Ursolic acid downregulates thymic stromal lymphopoietin through the blockade of intracellular calcium/caspase-1/NF-κB signaling cascade in HMC-1 cells

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Abstract. Thymic stromal lymphopoietin (TSLP) plays an important role in allergic disorders, including atopic dermatitis and asthma. Ursolic acid (UA) has various pharmacological properties, such as antioxidant, anti-inflammatory and anticancer. However, the effect of UA on TSLP regulation has not been fully elucidated. The aim of the present study was to analyze how UA regulates the production of TSLP in the human mast cell line HMC-1. Enzyme-linked immunosorbent assay, quantitative polymerase chain reaction analysis, western blotting, caspase-1 assay and fluorescent measurements of intracellular calcium levels were conducted to analyze the regulatory effects of UA. The results revealed that UA inhibited TSLP production and mRNA expression. In addition, UA reduced the activation of nuclear factor-κB and degradation of IκBα. Caspase-1 activity was increased by exposure to phorbol myristate acetate plus calcium ionophore, whereas it was reduced by UA. Finally, UA treatment prevented an increase in intracellular calcium levels. These results indicated that UA may be a useful agent for the treatment and/or prevention of atopic and inflammatory diseases, and its effects are likely mediated by TSLP downregulation.

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Introduction

Atopic dermatitis (AD) is a recurrent and chronic inflammatory skin disorder that affects children as well as adults (1,2). The prevalence of AD is ~1-3% in adults and 25% in children of industrialized countries (3), and it has increased in the urban areas of such countries over the past decade (4). As a result of the increasing prevalence of AD, the burden of AD-associated medical costs has increased in industrialized countries (5). In addition, the recurrent eczema lesions, itching, lack of sleep and restricted diet may compromise the quality of life of AD patients (5).

Thymic stromal lymphopoietin (TSLP) is considered as a pivotal factor in the pathogenesis of allergic diseases, such as AD and asthma. In patients with AD, TSLP gene expression increased by epicutaneous house dust mite injections (6). The protein and mRNA expression levels of TSLP in skin lesions of AD patients are higher compared with those in healthy controls (7). In addition to epithelial cells and keratinocytes, mast cells also play an important role in atopic diseases (8). The increases in the population and activation of mast cells in AD models reported by several researchers (9-11) indicate the significance of mast cells in AD. HMC-1 is a human mast cell line (12). The effects of UA on the HMC-1 cell line were examined, as similar levels of TSLP are produced by HMC-1 and bone marrow-derived mast cells (13).

In general, protease caspases play critical roles in apoptosis, whereas caspase-1 is implicated in inflammatory responses (14-16). Deficiency of caspase-1 ameliorates dextran sulfate sodium-induced intestinal inflammation (17). In addition, TSLP expression and production were found to be mediated by caspase-1 and nuclear factor (NF)-κB signaling in HMC-1 cells in a previous study (18). Additionally, caspase-1 inhibitor treatment may decrease NF-κB activation, suggesting that caspase-1 acts as an upstream regulator of NF-κB (18).

Ursolic acid (UA; Fig. 1), a pentacyclic triterpenoid found in holy basil and apple peels (19), has various pharmacological properties, such as antioxidant, anti-inflammatory and anticancer (20,21). Recently, Gan *et al* (22) reported that UA ameliorates CCl_4-induced liver fibrosis. However, the regulatory effect of UA on TSLP production by mast cells has not been fully elucidated. The aim of the present study was to investigate the effects of UA on the HMC-1 human mast cell line and determine whether UA can regulate TSLP production in mast cells.

Materials and methods

Materials. UA, phorbol myristate acetate (PMA), calcium ionophore A23187, avidin-peroxidase and dimethyl sulfoxide were obtained from Sigma-Aldrich; Merck KGaA. TMB substrate and tumor necrosis factor (TNF)-α antibodies were purchased from Pharmingen. Power SYBR®-Green PCR master mix was purchased from Applied Biosystems; Thermo Fisher Scientific, Inc. TSLP antibodies and caspase-1 assay kit were obtained from R&D Systems, Inc. Finally, IKKβ, PARP, GAPDH, IκBα and NF-κB p65 antibodies were obtained from Santa Cruz Biotechnology, Inc.

Cell culture. HMC-1 cells were cultured in IMDM with heat-inactivated fetal bovine serum (10%), streptomycin (100 µg/ml) and penicillin (100 U/ml) at 37˚C with 5% CO_2.

MTT assay. MTT assay was performed to measure cytotoxicity, as described previously (23). HMC-1 cells ($3x10^5$) were incubated with UA (0.002-0.2 µg/ml) in 24-well plates, which were subsequently incubated with MTT solution (5 mg/ml) for 4 h. To dissolve the MTT formazan, 1 ml of dimethyl sulfoxide was added and 200 µl of supernatant were removed and transferred to a 96-well microplate. Finally, each well was read at 540 nm.

Cytokine assay. HMC-1 cells ($3x10^5$) were pretreated with UA (0.002-0.2 µg/ml) for 1 h prior to stimulation with 0.05 µM PMA plus 1 µM calcium ionophore (PMACI), and then incubated for 7 h. TSLP and TNF-α levels were assessed in the culture supernatants using ELISA, as described previously (24).

Quantitative polymerase chain reaction (qPCR) analysis. HMC-1 cells ($1x10^6$) were pretreated with UA (0.002-0.2 µg/ml) for 1 h prior to PMACI stimulation, and then incubated for 5 h. qPCR was carried out using the Power SYBR-Green PCR master mix. mRNA detection was performed with the ABI StepOne real-time PCR system (Applied Biosystems; Thermo Fisher Scientific, Inc.) as described previously (25). PCR analysis was conducted using the following primers: TSLP, forward 5'-CCCAGGCTATTCGGAAACTCAG-3' and reverse 5'-CGCCACAATCCTTGTAATTGTG-3'; GAPDH, forward 5'-TCGACAGTCAGCCGCATCTTCTTT-3' and reverse 5'-ACCAAATCCGTTGACTCCGACCTT-3'.

Caspase-1 assay. HMC-1 cells ($5x10^6$) were pretreated with UA (0.002-0.2 µg/ml) for 1 h prior to PMACI stimulation, and then incubated for 1 h. Caspase-1 activation was evaluated using a caspase-1 assay kit, as described previously (26).

Nuclear and cytoplasmic extracts. HMC-1 cells ($5x10^6$) were pretreated with UA (0.002-0.2 µg/ml) for 1 h prior to PMACI stimulation, and then incubated for 2 h. Isolation of nuclear and cytoplasmic proteins was carried out as described previously (27). In brief, the cells were washed in ice-cold phosphate-buffered saline (PBS) and centrifuged at 15,000 x g for 1 min. The cells were resuspended in 40 µl of a cold hypotonic buffer (10 mM HEPES/KOH, 2 mM $MgCl_2$, 0.1 mM EDTA, 10 mM KCl, 1 mM DTT, and 0.5 mM PMSF, pH 7.9). Next, the cells were swollen on ice for 15 min, lysed gently with 2.5 µl 10% Nonidet P-40 and centrifuged at 15,000 x g for 3 min at 4˚C. The supernatant was then collected and used as the cytoplasmic extract. The pellets of nuclei were gently resuspended in 40 µl cold saline buffer (50 mM HEPES/KOH, 50 mM KCl, 300 mM NaCl, 0.1 mM EDTA, 10% glycerol, 1 mM DTT and 0.5 mM PMSF, pH 7.9) and placed on ice for 20 min. After centrifugation at 15,000 x g for 15 min at 4˚C, the aliquots of supernatant containing the nuclear proteins were frozen in liquid nitrogen and stored at -70˚C until analysis. Finally, the bicinchoninic acid protein assay (Sigma-Aldrich; Merck KGaA) was used to measure the protein concentrations.

Western blot analysis. HMC-1 cells ($5x10^6$) were pretreated with UA (0.002-0.2 µg/ml) for 1 h prior to PMACI stimulation. Proteins of obtained lysates were separated and transferred to nitrocellulose paper, as described previously (28). In brief, the cell lysates were prepared in a sample buffer containing sodium dodecyl sulfate (SDS). The samples were heated at 95˚C for 5 min and briefly cooled on ice. Following centrifugation at 15,000 x g for 5 min, the proteins in the cell lysates were separated by 10% SDS-polyacrylamide gel electrophoresis and transferred to nitrocellulose paper. The membrane was blocked with 5% skimmed milk in PBS-Tween-20 for 1 h at room temperature and then incubated with primary antibodies (1:500 dilution for all primary antibodies; NF-κB; cat. no. sc-8008; IκBα; cat. no. sc-847; IKKβ; cat. no. sc-7607; PARP; sc-8007; GAPDH; cat. no. sc-32233; all purchased from Santa Cruz Biotechnology, Inc.) overnight at 4˚C and secondary (mouse anti-rabbit IgG-HRP; 1:5,000; cat. no. sc-2357; goat anti-mouse IgG-HRP, 1:5,000; cat. no. sc-2005; all purchased from Santa Cruz Biotechnology, Inc.) antibodies for 1 h at room temperature. Finally, the protein bands were visualized by an enhanced chemiluminesence solution (Amersham; GE Healthcare) following the manufacturer's instructions. All protein expression levels were quantitated using ImageJ software (National Institutes of Health).

Fluorescent measurements of the intracellular calcium level. HMC-1 cells ($1x10^5$) were pretreated with Fura-2/AM for 30 min. After washing twice with medium containing the extracellular calcium chelator EGTA (0.5 mM), the cell suspension ($1x10^5$) was seeded into a 96-well plate and pretreated with UA (0.002-0.2 µg/ml) for 20 min. Next, the cells were stimulated with PMACI for 5 min. Plate fluorescence was measured at 440 nm (excitation, 360 nm) in a spectrofluorometer (29).

Statistical analysis. IBM SPSS 23.0 (IBM Corp.) was used to statistically analyze the results. Statistical analyses included performing independent t-tests and analysis of variance with Tukey's post hoc test. The differences were considered statistically significant at $P<0.05$, and the results are presented as mean ± standard error of the mean.

Results

Effect of UA on the production of TSLP. To evaluate the effect of UA on the production of TSLP in HMC-1 cells, HMC-1 cells

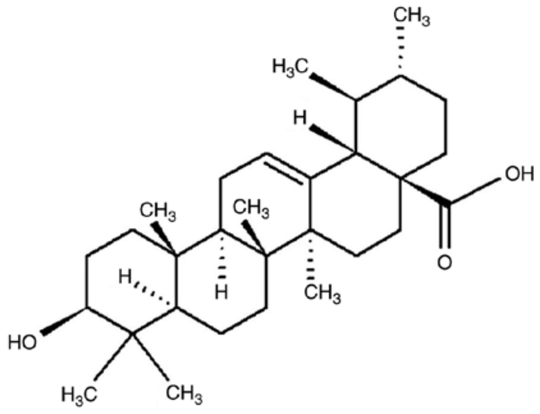

Figure 1. Chemical structure of ursolic acid.

were exposed to PMACI for 7 h. The levels of TSLP were evaluated with ELISA. Exposure to PMACI elevated the production of TSLP in HMC-1 cells (Fig. 2A); however, the elevated TSLP production was significantly lowered by UA (0.02 and 0.2 μg/ml; Fig. 2A). The TSLP production levels at concentrations of 0.002, 0.02 and 0.2 μg/ml were 0.127±0.006, 0.111±0.003 and 0.101±0.004, respectively. The levels of TSLP production in the blank and control groups were 0.079±0.002 and 0.135±0.008, respectively. Treatment with UA (0.2 μg/ml) reduced the TSLP production up to 61.442±6.947%. However, UA alone did not notably change the level of TSLP production from that in the blank (PBS-treated cells) group (data not shown). When HMC-1 cells were treated with UA at concentrations of 0.002-0.2 μg/ml, cell viability did not change (Fig. 2C). Higher concentrations of UA (2 and 20 μg/ml) did not achieve further TSLP inhibition (Fig. 2A). In addition, prolonged UA pretreatment did not achieve further TSLP inhibition (Fig. 2D). A 1-h pretreatment with UA inhibited TSLP production by up to ~60%, whereas a 24-h UA pretreatment produced a ~40% TSLP inhibition (Fig. 2D). This may be due to spontaneously released TSLP. Furthermore, when UA was added 1 h after PMACI stimulation, it did not significantly inhibit TSLP production (Fig. 2E).

Effect of UA on mRNA expression of TSLP. To determine the regulatory effect of UA on the TSLP mRNA expression, a variety of concentrations (0.002-0.2 μg/ml) of UA were added as pretreatment for 1 h prior to the exposure of HMC-1 cells to PMACI. Exposure to PMACI elevated TSLP mRNA expression, whereas the elevated TSLP mRNA expression was lowered by UA treatment (Fig. 2B). The TSLP mRNA expression values at concentrations of 0.002, 0.02 and 0.2 μg/ml were 22.667±2.333, 17.333±1.333 and 15.667±1.453, respectively. The relative expression levels of TSLP mRNA in the blank and control groups were 1.800±0.640 and 25.333±1.856, respectively.

Effects of UA on activation of NF-κB and degradation of IκBα. To investigate whether the regulatory effect of UA is mediated by NF-κB/IκBα signaling, the activation of NF-κB p65 and degradation of IκBα were assessed by western blot analysis. Exposure to PMACI elevated NF-κB activation in the nuclear extract, whereas the elevated NF-κB activation was lowered by UA treatment (Fig. 3). The relative intensity values for NF-κB activation in the blank, control and UA groups (0.002, 0.02 and 0.2 μg/ml) were 0.408±0.025, 0.629±0.039, 0.533±0.034, 0.455±0.028 and 0.424±0.053, respectively. However, UA treatment did not produce a significant change in cytoplasmic NF-κB protein levels (Fig. 3). Proteolytic degradation of IκBα results in activation of NF-κB (30,31); thus, we investigated whether the regulatory effect of UA is due to IκBα degradation. Exposure to PMACI elevated IκBα degradation in the cytoplasmic extract; however, the elevated IκBα degradation was lowered by UA treatment (Fig. 3). The relative intensity values of IκBα in the blank, control and UA groups were 0.438±0.019, 0.288±0.010, 0.304±0.016, 0.363±0.006 and 0.384±0.012, respectively. Phosphorylation and degradation of IκBα is due to IκB kinase (IKK) complex activation, and the IKK complex consists of three core subunits (IKKα, IKKβ and IKKγ), among which IKKβ is predominant (32); thus, we investigated whether IκBα degradation by UA is due to IKKβ. Exposure to PMACI elevated the IKKβ protein levels; however, the elevated IKKβ protein levels were reduced by UA treatment (Fig. 3). The relative intensity values of IKKβ in the blank, control and UA groups were 0.223±0.019, 0.298±0.004, 0.287±0.003, 0.253±0.006 and 0.251±0.007, respectively.

Effect of UA on the activation of caspase-1. The level of caspase-1 activation was evaluated with a caspase-1 assay kit to examine whether the effect of UA was mediated through caspase-1 activation. Exposure to PMACI increased the levels of caspase-1 activation, whereas the elevated caspase-1 activation was lowered by UA treatment (Fig. 4). The levels of caspase-1 activation in the blank, control and UA groups were 0.281±0.005, 0.335±0.007, 0.330±0.009, 0.307±0.004 and 0.299±0.007, respectively.

Effect of UA on calcium level. An increase in the intracellular calcium levels has been reported to enhance caspase-1 activation (33). Thus, the regulatory effect of UA on intracellular calcium levels was examined in HMC-1 cells. Exposure to PMACI increased intracellular calcium levels; however, this increase was prevented by UA treatment (Fig. 5).

Effect of UA on pro-inflammatory cytokine levels in HMC-1 cells. The pro-inflammatory cytokine tumor necrosis factor (TNF)-α is overexpressed in AD (34). To substantiate the presence of UA effects in AD, the levels of TNF-α were measured in HMC-1 cells. Exposure to PMACI increased TNF-α production in HMC-1 cells (Fig. 6); however, this increase in TNF-α production was markedly reduced by treatment with 0.2 μg/ml UA (Fig. 6).

Discussion

In the present study, UA was shown to suppress the production and mRNA expression of TSLP in HMC-1 cells. In addition, UA reduced NF-κB activation, IκBα degradation and caspase-1 activity in HMC-1 cells. Finally, it was demonstrated that UA downregulated intracellular calcium levels in HMC-1 cells.

When mast cells are activated, there are increases in the activation of protein kinase C (PKC) and intracellular calcium levels (35). To replicate this condition in the present study, PMA

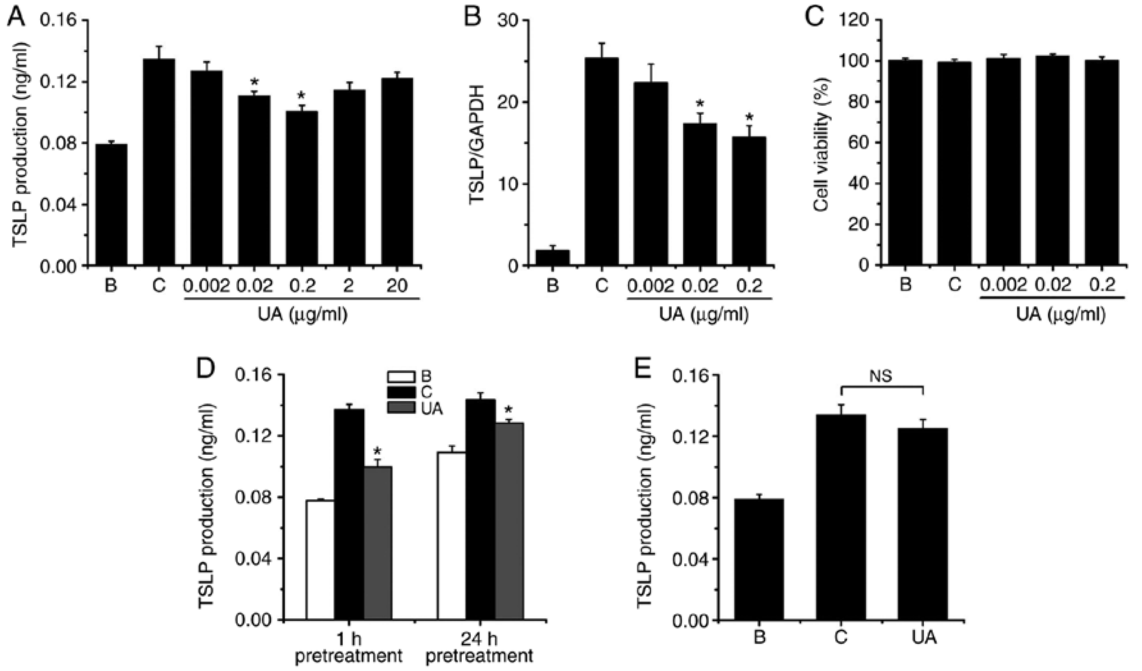

Figure 2. Effects of UA on the regulation of TSLP production and mRNA expression. (A) HMC-1 cells (3x10^5) were treated with various concentrations of UA (0.002-20 μg/ml) for 1 h, after which time the HMC-1 cells were stimulated with PMACI for 7 h. The TSLP levels were determined by ELISA. (B) HMC-1 cells (1x10^6) were exposed to PMACI for 5 h. The level of TSLP mRNA expression was evaluated with qPCR. (C) Various concentrations of UA (0.002-0.2 μg/ml) were applied to HMC-1 cells (3x10^5) for 1 h, and the HMC-1 cells were then stimulated with PMACI for 7 h. Cytotoxicity was analyzed by the MTT assay. (D) UA (0.2 μg/ml) pretreatment was applied to HMC-1 cells (3x10^5) for 24 or 1 h, after which time the HMC-1 cells were stimulated with PMACI for 7 h. The TSLP levels were determined by ELISA. (E) HMC-1 cells (3x10^5) were stimulated with PMACI for 7 h and UA (0.2 μg/ml) was added to the HMC-1 cells 1 h after PMACI stimulation. The TSLP levels were determined by ELISA. B, PBS-treated cells; C, PBS + PMACI-treated cells. Data are presented as mean ± standard error of the mean from three independent experiments. *P<0.05 vs. the PBS + PMACI-treated cells. NS, not significant. UA, ursolic acid; TSLP, thymic stromal lymphopoietin; PMACI, phorbol myristate acetate and calcium ionophore; HMC, human mast cell; qPCR, quantitative polymerase chain reaction; PBS, phosphate-buffered saline.

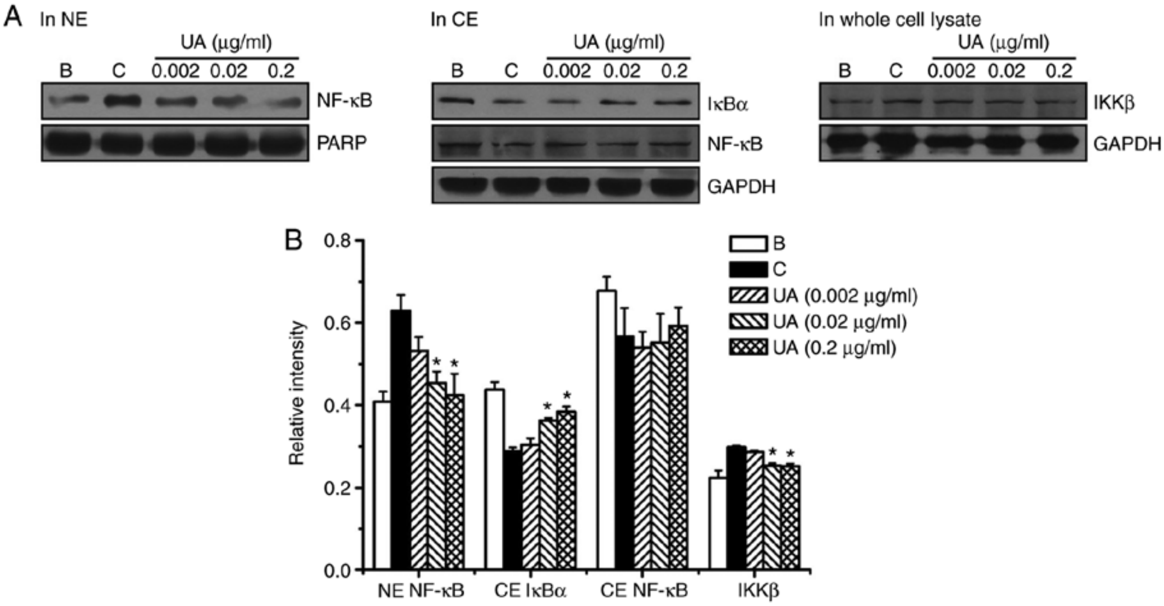

Figure 3. Effects of UA on the regulation of NF-κB p65 activation, IκBα degradation, and IKKβ activation. (A) UA (0.002-0.2 μg/ml) was added to HMC-1 cells (5x10^6) for 1 h, after which time the HMC-1 cells were stimulated with PMACI for 2 h. (B) The protein expression levels were quantitated by densitometry. B, PBS-treated cells; C, PBS + PMACI-treated cells. Data are presented as mean ± standard error of the mean from three independent experiments. *P<0.05 vs. PBS + PMACI-treated cells. UA, ursolic acid; NF-κB, nuclear factor-κB; HMC, human mast cell; PMACI, phorbol myristate acetate and calcium ionophore; NE, nuclear extract; CE, cytoplasmic extract; PARP, poly(ADP-ribose) polymerase.

was used to activate PKC, and calcium ionophore to increase the levels of intracellular calcium. Exposure to PMACI was reported to increase the production and mRNA expression of TSLP in HMC-1 cells (18), and high levels of TSLP

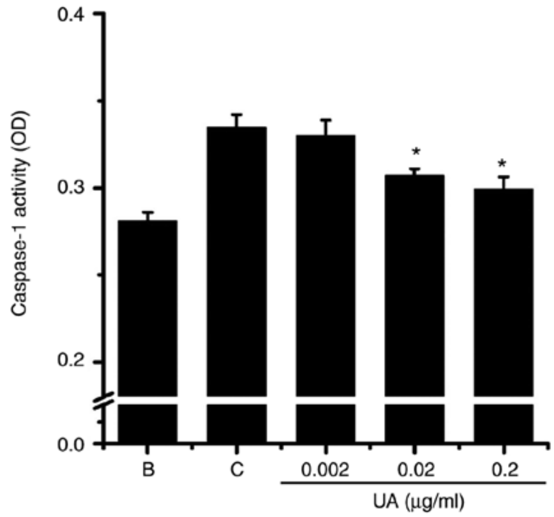

Figure 4. Effect of UA on the regulation of caspase-1 activation. UA (0.002-0.2 μg/ml) was added to HMC-1 cells ($5x10^6$) for 1 h, after which time the HMC-1 cells were stimulated with PMACI for 1 h. B, PBS-treated cells; C, PBS + PMACI-treated cells. Data are presented as mean ± standard error of the mean from three independent experiments. *P<0.05 vs. PBS + PMACI-treated cells. UA, ursolic acid; HMC, human mast cell; PMACI, phorbol myristate acetate and calcium ionophore; PBS, phosphate-buffered saline; OD, optical density.

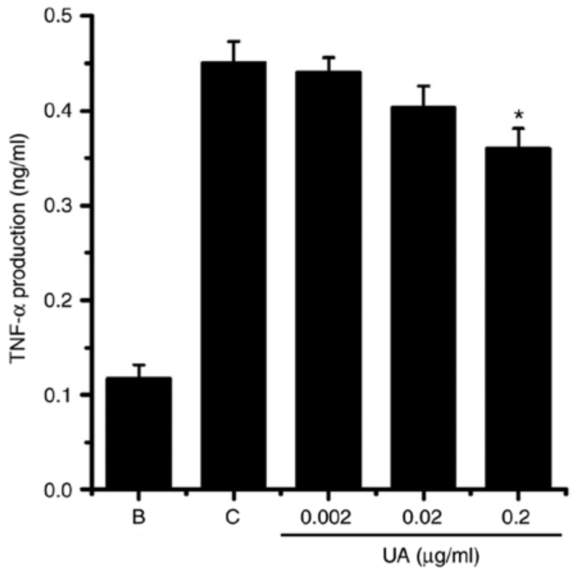

Figure 6. Effects of UA on the regulation of TNF-α production. Various concentrations of UA (0.002-0.2 μg/ml) were added to HMC-1 cells ($3x10^5$) for 1 h, after which time the HMC-1 cells were stimulated with PMACI for 7 h. The levels of TNF-α were determined by ELISA. B, PBS-treated cells; C, PBS + PMACI-treated cells. Data are presented as mean ± standard error of the mean from three independent experiments. *P<0.05 vs. PBS + PMACI-treated cells. UA, ursolic acid; TNF, tumor-necrosis factor; HMC, human mast cell; PMACI, phorbol myristate acetate and calcium ionophore; PBS, phosphate-buffered saline.

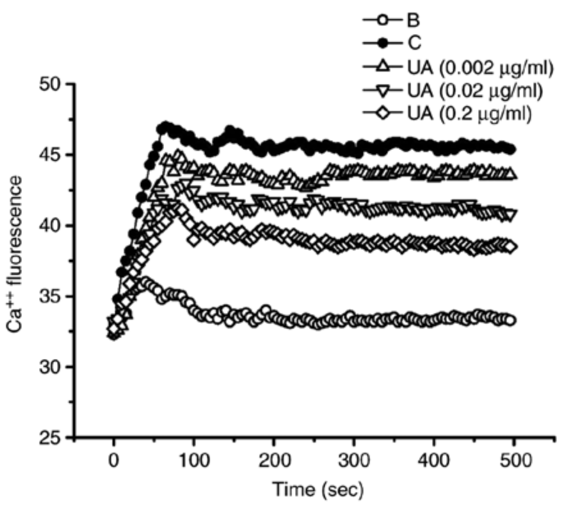

Figure 5. Effect of UA on the regulation of intracellular calcium levels. UA (0.002-0.2 μg/ml) was added to HMC-1 cells ($1x10^5$) for 20 min, after which time the cells were exposed to PMACI. B, PBS-treated cells; C, PBS + PMACI-treated cells. UA, ursolic acid; HMC, human mast cell; PMACI, phorbol myristate acetate and calcium ionophore; PBS, phosphate-buffered saline.

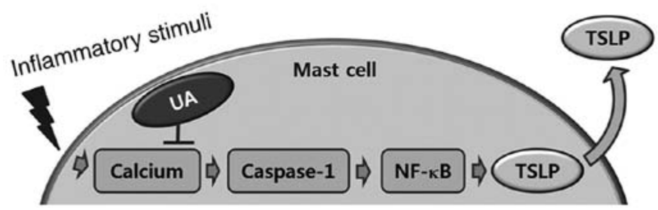

Figure 7. Schematic diagram of the proposed regulation of TSLP by UA. Upon inflammatory stimulation of mast cells, the intracellular calcium levels increased, and the increase in intracellular calcium activated caspase-1. The activation of caspase-1 led to NF-κB activation and, finally, the activation of NF-κB led to the release of TSLP. In this study, UA reduced TSLP production via inhibition of calcium/caspase-1/NF-κB signaling in mast cells. UA, ursolic acid; TSLP, thymic stromal lymphopoietin; NF-κB, nuclear factor-κB.

have been detected in the skin lesions of AD patients (36). Moreover, it has been suggested that TSLP enhances skin inflammatory responses in a murine AD model (37), whereas dexamethasone, an anti-inflammatory drug, inhibits expression of TSLP in a murine model of AD (38). The results of this study revealed that the production and mRNA expression of TSLP were reduced by UA treatment in HMC-1 cells (Fig. 2). Therefore, UA appears to be helpful in the treatment of atopic and inflammatory disorders.

Lee and Ziegler (39) suggested that TSLP expression is mediated by NF-κB. Our previous report clarified that TSLP production and mRNA expression were regulated via NF-κB signaling in mast cells (18). The present study demonstrated that NF-κB activation and IκBα degradation were lowered by UA treatment (Fig. 3). Furthermore, Shen *et al* (40) reported that NF-κB is a critical transcription factor for the production of TSLP. Thus, it may be hypothesized that UA reduces TSLP levels via blockade of NF-κB signaling in HMC-1 cells.

Pro-inflammatory stimuli generally activate caspase-1 (41). Several reports have demonstrated that caspase-1 activation results from pro-inflammatory stimulation, such as exposure to PMACI (42,43). In the present study, caspase-1 activation was found to be lowered by UA treatment (Fig. 4). Thus, it may be hypothesized that UA suppresses the production and mRNA expression of TSLP by blocking caspase-1 activation in HMC-1 cells.

The endoplasmic reticulum (ER) is an intracellular calcium store in mast cells (44), and mitochondria are involved in the modulation of intracellular calcium levels (45). Tang *et al* (45) reported that UA inhibits mitochondrial calcium release. In the present study, UA treatment prevented an increase in intracellular calcium, suggesting that UA contributes to the prevention of ER and mitochondrial calcium release (Fig. 5). An increase in intracellular calcium levels promotes the activation of caspase-1 (33), whereas caspase-1 activation in HMC-1 cells may be reduced by treatment with the calcium chelator BAPTA-AM (46). The results of the present study revealed that an increase in intracellular calcium may be prevented by UA treatment (Fig. 5). Thus, UA appears to decrease TSLP levels via blockade of calcium/caspase-1/NF-κB signaling in HMC-1 cells (Fig. 7). When UA was added following PMACI stimulation, it did not produce a significant change in TSLP inhibition (Fig. 2E). Thus, UA may exert a preventive rather than a therapeutic effect on AD. Finally, UA significantly attenuated the effects of PMACI; however, the levels of TNF-α, calcium fluorescence, TSLP/GAPDH and NF-κB/GAPDH did not return to those observed in non-PMACI-treated cells. High-fat diet exacerbated AD-like skin lesions in NC/Nga mice and increased TSLP levels in skin lesions, whereas pro-inflammatory cytokines, such as interleukin (IL)-4, IL-13, interferon-γ and TNF-α did not exhibit significant changes (47). To confirm the role of TSLP in AD-like skin lesions, when Moon *et al* (47) prepared TSLP knockout NC/Nga mice, TSLP deficiency markedly decreased AD-like skin lesions. Although the present conditions differ from those in the previous report (47), TSLP inhibition by UA may contribute significantly to the amelioration of the symptoms of allergic and atopic disorders.

In conclusion, the present study demonstrated that UA inhibits the production and mRNA expression of TSLP in HMC-1 cells. Moreover, UA decreased the activation of NF-κB, degradation of IκBα and activation of caspase-1. Furthermore, UA downregulated the levels of intracellular calcium. Therefore, these results suggest that UA, through its ability to downregulate TSLP, may be a valuable agent for the treatment and/or prevention of atopic and inflammatory diseases.

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Availability of data and materials

The data generated and analyzed during the present study are available from the corresponding authors on reasonable request.

Authors' contributions

PDM and NRH wrote the manuscript and conducted all experiments. JSL analyzed the data. HMK and HJJ designed the experiments. All authors read and approved the final manuscript.

Ethics approval and consent to participate

Not applicable.

Patient consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

References

1. Guttman-Yassky E, Hanifin JM, Boguniewicz M, Wollenberg A, Bissonnette R, Purohit V, Kilty I, Tallman AM and Zielinski MA: The role of phosphodiesterase 4 in the pathophysiology of atopic dermatitis and the perspective for its inhibition. Exp Dermatol 28: 3-10, 2019.
2. Yu JH, Jin M, Choi YA, Jeong NH, Park JS, Shin TY and Kim SH: Suppressive effect of an aqueous extract of *Diospyros kaki* calyx on dust mite extract/2,4-dinitrochlorobenzene-induced atopic dermatitis-like skin lesions. Int J Mol Med 40: 505-511, 2017.
3. Löwa A, Jevtić M, Gorreja F and Hedtrich S: Alternatives to animal testing in basic and preclinical research of atopic dermatitis. Exp Dermatol 27: 476-483, 2018.
4. Bieber T: Atopic dermatitis. Ann Dermatol 22: 125-137, 2010.
5. Plötz SG and Ring J: What's new in atopic eczema? Expert Opin Emerg Drugs 15: 249-267, 2010.
6. Landheer J, Giovannone B, Mattson JD, Tjabringa S, Bruijnzeel-Koomen CA, McClanahan T, de Waal Malefyt R, Knol E and Hijnen D: Epicutaneous application of house dust mite induces thymic stromal lymphopoietin in nonlesional skin of patients with atopic dermatitis. J Allergy Clin Immunol 132: 1252-1254, 2013.
7. Luo Y, Zhou B, Zhao M, Tang J and Lu Q: Promoter demethylation contributes to TSLP overexpression in skin lesions of patients with atopic dermatitis. Clin Exp Dermatol 39: 48-53, 2014.
8. Zhu Y, Pan WH, Wang XR, Liu Y, Chen M, Xu XG, Liao WQ and Hu JH: Tryptase and protease-activated receptor-2 stimulate scratching behavior in a murine model of ovalbumin-induced atopic-like dermatitis. Int Immunopharmacol 28: 507-512, 2015.
9. Schneider C, Döcke WD, Zollner TM and Röse L: Chronic mouse model of TMA-induced contact hypersensitivity. J Invest Dermatol 129: 899-907, 2009.
10. Han NR, Oh HA, Nam SY, Moon PD, Kim DW, Kim HM and Jeong HJ: TSLP induces mast cell development and aggravates allergic reactions through the activation of MDM2 and STAT6. J Invest Dermatol 134: 2521-2530, 2014.
11. Han NR, Moon PD, Yoou MS, Chang TS, Kim HM and Jeong HJ: Effect of massage therapy by VOSKIN 125+ painkiller® on inflammatory skin lesions. Dermatol Ther 31: e12628, 2018.
12. Gauchat JF, Henchoz S, Mazzei G, Aubry JP, Brunner T, Blasey H, Life P, Talabot D, Flores-Romo L, Thompson J, *et al*: Induction of human IgE synthesis in B cells by mast cells and basophils. Nature 365: 340-343, 1993.
13. Moon PD, Choi IH and Kim HM: Berberine inhibits the production of thymic stromal lymphopoietin by the blockade of caspase-1/NF-κB pathway in mast cells. Int Immunopharmacol 11: 1954-1959, 2011.
14. Schneider KS, Groß CJ, Dreier RF, Saller BS, Mishra R, Gorka O, Heilig R, Meunier E, Dick MS, Ćiković T, *et al*: The inflammasome drives GSDMD-independent secondary pyroptosis and IL-1 release in the absence of caspase-1 protease activity. Cell Rep 21: 3846-3859, 2017.
15. Han NR, Moon PD, Kim NR, Kim HY, Jeong HJ and Kim HM: Schisandra chinensis and its main constituent schizandrin attenuate allergic reactions by down-regulating caspase-1 in ovalbumin-sensitized mice. Am J Chin Med 45: 159-172, 2017.
16. Guo L, Kong Q, Dong Z, Dong W, Fu X, Su L and Tan X: NLRC3 promotes host resistance against Pseudomonas aeruginosa-induced keratitis by promoting the degradation of IRAK1. Int J Mol Med 40: 898-906, 2017.

17. Błażejewski AJ, Thiemann S, Schenk A, Pils MC, Gálvez EJC, Roy U, Heise U, de Zoete MR, Flavell RA and Strowig T: Microbiota normalization reveals that canonical caspase-1 activation exacerbates chemically induced intestinal inflammation. Cell Rep 19: 2319-2330, 2017.
18. Moon PD and Kim HM: Thymic stromal lymphopoietin is expressed and produced by caspase-1/NF-κB pathway in mast cells. Cytokine 54: 239-243, 2011.
19. Thakur R, Sharma A, Lingaraju MC, Begum J, Kumar D, Mathesh K, Kumar P, Singh TU and Kumar D: Ameliorative effect of ursolic acid on renal fibrosis in adenine-induced chronic kidney disease in rats. Biomed Pharmacother 101: 972-980, 2018.
20. Bhat RA, Lingaraju MC, Pathak NN, Kalra J, Kumar D, Kumar D and Tandan SK: Effect of ursolic acid in attenuating chronic constriction injury-induced neuropathic pain in rats. Fundam Clin Pharmacol 30: 517-528, 2016.
21. Lewinska A, Adamczyk-Grochala J, Kwasniewicz E, Deregowska A and Wnuk M: Ursolic acid-mediated changes in glycolytic pathway promote cytotoxic autophagy and apoptosis in phenotypically different breast cancer cells. Apoptosis 22: 800-815, 2017.
22. Gan D, Zhang W, Huang C, Chen J, He W, Wang A, Li B and Zhu X: Ursolic acid ameliorates CCl4-induced liver fibrosis through the NOXs/ROS pathway. J Cell Physiol 233: 6799-6813, 2018.
23. Ben Trivedi A, Kitabatake N and Doi E: Toxicity of dimethyl sulfoxide as a solvent in bioassay system with HeLa cells evaluated colorimetrically with 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-tetrazolium bromide. Agric Biol Chem 54: 2961-2966, 1990.
24. Han NR, Moon PD, Ryu KJ, Kim NR, Kim HM and Jeong HJ. Inhibitory effect of naringenin via IL-13 level regulation on thymic stromal lymphopoietin-induced inflammatory reactions. Clin Exp Pharmacol Physiol 45: 362-369, 2018.
25. Han NR, Moon PD, Yoo MS, Ryu KJ, Kim HM and Jeong HJ: Regulatory effects of chrysophanol, a bioactive compound of AST2017-01 in a mouse model of 2,4-dinitrofluorobenzene-induced atopic dermatitis. Int Immunopharmacol 62: 220-226, 2018.
26. Han NR, Moon PD, Kim HM and Jeong HJ: Cordycepin ameliorates skin inflammation in a DNFB-challenged murine model of atopic dermatitis. Immunopharmacol Immunotoxicol 40: 401-407, 2018.
27. Moon PD and Kim HM: Anti-inflammatory effect of phenethyl isothiocyanate, an active ingredient of Raphanus sativus Linne. Food Chem 131: 1332-1339, 2012.
28. Moon PD, Han NR, Lee JS, Kim HY, Hong S, Kim HJ, Yoo MS, Kim HM and Jeong HJ: β-eudesmol inhibits thymic stromal lymphopoietin through blockade of caspase-1/NF-κB signal cascade in allergic rhinitis murine model. Chem Biol Interact 294: 101-106, 2018.
29. Han NR, Moon PD, Ryu KJ, Jang JB, Kim HM and Jeong HJ: β-eudesmol suppresses allergic reactions via inhibiting mast cell degranulation. Clin Exp Pharmacol Physiol 44: 257-265, 2017.
30. Wu Z, Wang Y, Meng X, Wang X, Li Z, Qian S, Wei Y, Shu L, Ding Y, Wang P and Peng Y: Total C-21 steroidal glycosides, isolated from the root tuber of Cynanchum auriculatum Royle ex Wight, attenuate hydrogen peroxide-induced oxidative injury and inflammation in L02 cells. Int J Mol Med 42: 3157-3170, 2018.
31. Geng Q, Wei Q, Wang S, Qi H, Zhu Q, Liu X, Shi X and Wen S: Physcion 8-O-β-glucopyranoside extracted from Polygonum cuspidatum exhibits anti-proliferative and anti-inflammatory effects on MH7A rheumatoid arthritis-derived fibroblast-like synoviocytes through the TGF-β/MAPK pathway. Int J Mol Med 42: 745-754, 2018.
32. Perkins ND: Integrating cell-signalling pathways with NF-kappaB and IKK function. Nat Rev Mol Cell Biol 8: 49-62, 2007.
33. Rossol M, Pierer M, Raulien N, Quandt D, Meusch U, Rothe K, Schubert K, Schöneberg T, Schaefer M, Krügel U, *et al*: Extracellular Ca2+ is a danger signal activating the NLRP3 inflammasome through G protein-coupled calcium sensing receptors. Nat Commun 3: 1329, 2012.
34. Numerof RP and Asadullah K: Cytokine and anti-cytokine therapies for psoriasis and atopic dermatitis. BioDrugs 20: 93-103, 2006.
35. Moon PD, Han NR, Lee JS, Kim HM and Jeong HJ: Effects of Linalyl acetate on thymic stromal lymphopoietin production in mast cells. Molecules 23: E1711, 2018.
36. Ziegler SF: The role of thymic stromal lymphopoietin (TSLP) in allergic disorders. Curr Opin Immunol 22: 795-799, 2010.
37. Oyoshi MK, Venturelli N and Geha RS: Thymic stromal lymphopoietin and IL-33 promote skin inflammation and vaccinia virus replication in a mouse model of atopic dermatitis. J Allergy Clin Immunol 138: 283-286, 2016.
38. Mizuno K, Morizane S, Takiguchi T and Iwatsuki K: Dexamethasone but not tacrolimus suppresses TNF-α-induced thymic stromal lymphopoietin expression in lesional keratinocytes of atopic dermatitis model. J Dermatol Sci 80: 45-53, 2015.
39. Lee HC and Ziegler SF: Inducible expression of the proallergic cytokine thymic stromal lymphopoietin in airway epithelial cells is controlled by NFkappaB. Proc Natl Acad Sci USA 104: 914-919, 2007.
40. Shen D, Xie X, Zhu Z, Yu X, Liu H, Wang H, Fan H, Wang D, Jiang G and Hong M: Screening active components from Yu-ping-feng-san for regulating initiative key factors in allergic sensitization. PLoS One 9: e107279, 2014.
41. Humke EW, Shriver SK, Starovasnik MA, Fairbrother WJ and Dixit VM: ICEBERG: A novel inhibitor of interleukin-1beta generation. Cell 103: 99-111, 2000.
42. Moon PD, Choi IH and Kim HM: Naringenin suppresses the production of thymic stromal lymphopoietin through the blockade of RIP2 and caspase-1 signal cascade in mast cells. Eur J Pharmacol 671: 128-132, 2011.
43. Han NR, Moon PD, Kim HM and Jeong HJ: Tryptanthrin ameliorates atopic dermatitis through downregulation of TSLP. Arch Biochem Biophys 542: 14-20, 2014.
44. Tasaka K: Recent advances in the research on histamine release. Nihon Yakurigaku Zasshi 98: 197-207, 1991 (In Japanese).
45. Tang X, Gao J, Chen J, Fang F, Wang Y, Dou H, Xu Q and Qian Z: Inhibition by [corrected] ursolic acid of [corrected] calcium-induced mitochondrial permeability transition and release of two proapoptotic proteins. Biochem Biophys Res Commun 337: 320-324, 2005.
46. Han NR, Kim HM and Jeong HJ: Thymic stromal lymphopoietin is regulated by the intracellular calcium. Cytokine 59: 215-217, 2012.
47. Moon PD, Han NR, Kim HM and Jeong HJ: High-fat diet exacerbates dermatitis through up-regulation of TSLP. J Invest Dermatol 20: S0022-202X(18)32824-0, 2018.