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IFN-γ or IFN-α Ameliorates Chronic Proliferative Dermatitis by Inducing Expression of Linear Ubiquitin Chain Assembly Complex

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The linear ubiquitin chain assembly complex (LUBAC) ubiquitin ligase complex, composed of HOIL-1L–interacting protein (HOIP), heme-oxidized IRP2 ubiquitin ligase-1L (HOIL-1L), and SHANK-associated RH domain protein, specifically generates linear polyubiquitin chains and is involved in NF-κB activation. Lack of SHANK-associated RH domain protein, which drastically reduces the amount of HOIP and HOIL-1L, causes chronic proliferative dermatitis (cpdm) in mice. Impaired NF-κB activation and augmented apoptosis have been implicated in the pathogenesis of cpdm in mice. In this study, we found that IFN-γ increased the amount of LUBAC by inducing HOIP and HOIL-1L mRNA transcription and enhanced the signal-induced NF-κB activation in embryonic fibroblasts, keratinocytes, and bone marrow–derived macrophages from wild-type and/or cpdm mice; however, IFN-γ failed to augment NF-κB activation in mouse embryonic fibroblasts lacking linear polyubiquitination activity of LUBAC. Moreover, s.c. injection of IFN-γ for 3 wk into the skin of cpdm mice increased the amount of HOIP, suppressed apoptosis, and ameliorated the dermatitis. Inhibition of keratinocyte apoptosis by IFN-γ injection suppressed neutrophil, macrophage, and mast cell infiltration and the amount of TNF-α in the skin of cpdm mice. Similarly, IFN-α also enhanced the amount of HOIP as well as NF-κB activation, inhibited apoptosis, and ameliorated cpdm dermatitis. These results indicate that the IFNs enhance NF-κB activation and ameliorate cpdm dermatitis by augmenting expression of HOIP and HOIL-1L and linear polyubiquitination activity of LUBAC. The Journal of Immunology, 2014, 192: 3793–3804.
of TNF-α-induced apoptosis in the skin of cpdm mice. IFN-γ failed to induce signal-mediated NF-κB activation in cells lacking linear polyubiquitination activity of LUBAC, suggesting that IFN-γ enhances NF-κB activation through its augmenting effect on LUBAC. Moreover, s.c. injection of IFN-γ or IFN-α for 3 wk into the skin of cpdm mice led to a partial amelioration of chronic dermatitis. These results imply that LUBAC activity--inducing agents could be effective therapeutic drugs for diseases in which suppressed NF-κB activation and increased apoptosis are involved.

Materials and Methods

Mice, preparation of cells, and extracts

CPDM mice were maintained under specific pathogen-free conditions in the animal facilities of Osaka and Kyoto Universities. Primary keratinocytes were prepared from WT and cpdm mice at the age of 8–10 wk. Tails were excised and tail bones were removed. Tail skins were harvested by incubation with 4 mg/ml dispase in PBS for 1 h at 37°C. The epidermis was collected, and keratinocytes were then obtained by incubation with 0.5% trypsin for 5 min at 37°C. Bone marrow (BM) cells were isolated from WT and cpdm mice at the age of 8–10 wk. The femurs and tibias were cut out and BM cells were flushed with PBS. The preparation of BM-derived macrophages (BMDMs) was performed as previously reported (18). Skin extracts were prepared by homogenization of skin tissues with lysis buffer containing 50 mM Tris-HCl (pH 7.5), 150 mM NaCl, 1% Triton X-100, and 2 mM PMSF including complete protease inhibitor mixture EDTA-free (Roche) using Multi Beads Shocker (Yasui Kikai). All mouse protocols were approved by Kyoto and Osaka Universities.

Cells and cell cultures

Immortalized MEFs were derived from WT and cpdm mice as described previously (19). MEFs were cultured in DMEM (Sigma-Aldrich) containing 10% FBS (Sigma-Aldrich), 100 IU/ml penicillin G, and 100 μg/ml streptomycin. Keratinocytes were cultured in human keratinocyte serum-free medium (DS Pharma Biomedical) supplemented with bovine pituitary extract. BM cells were cultured in RPMI 1640 medium (Sigma-Aldrich) containing 10% FBS, 100 IU/ml penicillin G, 100 μg/ml streptomycin, and M-CSF derived from CMG14-12 cells.

Abbrevs and reagents

Anti-IκBα, anti-p-IκBα, anti-p-IκBα-IKK1/2, anti-cleaved caspase-3 Abs were purchased from Cell Signaling Technology. Anti–Ki-67 Ab was from Roche. Anti–p-IκBα, anti–p-IκBα-1, anti–p-IκBα-2, and anti–p-IκBα-3 Abs were from Santa Cruz Biotechnology. Anti–Gr-1 and anti-RIP1 Abs were from BD Pharmingen. Anti–Gr-1 and anti-RIP1 Abs were from BD Pharmingen. Anti–Gr-1 and anti-RIP1 Abs were from BD Pharmingen. Anti–Gr-1 and anti-RIP1 Abs were from BD Pharmingen. IFN-α, IFN-β, IFN-γ, IL-1β, IL-2, IL-4, IL-6, IL-8, TNF-α, TNF-β, TGF-β, TGF-β1, TGF-β2, and TGF-β3 were purchased from R&D systems. LPS from Escherichia coli was a gift from Dr. M. Ueno (Kyoto University). Etanercept was purchased from Pfizer. Recombinant mouse TNF-α, TNF-β, and IL-1β were purchased from R&D Systems.

Immunoblot analysis

Cells were lysed with lysis buffer containing 50 mM Tris-HCl (pH 7.5), 150 mM NaCl, 1% Triton X-100, and 2 mM PMSF and complete protease inhibitor mixture EDTA-free. For immunoprecipitation, lysates were incubated with the appropriate primary Ab overnight at 4°C followed by incubation with 4 mg/ml dispase in PBS for 1 h at 37°C. The epidermis was collected, and keratinocytes were then obtained by incubation with 0.5% trypsin for 5 min at 37°C. Bone marrow (BM) cells were isolated from WT and cpdm mice at the age of 8–10 wk. The femurs and tibias were cut out and BM cells were flushed with PBS. The preparation of BM-derived macrophages (BMDMs) was performed as previously reported (18). Skin extracts were prepared by homogenization of skin tissues with lysis buffer containing 50 mM Tris-HCl (pH 7.5), 150 mM NaCl, 1% Triton X-100, and 2 mM PMSF including complete protease inhibitor mixture EDTA-free (Roche) using Multi Beads Shocker (Yasui Kikai). All mouse protocols were approved by Kyoto and Osaka Universities.

Immunofluorescence staining

Skin tissue samples were fixed in 10% formaldehyde for 24 h, followed by paraffin embedding and microtome sectioning. Slides were stained with H&E or toluidine blue. For immunohistochemical analysis, sections were hydrated by passage through xylene and graded ethanol. After Ag retrieval for 10 min at 99°C in citric buffer (pH 6), the slides were blocked with 1% BSA and 1% FBS/PBS at room temperature for 1 h. Cells were incubated with the appropriate primary Ab for 16 h at 4°C followed by incubation with the secondary antibody Ab labeled with Alexa 488 (Invitrogen) and DAPI (Wako Pure Chemical Industries) for nuclear counterstaining. Images were obtained using a confocal microscope (FV1000; Olympus).

Immunohistochemical staining

Skin tissue samples were fixed in 10% formaldehyde for 24 h, followed by paraffin embedding and microtome sectioning. Slides were stained with H&E or toluidine blue. For immunohistochemical analysis, sections were hydrated by passage through xylene and graded ethanol. After Ag retrieval for 10 min at 99°C in citric buffer (pH 6), the slides were blocked with 1% BSA and 1% FBS/PBS at room temperature for 1 h. Cells were incubated with the appropriate primary Ab for 16 h at 4°C followed by incubation with the secondary antibody Ab labeled with Alexa 488 (Invitrogen) and DAPI (Wako Pure Chemical Industries) for nuclear counterstaining. Images were obtained using a confocal microscope (FV1000; Olympus).

Luciferase assay

NIH/3T3 cells were transfected with pGL4.14 containing upstream or downstream genomic fragments of mouse Rf8l1 or Rbkl genes and pGL4.73 (hRLuc/SV40). Sixteen hours after transfection, the cells were incubated with 300 U/ml IFN-γ for 6 h. Cells were then lysed, and luciferase activity was measured in a Lumat luminometer (Berthold) using the Dual-Luciferase Reporter or Bright-Glo luciferase assay system (Promega).

RNA extraction and real-time quantitative PCR

Total RNA was isolated from cells using RNeasy mini kit (Qiagen) with RNase-free DNase (Qiagen). The product was reverse transcribed into cDNA using high capacity RNA-to-cDNA kit (Applied Biosystems). Total RNA from skin tissues and spleens was extracted by sepsal (Nacalai Tesque) using Polytron (Kinematica) to homogenize the tissues and treated using the RNeasy mini kit (Qiagen). cDNA was made from RNA using Power SYBR Green PCR Master Mix (Applied Biosystems) or TaqMan MasterMix (Applied Biosystems) in Applied Biosystems Vii 7 (Applied Biosystems). GAPDH was used as a control. Sequence-specific primers were designed as follows: mouse myc, 5′-GGAAACCCCC-GGACAGACGACGAGATGCCC-3′ (sense) and 5′-AACAACTAGATGGAGAGAGAGGACCGCCGAGC-3′ (antisense); mouse IL-5, 5′-GATGAGGTTCCTGCTCTCTC-3′ (sense) and 5′-TGGACGTTTTTGGATACATACAC-3′ (antisense); mouse IL-13, 5′-AAGCAGGCACTGGTATGGA-GTG-3′ (sense) and 5′-TGGTCTCCTGTAGATGCGATTGC-3′ (antisense); mouse A20, 5′-AGCAAGCAGGAAAGACTGCTC-3′ (sense) and 5′-GC-TTCCAGGAGGAGTAACAG-3′ (antisense); mouse IFN-α, 5′-ATCCAAGAGCTCAACCCATCC-3′ (sense) and 5′-GAGAGCTGTATCATCAAGG-3′ (antisense); mouse IFN-β, 5′-GCCTTGGCCTACCAAGAGATGC-3′ (sense) and 5′-ACACTGTGTCGTGGATATGTC-3′ (antisense). TaqMan probes for mouse GAPDH, mouse HOIP, mouse HOIL-1L, mouse SHARPIN, mouse TNF-α, mouse IL-6, mouse IFN-γ, mouse IL12p40, mouse IL-4, and mouse VCAM-1 were purchased from Applied Biosystems.

Cytokine ELISA

The concentration of TNF-α was measured using Mouse TNF-α ELISA MAX purchased from BioLegend. NuncMaxiSorp flat-bottom 96-well plates were used.

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Therapeutic intervention

Back skins of 6-wk-old cpdm mice were injected s.c. with 2 ml IFN-\(\gamma\) (300 U/ml) or PBS. This treatment was performed six times per week for 3 wk. For etanercept treatment, back skins of 6-wk-old cpdm mice were s.c. injected with 0.5 µg/g body weight etanercept three times per week for 3 wk.

Evaluation of dermatitis severity

The severity of dermatitis was evaluated before and after the treatment as described previously (20). The development of 1) erythema/hemorrhage, 2) dryness/scaling, 3) edema, and 4) erosion/excoriation was scored as 0 (none), 1 (mild), 2 (moderate), or 3 (severe). The evaluated areas were rostral back and caudal back. The dermatitis score was the sum of each score obtained for rostral back and caudal back. Each dermatitis score was assessed by three observers in a blinded fashion.

Measurement of epidermal thickness

Intrafollicular epidermal thickness was calculated by averaging five locations in each section, which included at least one full-length hair follicle. Three sections from each mouse were evaluated.

Statistical analysis

The data are expressed as mean values ± SD. Statistical analysis was performed by Student t test. A p value < 0.05 was considered statistically significant.

Results

IFN-\(\gamma\) augments NF-\(\kappa\)B activation by increasing the amount of the LUBAC

The Rnf31 gene, which encodes HOIP, is located between the Psme2 gene and Irf9 gene on chromosome 14 in mice. Because the expression of both Psme2 and Irf9 genes is activated by IFN-\(\gamma\) (21–24), we examined whether IFN-\(\gamma\) regulates the expression of HOIP mRNA by real-time PCR. IFN-\(\gamma\) promoted the expression of HOIP mRNA in MEFs established from WT mice. In addition, IFN-\(\gamma\) induced the expression of HOIL-1L (Rbck1) transcripts to a small degree but did not induce the expression of SHARPIN (Sharpin) mRNA (Fig. 1A). We next investigated the cis-acting element for IFN-\(\gamma\)-mediated HOIP mRNA induction, using a luciferase assay in NIH3T3 fibroblastic cells. We found that the IFN regulatory factor 1 (IRF-1) (−773 to −762) binding sequence in the upstream region and the IFN-\(\gamma\)-activated site (+12416 to +12424) and \(\gamma\)-IFN–activated transcriptional element (+12434 to +12458) sequences, both of which are IFN-\(\gamma\)-responsive regulatory elements (23–26), in the downstream region of the Rnf31 gene, were involved in IFN-\(\gamma\)-mediated HOIP mRNA induction (Supplemental Fig. 1A–C). We also found that the IFN-stimulated response element (−37 to −23) sequence in the upstream genomic fragment of Rbck1 gene, which is involved in IFN-\(\gamma\)-induced transcription (25, 27), was responsible for IFN-\(\gamma\)-induced induction of HOIL-1L mRNA (Supplemental Fig. 1D).

Immunoblotting analyses revealed that IFN-\(\gamma\) increased the amounts of not only HOIP and HOIL-1L but also SHARPIN proteins in WT MEFs, BMDMs, and keratinocytes (Fig. 1B). To investigate the mechanism underlying the increase of SHARPIN mediated by IFN-\(\gamma\) in the absence of SHARPIN mRNA expression induction (Fig. 1A), gel filtration analyses were performed. The amount of HOIP, HOIL-1L, and SHARPIN proteins with high m.w. (fractions 9–11) was higher in IFN-\(\gamma\)-treated cells than in nontreated cells. Moreover, the amount of SHARPIN with low m.w. (fractions 13 and 14), which is present as a free form, was decreased in IFN-\(\gamma\)-treated cells (Fig. 1C). In addition, the amount of HOIL-1L and SHARPIN commmunoprecipitated with anti-HOIP Ab was increased in IFN-\(\gamma\)-treated cells, whereas the amount of SHARPIN and HOIL-1L was decreased in the unbound fraction (Fig. 1D). These results implied that SHARPIN becomes more stable in the LUBAC and the increase in the amount of SHARPIN in LUBAC contributes to the increase in the total amount of SHARPIN by IFN-\(\gamma\).

LUBAC plays a key role in signal-induced NF-\(\kappa\)B activation (1). Indeed, IFN-\(\gamma\) augmented TNF-\(\alpha\)-induced phosphorylation and degradation of IκB\(\alpha\), which are the hallmarks of NF-\(\kappa\)B activation, in both WT keratinocytes and MEFs (Fig. 1E, Supplemental Fig. 2A), and TNF-\(\alpha\)-induced expression of NF-\(\kappa\)B target genes in MEFs (Fig. 1F). Moreover, IFN-\(\gamma\) enhanced the IL-1\(\beta\)-mediated phosphorylation and degradation of IκB\(\alpha\) in MEFs (Supplemental Fig. 2B) and LPS-mediated NF-\(\kappa\)B activation in BMDMs (Fig. 1G). LPS-mediated expression of TNF-\(\alpha\) mRNA, an NF-\(\kappa\)B target gene, also was promoted by pretreatment with IFN-\(\gamma\) (Fig. 1H). To confirm whether IFN-\(\gamma\)-induced enhancement of NF-\(\kappa\)B activation is due to the increase in the amount of LUBAC by IFN-\(\gamma\), HOIP Δlinear MEFs, expressing a HOIP mutant (HOIP Δlinear) lacking the catalytic domains for linear polyubiquitination, were used (28). TNF-\(\alpha\)-mediated phosphorylation and degradation of IκB\(\alpha\) was profoundly suppressed in HOIP Δlinear MEFs. Importantly, IFN-\(\gamma\) pretreatment did not reverse the suppressed TNF-\(\alpha\)-mediated phosphorylation and degradation of IκB\(\alpha\) or induce the expression of NF-\(\kappa\)B target mRNAs, although IFN-\(\gamma\) did increase the expression of the HOIP Δlinear protein (truncated HOIP) (Fig. 1I, 1J). Considering that the HOIP Δlinear protein does not exhibit linear polyubiquitination activity, these results strongly indicated that IFN-\(\gamma\)-mediated NF-\(\kappa\)B activation is mediated by the increase in the linear polyubiquitination activity of the LUBAC ligase complex.

IFN-\(\gamma\)-mediated increase of HOIP and HOIL-1L–protected cpdm cells from TNF-\(\alpha\)-mediated apoptosis both in vitro and in vivo

cpdm mice are spontaneous mutant mice lacking SHARPIN (15, 29). As observed in the WT cells, IFN-\(\gamma\) increased the expression of HOIP and HOIL-1L mRNA in MEFs from cpdm mice (Fig. 2A). The amount of HOIP and HOIL-1L proteins was also increased by IFN-\(\gamma\) in MEFs and primary keratinocytes prepared from cpdm mice (Fig. 2B). Signal-induced NF-\(\kappa\)B activation is suppressed in cpdm cells because of the drastic decrease of the LUBAC caused by the lack of SHARPIN (16, 17, 19). IFN-\(\gamma\) pretreatment accelerated TNF-\(\alpha\)– and IL-1\(\beta\)-mediated phosphorylation and degradation of IκB\(\alpha\) in cpdm MEFs (Fig. 2C, Supplemental Fig. 2C). TNF-\(\alpha\)-induced NF-\(\kappa\)B activation also was enhanced by IFN-\(\gamma\) in primary keratinocytes prepared from cpdm mice (Fig. 2D). Moreover, TNF-\(\alpha\)-induced expression of NF-\(\kappa\)B target genes and the nuclear translocation of p65 were augmented in cpdm MEFs pretreated with IFN-\(\gamma\) (Fig. 2E, 2F). LUBAC-mediated linear polyubiquitination of NEMO may play a crucial role in NF-\(\kappa\)B activation (1). We therefore examined the effect of IFN-\(\gamma\) on TNF-\(\alpha\)-induced linear polyubiquitination of NEMO. Immunoblotting analysis showed that TNF-\(\alpha\)-mediated linear polyubiquitination of NEMO was accelerated by pretreatment with IFN-\(\gamma\) (Fig. 2G).

The cells derived from cpdm mice are more susceptible to TNF-\(\alpha\)-induced apoptosis than WT cells (19). Our immunostaining analyses revealed that IFN-\(\gamma\) suppressed TNF-\(\alpha\)-induced apoptosis in cpdm MEFs (Fig. 2H). Ubiquitination of RIP1 in the TNFR1 signaling complex (TNF-RSC) protects the cells from TNF-\(\alpha\)-mediated apoptosis (30–32). The amount of RIP1 coprecipitated with TRADD, which is recruited to TNF-RSC upon TNF-\(\alpha\) stimulation, was increased in IFN-\(\gamma\)-pretreated cpdm MEFs, suggesting that IFN-\(\gamma\) treatment increased the amount of RIP1 recruited to TNF-RSC by TNF-\(\alpha\). Moreover, TNF-\(\alpha\)-induced RIP1 polyubiquitination was also promoted by pretreatment with IFN-\(\gamma\) (Fig. 2I). Taken together, our findings suggest that IFN-\(\gamma\) enhances NF-\(\kappa\)B activation and suppresses apoptosis induced by TNF-\(\alpha\) by augmenting NEMO and RIP1 ubiquitination, respectively.
Next, we examined whether IFN-γ enhances NF-κB activation and suppresses apoptosis mediated by TNF-α in vivo. Subcutaneous injection of IFN-γ for 2 consecutive days increased the amount of HOIP and HOIL-1L in the skin of cpdm mice (Fig. 3A). We next injected TNF-α into the ear of cpdm mice after pretreatment with PBS or IFN-γ. Immunostaining analysis showed that IFN-γ enhanced TNF-α-induced phosphorylation of IKK1/2, which is one of the hallmarks of NF-κB activation (Fig. 3B). Moreover, HOIP expression was induced and cleaved caspase-3 and TUNEL-positive cells were reduced in the ear treated with IFN-γ (Fig. 3C, 3D). Collectively, these findings suggest that IFN-γ enhances NF-κB activation and protects cpdm cells from TNF-α-induced apoptosis by increasing the amount of HOIP both in vitro and in vivo.

Amelioration of dermatitis by s.c. injection of IFN-γ in cpdm mice

Although the precise mechanism underscoring chronic dermatitis in cpdm mice has not been clarified yet, both TNF-α and increased keratinocyte apoptosis have been suggested to be involved in the pathogenesis of dermatitis (16, 29). Because we observed that IFN-γ protects cpdm keratinocytes from TNF-α-induced apoptosis and activates NF-κB both in vitro and in vivo, we injected IFN-γ once a day into the back of cpdm mice for 3 wk to evaluate
the effect of IFN-γ on the severity of cpdm dermatitis. The amount of HOIP was larger in mice treated with IFN-γ than mice treated with PBS, confirming that IFN-γ increased the amount of HOIP even with longer treatment (Fig. 4A, 4B). Before treatment, the average dermatitis scores of PBS and IFN-γ–treated mice were 0.7 and 0.7, respectively (data not shown). The average severity score in mice treated with IFN-γ for 3 wk was much lower than that of mice treated with PBS (Fig. 4C, 4D). The average severity scores in mice treated with PBS and IFN-γ were 6.0 and 2.8, respectively. Epidermal thickening, which is one of the major characteristics of cpdm dermatitis, was significantly lower in IFN-γ–treated mice than in PBS-treated mice (Fig. 4E). In addition, the number of cleaved caspase-3 and TUNEL-positive cells was much higher in the epidermis of PBS-treated mice than that of IFN-γ–treated mice (Fig. 4F, 4G). HMGB1, one of the damage-associated molecular patterns, is normally located in the nucleus and translocates into the cytoplasm prior to its release from keratinocytes at the later stage of apoptosis (33–35). Immunohistochemical staining showed that the amount of HMGB1 located outside the nucleus of keratinocytes was increased in the skin of cpdm mice, whereas in keratinocytes of WT mice, HMGB1 was detected in the nucleus (Supplemental Fig. 3A). In IFN-γ–treated cpdm mice, the amount of cytoplasmic HMGB1 was decreased (Fig. 4H). An increase in the number of proliferative keratinocytes is another characteristic of cpdm dermatitis (14, 15). Keratinocytes expressing the proliferation markers Ki67 and Keratin 6 were decreased in IFN-γ–treated mice, as compared with PBS-treated mice (Fig. 4I, 4J). These results suggested that IFN-γ treatment ameliorates cpdm dermatitis.

Reduction of macrophage, neutrophil, and mast cell infiltration and the amount of TNF-α in the skin of cpdm mice by IFN-γ

Infiltration of inflammatory cells into the affected skin has been reported in cpdm mice (14). We confirmed that neutrophils (Gr-1+), macrophages (F4/80+), and T cells (CD3+ and CD4+) infiltrated...
the skin of cpdm mice, but we did not detect CD8+ cells. The number of mast cells (toluidine blue positive) in the skin was higher in cpdm (202.1 ± 4.7/mm²) than in WT mice (109.7 ± 13.5/mm²) (Supplemental Fig. 3B). The amount of TNF-α, which is suggested to be involved in cpdm dermatitis (16, 17, 19), was greater in the skin of cpdm mice than that of WT mice (Supplemental Fig. 3C, 3D), and macrophages, neutrophils, and mast cells were the major producers of TNF-α in the skin of cpdm mice (Supplemental Fig. 3E). Because IFN-γ treatment reduced the number of infiltrating macrophages, neutrophils, and mast cells (Fig. 5A, 5B), the amount of TNF-α protein and mRNA in the skin of IFN-γ and PBS-treated mice was examined. Both TNF-α protein and mRNA were lower in IFN-γ-treated mice than PBS-treated mice (Fig. 3C, 3D). Immunostaining analysis confirmed that IFN-γ reduced the amount of TNF-α in cpdm skin (Fig. 5E). The increase of cytokines produced by Th2 cells including IL-5 and IL-13 in the skin and spleen of cpdm mice plays a role in the pathogenesis of dermatitis (36). We confirmed that the amount of IL-5 and IL-13 mRNA was higher and that of Th1 cytokines IL-12 and IFN-γ was lower in the spleen of cpdm mice than in WT mice. The amount of IFN-α and IFN-β in the spleen did not differ between WT and cpdm mice. (Supplemental Fig. 3F). There was no significant difference in the amount of IL-12, IFN-γ, IL-13, and IL-6 mRNA, whereas the amount of IL-13 was higher in the skin of cpdm mice than that of WT mice (Supplemental Fig. 3G). We then assessed the effect of IFN-γ injection on the amount of Th1, Th2 cytokines, and type I IFNs mRNA in the spleen and skin of cpdm mice. Subcutaneous IFN-γ injection did not decrease Th2 nor increase Th1 cytokines significantly in either spleen or skin of cpdm mice. Similarly, there was no significant change in Type I IFNs mRNA expression in the spleen and skin (Fig. 5F, 5G). These results suggested that s.c. IFN-γ ameliorates cpdm dermatitis by increasing the amount of HOIP but not by suppressing the production of Th2 cytokines.

TNF-α is suggested to be involved in the pathogenesis of cpdm (16). We have observed that the amount of TNF-α is reduced by IFN-γ treatment in the skin of cpdm mice. To confirm the involvement of TNF-α in cpdm, we treated cpdm mice with etanercept, which blocks the effect of TNF-α (37, 38). Etanercept treatment ameliorated cpdm and inhibited keratinocyte apoptosis and infiltration of inflammatory cells such as granulocytes, macrophages, and mast cells (Supplemental Fig. 4). These findings indicated that TNF-α is involved in the pathogenesis of cpdm and that IFN-γ-mediated amelioration of cpdm is partly due to the reduction of TNF-α in the skin.

**FIGURE 3.** IFN-γ augmented the amount of LUBAC and TNF-α-mediated NF-κB activation and suppressed TNF-α-mediated apoptosis in the skin of cpdm mice. (A) Skin extracts from two cpdm mice injected with PBS (left back) or IFN-γ (right back) were probed as indicated. (B) Immunohistochemical analyses of p-IKK1/2 in the ear of cpdm mice treated with a single s.c. injection of PBS or IFN-γ, followed by TNF-α (5 μg/ml for 45 min) stimulation 24 h later. Nuclei were stained with DAPI. (C) Immunohistochemical staining with anti-cleaved caspase-3, anti-HOIP Abs, and TUNEL staining of the ear of cpdm mice treated with a single s.c. injection of PBS or IFN-γ, followed by TNF-α (5 μg/ml for 6 h) stimulation 24 h later. (D) The number of cleaved caspase-3 and TUNEL-positive cells shown in (C). Scale bars, 100 μm. Error bars indicate mean ± SD. *p < 0.05

**IFN-γ suppresses apoptosis but does not effectively augment NF-κB target gene induction mediated by a low dose of TNF-α**

We next dissected the mechanism underscoring the IFN-γ–mediated amelioration of cpdm. As shown in Figs. 1 and 2, IFN-γ increased the amount of LUBAC and TNF-α–induced expression of NF-κB target genes in keratinocytes, fibroblasts, and macrophages in vitro. Subcutaneous injection of IFN-γ also augmented LUBAC in not only keratinocytes but also in cells in the dermis such as fibroblasts and macrophages (Fig. 6A). However, s.c. injection of IFN-γ for 2 d failed to enhance the production of transcripts of NF-κB target genes including TNF-α, IL-6, and VCAM-1 in the skin of cpdm mice (Fig. 6B). The amount of IL-6 mRNA was increased by IFN-γ slightly, although the increase was not statistically significant. Previous studies suggested that the physiological levels of TNF-α are much lower than those that we use in in vitro experiments (10 ng/ml) (39, 40). Thus, we stimulated cpdm MEFs with 0.1 ng/ml TNF-α and found that IFN-γ pretreatment did not increase the amount of TNF-α and VCAM-1 mRNA, although it significantly induced IL-6 mRNA (Fig. 6C). IL-6 mRNA expression in vivo was not induced by IFN-γ treatment, and there are no previous studies suggesting that IL-6 is important in the pathogenesis of cpdm in mice. However, IFN-γ pretreatment inhibited the activation of caspase-3 in cpdm MEFs.
stimulated with 0.1 ng/ml TNF-α (Fig. 6D). Thus, these results suggest that IFN-γ–mediated increase of LUBAC exhibits a profound effect on the suppression of TNF-α–induced apoptosis compared with the effect on NF-κB activation in cpdm cells. Apoptosis of keratinocytes and TNF-α are known to be involved in the pathogenesis of cpdm (16, 29), and we found that s.c. injection of IFN-γ for 2 d suppressed TNF-α–mediated apoptosis of keratinocytes (Figs. 3C, 3D). However, the 2-d IFN-γ treatment...
failed to reduce the number of infiltrated inflammatory cells (Fig. 6E). TNF-α, IL-6, and VCAM-1 mRNA expression also was not changed by IFN-γ treatment (Fig. 6B). We thus suspect that the effects of IFN-γ on keratinocytes may be the initial event leading to amelioration of cpdm dermatitis, although both keratinocytes and leukocytes are the targets of IFN-γ.

**IFN-α increased the amount of LUBAC and ameliorated dermatitis in cpdm mice**

We observed that in addition to IFN-γ, a type I IFN, IFN-α also increased the amount of LUBAC in keratinocytes and BMDMs from WT mice (Fig. 7A). IFN-α increased the amount of HOIP and HOIL-1L in cpdm MEFs, although IFN-α was a weaker inducer of LUBAC than IFN-γ (Fig. 7B). In addition, IFN-α augmented TNF-α–mediated IkBα phosphorylation and degradation in cpdm keratinocytes (Fig. 7C). These results indicated that IFN-α also enhances NF-κB activation via an increase of LUBAC composed of HOIP and HOIL-1L in cpdm cells. We also evaluated the in vivo effect of IFN-α. Subcutaneous injection of IFN-α into the ear, as performed with IFN-γ in Fig. 4, increased the amount of HOIP and inhibited TNF-α–mediated apoptosis of keratinocytes (Fig. 7D). Next, IFN-α was s.c. injected into the back of cpdm mice using an identical protocol to IFN-γ injection. Immunoblotting analysis and immunofluorescent staining confirmed that the amount of HOIP was increased by the IFN-α injection (Fig. 7E, 7F). The average dermatitis scores of PBS and IFN-α–treated mice before treatment were 1.1 and 0.9, respectively (data not shown). They were not significantly different. As shown in Fig. 7G, the severity score of cpdm dermatitis was significantly decreased by IFN-α injection. The average scores of PBS and IFN-α–treated mice after treatment were 6.9 and 4.2, respectively. Histological analyses showed a reduction of epidermal thickness and the number of cleaved caspase-3–positive cells in IFN-α–treated cpdm mice (Fig. 7H, 7I). It is of note that s.c.

![Figure 5](http://www.jimmunol.org/Downloadedfrom/3800%20INCREASE%20OF%20LUBAC%20BY%20IFNs)
injection of IFN-γ did not overtly affect the amount of IL-4, IL-5, IL-12, IL-13, and IFN-γ mRNA (Fig. 7J). These results indicated that enhanced NF-κB activation by IFN-γ as well as IFN-γ through the increase of LUBAC composed of HOIP and HOIL-1L ameliorated cpdm dermatitis.

Discussion

cpdm mice are characterized by various symptoms including chronic proliferative dermatitis (15, 29). Because of the lack of SHARPIN, the amount of the other two subunits of LUBAC is drastically reduced in cpdm mice. Suppressed NF-κB activation and increased apoptosis, which appears to be mediated by the reduction of LUBAC, are thought to provoke chronic proliferative dermatitis (16, 17). In this study, we could ameliorate cpdm dermatitis by augmenting NF-κB activation and suppressing TNF-α–mediated apoptosis via IFN-γ– or IFN-α–mediated increase of LUBAC.

In cpdm mice, augmented production of cytokines generated by Th2 cells such as IL-5 and IL-13, and an impaired ability of dendritic cells from cpdm mice to induce Th1 cells, have been reported previously (41). Moreover, suppressed IFN-γ secretion, which has been reported in cpdm mice (36), might be involved in the pathogenesis of dermatitis. Because IFN-γ is produced by Th1 cells and is able to induce Th1 cells, it is possible that in our study, IFN-γ ameliorated the dermatitis by inducing Th1 cells in cpdm mice. Moreover, systemic administration of IL-12, which is known to induce Th1 cells, resolves chronic dermatitis in cpdm mice (36). However, we observed that the amount of type 1 and type 2 cytokines was not significantly affected by s.c. injection of IFN-α, which has been reported in cpdm mice (36), might be involved in the pathogenesis of dermatitis. Because IFN-γ is produced by Th1 cells and is able to induce Th1 cells, it is possible that in our study, IFN-γ ameliorated the dermatitis by inducing Th1 cells in cpdm mice. Moreover, systemic administration of IL-12, which is known to induce Th1 cells, resolves chronic dermatitis in cpdm mice (36). However, we observed that the amount of type 1 and type 2 cytokines was not significantly affected by s.c. injection of IFN-γ. In addition, s.c. injected IFN-α significantly ameliorated dermatitis in cpdm mice, albeit less effectively than IFN-γ, without affecting the production of type 1 and type 2 cytokines. The amount of IFNs in the skin was not overtly affected by the s.c. injection of IFN-γ or IFN-α. Thus, we concluded that IFN-γ and IFN-α ameliorate dermatitis in cpdm mice mainly by increasing the amount of LUBAC. However, we could not rule out the possibility that an induction of Th1 cells might be involved in the resolution of cpdm dermatitis by IFN-γ, because IFN-γ improved the dermatitis more prominently than IFN-α. A recent study reported that an increased expression of β1-integrin might be involved in the pathogenesis of...
cpdm dermatitis (42). However, it may not play a major role in cpdm dermatitis because intercrossing of cpdm mice with TNFR1 knockout (KO) mice drastically ameliorates cpdm dermatitis (16). Therefore, it seems plausible that impaired NF-κB activation and enhanced TNF-α–induced apoptosis are involved in the pathogenesis of cpdm dermatitis.

Keratinocyte-specific ablation of IKK2, the catalytic component of the canonical IKK complex, results in the development of dermatitis, characterized by increased proliferation of keratinocytes. It has been shown that impaired signal-induced NF-κB activation and TNF-α signaling play an essential role in the pathogenesis of dermatitis in the keratinocyte-specific IKK2 KO mice (43). Keratinocyte-specific expression of mutant IκBα, which is resistant to degradation triggered by the IKK-mediated phosphorylation of the protein, also resulted in the development of severe proliferative dermatitis in mice (44). Therefore, in dermatitis characterized by increased proliferation of keratinocytes, suppressed NF-κB activation might augment the inflammation process, even though NF-κB is known to be a proinflammatory transcription factor (45). Enhanced apoptosis of keratinocytes is observed in cpdm skin and keratinocyte apoptosis can be suppressed by intercrossing with TNFR1 KO mice (16). We also observed that the protection of keratinocytes from apoptosis appears to be the initial event leading to the amelioration of skin inflammation in cpdm mice following s.c. injection of IFN-γ. Thus, increased TNF-α-mediated apoptosis of keratinocytes might be involved in the pathogenesis of cpdm dermatitis. Indeed, induced apoptosis of keratinocytes has been observed in pathological skin conditions such as sunburn, toxic epidermal necrolysis, pemphigus, eczematous dermatitis, and graft-versus-host disease (46). However, some unknown mechanism might also be involved in cpdm dermatitis because no overt keratinocyte death could be observed in keratinocyte-specific IKK2 KO
mice, whose dermatitis resembles that of cpdm mice (43). Nevertheless, in HOIL-IL KO mice, dermatitis was not observed, although TNF-α–induced NF-κB activation was heavily suppressed by the reduction of LUBAC, as observed in cdpm mice (1). This finding might be attributed to the differential sensitivity to TNF-α–mediated apoptosis, because HOIL-IL KO MEFs are more resistant to TNF-α–mediated apoptosis than cdpm MEFs (19). Further work will be needed to elucidate the precise mechanism underlying the amelioration of cpdm dermatitis by the increase of LUBAC.

In this study, we demonstrated that IFN-γ induces LUBAC not only in keratinocytes but also in BMDMs. It has been shown that priming with IFN-γ augments NF-κB activation and the expression of NF-κB target genes induced by ligands of TLRs, including LPS in macrophages (47). The molecular mechanism underlying the augmentation of NF-κB activation by IFN-γ pretreatment is not well understood, although the combined presence of the binding sites of STAT1, which is an IFN-γ–inducible transcriptional activator, and the NF-κB binding sites in the promoter region of many NF-κB target genes has been demonstrated (47–49). We also showed that IFN-γ increases the amount of LUBAC and LPS-mediated NF-κB activation in BMDMs. In addition, TNF-α– and IL-1β–mediated NF-κB activation was augmented by IFN-γ in MEFs and keratinocytes. Because IFN-γ failed to augment NF-κB activation in MEFs lacking the catalytic activity of LUBAC, the present results strongly indicate that LUBAC is the main target for IFN-γ–mediated increase of NF-κB activation, involved in LUBAC-mediated linear polyubiquitination by various stimuli such as LPS, TNF-α, and IL-1β.

LUBAC has recently been reported to play a key role in human disease (50). In addition, a strong genetic link with A20 and A20 binding and inhibitor of NF-κB in psoriasis has been reported previously (51, 52). Both A20 and A20 binding and inhibitor of NF-κB can bind to linear ubiquitin chains that are specifically generated by LUBAC (53–55). Psoriasis is characterized by increased proliferation of keratinocytes as observed in cpdm dermal infiltrates with chronic proliferative dermatitis (cpdm) generated by LUBAC (53–55). Psoriasis is characterized by increased expression of cytokines in psoriatic skin lesions, and cpdm mice, whose dermatitis resembles that of cpdm mice, are natural models to study chronic skin inflammation (43). We thank Fuminori Tokunaga and Tomoko Nakagawa for providing advice on the preparation of this manuscript.

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Disclosures

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