

IL-33 stimulates CXCL8/IL-8 secretion in goblet cells but not normally differentiated airway cells

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Clinical & Experimental Allergy

Summary

Background IL-13, a helper T cell type 2 (Th2) cytokine, transforms cultured airway epithelial cells to goblet cells, and this is not inhibited by corticosteroids. IL-33 stimulates Th2 cytokines and is highly expressed in airways of persons with asthma. The effect of IL-33 on goblet cell differentiation and cytokine secretion has not been described.

Objective We examined the effect of IL-33 on CXCL8/IL-8 secretion from goblet or normally differentiated human bronchial epithelial (NHBE) cells and signalling pathways associated with IL-33 activation in these cells.

Methods Normal human bronchial epithelial cells were grown to goblet or normally differentiated ciliated cell phenotype at air–liquid interface in the presence or absence of IL-13. After 14 days, differentiated cells were exposed to IL-33 for 24 h.

Results CXCL8/IL-8 secretion into the apical (air) side of the goblet cells was greater than from normally differentiated cells ($P < 0.01$), and IL-33 stimulated apical CXCL8/IL-8 release from goblet cells, but not from normally differentiated cells ($P < 0.01$). IL-33 increased ERK 1/2 phosphorylation in goblet cells ($P < 0.05$), and PD98059, a MAPK/ERK kinase inhibitor, attenuated IL-33-stimulated CXCL8/IL-8 secretion from goblet cells ($P < 0.001$). IL-13 induced ST2 mRNA ($P < 0.02$) and membrane-bound ST2 protein expression on the apical side surface of goblet cells compared with normally differentiated cells, and neutralization with anti-ST2R antibody attenuated IL-33-induced apical CXCL8/IL-8 secretion from goblet cells ($P < 0.02$).

Conclusions and Clinical Relevance Goblet cells secrete CXCL8/IL-8, and this is increased by IL-33 through ST2R-ERK pathway, suggesting a mechanism for enhanced airway inflammation in the asthmatic airway with goblet cell metaplasia.

Keywords airway, asthma, goblet cell hyperplasia, IL-13, mucin, normal human bronchial epithelial cell, Th2 cytokine

Submitted 7 May 2013; revised 23 January 2014; accepted 27 January 2014

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Cite this as: T. Tanabe, T. Shimokawaji,
S. Kanoh and B. K. Rubin, *Clinical &
Experimental Allergy*, 2014 (44) 540–
552.

Introduction

Asthma is characterized by structural and functional abnormalities of the bronchial epithelium, accumulation of inflammatory cells in the bronchial mucosa and airway remodelling [1, 2]. The severity of mucus hypersecretion and airway goblet cell hyperplasia is associated with morbidity and mortality in asthma [3–5].

Allergen inhalation can trigger helper T cell type 2 (Th2)-type dominant inflammation in the lungs [6, 7]. The Th2 cytokines, IL-4, IL-9 and IL-13, can stimulate mucus production, bronchial hyperresponsiveness and airway remodelling [2]. IL-13, in particular, has been shown to increase mucus production and goblet cell metaplasia *in vivo* and *in vitro* [2, 8–13].

IL-33 is a member of the IL-1 family that is a ligand for the orphan IL-1 family receptor ST2, and an inducer of Th2 immunity. IL-33 signals through a complex including the membrane-bound ST2 (ST2L) protein [14]. ST2 is present on Th2 cells as well as mast cells, basophils, eosinophils, natural killer T cells [15] and bronchial epithelial cells [16]. The IL-33/ST2 axis triggers the release of pro-inflammatory chemokines and cytokines and stimulates Th2 inflammation [14]. The IL-33/ST2 pathway also contributes to allergen-induced airway inflammation and hyperresponsiveness [17].

A likely source of IL-33 is the airway epithelium. IL-33 expression is increased in biopsies from the airways of subjects with asthma compared to healthy individuals and is greater still in subjects with severe

asthma [18]. IL-33 expression is refractory to the effects of corticosteroids [18]. These data support a role for IL-33 in the pathogenesis of severe asthma.

Neutrophils are found in the airways of subjects with severe asthma, and the extent of neutrophilia is related to the disease severity [19]. IL-8, now known as cysteine-X-cysteine chemokine 8 (CXCL8), is an important chemoattractant for neutrophil recruitment into airways of patients with severe asthma [20–22]. Normal human bronchial epithelial (NHBE) cells treated with IL-13 over 7 days have increased CXCL8/IL-8 secretion [23], and IL-13 exposure increases CXCL8/IL-8 in airway epithelial cells from healthy subjects and asthmatics [24].

IL-33-exposed mice have hypertrophy of the airway epithelium with large amounts of mucus and inflammatory infiltrates of neutrophils, mononuclear cells and eosinophils in lung tissue and bronchoalveolar lavage fluid [14, 25].

We speculated that IL-33 would stimulate cultured NHBE cells towards goblet cell differentiation and stimulate CXCL8/IL-8 production in these goblet cells by activating the ST2 receptor (ST2R) pathway.

Materials and methods

Reagents

Recombinant human IL-13 (rhIL-13), human ST2/IL-1 R4 antibody as well as anti-goat-IgG horseradish peroxidase (HRP) antibody were obtained from R&D Systems Inc. (Minneapolis, MN, USA). Recombinant human IL-33 (rhIL-33) was obtained from Pepro Tech Inc. (Rocky Hill, NJ, USA). Anti-MUC5AC monoclonal antibody (45M1) was obtained from Lab Vision (Fremont, CA, USA). PD98059 (2'-amino-3'-methoxyflavone), an MAPK/ERK kinase (MEK) inhibitor (an upstream kinase of ERK1/2), was obtained from Calbiochem (La Jolla, CA, USA). Phospho- and non-phospho-specific ERK1/2 and anti-rabbit-IgG HRP antibody were purchased from Cell Signaling Technology, Inc (Beverly, MA, USA). Dimethyl sulphoxide (DMSO), anti- β -actin, anti-mouse-IgG HRP antibody and all other reagents were purchased from Sigma-Aldrich Co. (St. Louis, MO, USA) unless otherwise indicated.

Culture and differentiation of NHBE cells

Normal human bronchial epithelial cells (Clonetics™, Lonza, Basel, Switzerland) were plated at 3500 cells/cm² in small airway epithelial cell growth medium (SAGM, Clonetics™, Lonza) and cultured at 37°C in a 5% CO₂ incubator. Second-passage NHBE cells were seeded at a density of 2.0×10^5 /cm² onto polyester inserts (6.5 mm diameter, 0.4 μ m pore size and 10 μ m thickness; Costar Transwell® Clear; Costar, Cambridge,

MA, USA) coated with type I rat tail collagen (Sigma, St. Louis, MO, USA) and then cultured in serum-free DMEM/F12 medium containing insulin–transferrin–selenium–sodium pyruvate (ITS-A) (1.0%; Invitrogen, Carlsbad, CA, USA), triiodothyronine (10 ng/mL; ICN, Irvine, CA, USA), epidermal growth factor (recombinant human EGF, 0.5 ng/mL; Invitrogen), all-trans retinoic acid (all-trans RA, 10^{-7} M; Sigma), hydrocortisone (0.5 μ g/mL; ICN), bovine serum albumin (2.0 μ g/mL; Sigma), bovine pituitary extract (30 μ g/mL; Invitrogen) and antibiotic–antimycotic solution (1.0%; Invitrogen). Culture medium was added to both the apical and basolateral side of the inserts, and the cells were cultured submerged in medium. The culture medium was changed every 2 days. Confluence was reached within 5 days, and the cells were then cultured at an air–liquid interface (ALI), feeding from the basolateral side only. The culture medium was changed every 2 days, and the cells were maintained in an incubator under a humidified 5% CO₂ atmosphere at 37°C [8, 13, 26, 27].

IL-13 exposure

Normal human bronchial epithelial cells were grown from day 0 to day 14 with rhIL-13 at 2, 5 or 10 ng/mL, or vehicle (PBS). The culture medium with IL-13 or vehicle was changed every 48 h.

IL-33 exposure

Normal human bronchial epithelial cells were grown from day 0 to day 14 with rhIL-33 at 0.5, 5 or 10 ng/mL, or vehicle (PBS). The culture medium with IL-33 or vehicle was changed every 48 h.

IL-13 & IL-33 exposure

Normal human bronchial epithelial cells were grown with 5 ng/mL rhIL-13 or rhIL-13 vehicle (PBS) for 14 days. Cells were exposed from the basolateral side or the apical side to rhIL-33 (0, 0.5 or 5 ng/mL) for 24 h. To collect samples, Hank's balanced salt solution was added to the apical (air) side of the inserts, and 24-h culture supernatants from the apical side and culture media from the basolateral side of inserts were harvested on day 14.

CXCL8/IL-8 secretion by ELISA

CXCL8/IL-8 proteins in the supernatants and culture media were measured using human CXCL8/IL-8 ELISA DuoSet (R&D Systems). The minimum detection level of CXCL8/IL-8 was 7.5 pg/mL. Optical density was measured at 450 nm using a microtiter plate reader (Spectra Max Plus; Molecular Devices, Sunnyvale, CA, USA)

with software (Soft Max Pro version 2.0; Molecular Devices). The concentration of each sample was obtained from standard curves and calculated as the mean of the results.

RT-PCR

To examine the effect of IL-13 on mRNA expression of CXCL8/IL-8, RNA was extracted from the cells grown with rhIL-13 (0 or 5 ng/mL) for 14 days and exposed from the basolateral side or the apical side to rhIL-33 (0, 0.5 or 5 ng/mL) for 1 h at day 14. To examine temporal mRNA expression of ST2, RNA was extracted from cells 5, 10 or 14 days after growing with rhIL-13 (0, 2, 5, 10 ng/mL). The preparation for RT-PCR was previously described [8, 13, 26, 27]. The apical side of the cells was washed three times with PBS, and total RNA from the cells was extracted using iScript RT-qPCR sample preparation reagent (Bio-Rad laboratories Inc., Hercules, CA, USA). The total RNA was then used to synthesize the first-strand cDNA using the iScript cDNA synthesis kit (Bio-Rad). RT-PCR was performed on the C 1000™ thermal cycler equipped with CFX96™ real-time PCR system (Bio-Rad). For the relative quantification of ST2 mRNA expression, the mRNA expression of glyceraldehyde-3-phosphate dehydrogenase (GAPDH) served as an internal control. EvaGreen was used as a DNA intercalator dye to monitor amplified DNA quantification, and real-time quantitative PCR curves were analysed by the CFX Manager™ software (Bio-Rad) in order to obtain threshold cycle (C_t) values for each sample. mRNA expression level was calculated based on a generated standard curve.

The following primers were used [26–28]:

CXCL8/IL-8 forward: 5'-CTGCGCCAACACAGAAATTA-3'

CXCL8/IL-8 reverse: 5'-ACTTCTCCACAACCCTCTGC-3'

ST2L forward: 5'-CTGTCTGGCCCTGAATTTGC-3'

ST2L reverse: 5'-AGCAGAGTGGCCTCAATCCA-3'

soluble ST2 (sST2) forward: 5'-CTGTCTGGCCCTGAATTTGC-3'

sST2 reverse: 5'-TGGAACCACACTCCATTCTGC-3'

GAPDH forward: 5'-TGAACGGGAAGCTCACTGG-3'

GAPDH reverse: 5'-TCCACCACCTGTTGCTGTA-3'.

Histochemical analysis

The cells on porous filters were fixed in 10% formalin neutral buffer, embedded in paraffin and cut into 8- μ m slices. To examine morphology, haematoxylin–eosin (H&E) staining and periodic acid–Schiff (PAS) staining were performed [8, 13, 27]. Mucin production was confirmed using PAS staining, and goblet cells with secretory granules were evaluated with a light microscope

(CKX41; Olympus, Tokyo, Japan) using a digital camera system (AxioCam ICc 1; Carl Zeiss, Thornwood, NY, USA).

Immunohistochemical analysis

MUC5AC protein or ST2 expression was evaluated using immunohistochemistry. Sections were stained with anti-MUC5AC antibody or anti-ST2 antibody as first antibody. EnVision™ + Dual Link System-HRP (DAKO, North America Inc., Carpinteria, CA, USA) for MUC5AC or anti-goat IgG HRP for ST2 was added as the second antibody. Antigen–antibody complexes were visualized using Liquid DAB+ Substrate Chromogen System (DAKO) [8, 13, 26, 27, 29].

Immunofluorescent confocal microscopy analysis

Acetylated α -tubulin (cilia protein) and MUC5AC (mucin) were identified in NHBE cells using immunofluorescence techniques and confocal microscopy [30, 31]. For the apical surface view, cultured NHBE cell membranes were cut from the insert using a scalpel and fixed in 3% formaldehyde. For the z-stack view, the cell membrane was embedded in Tissue-Tek OCT Compound (Sakura Finetechnical, Tokyo, Japan), frozen in liquid nitrogen and stored at -80°C . The frozen samples were cut into 8- μ m slices using a cryostat at -20°C , mounted on slides and warmed to room temperature before fixation in 3% formaldehyde. The secondary antibodies were goat anti-mouse Alexa Fluor 488 (Invitrogen) for MUC5AC and goat anti-rabbit Alexa Fluor 568 (Invitrogen) for acetylated α -tubulin. After incubation with the primary and secondary antibodies, the slides were rinsed with PBS three times, and nuclei were stained with DAPI (Invitrogen) for 1 min in the dark. The slides were again rinsed three times with PBS and immersed in VECTASHIELD® Mounting Medium for fluorescence (Vector Laboratories, Inc., Burlingame, CA, USA). Coverslips were applied and the slides were stored at 4°C in the dark. Slides were examined within 24 h of staining using confocal laser scanning microscopy (LSM 700; Zeiss, Oberkochen, Germany). Immunostaining was visualized with a blue diode, argon ion and helium neon laser using at 405-, 488- and 568-nm laser lines, respectively.

The percentile ratios of MUC5AC (green)- or acetylated α -tubulin (red)-stained area to total area were calculated using NIH Image J software (National Institutes of Health, Bethesda, MD, USA). For the apical surface view, the stained areas were measured at a low magnification of $\times 20$ in five random fields per specimen from six different inserts of cultured NHBE cells. For the z-stack view, the stained areas at apical surface of the cells were measured over 150 μ m in five random sites

per specimen from six different inserts of cultured NHBE cells.

Western blot analysis

For Western blot analysis, cells were washed with cold PBS and lysed on ice in a modified ratio immunoprecipitation buffer (1% Nonidet P-40, 1% sodium deoxycholate, 150 mM NaCl, 10 mM Tris pH 7.5, 5 mM sodium pyrophosphate, 1 mM NaVO₄, 5 mM NaF, 1 µg/mL aprotinin, 1 µg/mL leupeptin and 0.1 mM phenylmethylsulfonyl fluoride) for 15 min and scraped from the plates. DNA was collected by passing the lysate through a 27-gauge needle, and insoluble material was removed by centrifugation at 20 000 × g for 15 min at 4°C. The protein concentration of the supernatants was quantified using the Detergent Compatible (DC) Protein Assay (Bio-Rad). Equal amounts of protein extracts were loaded on a 12% sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE) mini gel and transferred to a nitrocellulose membrane (Bio-Rad) by Trans-Blot® Turbo™ Transfer system (Bio-Rad). Membranes were rinsed with distilled water, incubated overnight at 4°C in Tris-buffered saline (0.8% NaCl and 20 mM Tris pH 7.6) with 0.1% Tween 20 (TBS-T) with 5% non-fat dry milk to block non-specific interactions, rinsed twice and washed 3 times for 10 min with TBS-T. After washing, membranes were rinsed and

incubated with the primary antibodies phospho-p44/42 MAPK (ERK1/2) (Thr202/Tyr204) or p44/42 MAPK (ERK1/2) rabbit polyclonal IgG (Cell Signaling Technology), human ST2/IL-1 R4 goat polyclonal IgG, or human β-actin mouse monoclonal IgG for 2 h in TBS-T. The membranes were then incubated for 2 h with the anti-rabbit IgG HRP secondary antibody, the anti-goat IgG HRP secondary antibody or the anti-mouse IgG HRP secondary antibody. After washing, antibody binding was detected using LumiGLO chemiluminescent substrate peroxide (Cell Signaling Technology). Membranes were stripped with a stripping buffer (100 mM 2-mercaptoethanol, 2% sodium dodecyl sulphate and 62.5 mM Tris-HCL pH 6.7) for 20 min. Western blot images were scanned and analysed using NIH Image J software (National Institutes of Health).

Statistical analysis

Data are expressed as mean values ± SEM. Comparisons between the two groups were made by unpaired two-tailed Student's *t*-test. Multiple comparisons were made by one-way analysis variance (ANOVA) except for ST2 mRNA expression over time, which was analysed by two-way repeated-measures ANOVA. A *post hoc* analysis for multiplicity was performed by using the Bonferroni's method. Conventionally, *P* < 0.05 was considered significant.

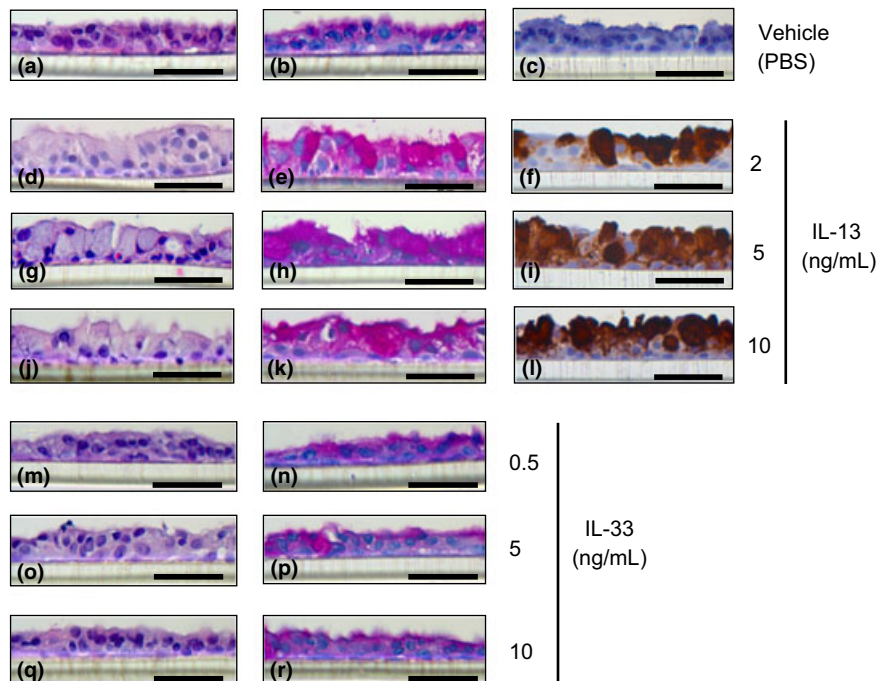


Fig. 1. Haematoxylin and eosin (HE) staining (a, d, g, j, m, o, q), periodic acid-Schiff (PAS) staining (b, e, h, k, n, p, r) and MUC5AC immunohistochemical staining (c, f, i, l) of normal human bronchial epithelial (NHBE) cells grown for 14 days at an air-liquid interface (ALI) with IL-13 at 2 (d-f), 5 (g-i) or 10 (j-l) ng/mL, IL-33 at 0.5 (m, n), 5 (o, p) or 10 (q, r) ng/mL, or vehicle (PBS) (a-c). Bar = 50 µm.

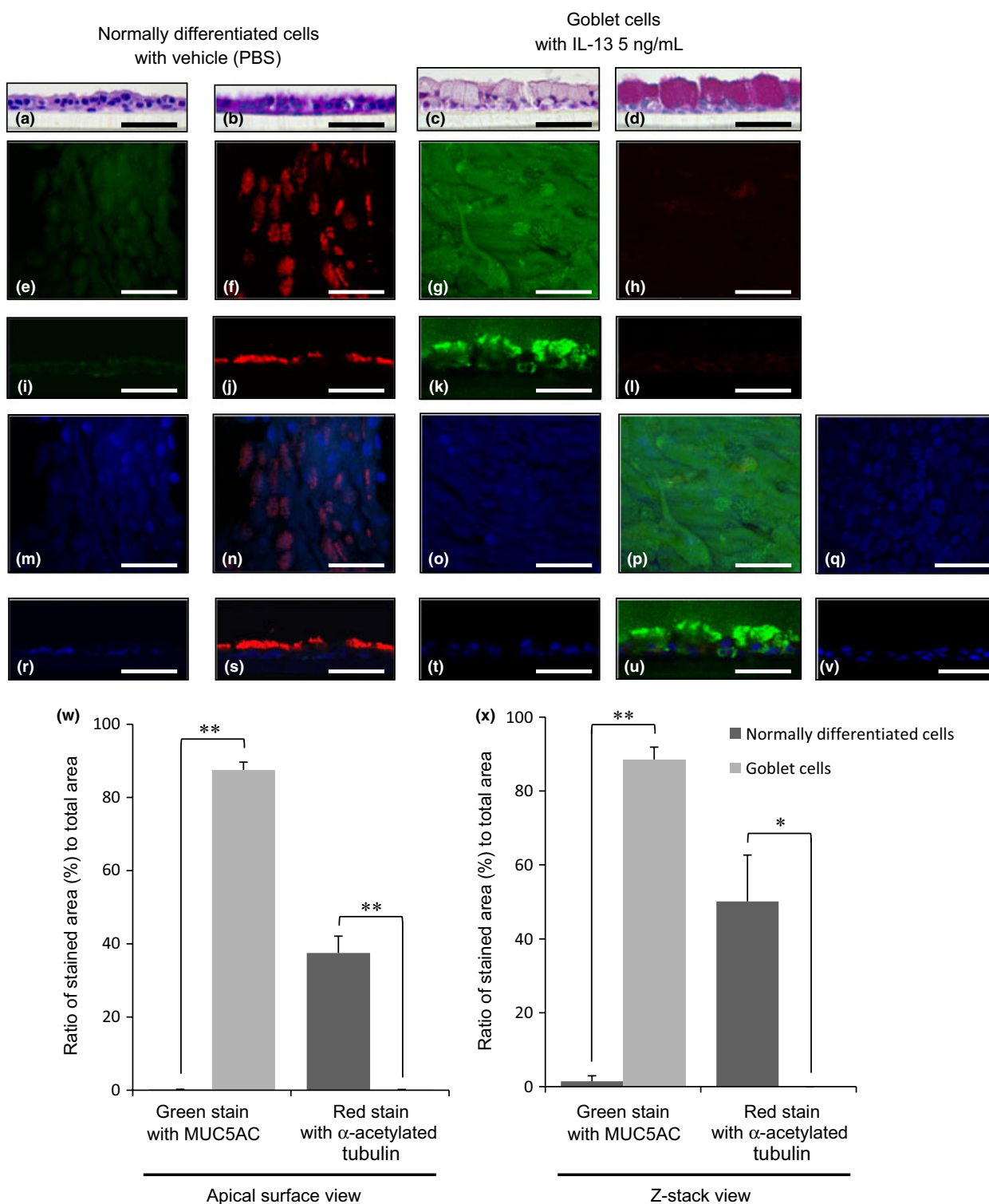


Fig. 2. HE staining (a, c), PAS staining (b, d) and immunofluorescence with laser confocal microscopy (e–v) of NHBE cells grown at an ALI with IL-13 vehicle (PBS) (a, b, e, f, i, j, m, n, r, s) or 5 ng/mL IL-13 (c, d, g, h, k, l, o, p, q, t, u, v) for 14 days. Representative images of apical surface (e–h, m–q) and z-stack (i–l, r–v). Immunofluorescence shows MUC5AC (Alexa Fluor 488, green; e, i, g, k), acetylated α -tubulin (Alexa Fluor 568, red; f, j, h, l), nuclei (DAPI, blue; m, r, o, t) and merged image of the double staining and DAPI (n, s, p, u). The negative control of NHBE cells with 5 ng/mL IL-13 without the primary antibodies (q, v). Bar = 50 μ m. Ratio of green stained area with MUC5AC or red stained area with α -acetylated tubulin to total area at (w) apical surface view or (x) z-stack view in immunofluorescence of NHBE cells grown with IL-13 vehicle (PBS) (normally differentiated cells) or 5 ng/mL IL-13 (goblet cells). The results are the means $\pm$ SEM from 6 samples. Significant differences are indicated by * P < 0.01, ** P < 0.001.

Results

IL-13-induced goblet cell differentiation

NHBE cells cultured at ALI demonstrated a well-differentiated morphology with ciliated cells at the surface of epithelial layers (referred to normally differentiated cells for convenience) (Figs 1a–c, 2a,b,e,f,i,j,m,n,r,s) and weakly stained with PAS (Figs 1b, 2b) and MUC5AC (Figs 1c, 2e,i) and strongly stained with

acetylated α -tubulin (Fig. 2f,j,n,s). In the presence of IL-13 at 2 (Fig. 1d–f), 5 (Figs 1g–i, 2c,d,g,h,k,l,o,p,t,u) or 10 (Fig. 1j–l) ng/mL, NHBE cells differentiated into goblet cells with secretory granules (goblet phenotype) (Figs 1d,g,j, 2c) strongly stained with PAS (Figs 1e,h,k, 2d) and MUC5AC (Figs 1f,i,l, 2g,k,p,u), but not with acetylated α -tubulin (Figs 2h,l,p,u). The apical surface of normally differentiated cells is shown in red immunofluorescence using acetylated α -tubulin (Fig. 2f,j,n,s) and goblet cells in green using MUC5AC (Fig. 2g,k,p,u).

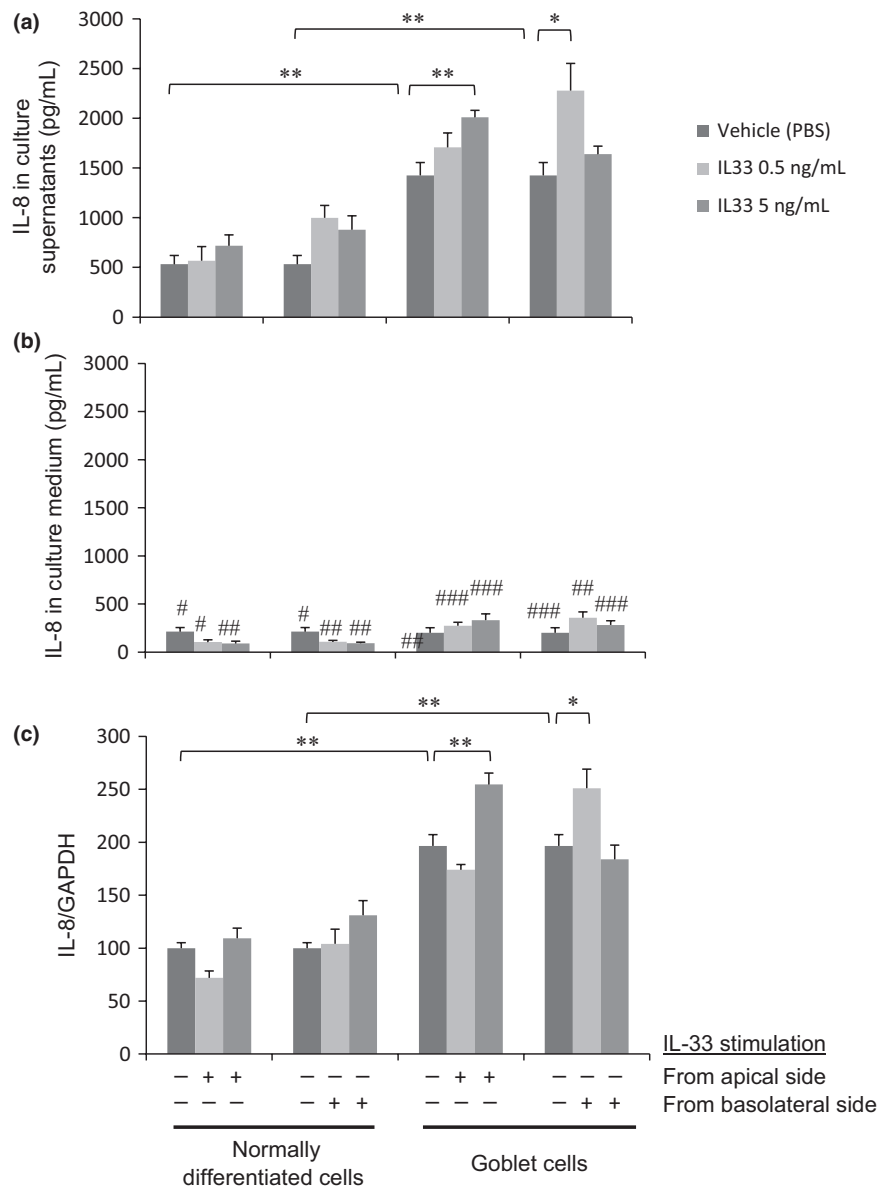


Fig. 3. Apical or basolateral IL-13 stimulated CXCL8/IL-8 secretion in (a) apical culture supernatants or (b) basolateral culture medium from normally differentiated cells or goblet cells. IL-13 (0.5 or 5 ng/mL) was introduced at the apical or basolateral side of cells for 24 h on day 14 of growth. The results are the means $\pm$ SEM from 6 samples. Significant differences are indicated by * P < 0.05, ** P < 0.01. Significant differences from culture supernatant at each condition are indicated by # P < 0.05, ## P < 0.01, ### P < 0.001, #### P < 0.0001. (c) Apical or basolateral IL-13 stimulated CXCL8/IL-8 mRNA expression in normally differentiated cells or goblet cells. IL-13 (0.5 or 5 ng/mL) was introduced at the apical or basolateral side of cells for 1 h on day 14 of growth. The results are the means $\pm$ SEM from four samples. Significant differences are indicated by * P < 0.05, ** P < 0.01.

Images (Fig. 2c,d,g,h,k,l,o,p,t,u) show predominantly goblet cells with few or no ciliated cells after growth with 5 ng/mL IL-13. The ratio of green stained area with MUC5AC to total area increased to $87.53 \pm 2.13\%$ at apical surface view (Fig. 2w) and $88.52 \pm 3.34\%$ at z-stack view (Fig. 2x) in goblet cells compared to $0.19 \pm 0.084\%$ at apical (Fig. 2w) and $1.48 \pm 1.48\%$ at z-stack (Fig. 2x) in normally differentiated cells ($P < 0.001$). In contrast, the red stained area with acetylated α -tubulin decreased to $0.18 \pm 0.046\%$ at apical (Fig. 2w) and was undetectable at z-stack (Fig. 2x) in goblet cells compared to $37.53 \pm 4.59\%$ at apical (Fig. 2w) and $50.13 \pm 12.54\%$ at z-stack (Fig. 2x) in normally differentiated cells ($P < 0.01$).

IL-33 did not affect NHBE cells morphology

IL-33 at 0.5 (Fig. 1m,n), 5 (Fig. 1o,p) or 10 (Fig. 1q,r) ng/mL did not affect NHBE cell differentiation (Fig. 1m–r) and cells grown with exposure to IL-33 were morphologically indistinguishable from cells grown without exposure to IL-33 (Fig. 1a,b).

IL-33 stimulated CXCL8/IL-8 protein secretion and mRNA expression in goblet cells

On day 14 after 24 h after exposure to IL-33 (0, 0.5 or 5 ng/mL), CXCL8/IL-8 concentration was greater in the apical supernatants than in the culture medium (Fig. 3a,b; $P < 0.01$). IL-13 at 5 ng/mL further increased apical CXCL8/IL-8 secretion (Fig. 3a; IL-8 1426 ± 129 pg/mL with 5 ng/mL of IL-13 compared

with no IL-13 $P < 0.01$), but not in the basal culture medium ($P = 0.86$). IL-13 at 5 ng/mL increased CXCL8/IL-8 mRNA expression (Fig. 3c; compared with no IL-13 $P < 0.01$). The IL-13-exposed cells had >2-fold increase in the CXCL8/IL-8 mRNA/GAPDH ratio (Fig. 3c) compared to no IL-13-exposed culture. Apical exposure to 5 ng/mL IL-33 ($P < 0.01$), or basolateral exposure ($P < 0.02$), increased CXCL8/IL-8 concentration in the supernatants of goblet cells, but not normally differentiated cells (Fig. 3a). Exposure to IL-33 did not affect CXCL8/IL-8 concentration in the basolateral side culture medium (Fig. 3b). Apical exposure to 5 ng/mL IL-33 ($P < 0.01$), or basolateral exposure ($P < 0.05$), increased CXCL8/IL-8 mRNA expression in goblet cells, but not normally differentiated cells (Fig. 3c).

Western blot analysis of IL-33-stimulated phosphorylation of p44/42 MAPK (ERK1/2)

IL-33 phosphorylated ERK at 30, 60, 120 and 240 min in both normally differentiated cells (Fig. 4a) and goblet cells (Fig. 4b). Western blot analysis of cell lysates showed that IL-33 significantly increased p-ERK expression at 120 or 240 min in goblet cells ($P < 0.05$) (Fig. 4b), but not normally differentiated cells (Fig. 4a). This was suppressed by PD98059 (2 or 20 μ M) (Fig. 5a) or anti-ST2 R antibody (20 μ g/mL) at the apical side of goblet cells (Fig. 7a). IL-33 alone increased the p-ERK/t-ERK ratio ($P < 0.01$), and this was attenuated by PD98059 at 2 or 20 μ M (2 μ M; $P < 0.03$, 20 μ M; $P < 0.05$) (Fig. 5a), or anti-ST2R antibody (20 μ g/mL; $P < 0.05$) (Fig. 7a).

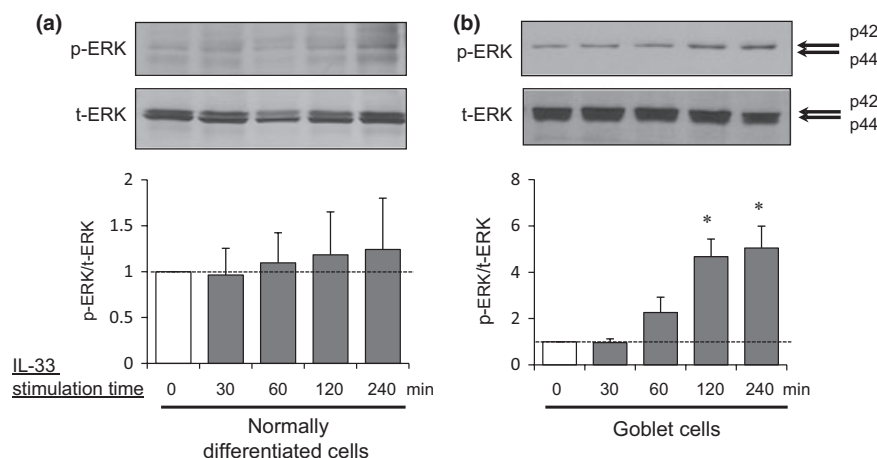


Fig. 4. NHBE cells were grown to normally differentiated ciliated cells or goblet cells with IL-13 vehicle (PBS) or 5 ng/mL IL-13 at an ALI. The cells were then grown without IL-13 and supplements for 48 h before IL-33 stimulation to avoid the influence of IL-13 and growth factors on cell signalling. Cell lysates with (a) normally differentiated cells or (b) goblet cells were harvested on day 16 after 0-, 30-, 60-, 120- or 240-min apical exposure to 5 ng/mL IL-33. Western blot of phosphorylated p44/42 MAPK (ERK1/2) (p-ERK), p44/42 MAPK (ERK1/2) (t-ERK) expressed as the ratio of p-ERK/t-ERK. The results are the means $\pm$ SEM from three samples. Significant differences from 0 min are indicated by * $P < 0.05$.

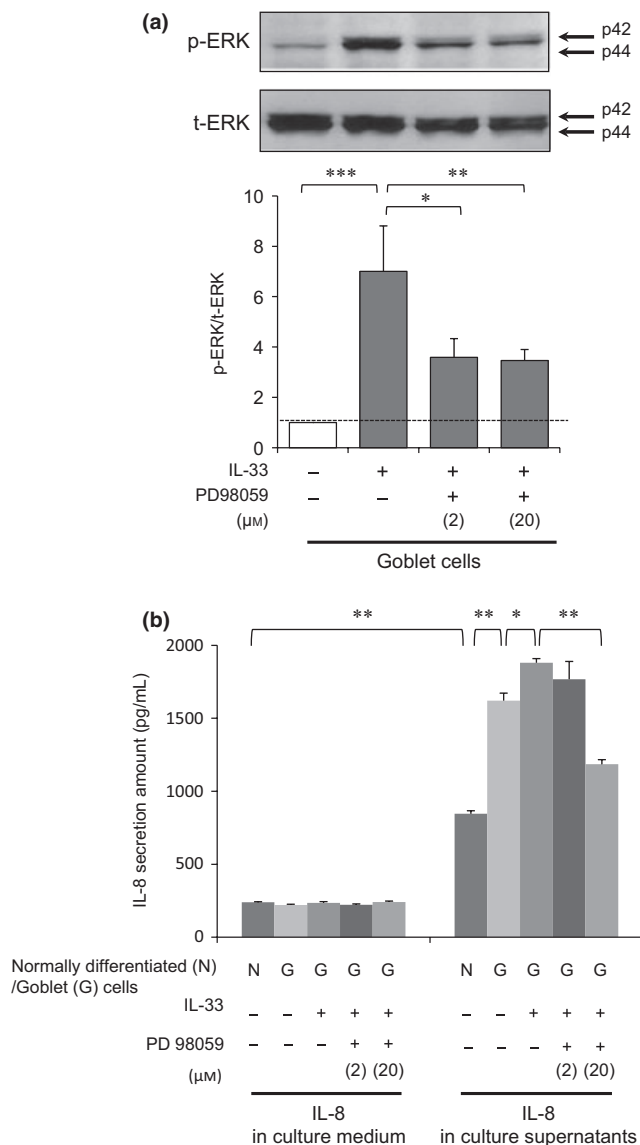


Fig. 5. (a) NHBE cells were differentiated to goblet cells with 5 ng/mL IL-13 at an ALI. The cells were then grown without IL-13 and supplements for 48 h before IL-33 stimulation to avoid the influence of IL-13 and growth factors on cell signalling. Cell lysates were harvested on day 16 after 120-min apical exposure to 5 ng/mL IL-33 or PBS after 2-h pretreatment with PD98059 (0, 2 or 20 μ M). Western blot data are expressed as the ratio of p-ERK to t-ERK. The results are the means $\pm$ SEM from four samples. Significant differences are indicated by * P < 0.05, ** P < 0.03, *** P < 0.01. (b) Apical IL-33 stimulated CXCL8/IL-8 secretion from goblet cells, and this was attenuated by the MEK inhibitor, PD 98059. On day 14, cells were exposed to IL-33 after 2 h of treatment with PD98059 at 0, 2 or 20 μ M. The results are the means $\pm$ SEM from 6 samples. Significant differences are indicated by * P < 0.01, ** P < 0.001.

Effect of PD98059 on IL-33-stimulated CXCL8/IL-8 secretion from goblet cells

NHBE cells were grown with 0 or 5 ng/mL IL-13 at ALI, and on day 14, PD98059 at 0, 2 or 20 μ M was added to

the basal culture medium. Apical supernatants and basal medium were collected after an additional 24-h exposure to 0 or 5 ng/mL IL-33. This pretreatment with PD98059 at 20 μ M attenuated IL-33-stimulated apical CXCL8/IL-8 secretion from the goblet cells (Fig. 5b; P < 0.001).

ST2 mRNA expression in goblet cells

IL-13 increased membrane-bound ST2 mRNA expression (Fig. 6a; P < 0.02 to PBS). The soluble ST2 mRNA expression also increased with exposure to IL-13 at 2, 5 or 10 ng/mL as shown in Fig. 6b (P < 0.01 at 2 or 5 ng/mL, P < 0.001 at 10 ng/mL of IL-13 when compared with normally differentiated cells at each time-point).

ST2 protein expression

Western blot analysis of cell lysates showed that the ST2L was expressed more in goblet cells than in normally differentiated cells, while the sST2 was similar in these cell types (Fig. 6c). Immunostaining showed that the apical side surface of goblet cells strongly stained with ST2 compared to normally differentiated cells (Fig. 6d).

Effects of anti-ST2/IL-1 R4 antibody on IL-33-stimulated CXCL8/IL-8 secretion

Pretreatment with anti-ST2R antibody (20 μ g/mL) at the apical side of goblet cells attenuated IL-33-stimulated CXCL8/IL-8 secretion compared with PBS (Fig. 7b; P < 0.02). Pretreatment with a normal goat polyclonal IgG control antibody at the apical side did not affect CXCL8/IL-8 secretion from goblet cells (data not shown). The 50% neutralization dose (ND₅₀) with the anti-ST2/IL-1 R antibody is typically 3–10 μ g/mL.

Discussion

Because CXCL8/IL-8 is increased in more severe asthma, we hypothesized that, similar to the IL-13 data, IL-33 would drive cultured NHBE cells towards goblet cell differentiation and stimulate CXCL8/IL-8 production in these goblet cells by activating the ST2R pathway. IL-13-exposed cells were transformed to highly enriched goblet cells with MUC5AC protein covering the apical surface but cilia were not seen and that cilia, but not mucin, were seen in the cells without exposure to IL-13. Although NHBE cells in the presence of IL-33 did not differentiate into goblet cells, exposure to IL-33 significantly increased CXCL8/IL-8 mRNA expression and apical CXCL8/IL-8 release from goblet cells, but not from normally differentiated ciliated cells.

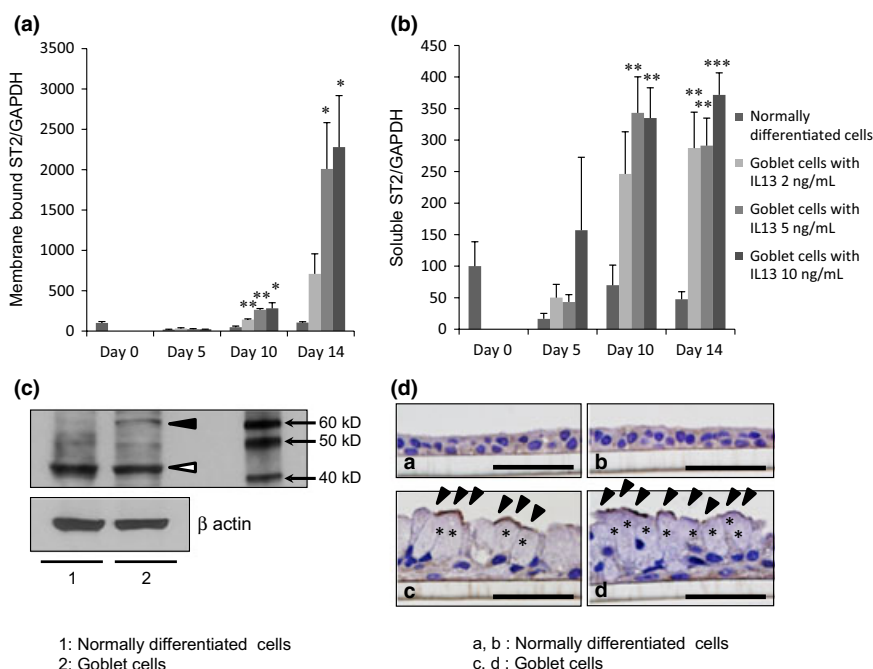


Fig. 6. The (a) membrane-bound ST2 (ST2L) and (b) soluble ST2 (sST2) mRNA expression was increased in goblet cells with IL-13. (a) ST2L or (b) sST2 mRNA expression in cell lysates grown with basolateral exposure to IL-13 (0, 2, 5 or 10 ng/mL), for 0, 5, 10 or 14 days. The results are the mean $\pm$ SEM from 4 samples. Significant differences from PBS vehicle at each date are indicated by * $P < 0.02$, ** $P < 0.01$, *** $P < 0.001$. (c) ST2 was increased in goblet cells. NHBE cells were differentiated to goblet cells IL-13 at 5 ng/mL and the cell lysates were harvested on day 14. Representative Western blots of three separate experiments for ST2. β -Actin was used as an internal housekeeping control. The white arrowhead identifies the sST2, and the black arrowhead, the ST2L. (d) Representative figures with ST2 immunohistochemical staining of (a, b) normally differentiated cells with IL-13 vehicle (PBS) or (c, d) goblet cells with 5 ng/mL IL-13 at an ALI. The asterisks indicated mucous granules and the black arrowheads identified strong staining with anti-ST2 antibody, suggesting the strong expression with ST2L on the apical side surface of goblet cells. Bar = 50 μ m.

IL-33 is involved in the pathogenesis of allergic diseases, such as asthma [32], allergy [33] and atopic dermatitis [34]. IL-33 increases the production of Th2 cytokines from hematopoietic cells that express ST2 [14, 35–39]. It has been reported that ST2 is preferentially expressed in NHBE cells and IL-33 induces CXCL8/IL-8 production via ST2 [28]. There is an increased expression of IL-33 and ST2 in the nasal epithelial cells of patients with allergic rhinitis, and IL-33 promoted the production of CXCL8/IL-8 and GM-CSF via ST2 [40]. A genome-wide association study suggested that polymorphic variation in ST2 is associated with asthma severity [41]. We show here that IL-13 induced ST2 mRNA and ST2L protein expression on the apical side surface of goblet cells and that anti-ST2R antibody attenuated IL-33-induced apical CXCL8/IL-8 secretion from these goblet cells. These findings further support the relevance of the IL-33/ST2 pathway in the asthmatic airway.

ST2 is produced as two isoforms. The membrane-bound isoform (ST2L) induces an immune response when bound to its ligand, IL-33. The other isoform is a soluble protein (sST2) that is thought to be a decoy

receptor for IL-33 signalling [42]. We surmise that sST2 can be a negative feedback system in IL-33-induced neutrophil inflammation on asthmatic airway.

Binding of IL-33 to ST2 activates NF- κ B and MAPKs, including ERK1/2, p38 MAPK and JNK, and induces Th2 cytokine expression [14, 34]. It was reported that IL-33 increases ERK phosphorylation in NHBE cells [28] and human nasal epithelial cells [40]. In contrast with these reports, we show that IL-33 mediated the production of CXCL8/IL-8 from goblet cells, but not normally differentiated ciliated cells, and this is significantly attenuated by an ERK inhibitor or ST2 neutralization.

The exogenous administration of recombinant IL-33 to mice [14, 25, 32, 43] or the transgenic overexpression of IL-33 in mice [44] suggests that increased expression of IL-33 *in vivo* can increase the number of inflammatory cells in the airway through the release of endogenous Th2 cytokines and chemokines and administering anti-IL-33 attenuates cytokine secretion and eosinophilic recruitment [45]. IL-33-deficient mice are resistant to allergen-induced bronchial hyperresponsiveness [46]. Both administration [25] and transgenic overexpression [44] of IL-33 in mice increases the number

of airway neutrophils and eosinophils, but neutrophils are not directly IL-33 responsive because they have few ST2 receptors [28].

Goblet cell metaplasia and mucus plugging are common in patients with severe asthma. These patients also show neutrophil recruitment into the airways [47–49]. Our results suggest that basolateral-secreted CXCL8/IL-8 from bronchial cells may induce neutrophil migration to subepithelial connective tissue from submucosal blood vessels and these neutrophils may then migrate to the airway surface along a CXCL8/IL-8 concentration gradient from the basolateral side to apical side of bronchial epithelium. We surmise that IL-33 can promote neutrophil infiltration into the airway through IL-33-induced release of neutrophil chemoattractants, including CXCL8/IL-8 primarily from goblet cells. This may be one mechanism that prolongs neutrophil inflammation in the asthmatic airway.

Glucocorticosteroids are highly effective in controlling mild to moderate asthma [50]. Inhaled corticosteroids decrease IL-13 mRNA expression in steroid-sensitive asthmatics, but not in steroid-resistant asthmatics [51]. Corticosteroids are less effective in suppressing IL-13-induced goblet cell metaplasia in animal models of asthma [52]. We have shown that dexamethasone does not inhibit goblet cell differentiation by IL-13, suggesting a possible mechanism of steroid resistant in severe asthma [13]. It has been suggested that because IL-33-mediated inflammation is also corticosteroid resistant, this may be another mechanism for steroid resistance in severe asthma [28]. Dexamethasone does not affect TNF- α -induced IL-33 produced by cultures of human airway smooth muscle cells [18], further supporting that IL-33-mediated inflammation is important in the pathogenesis of steroid-resistant asthma.

IL-33 and sST2 levels in induced sputum and serum are significantly higher in asthma compared with healthy subjects [53]. IL-33 promotes airway remodeling in asthma airways that is resistant to high-dose steroid therapy and IL-33 is a less steroid sensitive than IL-13 in subjects with severe asthma [54].

There are several possible explanations for why the culture system we use creates a more enriched goblet cell phenotype compared to other studies [30, 55–57]. First, while other studies calculate the number of goblet cell nuclei to total cell nuclei [30, 56, 57], we calculated the MUC5AC-positive staining area to the total area from confocal images. In addition, the NHBE cell culture system with IL-13 that we developed differs in several ways including our use of different culture media and supplements [8, 12, 13]. For example, we use higher concentration of retinoic acid (RA) and epidermal growth factor (EGF) than used in the studies [30, 56] where the goblet cell number was in the range of 20–40%. Other studies [55, 57] used 2% UltroSer G

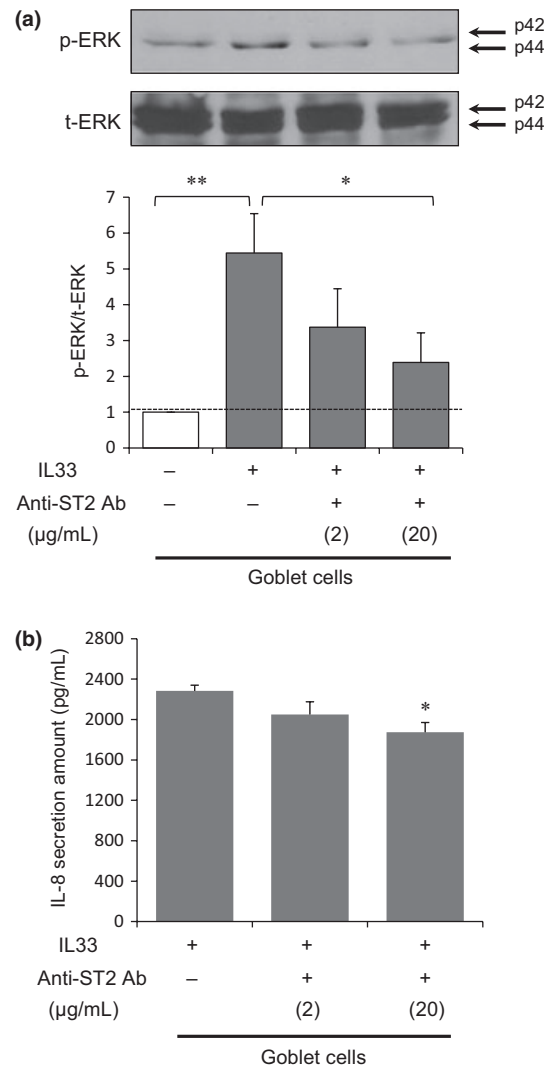


Fig. 7. (a) Goblet cells were differentiated with 5 ng/mL IL-13 for 14 days at an ALL. The cells were then grown without IL-13 and supplements for 48 h before IL-33 stimulation to avoid the influence of IL-13 and growth factors on cell signalling. Cell lysates were harvested on day 16 after 120-min apical exposure to 5 ng/mL IL-33 or PBS after 2-h pretreatment with anti-ST2R antibody (0, 2 or 20 μg/mL). Western blot data are expressed as the ratio of p-ERK to t-ERK. The results are the means $\pm$ SEM from 4 samples. Significant differences are indicated by * P < 0.05, ** P < 0.01. (b) Goblet cells in culture were apically pretreated with anti-ST2R antibody (0, 2 or 20 μg/mL) before apical exposure to 5 ng/mL IL-33 for 24 h on day 14. The results are the mean $\pm$ SEM from five samples. Significant differences from anti-ST2 antibody vehicle (PBS) are indicated by * P < 0.02.

serum substitute (Pall Bio Septra, Cergy Saint Christophe, France) instead of RA, EGF and growth factors. The concentration of EGF can affect MUC5AC expression [58], and the concentration of RA affects differentiation of NHBE cells under stimulation by IL-13 [59]. Finally others performed cultures using IL-13 at 10 [57], 20 [30] or 25 ng/mL [56] and for 48 h [56], 5 days [55],

7 days [57] or 28 days [30] while we have demonstrated that in our cultures, the greatest goblet cell enrichment occurs at 14 days and with 5 ng/mL IL-13. None of these differences stands out as an explanation for why our culture conditions lead to such a highly enriched goblet cell phenotype but the results are consistent in our laboratory for over 5 years [8, 12, 13].

This study showed that IL-33 acts directly on goblet cells to stimulate CXCL8/IL-8 production. This may be a mechanism contributing to the mucus hypersecretion and neutrophil inflammation in the airways of persons with severe asthma [60, 61].

Acknowledgements

We thank the Department of Allergy and Immunology, National Research Institute for Child Health and Development, Akio Matsuda, PhD, for advice regarding design with PCR primers and the Anatomic Pathology Research Services at Virginia Commonwealth University (VCU) Medical Center, Jorge A. Almenara, PhD, and histotechnologists for technical assistance in tissue processing, sectioning and staining. Microscopy was performed at the VCU Department of Anatomy and

Neurobiology Microscopy Facility, supported, in part, with funding from the NIH-NINDS Center Core Grant (5P30NS047463). Also, we thank Melissa A. Yopp, Jennifer L. Bradley and Frances K. A. White for technical assistance and Erika Tokita, MD, PhD, for helpful discussions. This research was funded in part by a grant from the Denny Hamlin Foundation.

Conflict of interests

The authors declare no conflict of interest.

Author contributions

Dr. Tanabe is the principal investigator and guarantor of this manuscript. He contributed to the study design, conducting the experiments, data analysis and preparing the draft of the manuscript and figures. Dr. Shimokawaji contributed to the data analysis and the performance of the study. Dr. Kanoh contributed to data collection and revising of the manuscript. Dr. Rubin contributed to the study concept and design, analysis of the results and editing of the manuscript for publication.

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