2+} or Mg^{2+}, for 10 min each at 37℃. DRGs were triturated for dissociation to prepare a single-cell suspension in plating medium containing 10% FBS, 10% horse serum, 1.5 mg/ml glucose, 1% penicillin/streptomycin/glutamine, 2% B27, 140 μg/ml DNase, and 2 mM GlutaMax in DMEM, followed by straining through a 70 μm cell strainer. DRG neurons were plated on poly-L-lysine-coated cover glasses coated with 0.5% laminin, and incubated for 4 h at 37℃ and 5% CO_2. Stimulation reagents were applied in feeding medium containing 1% penicillin/streptomycin/glutamine, 2% B27, and 0.5 mM GlutaMax in Neurobasal™-A medium. Cultured DEGs were stimulated with 10, 50, or 100 nM EDN1, 6.3 nM IL-31, or medium as vehicle control for the indicated time points. In selected experiments, 100 μM bosentan, or 10 μM U0126, PD98059, SB202190, SP600125, or medium as vehicle

control was applied 1 h before EDN1 stimulation.

Immunofluorescence and image analysis

Primary cultured DRG neurons were fixed in 4% paraformaldehyde at room temperature for 10 min, and permeabilized with 0.2% Triton X-100 in phosphate-buffered saline for 10 min. Then, they were blocked with 1% bovine serum albumin and 0.1% Tween 20 in phosphate-buffered saline for 30 min. Samples were incubated overnight with anti-βⅢ-tubulin antibody in blocking solution, and goat anti-mouse IgG (H+L) cross-adsorbed secondary antibody, Alexa Fluor 488, was added for 1 h. Finally, the cells were mounted with Mounting Medium with DAPI. The total length of all branched structures of dendrites was measured by ImageJ 1.51k.

Statistics

All data are presented as mean ± standard error of the mean (SEM). The statistical significance of the differences between values was determined by one-way analysis of variance, followed by Bonferroni's multiple comparison test, using GraphPad PRISM5 software version 5.02. A p-value of less than 0.05 was considered statistically significant.

Results

Topical application of endothelin receptor antagonist bosentan alleviates the clinical symptoms of mite-induced dermatitis in NC/Nga mice

As shown previously,[32] the epicutaneous application of mite antigen in this study appeared to evoke severe dermatitis, ear swelling, and scratching in the AD-ethanol group compared with the status in the control-ethanol group (Fig. 1B–E). Topical application of the specific EDNR antagonist bosentan significantly reduced the clinical manifestations (Fig. 1B), dermatitis score (Fig. 1C), ear thickness (Fig. 1D), and scratching behavior (Fig. 1E) in the AD-bosentan group compared with those in the AD-ethanol group. Significant differences in dermatitis score were observed between the AD-ethanol group and the AD-bosentan group on days 10, 14, 17, and 21 (Fig. 1C) and in ear thickness on days 14, 17, and 21 (Fig. 1D). However, in comparison to those in the control-ethanol group, dermatitis score (Fig. 1C) and ear thickness (Fig. 1D) were still significantly higher in the AD-bosentan group. We also compared the control-ethanol group and the group with bosentan and no mite application, but there were no significant differences in skin manifestations and scratching behavior (data not shown).

Topical application of bosentan attenuates the histological changes of mite-antigen-induced dermatitis in mice

Consistent with the clinical scores and scratching behavior, histological analysis of skin samples on day 22 showed more intense inflammatory cell infiltration in AD-ethanol mice than in control-ethanol mice (Fig. 2A and 2B). Topical bosentan significantly reduced the number of dermal inflammatory cells in the AD-bosentan group compared with that in the AD-ethanol group (Fig. 2A and 2B). Significant reduction of the number of infiltrating eosinophils stained with anti- eosinophil cationic protein antibody was also observed in the AD-bosentan group compared with that in the AD-ethanol group (Fig. 2C). Moreover, mast cell infiltration visualized by staining with anti-tryptase antibody (Fig. 2A) was also significantly decreased

in the AD-bosentan group compared with that in the AD-ethanol group (Fig. 2D). However, significant infiltration of these cells still remained upon comparison between the control-ethanol group and the AD-bosentan group (Fig. 2A–D). We also compared the control-ethanol group and the group with bosentan and no mite application, but there were no significant differences in the dermal infiltration of inflammatory cells, eosinophils and mast cells (data not shown).

Topical bosentan inhibits the lesional *Il13*, *Il17a*, and *Ifng* expression and serum TARC and mite-specific IgG levels in AD mice

We next examined the mRNA levels of dermatitis-related cytokines in the lesional skin of AD-like dermatitis with or without bosentan treatment. Skin samples were taken from mite-antigen-treated ear skin and the mRNA levels of *Il4*, *Il13*, *Il17a*, and *Ifng* were determined by qRT-PCR. In the AD-ethanol group, all of these mRNA levels were significantly increased compared with those in the control-ethanol group. Topical bosentan application significantly decreased the expression of *Il13*, *Il17a*, and *Ifng,* but not that of *Il4* (Fig. 3), although *Il13* expression was not completely inhibited by bosentan application. Serum samples were taken from the mice and TARC, eotaxin, and mite-specific IgG levels were measured by ELISA. Compared with those in the control-ethanol group, the TARC and mite-specific IgG levels in the AD-ethanol group were significantly elevated, but were again significantly inhibited in the AD-bosentan group (Fig. 4). Eotaxin in serum was not involved in this mite-induced AD mouse model (Fig. 4B). The expression of IL-25 was immunohistologically strongly augmented throughout all epidermal layers in the AD-ethanol group (Supplementary Fig. S1A). The epidermal IL-25 expression was significantly inhibited to almost the same level as the control by topical bosentan (Supplementary Fig. S1B).

Topical bosentan inhibits epidermal EDN1 expression and the number of intraepidermal nerve fibers

Although the expression of EDN1 was immunohistologically confined to the lower part of the epidermis in

the control-ethanol group, it was strongly augmented throughout all epidermal layers in the AD-ethanol group (Fig. 5A), as was previously reported.[24] Notably, the epidermal EDN1 expression appeared to be inhibited to the same level as in the control by the topical bosentan (Fig. 5A). As bosentan inhibited pruritus/scratching in the present experiments, we next measured the number of epidermal nerve fibers by PGP9.5 immunostaining. In the AD-ethanol group, the number of epidermal nerve fibers was significantly increased compared with that in the control-ethanol group (Fig. 5B and 5C). Topical bosentan application significantly reduced the number of epidermal nerve fibers in AD-bosentan mice compared with that in AD-ethanol mice, but there was not a complete reduction to the level in the control-ethanol group (Fig. 5B and 5C).

EDN1 promotes neuronal elongation and branching in small-diameter DRG neurons, which is inhibited by bosentan

As the number of epidermal nerve fibers was increased in the EDN1-rich epidermis (Fig. 5), we next analyzed the effects of EDN1 on DRG neurons. We used cultured dissociated DRG neurons that we treated with IL-31 (which has attracted attention as a pruritogen in patients with AD),[7] EDN1, or vehicle control for 24 h. Regarding the pruritogen IL-31,[7] Feld et al. recently reported that it promoted the growth of sensory nerves in vitro and in vivo.[33] In DRG neurons with a small diameter (≤20 μm), EDN1 as well as IL-31 induced neurite elongation and branch formation compared with the status of neurons treated with vehicle control (Fig. 6A and 6B). Interestingly, both EDN1 and IL-31 affected neither neurite elongation nor branch formation in large-diameter DRG neurons (>20 μm) (Supplementary Fig. S2). Small-diameter DRG cells were stimulated with 0–100 nM EDN1. As shown in Supplementary Fig. S3, both neurite elongation and branch formation were significantly upregulated in DRG neurons by EDN1, with an optimal dose of approximately 50 nM. The neurostimulatory effects of EDN1 were shown to occur in an incubation time-dependent manner (Supplementary Fig. S2). Bosentan significantly inhibited the EDN1-induced

neurite elongation and branch formation of small-diameter DRG neurons (Fig. 6C). We finally examined the cell signaling associated with the neurostimulatory effects of EDN1 and focused on the MAPK pathway, one of the signaling pathways related to the EDN. The EDN1-mediated upregulation of neurite elongation and branch formation in small-diameter DRG neurons was completely abrogated by the p38 MAPK inhibitor SB202190 and the JNK inhibitor SP600125, but not by the ERK1/2 inhibitor U0126 or the MEK1/2 inhibitor PD98059 (Supplementary Fig. S4). Interestingly, baseline neurite elongation and branch formation were rather augmented by U0126 or PD98059 (Supplementary Fig. S4).

Discussion

Although EDN1 induces pruritus and might be involved in chronic AD inflammation,[7] the effects of EDNR blockade on AD remain unresolved. Here, we report for the first time that topical application of the EDNR antagonist bosentan efficiently reduced skin inflammation, pruritus, and the number of intraepidermal nerve fibers of the mite-antigen-induced AD-like murine model.

This AD-like murine model used in this study mimics human AD. The lesional skin in AD mice manifests erythema, scaling, and lichenification with itching/scratching behavior.[32] In the present study, we also found elevated plasma TARC levels, upregulated expression of epidermal EDN1, and an increased number of intraepidermal nerve fibers. Blockade of EDNR by bosentan significantly alleviated the clinical dermatitis scores, ear thickness, and itching/scratching behavior. In parallel with this, bosentan attenuated the infiltration of inflammatory cells (eosinophils and mast cells) in the lesional dermis. Plasma TARC levels were also downregulated by topical bosentan. These anti-inflammatory effects of bosentan have been reported in previous studies. For example, bosentan was previously reported to reduce the release of secondary mediators such as IL-1, IL-6, IL-8, and tumor necrosis factor-α (TNF-α) produced by monocytes stimulated with endothelin.[30,31] It could also inhibit the upregulation of cell adhesion molecules on the endothelium and leukocytes such as neutrophils and T cells.[34-36] Furthermore, the effectiveness of bosentan has been reported in several mouse or rat disease models. For example, in an ovalbumin-induced allergic rhinitis rat model, oral bosentan significantly inhibited nasal symptoms and serum IgE level.[37] In addition, in a murine model of inflammatory bowel disease and a rat colitis model, bosentan significantly reduced clinical and histological inflammation.[38,39] Moreover, in rat models of airway inflammation, bosentan also reduced the levels of eosinophils and several cytokines including IL-4, TNF-α, IFN-γ, and IL-1β in bronchoalveolar lavage fluid and lung inflammation.[40,41] These results suggest that bosentan has a sufficient anti-inflammatory effect and that its topical application could potentially be used for protective drugs against AD. Further examinations will be required to determine whether it can be used as a therapeutic

agent for AD and how effective bosentan is compared to other topical products such as topical corticosteroid or tacrolimus ointment. Furthermore, this study was only performed in one AD mouse model. Since atopic dermatitis is a multifactorial disease, further studies will be needed to reveal its relationship to other factors.

While multiple molecules have been implicated in AD, studies in mice and humans have elucidated central roles of IL-4 and IL-13.[42,43] The essential role of the type 2 axis was confirmed by the clinical success of dupilumab, an anti-IL-4Rα antibody that modulates the signaling of both IL-4 and IL-13 pathways.[44] In the present study, bosentan significantly suppressed mRNA of *Il13*, *Il17*, and *Ifng* but not *Il4* in the analysis of cytokine expression in the skin. Bosentan application significantly suppressed the dermatitis and pruritus in the mite-induced AD mouse model even though it did not suppress IL-4 expression in the skin, which would indicate that IL-13 plays a greater role than IL-4 in this mite-induced AD mouse model. In fact, it has been reported that two anti-IL-13 antibodies, tralokinumab and lebrikizumab, were effective in a phase 2 clinical trial of AD.[45,46] Gene expression studies in AD patients also suggested that IL-13 might be of particular pathophysiological importance.[47] However, in the present study, bosentan did not completely abrogate the inflammation and pruritus of the mite-induced mouse model. In regard to the relative efficacy of biologics, it was reported that the strongest evidence is currently available for dupilumab, which modulates the signaling of both IL-4 and IL-13 pathways.[48] These results suggest that IL-13 may be more important but IL-4 would also be involved in the inflammation of AD.

In the present study, blockade of EDNR by bosentan abrogated the mRNA expression of *Il13*, *Il17*, and *Ifng*, but not *Il4*. This might be consistent with the fact that EDN1 induces the release of IL-25 in keratinocytes as we showed previously[48] and in Supplementary Fig. S1, and IL-25 induces the activation of ILC2, which releases high levels of IL-13, IL-5, and IL-9, but not IL-4.[25] Further investigations will be needed to determine whether ILC2 increases in this AD mouse model and whether blockade of EDNR by bosentan can inhibit ILC2 infiltration through IL-25 suppression.

The density of epidermal nerve fibers is higher in the skin of patients with AD than in that of healthy controls; this has been suggested to be partly responsible for the hyperkinesis—a state of hypersensitivity of the itch sensation—seen in these patients.[49-51] As the epidermal EDN1 expression was augmented with an increased number of lesional intraepidermal nerve fibers, which were significantly inhibited by topical bosentan, we assumed that EDN1 might affect neuronal growth. Therefore, we next examined the effects of EDN1 and bosentan in DRG neurons. EDN1 potently accelerated the neuronal elongation and branching of DRG cells, which were effects similar to those of IL-31, a pruritogen reported to promote the growth of sensory nerves in vitro and in vivo.[33] EDNR blockade with bosentan abrogated the nerve length and number of branches of DRG by EDN1, as expected. The EDN1-mediated neurostimulatory effects were evident only in small-diameter (< 20 μm) DRG cells, but not in large-diameter ones. Similar neurostimulatory effects have been reported for IL-31 and histamine, which are related to the pathogenesis of atopic inflammation and itch.[33,52,53] Specifically, the pruritogenic IL-31 and histamine have been shown to upregulate the neurite elongation of small-diameter DRG neurons.[33,53] These results reinforce the assertion that EDN1 is a plausible candidate to be included among these itch-related mediators in the pathogenesis of AD.

Interestingly, in the present study, nerve elongation was augmented by EDN1 in a dose-dependent manner up to 100 nM, while the increase of branching peaked at 50 nM and was not observed at 100 nM. Recently, intensive research has focused on understanding the mechanisms of outgrowth and branching of neurons.[54-56] In particular, several glycerophospholipids and several of their interacting proteins are involved in the elongation and branching of neurons.[57] It has been found that different specific lipids are needed in the extension and branching of neurons. The heterogeneous responsiveness of nerve elongation and branching to EDN1 in this study might have been caused by the differences in mechanisms between nerve elongation and branching. However, the precise mechanisms of the preventive effects of bosentan in the AD-like mouse model and on epidermal innervation are not fully understood. Further investigation is

warranted to explore the subcellular molecular mechanisms involved.

The EDN1-induced neurostimulatory effects were dependent on the p38 MAPK and JNK, but not MEK/ERK, pathways. Previous studies reported that IL-31-induced neuronal outgrowth was mediated via the activation of signal transducer and activator of transcription 3[33] and that histamine-induced neurite outgrowth was possibly mediated by the protein kinase Cδ-mediated cell signaling pathway.[53] It has been reported that the JNK, p38 MAPK, and MEK/ERK pathways are differentially involved in neurite growth and branching in a stimulus-dependent manner.[58-61] Further investigation is warranted to clarify the signaling pathways leading to neuronal elongation and branching in peripheral nerves.

In conclusion, our study revealed that the topical application of bosentan efficiently reduced the mite-induced dermatitis, itching/scratching, intraepidermal nerve fibers, epidermal EDN1 expression, and circulating TARC levels in a murine AD model. EDN1 potently accelerated the nerve elongation and branching in small-diameter DRG neurons, which was significantly inhibited by the EDNR antagonist bosentan. Considering the pruritogenic activity of EDN1 in mice and humans,[19-21] the EDN1/EDNR system should be better integrated into our understanding of the pathogenesis of AD. Moreover, EDNR blockade is a potential therapeutic target for AD.

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Figure legends

Fig. 1

Bosentan provided relief of the mite-induced dermatitis symptoms in NC/Nga mice. (A) Schema of the animal model. These mice were topically treated with 200 ml of 5% bosentan (AD-bosentan group) or vehicle (AD-ethanol group and control-ethanol group) every day for 3 weeks on the dorsal back and ear skin. After 1 or 2 h, 100 mg of mite antigen (*Dermatophagoides farinae* extract; Biostir AD) was epicutaneously applied to the same site twice a week for 3 weeks (AD-ethanol group and AD-bosentan group). (B) Macroscopic features of skin lesions of control-ethanol, AD-ethanol, and AD-bosentan groups on day 21. (C) Dermatitis scores were assessed at each time of mite antigen stimulation. (D) Ear thickness was measured at each time of mite antigen stimulation. (E) Scratching behavior was measured after the last mite antigen stimulation for 4 h. (C, D) *$p<0.05$, **$p<0.01$, ***$p<0.001$ compared with the control group. #$p<0.05$, ##$p<0.01$, ###$p<0.001$ compared with the AD group. (E) **$p<0.01$, ***$p<0.001$. Each group consisted of seven mice. Representative data of three independent experiments are shown.

Fig. 2

Topical application of bosentan histologically improved mite-antigen-induced dermatitis in NC/Nga mice. (A) Histological appearance of skin lesions of control-ethanol, AD-ethanol, and AD-bosentan groups on day 22. Upper, middle, and lower panels show hematoxylin-eosin staining and staining with anti-tryptase antibody and anti-eosinophil cationic protein antibody, respectively. (B–D) Numbers of total inflammatory cells (B), eosinophils (C), and mast cells (D) in the dermis of mice. *$p<0.05$, **$p<0.01$, ***$p<0.001$. Scale bar: 40 μm. Each group consisted of seven mice. Representative data of three independent experiments are shown.

Fig. 3

Topical bosentan inhibits the lesional *Il13*, *Il17a*, and *Ifng* expression in AD mice. (A) IL-4, (B) IL-13, (C) IL-17, and (D) IFN-γ mRNA levels were analyzed by real-time PCR in ear skin of NC/Nga mice. *p<0.05, **p<0.01, ***p<0.001. Each group consisted of seven mice. Representative data of three independent experiments are shown.

Fig. 4

Increases of serum TARC levels and mite-specific IgG in AD mice were suppressed by bosentan. Serum TARC (A), eotaxin (B), and mite-specific IgG levels (C) in mice were measured by ELISA. *p<0.05, **p<0.01. Each group consisted of seven mice. Representative data of three independent experiments are shown.

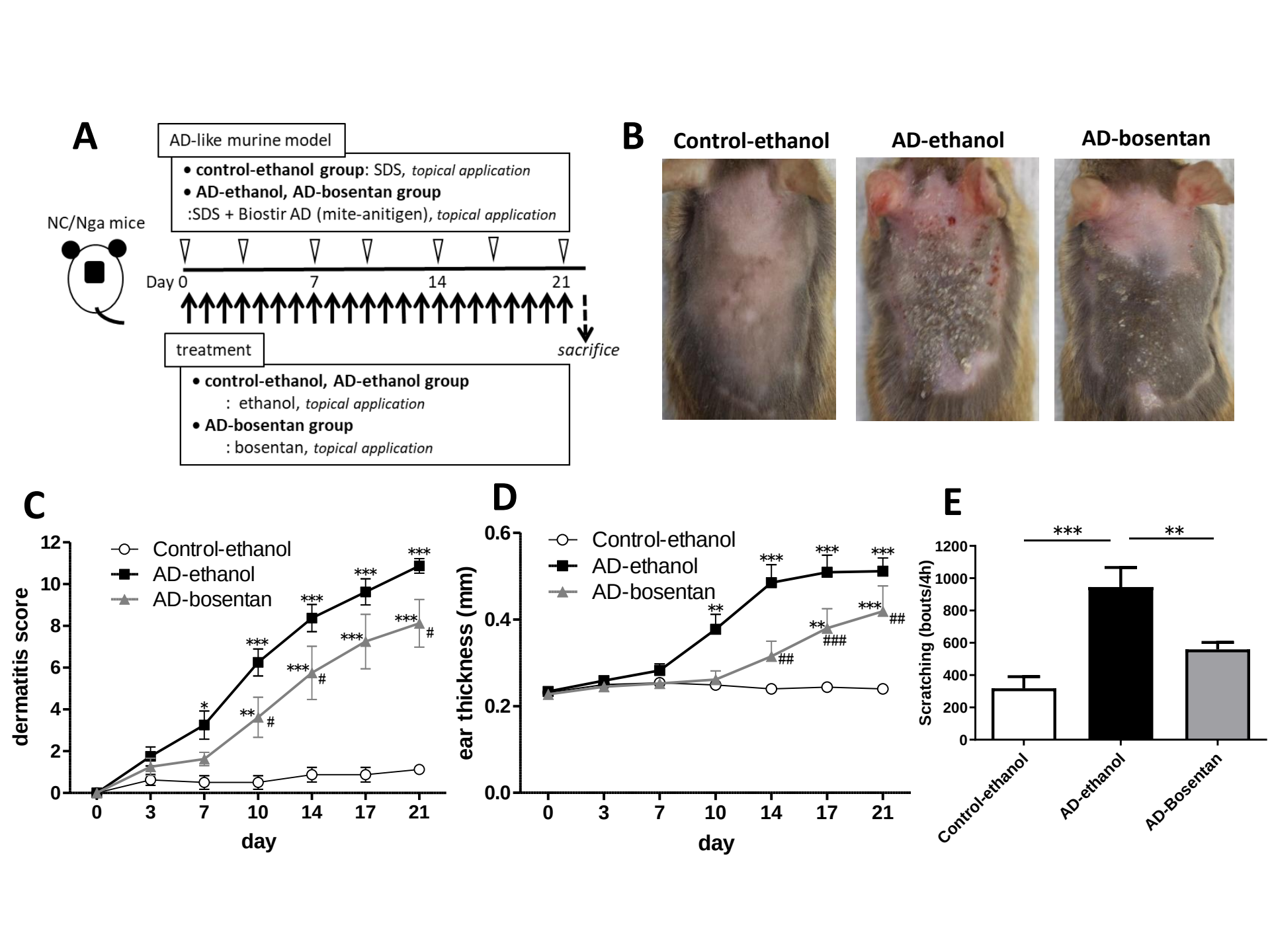
Fig. 5

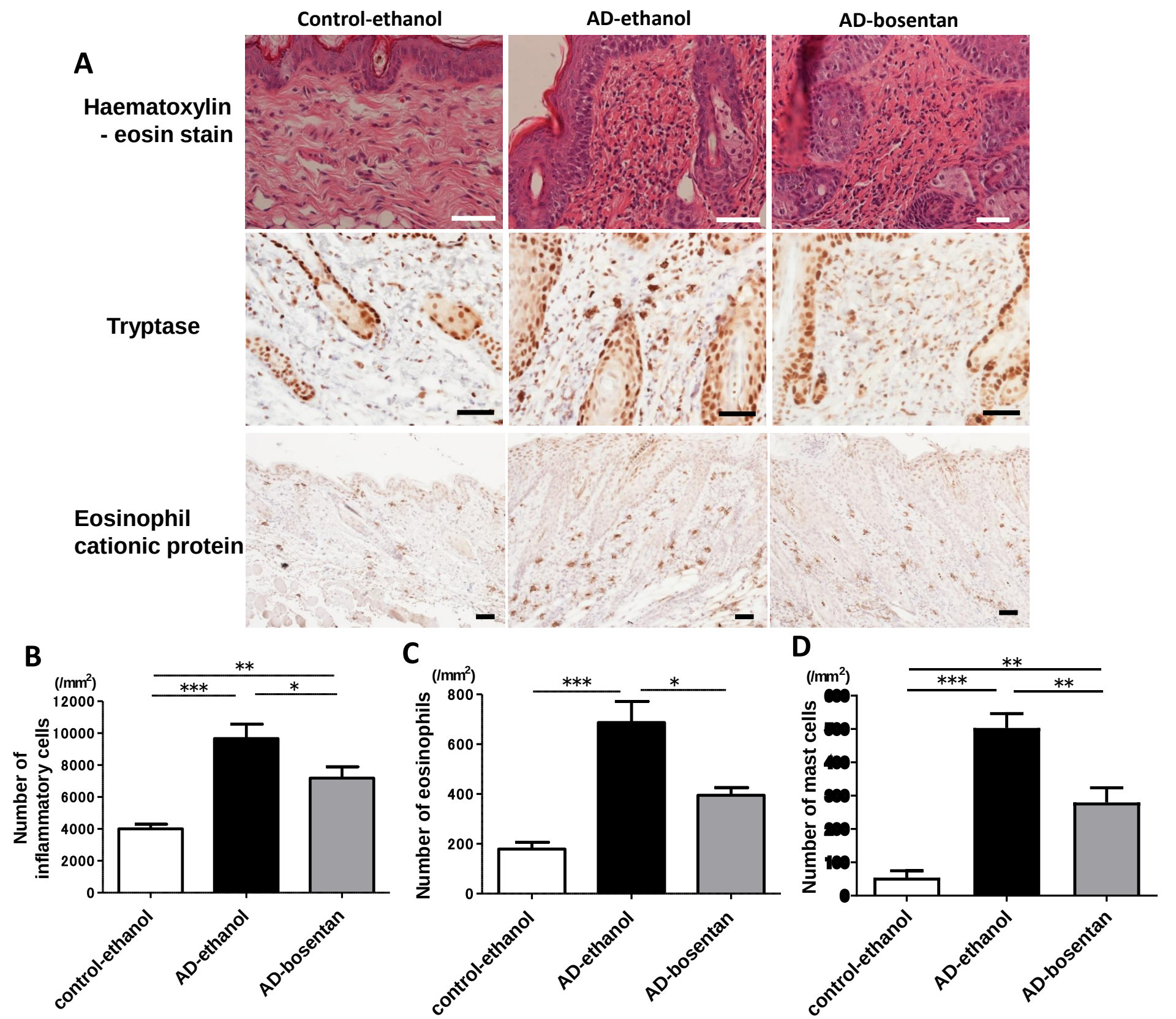
Topical bosentan suppresses the augmentation of epidermal EDN1 expression and intraepidermal nerve fibers in AD mice. (A) Immunohistochemical staining for EDN1 of skin lesions of control-ethanol, AD-ethanol, and AD-bosentan groups. (B) Representative images of PGP9.5-positive nerves in back skin of mice. (C) The number of intradermal PGP9.5-positive nerves was counted and calculated per high-power field. ***p<0.001. Scale bar: 40 μm. Each group consisted of seven mice. Representative data of three independent experiments are shown.

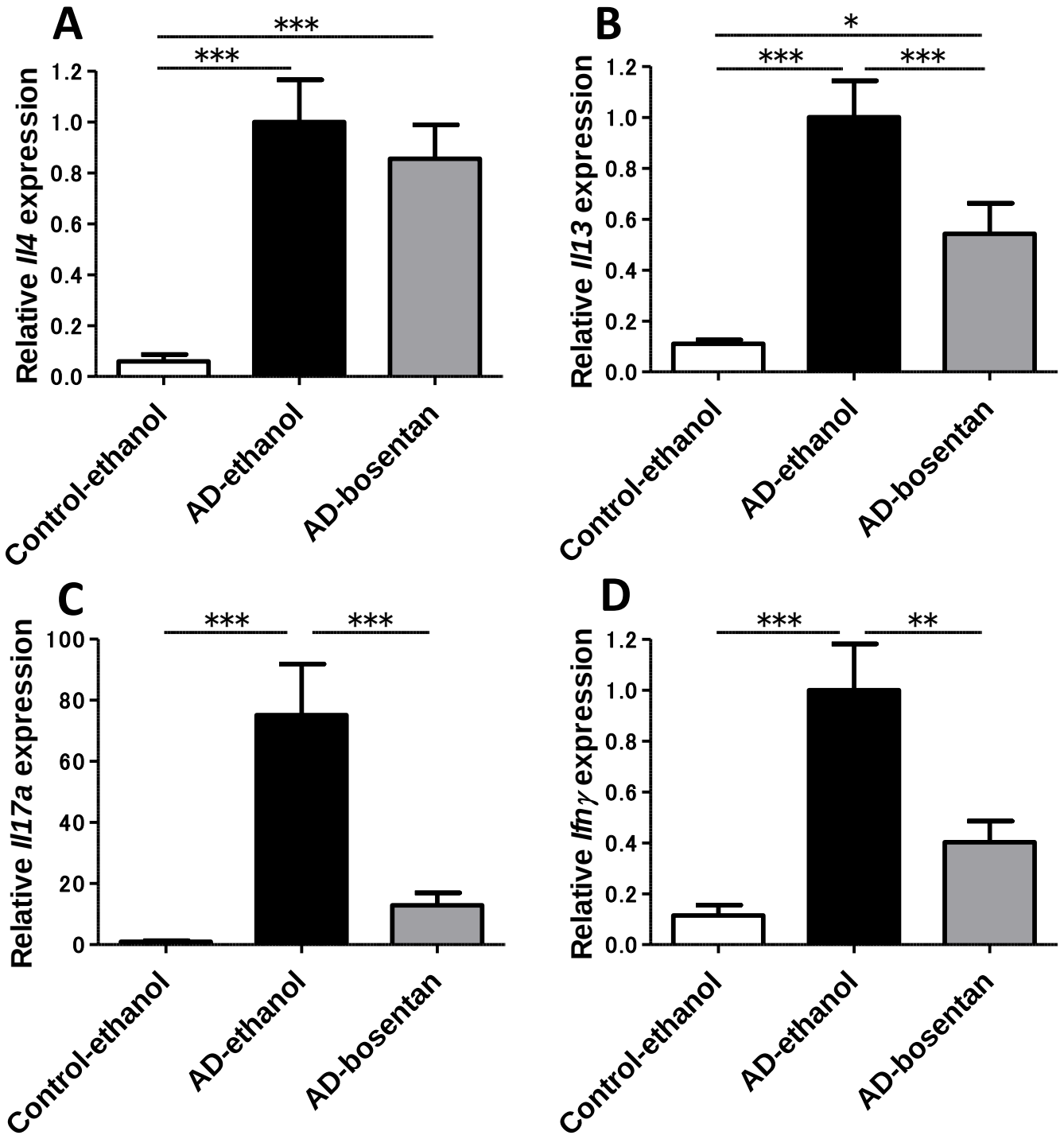
Fig. 6

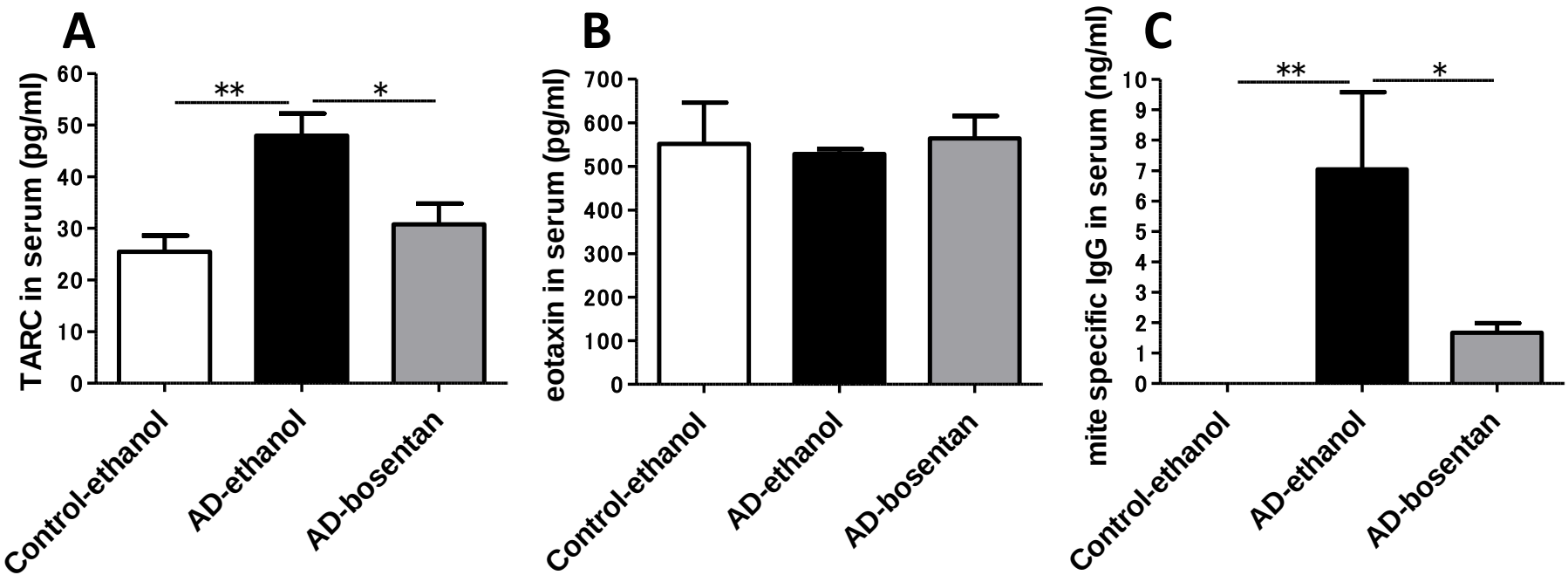
EDN1 induces neurite elongation and branching in small-diameter DRG neurons, which is inhibited by bosentan. (A) Neurite outgrowth from small-diameter (≤20 μm) DRG neurons stimulated with EDN1, IL-31, or control medium. (B) Quantification of the neurite length and branching in small-diameter DRG neurons incubated with control medium, IL-31 (100 ng/ml), or EDN1 (50 nM) for 24 h (n=6–10). (C)

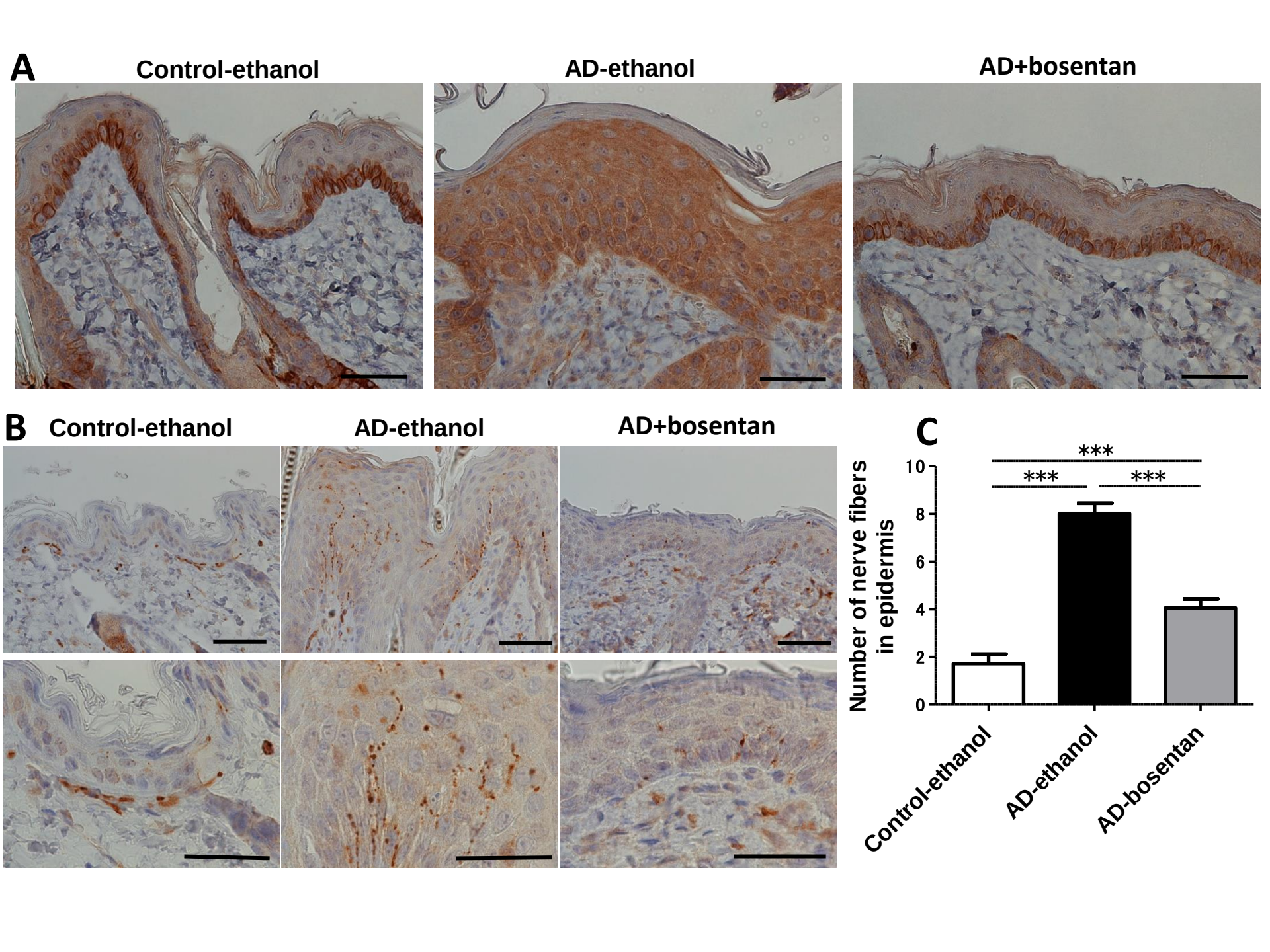
Small-diameter DRG neurons were stimulated with EDN1 (50 nM) alone or control medium for 24 h. Bosentan (100 μM) or control medium was applied 1 h before EDN1 stimulation (n=8–11). *p<0.05, **p<0.01, ***p<0.001. Scale bar: 75 μm. Representative data of three independent experiments are shown.

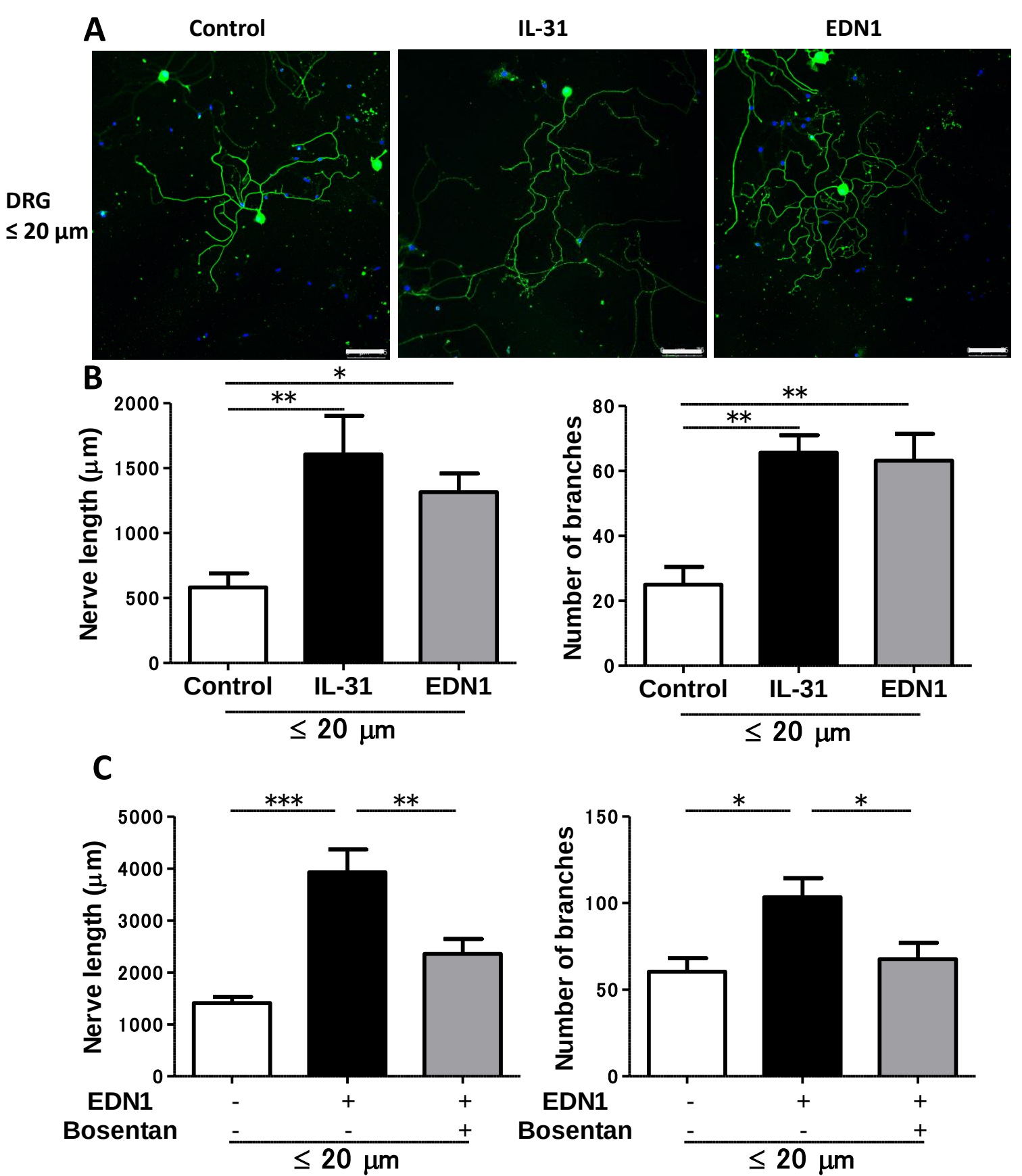

A
AD-like murine model
• control-ethanol group: SDS, topical application
• AD-ethanol, AD-bosentan group
:SDS + Biostir AD (mite-anitigen), topical application
NC/Nga mice
Day 0
7
14
21
sacrifice
treatment
• control-ethanol, AD-ethanol group
: ethanol, topical application
• AD-bosentan group
: bosentan, topical application
B
Control-ethanol
AD-ethanol
AD-bosentan
C
dermatitis score
Control-ethanol
AD-ethanol
AD-bosentan
day
D
ear thickness (mm)
Control-ethanol
AD-ethanol
AD-bosentan
day
E
Scratching (bouts/4h)
Control-ethanol
AD-ethanol
AD-Bosentan


A
Control-ethanol
AD-ethanol
AD-bosentan
Haematoxylin
- eosin stain
Tryptase
Eosinophil
cationic protein
B
(/mm²)
Number of
inflammatory cells
12000
10000
8000
6000
4000
2000
0
**
***
*
control-ethanol
AD-ethanol
AD-bosentan
C
(/mm²)
Number of eosinophils
800
600
400
200
0
***
*
control-ethanol
AD-ethanol
AD-bosentan
D
(/mm²)
Number of mast cells
**
***
**
control-ethanol
AD-ethanol
AD-bosentan


A
***
***
Relative Il4 expression
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Control-ethanol
AD-ethanol
AD-bosentan
B
*
***
***
Relative Il13 expression
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Control-ethanol
AD-ethanol
AD-bosentan
C
***
***
Relative Il17a expression
100
80
60
40
20
0
Control-ethanol
AD-ethanol
AD-bosentan
D
***
**
Relative Ifnγ expression
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Control-ethanol
AD-ethanol
AD-bosentan


A
TARC in serum (pg/ml)
60
50
40
30
20
10
0
**
*
Control-ethanol
AD-ethanol
AD-bosentan
B
eotaxin in serum (pg/ml)
700
600
500
400
300
200
100
0
Control-ethanol
AD-ethanol
AD-bosentan
C
mite specific IgG in serum (ng/ml)
10
9
8
7
6
5
4
3
2
1
0
**
*
Control-ethanol
AD-ethanol
AD-bosentan


A
Control-ethanol
AD-ethanol
AD+bosentan
B
Control-ethanol
AD-ethanol
AD+bosentan
C
Number of nerve fibers in epidermis
***
***
***
10
8
6
4
2
0
Control-ethanol
AD-ethanol
AD-bosentan


A
Control
IL-31
EDN1
DRG
≤ 20 µm
B
Nerve length (µm)
2000
1500
1000
500
0
*
**
Control
IL-31
EDN1
≤ 20 µm
Number of branches
80
60
40
20
0
**
**
Control
IL-31
EDN1
≤ 20 µm
C
Nerve length (µm)
5000
4000
3000
2000
1000
0
***
**
EDN1
-
+
+
Bosentan
-
-
+
≤ 20 µm
Number of branches
150
100
50
0
*
*
EDN1
-
+
+
Bosentan
-
-
+
≤ 20 µm