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Contrasting roles for the receptor for advanced glycation end-products on structural cells in allergic airway inflammation vs. airway hyperresponsiveness

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Submitted 24 March 2015; accepted in final form 17 August 2015

Taniguchi A, Miyahara N, Waseda K, Kurimoto E, Fujii U, Tanimoto Y, Kataoka M, Yamamoto Y, Gelfand EW, Yamamoto H, Tanimoto M, Kanehiro A. Contrasting roles for the receptor for advanced glycation end-products on structural cells in allergic airway inflammation vs. airway hyperresponsiveness. *Am J Physiol Lung Cell Mol Physiol* 309: L789–L800, 2015. First published August 21, 2015; doi:10.1152/ajplung.00087.2015.—The receptor for advanced glycation end-products (RAGE) is a multiligand receptor that belongs to the immunoglobulin superfamily. RAGE is reported to be involved in various inflammatory disorders; however, studies that address the role of RAGE in allergic airway disease are inconclusive. RAGE-sufficient (RAGE+/+) and RAGE-deficient (RAGE–/–) mice were sensitized to ovalbumin, and airway responses were monitored after ovalbumin challenge. RAGE–/– mice showed reduced eosinophilic inflammation and goblet cell metaplasia, lower T helper type 2 (Th2) cytokine production from spleen and peribronchial lymph node mononuclear cells, and lower numbers of group 2 innate lymphoid cells in the lung compared with RAGE+/+ mice following sensitization and challenge. Experiments using irradiated, chimeric mice showed that the mice expressing RAGE on radio-resistant structural cells but not hematopoietic cells developed allergic airway inflammation; however, the mice expressing RAGE on hematopoietic cells but not structural cells showed reduced airway inflammation. In contrast, absence of RAGE expression on structural cells enhanced innate airway hyperresponsiveness (AHR). In the absence of RAGE, increased interleukin (IL)-33 levels in the lung were detected, and blockade of IL-33 receptor ST2 suppressed innate AHR in RAGE–/– mice. These data identify the importance of RAGE expressed on lung structural cells in the development of allergic airway inflammation, T helper type 2 cell activation, and group 2 innate lymphoid cell accumulation in the airways. RAGE on lung structural cells also regulated innate AHR, likely through the IL-33-ST2 pathway. Thus manipulating RAGE represents a novel therapeutic target in controlling allergic airway responses.

RAGE; allergic airway inflammation; airway hyperresponsiveness; asthma

ALLERGIC ASTHMA IS CHARACTERIZED by inflammatory airway obstruction and airway hyperresponsiveness (AHR) (4, 7). Airway inflammation in allergic asthma is associated with mucous membrane swelling and infiltration of cells, including eosinophils, T lymphocytes, and mast cells (4, 31). The progressive inflammation leads to airway fibrosis, hypertrophy of smooth muscle cells, bronchial wall thickening, increased mucous-producing goblet cells, and obstruction of the airways (3, 12, 23). Allergen-specific memory T helper type 2 (Th2) cells are thought to play a central role in the development of these responses (32). Recently, group 2 innate lymphoid cells (ILC2s), newly identified innate immune cells with the ability to release Th2 cytokines (formerly termed natural helper cells), have been reported to induce and enhance Th2 allergic inflammation (8, 13, 32).

The receptor for advanced glycation end-products (RAGE) is a multiligand receptor that belongs to the immunoglobulin superfamily and recognizes a variety of ligands, including high-mobility group box 1 (HMGB-1), S100 family of proteins, advanced glycation end-products (AGE), β -sheet fibrillar materials, and prions (10, 33, 37). The receptor is expressed as a single-chain transmembrane receptor on epithelial, neuronal, vascular, and inflammatory cells, usually at low levels under homeostatic conditions. In contrast, especially in the lung, high basal levels of RAGE expression have been identified relative to expression in other tissues (10, 26, 33, 34, 37).

AGE and RAGE were initially reported to be involved in microvascular and macrovascular complications of diabetes mellitus, renal failure, and peritoneal injury in long-term peritoneal dialysis patients (17, 30, 36). Recently, RAGE was implicated in the pathogenesis and progression of various chronic immune/inflammatory disorders (10, 33, 34). The RAGE/HMGB-1 pathway has also been reported to play an important role in acute lung injury (45) and fibrosing lung disease (15). Recently, serum levels of soluble RAGE, soluble

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forms of membrane RAGE, were shown to be decreased in patients with asthma (38). Using mouse models of allergen-induced airway disease, Milutinovic et al. (27) demonstrated that allergen-induced airway inflammation in RAGE^{-/-} mice was attenuated compared with wild-type mice; however, the mechanisms defining how RAGE mediated these responses were not defined.

In the present study, we investigated the role of RAGE in a model of allergen-induced disease using RAGE-deficient (RAGE^{-/-}) mice. RAGE^{-/-} mice showed decreased airway inflammation, reduced Th2 cytokine production, and accumulation of ILC2 compared with RAGE-sufficient (RAGE^{+/+}) mice. Experiments using chimeric mice revealed a requirement for RAGE expression on structural cells for development of allergic airway inflammation. In contrast, absence of RAGE on structural cells enhanced innate AHR. Thus manipulating RAGE on structural cells may be beneficial for controlling asthmatic responses.

MATERIALS AND METHODS

Animals. RAGE^{-/-} mice were generated as described (30). Briefly, RAGE mutant mice were originally created using E14.1 ES cells (129 background). After the bone marrow chimeric mice were generated, they were crossbred with Cre-transgenic mice (CD-1 background) that transiently express Cre recombinase in eggs. The resultant RAGE^{-/-} mice were then backcrossed to C57BL/6J (Charles River, Yokohama, Japan) for nine generations. Ten-week-old female RAGE^{-/-} mice and their littermates (RAGE^{+/+} mice) were used in all experiments. RAGE^{-/-} mice were viable and displayed normal reproductive fitness without a striking phenotype. When housed under specific pathogen-free conditions, no spontaneous disease development was observed in the RAGE^{-/-} mice for up to 6 mo of age.

All experiments were performed in accordance with the National Institutes of Health (NIH) guidelines. All procedures were conducted under a protocol approved by the Institutional Animal Care and Use Committee of Okayama University (Okayama, Japan).

Experimental protocol (sensitization and airway challenge). RAGE^{+/+} and RAGE^{-/-} mice were sensitized with 20 μ g of ovalbumin (OVA) (Grade V; Sigma Chemical, St. Louis, MO) emulsified in 2.25 mg of alum (ImjectAlum; Pierce, Rockford, IL) by intraperitoneal injection on days 0 and 14. Mice were subsequently challenged by inhalation exposure to aerosols with OVA (1% in saline) via the airways using ultrasonic nebulizer for 20 min on days 28, 29, and 30. Forty-eight hours after the last challenge, AHR was measured as described below, followed by collection of samples for further analyses (16).

Determination of airway responsiveness. Airway responsiveness was assessed by measuring changes in lung resistance in response to increasing doses of inhaled methacholine (MCh) (41) using a flex-iVent small-animal ventilator (SCIREQ, Montreal, PQ, Canada). Before testing, mice were anesthetized by intraperitoneal injection of pentobarbital (80 mg/kg), tracheostomized, and mechanically ventilated. There were no significant differences in baseline values among the different groups.

Bronchoalveolar lavage. Immediately after assessment of airway function, lungs were lavaged via the tracheal tube with Hanks' balanced salt solution (2 $\times$ 1 ml, 37°C). The volume of the collected bronchoalveolar lavage (BAL) fluid was measured in each sample, and the number of cells in BAL fluid was counted. Cytospin slides were stained with May-Giemsa and differentiated in a blinded fashion by counting at least 200 cells under light microscopy.

Lung histology. Lungs were fixed in 10% formalin and cut around the main bronchus and embedded in paraffin blocks. The slides were stained with hematoxylin-eosin (HE) and periodic acid Schiff (PAS)

for identification of mucus-containing cells and were examined under light microscopy. In HE-stained lung sections, the numbers of inflammatory cells per square millimeter in the peribronchial and perivascular tissue were analyzed using the NIH Image Analysis system for quantitative evaluation. More than 10 bronchioles in a minimum of 10 high-power fields per lung were randomly examined in a blinded fashion. The numbers of mucus-containing cells (goblet cells) were counted in more than 8 bronchioles in 10 high-power fields per animal by measuring the length of epithelium defined along the basement membrane and luminal area using the NIH Image Analysis system (11, 20).

Culture of mononuclear cells from spleen and peribronchial lymph nodes. Spleens of OVA-sensitized and challenged mice were removed and placed in PBS (11). Cells were dispersed, and mononuclear cells (MNCs) were separated by a density gradient cell centrifugation using Histopaque (Sigma-Aldrich, St. Louis, MO). Cells were washed, counted, and resuspended to a fixed concentration in RPMI-1640 (Wako Pure Chemical Industries, Osaka, Japan) containing heat-inactivated 10% FCS and penicillin/streptomycin. Peribronchial lymph nodes (PBLNs) were similarly manipulated. Cells (4×10^5) were plated in each well of 96-well round-bottom plates and cultured at 37°C in a 5% CO₂ atmosphere in the presence or absence of 10 μ g/ml OVA. Forty-eight hours after the last challenge, the supernatants were removed, and cytokine levels were analyzed by ELISA as described below.

Measurement of cytokines and chemokines. Cytokine levels in the BAL fluid were measured by ELISA. All cytokines and chemokines ELISAs were performed according to the manufacturer's directions. The limits of detection were 1 ng/ml for HMGB-1, 7 pg/ml for interleukin (IL)-5, 1.5 pg/ml for IL-13, 3 pg/ml for IL-1 β , 2 pg/ml for KC, 1.5 pg/ml for macrophage inflammatory protein-2, 2.8 pg/ml for IL-33, 0.71 pg/ml for thymic stromal lymphopoietin (TSLP), and 15 pg/ml for IL-25. All kits, except for IL-25 (BioLegend, San Diego, CA) and HMGB-1 (Shino-Test, Sagami-hara, Japan), were from R&D Systems (Minneapolis, MN). Lung homogenates were prepared as described (22).

Lung cell isolation. Lungs of OVA-sensitized and challenged mice were separated from the associated lymph nodes, removed, and placed in PBS containing heat-inactivated 10% FCS. Lung tissue was minced and incubated for 1 h at 37°C in 5 ml PBS containing 0.05% collagenase I (Sigma-Aldrich), and then lung tissue was dispersed by passing through a 20-G needle several times, and the suspensions were strained through a cell strainer. The pulmonary MNCs were isolated by density gradient cell centrifugation over Histopaque (Sigma-Aldrich) (22).

Flow cytometry. Cells were incubated with peridinin chlorophyll protein or antigen-presenting cell (APC)-conjugated anti-CD3, phycoerythrin-conjugated anti-CD8, and FITC-conjugated anti-CD4 antibodies (BD Biosciences, San Diego, CA) and then analyzed by flow cytometry on MACSQuant Analyzers (Miltenyi Biotec, Bergisch Gladbach, Germany).

Intracellular cytokine staining. Lung MNCs were stimulated for 5 h with phorbol 12-myristate 13-acetate (10 ng/ml) and ionomycin (500 μ g/ml) in the presence of brefeldin A (10 μ g/ml). After washing, cells were stained for cell surface markers with monoclonal antibodies (MAbs) against CD3 (145-2C11, hamster IgG), CD4 (RM4-5, rat IgG2a), and CD8 (53-6.7, rat IgG2a). All fluorochrome-labeled MAbs were purchased from BD Biosciences. After fixation and permeabilization, cells were stained with PE- or FITC-conjugated anti-cytokine antibodies purchased from BD Biosciences. Staining was monitored by flow cytometry on MACSQuant Analyzers. The number of cytokine-producing CD4 or CD8 T cells per lung was calculated from the percentage of cytokine-producing cells and the number of CD4 or CD8 T cells isolated from the lung.

Analyses of ILC2s. The cells isolated from digested lungs were stained with biotin-conjugated antibody mixtures for lineage markers (CD4, CD5, CD8, CD11c, CD11b, CD19, NK1.1, Gr-1, TER119,

FcεRI, and B220), Pacific blue-conjugated anti-Sca-1, PECy7-conjugated c-Kit (CD117), APC-conjugated anti-IL-7Rα (CD127), FITC-conjugated anti-T1/ST2, APC-Cy7-conjugated anti-CD25, and PE-conjugated anti-streptavidin, and analyzed using MACSQuant Analyzer. Lin⁺Sca⁺c-Kit⁺IL-7Rα⁺CD25⁺ST2^{dim} cells were identified as lung ILC2s (18). The data were analyzed by FlowJo (TreeStar, Ashland, OR). APC-Cy7-conjugated anti-CD25; Pacific blue-conjugated anti-Sca-1; biotin-conjugated anti-CD4, anti-CD5, anti-CD8, anti-CD11b, anti-NK1.1, anti-Gr-1, anti-TER119, and anti-B220; and PE-conjugated anti-streptavidin were obtained from BD Biosciences. FITC-conjugated anti-T1/ST2 was from MD Bioscience (St Paul, MN). APC-conjugated anti-IL-7Rα and biotin-conjugated anti-FcεRI were from BioLegend (San Diego, CA). PECy7-conjugated c-Kit was from eBioscience (La Jolla, CA). Biotin-conjugated anti-CD11c and anti-CD19 were from TONBO Biosciences (San Diego, CA).

Immunohistochemistry. Paraffin sections (5 μm thick) were cut and mounted on poly-L-lysine-coated glass slides. After the paraffin was removed, endogenous peroxidases were quenched with 3% H₂O₂ in methanol. After washing, sections were incubated with rat anti-RAGE or isotype-matched control MAb (R&D Systems) and incubated for another 20 min with Histofine Simple Stain MAX-PO (Nichirei Biosciences, Tokyo, Japan). The sections were immersed in diaminobenzidine as a chromogen for 2 min, counterstained with hematoxylin, and mounted under coverslips.

Generation of bone marrow chimeras. Femurs and tibias were obtained from 8- to 12-wk-old RAGE^{+/+} and RAGE^{-/-} donor mice, and bone marrow cells were harvested as previously described (42). Seven- to ten-week-old RAGE^{+/+} and RAGE^{-/-} recipient mice, respectively, received 12 Gy total body irradiation on day -56. After total body irradiation, 8 × 10⁶ bone marrow-derived cells from donor mice were injected intravenously into recipients on the same day.

For assessment of bone marrow cell homing and differentiation, transplantation with the same method using CD45.1⁺ donor mice and CD45.2⁺ recipient mice was performed. The spleen MNCs, cells of PBLNs, and alveolar macrophages from BAL fluid were obtained. The degree of chimerism of B220⁺ B cells, CD11c⁺ dendritic cells (DCs), lung ILC2s, and CD11b⁺ alveolar macrophages, known to be slowly repopulated following irradiation, was confirmed by staining of CD45.1 or CD45.2. Spleen MNCs, PBLN MNC, and alveolar macrophages from BAL fluid were obtained and stained with APC-labeled anti-CD11b, anti-CD11c, anti-B220, FITC-labeled anti-CD45.1, and PE-labeled anti-CD45.2 antibodies (BD Biosciences) and analyzed by flow cytometry.

Total RNA isolation and quantitative real-time PCR. The left lung was homogenized, and total RNA was extracted using TRIzol reagent (Invitrogen, Carlsbad, CA) and treated with DNase (Qiagen, Valencia, CA), according to the manufacturers' instructions. Reverse transcription was performed using oligo(dT) primers and the Invitrogen Superscript II Reverse Transcriptase (Life Technologies, Grand Island, NY) to obtain cDNA for PCR. Quantitative real-time PCR was performed in a 25-μl reaction using SYBR Green master mix (Applied Biosystems, Foster City, LA) and the StepOnePlus Real-Time PCR system (Applied Biosystems). Primers sequences were as follows: RAGE, forward, 5'-ACTACCGAGTCCGAGTCTACC-3, and reverse, 5'-GTAGCTTCCCTCAGACACACA-3; granulocyte-macrophage colony-stimulating factor (GM-CSF), forward, 5'-GCGCCTTGAACATGACAGC-3, and reverse, 5'-GGCTGTCTATGAAATCCGC-3; GAPDH, forward, 5'-TATGTCTGGAGTCTACTGGT-3, and reverse, 5'-GAGTTGTCATATTTCTCGTGG-3. Relative expression levels for each target were normalized to GAPDH and calculated using the ΔΔ cycle threshold method. There were no changes in GAPDH expression among groups.

Generation of bone marrow-derived DCs. Bone marrow cells obtained from femurs and tibias of RAGE^{+/+} or RAGE^{-/-} mice were cultured and pulsed with recombinant mouse GM-CSF (10 ng/ml; R&D Systems) and recombinant mouse IL-4 (10 ng/ml; R&D

Systems) on days 1 and 5. On day 8, cells were pulsed with OVA (200 μg/ml, grade V; Sigma-Aldrich) for 24 h and washed three times with PBS. More than 90% of the cells were determined to be myeloid DCs (CD11c⁺, CD11b⁺, Gr-1⁻) (28).

Transfer of bone marrow-derived DCs. Under anesthesia, 1 × 10⁶ OVA-pulsed bone marrow-derived DCs (BMDCs) in 40 μl of PBS were instilled into naive RAGE^{+/+} through the trachea under fiber-optic illumination (28). Control groups of mice received OVA-nonpulsed BMDCs. Ten days after BMDC transfer, mice were exposed to aerosolized OVA (1% in saline) for 20 min/day for 3 consecutive days; 48 h after the last challenge, AHR was assessed and BAL fluid was obtained.

Blockage of IL-33 receptor ST2. Rat anti-mouse ST2/IL-1 R4 (anti-ST2) MAb (40 μg; R&D Systems) or isotype-matched control antibody (R&D Systems) in 40 μl of PBS was administered intratracheally to RAGE^{+/+} or RAGE^{-/-} mice under anesthesia, and, 12 h later, AHR was measured.

Statistical analysis. All results were expressed as the means ± SE. ANOVA was used to determine the levels of difference between all groups. Pairs of groups of samples distributed parametrically were compared by unpaired two-tailed Student *t*-test, and those samples distributed nonparametrically were compared by Mann-Whitney *U*-test. Significance was assumed at *P* values of <0.05.

RESULTS

Allergic inflammation in the airways is decreased in RAGE^{-/-} mice. Numbers of inflammatory cells in BAL fluid were assessed 48 h after the last OVA challenge in RAGE^{+/+} and RAGE^{-/-} mice. In sensitized and challenged (OVA/OVA) mice, total cells, lymphocytes, and eosinophils were significantly increased compared with nonsensitized but challenged (PBS/OVA) mice. However, numbers of eosinophils were significantly lower in the BAL fluid of RAGE^{-/-} mice compared with RAGE^{+/+} mice (Fig. 1A).

Inflammatory cell infiltration of the lungs was further investigated by histological examination. In HE-stained lung sections from RAGE^{-/-} mice, lower numbers of inflammatory cells were detected following sensitization and challenge (Fig. 1, B and C). The numbers of PAS-positive goblet cells were also significantly lower in RAGE^{-/-} mice compared with RAGE^{+/+} mice following sensitization and challenge with OVA (Fig. 1, D and E).

Cytokine levels in the airways. We measured cytokine levels in the BAL fluid by ELISA. OVA sensitization and challenge resulted in significant increases in IL-4, IL-5, and IL-13 levels in RAGE^{+/+} mice. In contrast, RAGE^{-/-} mice showed significantly lower levels of IL-4, IL-5, and IL-13 following sensitization and challenge (Fig. 2A). The levels of KC, macrophage inflammatory protein-2, and IL-1β were also lower in RAGE^{-/-} mice compared with RAGE^{+/+} mice (Fig. 2B).

Spleen and PBLN MNCs from RAGE^{-/-} mice release lower levels of Th2 cytokines. To determine whether the attenuated Th2 cytokine secretion observed in vivo in RAGE^{-/-} mice was due to impaired Th2 cytokine production, we assessed cytokine production in spleen and PBLN MNCs in vitro. The levels of IL-5 and IL-13 from OVA-restimulated spleen MNCs of RAGE^{-/-} mice were significantly lower compared with those of RAGE^{+/+} mice (Fig. 2C). There were no significant differences in IL-17 and IFN-γ levels in the two strains of mice (data not shown). IL-5 and IL-13 levels from the PBLN MNCs were lower in RAGE^{-/-} mice compared with RAGE^{+/+} mice (Fig. 2D). These data

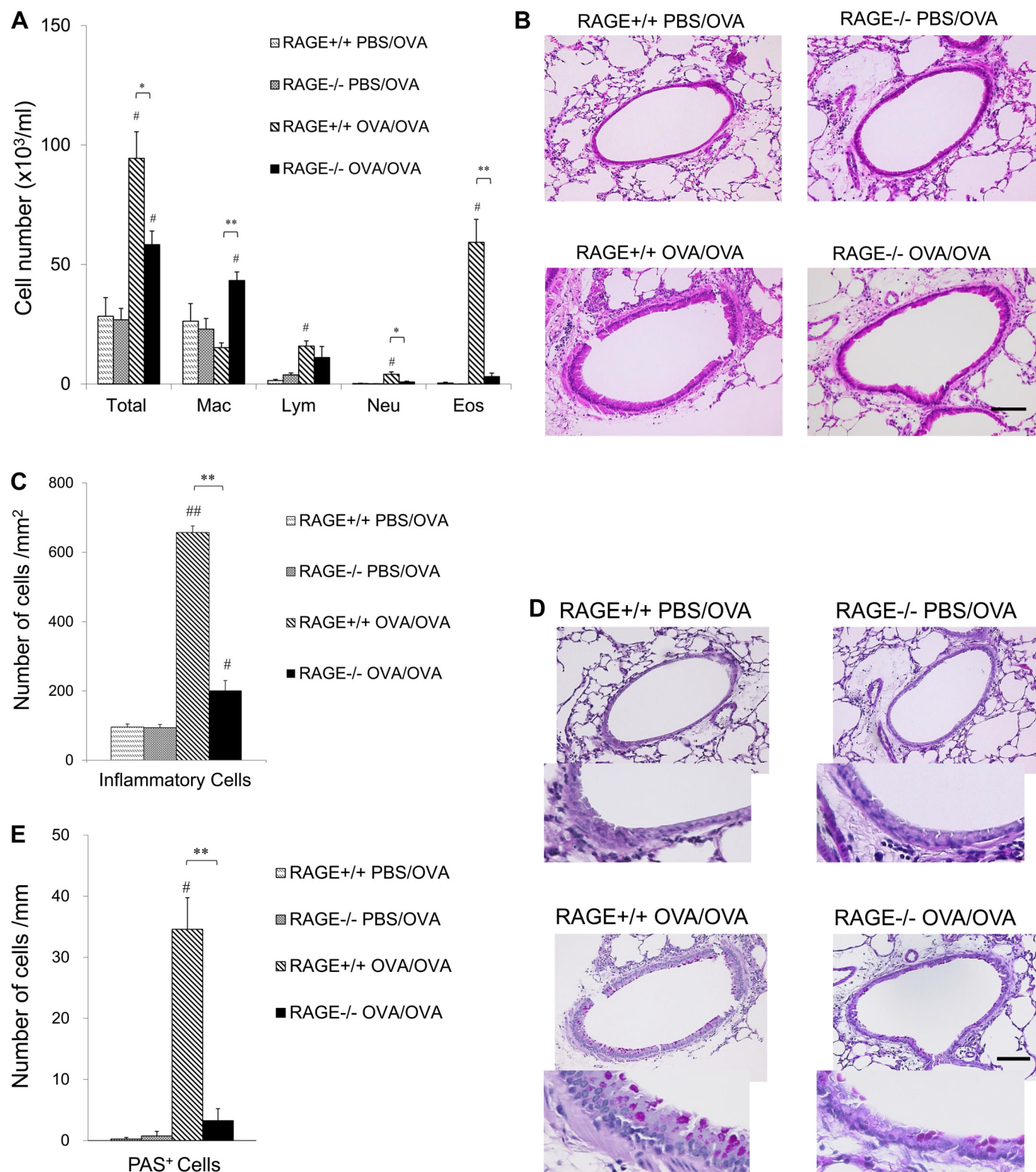


Fig. 1. Receptor for advanced glycation end-products (RAGE)^{-/-} mice develop reduced airway inflammation following sensitization and challenge. **A**: cellular composition in bronchoalveolar lavage (BAL) fluid. Values are means $\pm$ SE ($n = 8-9$ in each group). Significant differences ($*P < 0.05$; $**P < 0.01$) between RAGE+/+ and RAGE-/- mice. # $P < 0.01$ compared with challenged-only mice. **B**: hematoxylin and eosin-stained lung sections. Scale bar: 100 μm . **C**: inflammatory cell numbers in the peribronchial and perivascular tissue ($n = 4$ in each group). Significant differences ($*P < 0.05$; $**P < 0.01$) between RAGE+/+ and RAGE-/- mice. # $P < 0.05$ and ## $P < 0.01$ compared with challenged-only mice. **D**: development of goblet cell metaplasia in the airways of RAGE+/+ and RAGE-/- mice. Scale bar: 100 μm . **E**: goblet cell metaplasia was quantified in periodic acid Schiff (PAS)-stained sections, as described in MATERIALS AND METHODS. Significant differences ($**P < 0.01$) between RAGE+/+ and RAGE-/- mice. # $P < 0.01$ compared with challenged-only mice. OVA, ovalbumin; Mac, macrophage; Lym, lymphocyte; Neu, neutrophil; Eos, eosinophil.

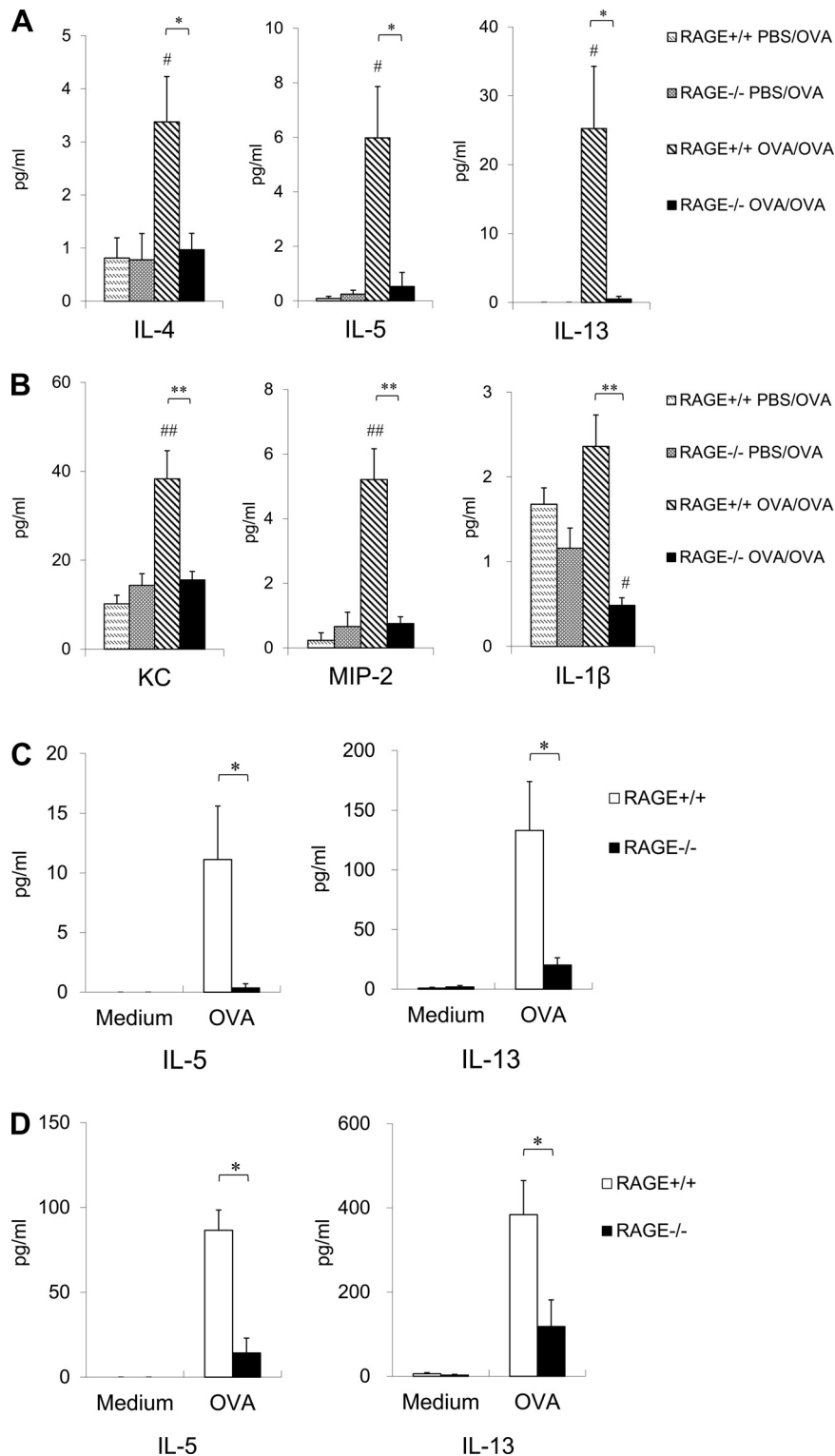


Fig. 2. Cytokine levels and numbers of cytokine-producing cells in the airways and T helper type 2 (Th2) cytokine production from spleen and peribronchial lymph node (PBLN) mononuclear cells. Th2 cytokine levels [interleukin (IL)-4, IL-5 and IL-13; A] and Neu-related chemokines [KC and macrophage inflammatory protein-2 (MIP-2)] and IL-1 β (B) in BAL fluid were measured by ELISA, as described in MATERIALS AND METHODS. The results for each group are expressed as means $\pm$ SE ($n = 6-8$ in each group). C: IL-5 and IL-13 levels in supernatants from spleen cultured in the presence or absence of OVA (10 mg/ml) determined by ELISA ($n = 7-8$ in each group). D: IL-5 and IL-13 levels in supernatants from PBLNs cultured in the presence or absence of OVA ($n = 4$ in each group). Values are means $\pm$ SE. Significant differences (* $P < 0.05$; ** $P < 0.01$) between RAGE+/+ and RAGE-/- mice. # $P < 0.05$ and ## $P < 0.01$ compared with challenged-only mice.

suggest that RAGE contributes to not only systemic sensitization of Th2 cells, but also activation of Th2 cells in the airways.

Numbers of Th2 cells in the lungs. To determine whether the accumulation of T cells in the airways of sensitized and challenged mice was affected by expression of RAGE, we assessed the numbers of T cells and cytokine-producing T cells in the lungs. There were no differences between the two strains

of mice in numbers of CD3⁺, CD4⁺, and CD8⁺ T cells (data not shown). The numbers of CD4⁺IL-13⁺ cells and CD4⁺IL-5⁺ cells in the lungs were not lower in RAGE-/- mice, despite the lower levels of IL-5 and IL-13 in BAL fluid from sensitized and challenged RAGE-/- mice (Fig. 3A). There were also no significant differences in IL-17⁺ and IFN- γ ⁺ cells in the two strains of mice (data not shown).

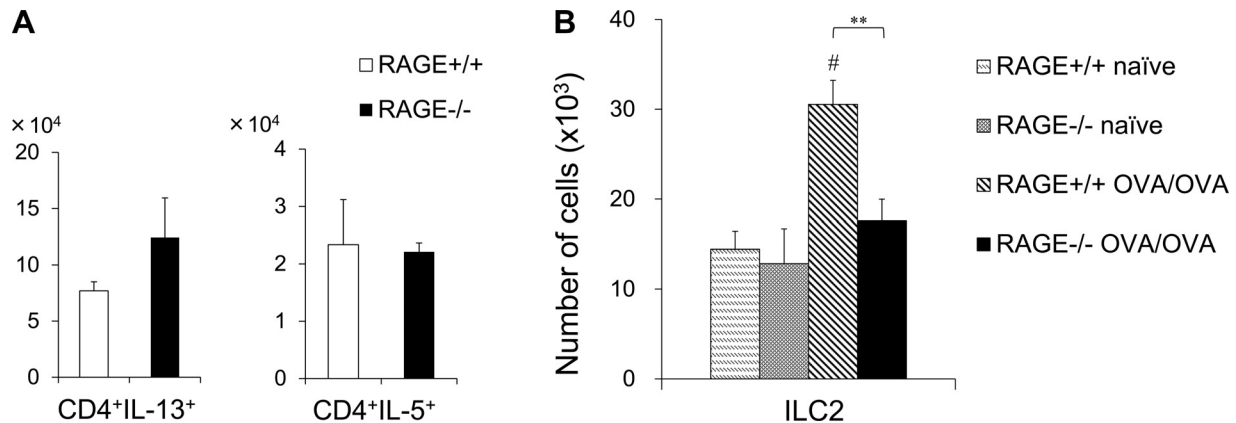


Fig. 3. Numbers of T cells and group 2 innate lymphoid cells (ILC2s) in the lung following sensitization and challenge. **A**: numbers of IL-13- and IL-5-producing CD4⁺ T cells in the lung after sensitization and challenge. Numbers of cells in the lung were determined as described in MATERIALS AND METHODS. There were no significant differences between RAGE+/+ and RAGE-/- mice. **B**: numbers of ILC2 in the lungs of RAGE+/+ and RAGE-/- mice following sensitization and challenge. Values are means $\pm$ SE ($n = 7$ in each group). $^{\#}P < 0.01$ compared with challenged-only mice. $^{**}P < 0.01$.

The numbers of ILC2s in the lungs of RAGE-/- mice were lower compared with RAGE+/+ mice following sensitization and challenge. Recently, ILC2s have been reported to contribute to allergic airway inflammation independent of Th2-cell-mediated immunity (8, 14, 24). We assessed numbers of ILC2s in the airways of RAGE+/+ and RAGE-/- mice following sensitization and challenge with OVA. Interestingly, the numbers of ILC2s in the lungs of RAGE-/- mice were significantly lower compared with those of RAGE+/+ mice following sensitization and challenge (Fig. 3B). These data suggest that RAGE contributes to the accumulation of ILC2s in the airways in this model of OVA-induced allergic airway inflammation.

RAGE expression in lung tissues. The distribution of RAGE in lung tissue was determined by immunohistochemistry. Many RAGE⁺ cells were found in the alveolar wall areas of non-

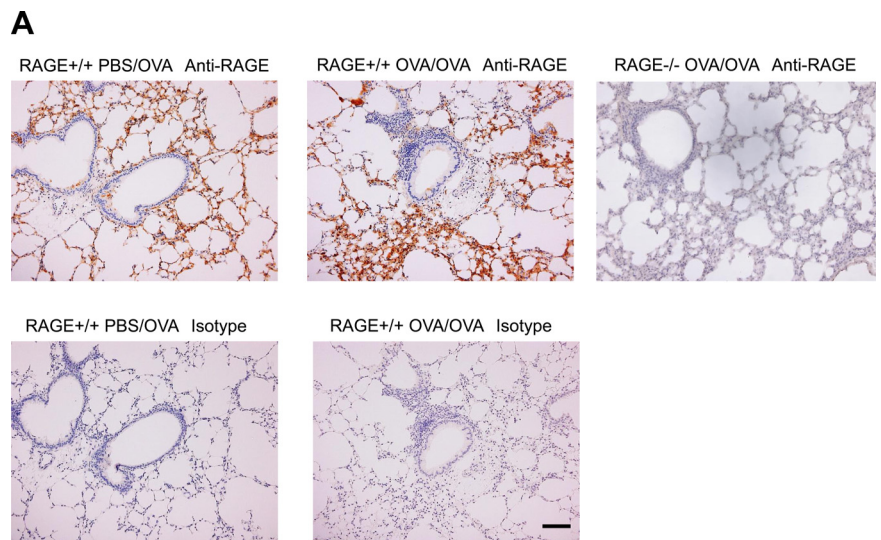
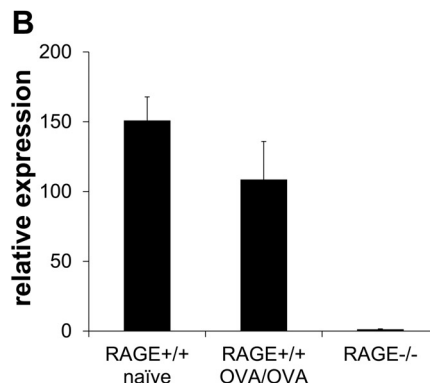


Fig. 4. RAGE expression in lung tissue. **A**: RAGE expression was evaluated by immunohistochemistry 48 h after the last challenge with OVA, as described in MATERIALS AND METHODS. RAGE⁺ cells are indicated by brown staining. RAGE expression was found mainly on alveolar epithelial cells in both RAGE+/+ mice without sensitization and RAGE+/+ mice following sensitization and challenge with OVA. Scale bar: 100 μ m. **B**: mRNA expression levels of RAGE in the lungs of RAGE+/+ and RAGE-/- mice following sensitization and challenge. Values are means $\pm$ SE ($n = 4$ in each group).



sensitized RAGE^{+/+} mice (Fig. 4A). OVA-sensitized and challenged RAGE^{+/+} mice also showed many RAGE⁺ cells in alveolar wall areas, similar to nonsensitized mice. The RAGE mRNA levels in sensitized and challenged RAGE^{+/+}

mice were not different from those in nonsensitized RAGE^{+/+} mice (Fig. 4B), suggesting that RAGE is spontaneously expressed in the lung, and expression levels were not affected by sensitization and challenge.

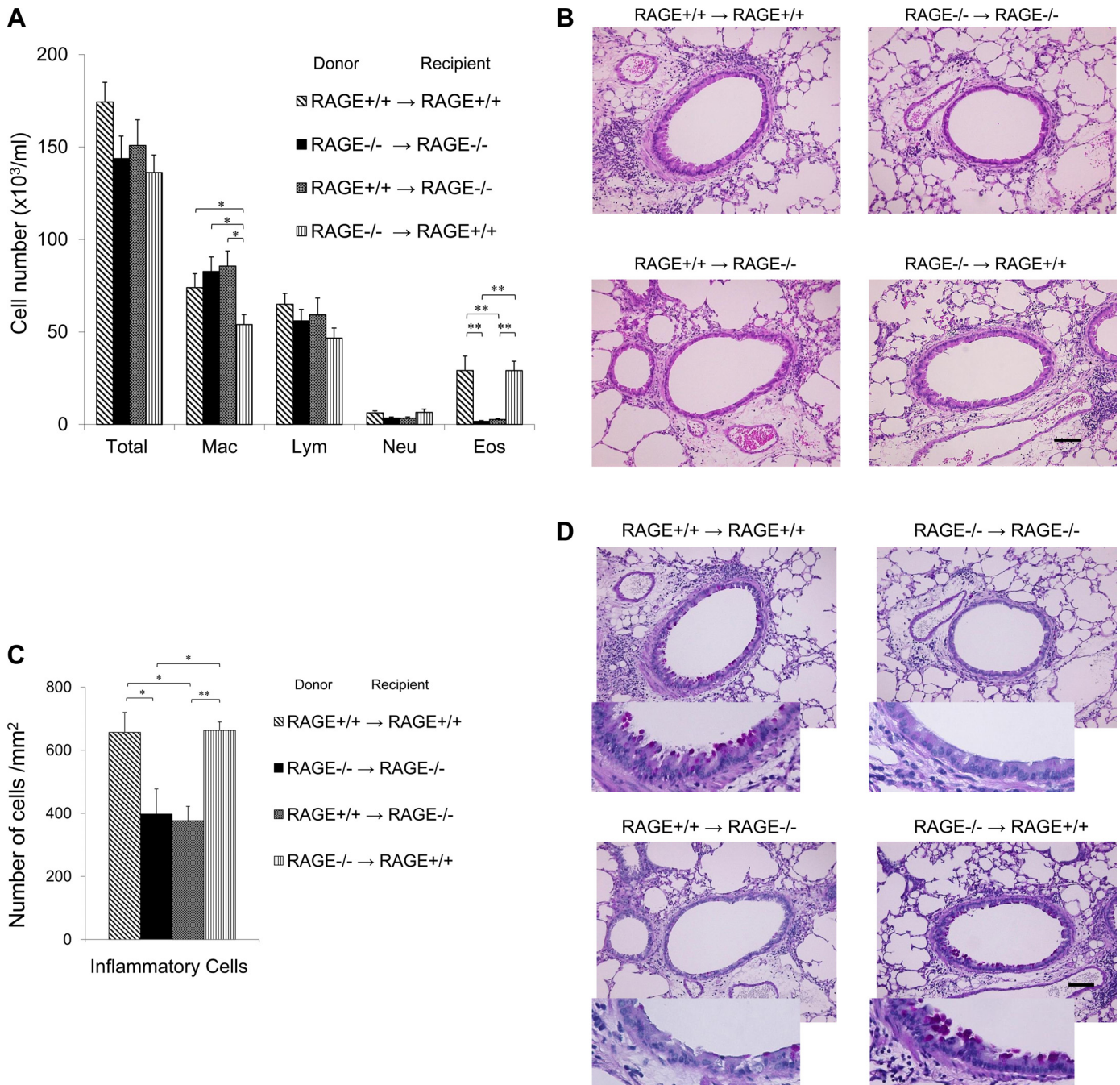


Fig. 5. RAGE expression on radio-resistant structural cells contributes to allergic airway inflammation. **A:** cellular composition in BAL fluid of chimeric mice. Values are means $\pm$ SE ($n = 10$ – 12 in each group). $*P < 0.05$. $**P < 0.01$. **B:** hematoxylin and eosin-stained lung sections. Scale bar: 100 μ m. **C:** inflammatory cell numbers in the peribronchial and perivascular tissue ($n = 4$ in each group). $*P < 0.05$. $**P < 0.01$. **D:** development of goblet cell metaplasia in the airways of chimeric mice. Scale bar: 100 μ m. **E:** goblet cell metaplasia was quantified in PAS-stained sections, as described in MATERIALS AND METHODS ($n = 4$ – 6 in each group). $*P < 0.05$. $**P < 0.01$. **F:** IL-13 levels in BAL fluid of chimeric mice measured by ELISA ($n = 12$ – 14 in each group). $*P < 0.05$. **G:** cellular composition in BAL fluid of recipients of OVA-pulsed dendritic cells (DCs). 1×10^6 OVA-pulsed bone marrow-derived DCs from RAGE^{+/+} or RAGE^{-/-} mice (donor) were instilled intratracheally into naive RAGE^{+/+} mice (recipient), followed by challenge with OVA, as described in MATERIALS AND METHODS ($n = 6$ in each group). There were statistically no differences among the two groups. **H:** IL-33, thymic stromal lymphopoietin (TSLP), and IL-25 levels in the lung tissues following sensitization and challenge with OVA compared with challenged-only mice. RAGE^{+/+} and RAGE^{-/-} mice were sensitized and challenged with OVA, as described in MATERIALS AND METHODS. The levels of these cytokines were measured by ELISA (PBS/OVA group: $n = 3$ – 4 , OVA/OVA group: $n = 6$ – 9). Significant differences ($*P < 0.01$) between RAGE^{+/+} and RAGE^{-/-} mice. $\#P < 0.05$ and $\#\#P < 0.01$ compared with challenged only mice.

RAGE expression on radio-resistant structural cells contributes to allergic airway inflammation. To determine the relative contribution of RAGE signaling on lung structural cells vs. hematopoietic cells following allergen sensitization and challenge, we generated radiation-induced bone marrow chimeric mice. Eight weeks after reconstitution, chimerism was confirmed by flow cytometry in lymph node B lymphocytes, DCs, lung ILC2s, and alveolar macrophages.

The populations of inflammatory cells in the BAL fluid from the bone marrow chimeric mice following sensitization and challenge were evaluated (Fig. 5A). RAGE^{+/+} → RAGE^{+/+} mice had significantly increased numbers of eosinophils in the BAL fluid compared with RAGE^{-/-} → RAGE^{-/-} mice, but this response was markedly reduced in RAGE^{+/+} → RAGE^{-/-} animals. In contrast, RAGE^{-/-} → RAGE^{+/+}

mice had increased numbers of eosinophils in BAL fluid, comparable to RAGE^{+/+} → RAGE^{+/+} mice.

In HE-stained lung sections of RAGE^{-/-} → RAGE^{+/+} mice and RAGE^{+/+} → RAGE^{+/+} mice, accumulation of inflammatory cells following sensitization and challenge was detected. In contrast, very few cells were detected in RAGE^{-/-} → RAGE^{-/-} mice and RAGE^{+/+} → RAGE^{-/-} mice (Fig. 5, B and C). The numbers of PAS-positive cells in RAGE^{-/-} → RAGE^{+/+} mice and RAGE^{+/+} → RAGE^{+/+} mice were also significantly higher compared with those of RAGE^{-/-} → RAGE^{-/-} mice and RAGE^{+/+} → RAGE^{-/-} mice (Fig. 5, D and E). IL-13 levels in BAL fluid of RAGE^{+/+} → RAGE^{-/-} mice were significantly lower compared with those in RAGE^{+/+} → RAGE^{+/+} mice (Fig. 5F). In contrast, RAGE^{-/-} →

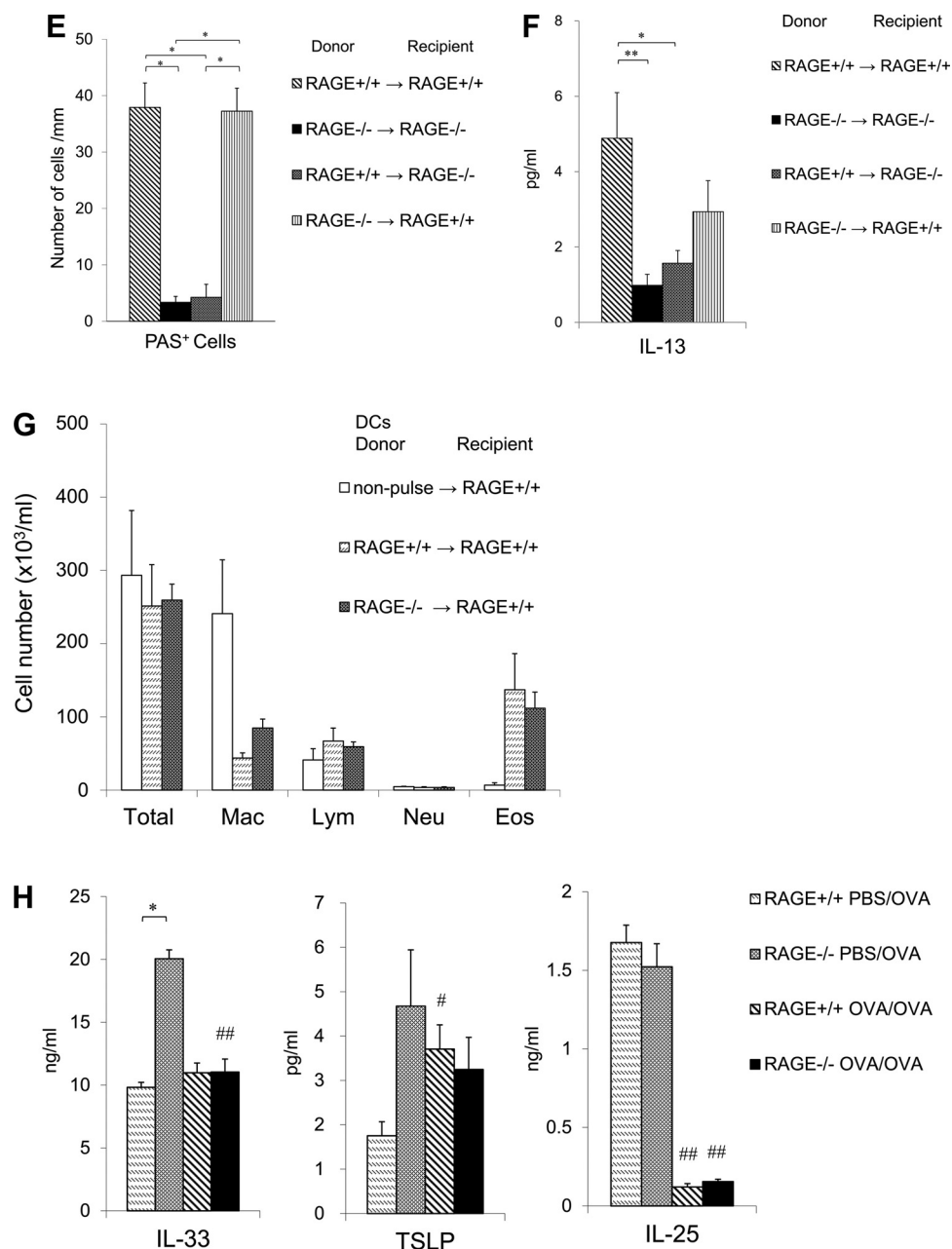


Fig. 5. Conitnued.

RAGE^{+/+} mice showed increased IL-13 levels comparable to those of RAGE^{+/+} → RAGE^{+/+} mice. These data suggested that expression of RAGE on structural cells is important for the full development of allergic airway inflammation and Th2 cytokine production in the airways following sensitization and challenge.

In vitro-allergen-pulsed RAGE^{-/-} DCs induce eosinophilic inflammation. Our results using bone marrow chimeric mice suggested that RAGE expression on hematopoietic cells was less important than RAGE expression on radio-resistant structural cells. The influence of RAGE expression on DC function has also been reported (9). To directly evaluate the role of RAGE expression on DCs, we investigated the ability of antigen-pulsed BMDCs to induce allergic airway responses after intratracheal instillation. BMDCs from RAGE^{+/+} or RAGE^{-/-} mice were pulsed with OVA and instilled intratracheally into RAGE^{+/+} mice, followed by aerosolized OVA challenge (11). These experiments showed that OVA-pulsed RAGE^{+/+} DCs and RAGE^{-/-} DCs were comparable in inducing increases in eosinophilic inflammation, confirming the functional competence of *in vitro* OVA-pulsed RAGE^{-/-} DCs in facilitating the development of allergic airway responses (Fig. 5G).

IL-33, TSLP, and IL-25 levels in the lungs. Cytokines and chemokines produced by airway epithelial cells (ECs), such as IL-33, TSLP, and IL-25, play important roles in adaptive Th2 cell-mediated immunity, but also in innate immunity, including activation of ILC2s for induction of allergic airway responses (6, 18, 21, 43); therefore, we assessed levels of these cytokines in lung tissue. However, the levels of IL-33, TSLP, and IL-25 were not different in the two strains of mice after sensitization and challenge (Fig. 5H). IL-33 levels in challenged-only RAGE^{-/-} mice were significantly higher compared with those in challenged-only RAGE^{+/+} mice (Fig. 5H).

AHR in RAGE^{+/+} and RAGE^{-/-} mice after sensitization and challenge. We then monitored AHR following sensitization and challenge with OVA. Intraperitoneal OVA sensitization and airway challenge led to the development of increased AHR in RAGE^{+/+} mice, as shown by significant increases in lung resistance compared with that in nonsensitized but challenged mice (Fig. 6). Challenged-only RAGE^{-/-} mice showed significantly higher AHR compared with challenged-only RAGE^{+/+} mice. AHR in sensitized and challenged RAGE^{-/-} mice was not higher than that in challenged-only RAGE^{-/-} mice. Thus AHR in RAGE^{-/-} mice was not further increased after sensitization and challenge.

Naive RAGE^{-/-} mice demonstrate increased AHR. We next assessed AHR to increasing doses of inhaled MCh in naive RAGE^{-/-} mice and naive RAGE^{+/+} mice. RAGE^{-/-} mice showed significantly higher (baseline) MCh-responsiveness compared with RAGE^{+/+} mice (Fig. 7A).

Absence of RAGE expression on radio-resistant structural cells upregulates AHR. To determine whether the expression of RAGE on radio-resistant structural cells or on hematopoietic cells contributed to innate AHR, we utilized the irradiated bone marrow chimeric mice. RAGE^{-/-} → RAGE^{-/-} mice showed significantly higher AHR compared with RAGE^{+/+} → RAGE^{+/+} mice. RAGE^{+/+} → RAGE^{-/-} mice also showed significantly higher AHR compared with RAGE^{+/+} → RAGE^{+/+} mice, whereas RAGE^{-/-} → RAGE^{+/+} mice showed significantly

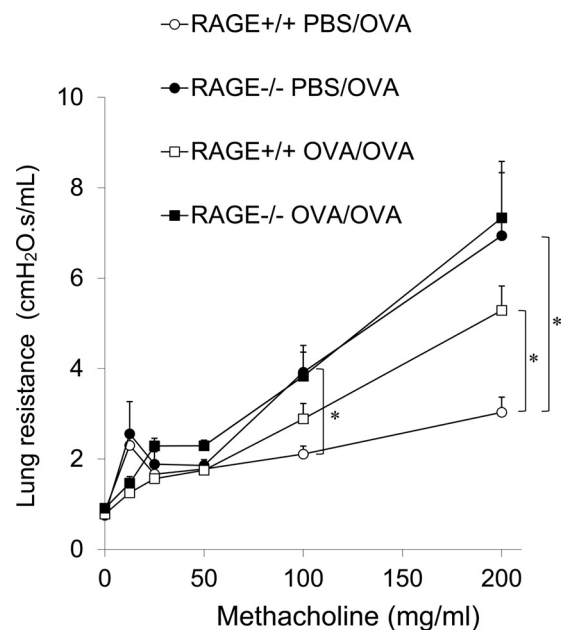


Fig. 6. Airway hyperresponsiveness (AHR) in RAGE^{+/+} and RAGE^{-/-} mice after sensitization and challenge with OVA. Forty-eight hours after the last challenge, lung resistance (RL) was monitored in response to increasing concentrations of inhaled methacholine, as described in MATERIALS AND METHODS. Values are means $\pm$ SE ($n = 9-11$ in each group). * $P < 0.05$.

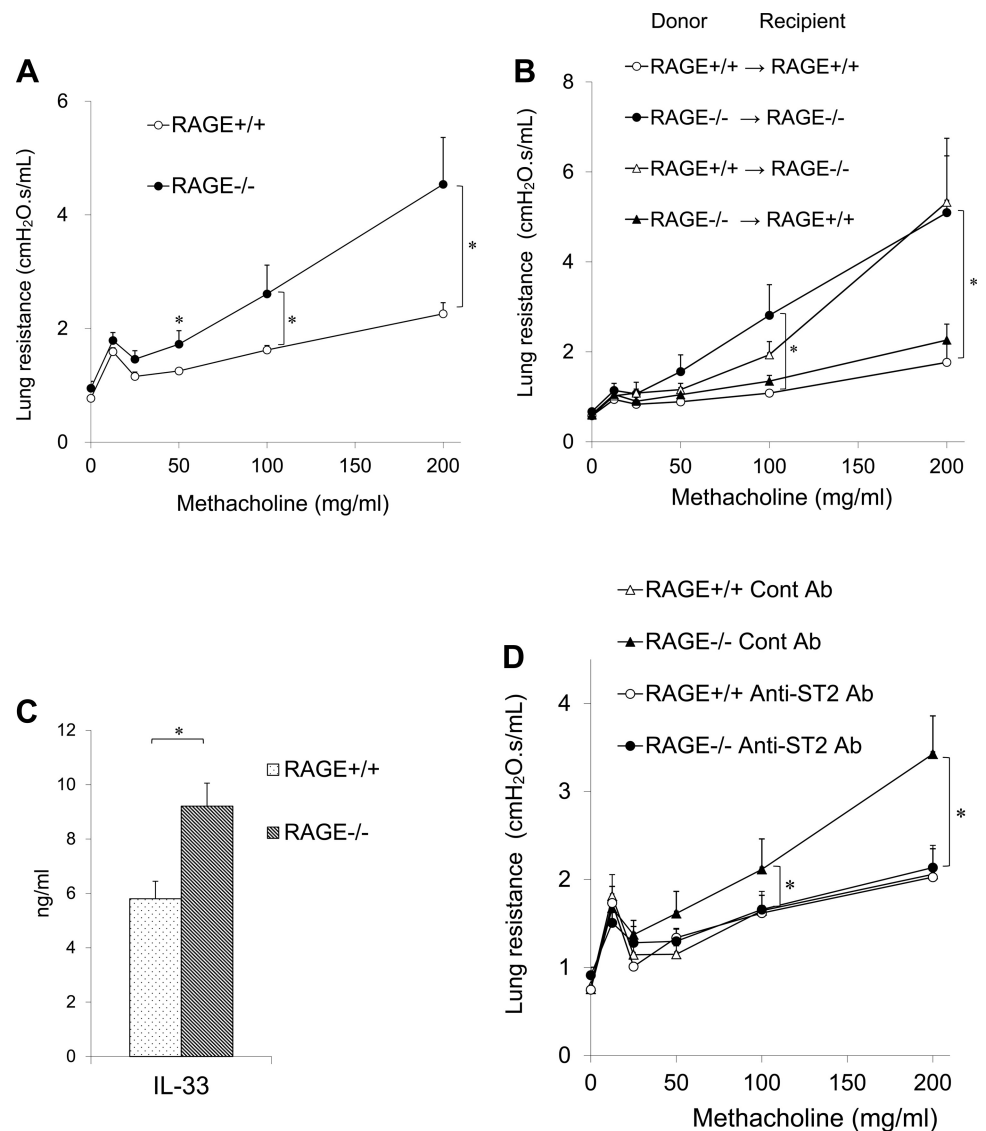
lower AHR compared with RAGE^{-/-} → RAGE^{-/-} and RAGE^{+/+} → RAGE^{-/-} mice (Fig. 7B). These data suggested that absence of RAGE expression on radio-resistant structural cells results in increased AHR.

Blockage of IL-33 receptor ST2 attenuates innate AHR in RAGE^{-/-} mice. Experiments using chimeric mice showed that absence of RAGE expression on radio-resistant structural cells enhanced innate AHR. Because challenged-only RAGE^{-/-} mice showed higher IL-33 levels in the lung compared with RAGE^{+/+} mice (Fig. 5G), we assessed IL-33 levels in naive mice and confirmed that IL-33 levels in the lungs of naive RAGE^{-/-} mice were higher than in naive RAGE^{+/+} mice (Fig. 7C). These data suggested that high levels of IL-33 in the lung might have contributed to innate AHR in RAGE^{-/-} mice. To verify this hypothesis, we investigated whether blockade of IL-33 receptor ST2 attenuated AHR in RAGE^{-/-} mice. RAGE^{-/-} mice treated with anti-ST2 antibody showed significantly lower AHR compared with mice that received control antibody, suggesting that IL-33 in the lung was a key regulator of AHR in naive RAGE^{-/-} mice (Fig. 7D).

DISCUSSION

In the present study, we demonstrated that RAGE contributes to both systemic sensitization and local activation of Th2 cells, as well as the accumulation of ILC2s in the airways following sensitization and challenge with allergen. Spleen MNCs as well as PBLN MNCs from RAGE^{-/-} mice showed impaired Th2 cytokine production. Accumulation of ILC2s in the airway was reduced in the absence of RAGE, although the numbers of Th2 cells were not different in the two strains of mice following sensitization and challenge. We demonstrated for the first time, to the best of our knowledge, that RAGE

Fig. 7. Absence of RAGE expression on radio-resistant structural cells is associated with increased AHR. **A:** AHR in naive RAGE^{-/-} and RAGE^{+/+} mice ($n = 14$ – 16 in each group). **B:** AHR in irradiated chimeric mice. The analysis was performed 8 wk after bone marrow transplantation, as described in MATERIALS AND METHODS ($n = 5$ – 7 in each group). **C:** IL-33 levels in the lungs of naive mice, measured by ELISA ($n = 5$ in each group). **D:** effects of IL-33 receptor ST2 blockade on innate AHR in RAGE^{-/-} mice. Twelve hours after intratracheal administration of anti-ST2 antibody (Ab) or control Ab, RL was monitored, as described in MATERIALS AND METHODS ($n = 4$ – 5 in each group). Values are means $\pm$ SE. *Significant differences ($P < 0.05$) between RAGE^{+/+} and RAGE^{-/-} mice.



expression on radio-resistant structural cells plays a critical role in the full development of allergen-induced airway inflammation. Although RAGE is expressed on both hematopoietic and structural cells, we show in chimeric mice that the mice expressing RAGE on structural cells but not hematopoietic cells develop allergic airway inflammation.

Recently, ILC2s, newly identified innate immune cells with the capacity for Th2 cytokine production in response to airway EC-derived IL-25, IL-33, and TSLP, have been reported to induce innate immune responses and enhance Th2 allergic inflammation (8, 13, 32). Previous studies have focused on the role of protease-allergens such as papain, house dust mite (HDM), and cockroach to induce ILC2s. In the present study, we demonstrated that RAGE might contribute to accumulation of ILC2s in the lungs of OVA-sensitized and challenged mice. Halim et al. (14) demonstrated that OVA, together with IL-33, induces migration of Th2 cells to regional lymph nodes in the presence of ILC2s. In the present study, numbers of ILC2s in the lungs of RAGE^{-/-} mice were significantly lower compared with those in RAGE^{+/+} mice. Therefore, RAGE may contribute to accumulation of ILC2s in the airways, and Th2

cells may collaborate with ILC2s to trigger allergic airway responses through RAGE signaling.

It has been reported that RAGE is constitutively expressed at high levels on lung structural cells (33). In contrast, there was relatively low expression of RAGE on vascular endothelial cells and inflammatory cells, including neutrophils, monocytes/macrophages, lymphocytes, and DCs (33). Using chimeric mice, we demonstrated that the expression of RAGE, especially on radio-resistant structural cells, was essential to the development of allergen-induced airway inflammation. Airway structural cells, including ECs, have been reported to be essential controllers of inflammatory, immune, and regenerative responses to allergens, viruses, and environmental pollutants that contribute to asthma pathogenesis (23). ECs express many pattern recognition receptors, including RAGE and Toll-like receptors (TLR) (23, 33, 37). EC triggering of TLR-4 by HDM induced production of TSLP, GM-CSF, IL-25, and IL-33 (23). These innate cytokines have been implicated in the development of allergic airway inflammation and played a critical role in enabling APCs to sensitize Th2 cells (2, 5, 6, 21, 25, 39, 43, 44). In the present study, RAGE^{-/-} mice were less

responsive to allergen challenge, and, somewhat similar to the role of TLR4, RAGE on structural cells may contribute to secretion of IL-33, IL-25, and TSLP, and increase APC sensitization of Th2 cells. These innate cytokines have also been implicated in induction of ILC2s (8, 13). In addition to ECs, alveolar cells were reported to have the capacity to secrete innate cytokines, such as IL-33 (19). Therefore, RAGE expression in alveolar cells may also induce activation of Th2 cells and accumulation of ILC2s in the airways and, as a result, amplify the full development of allergic airway inflammation.

DCs, representative of lung APCs, are critical to the activation of lung immune responses (35). Dumitriu et al. (9) reported the importance of RAGE for DC maturation. During the preparation of this manuscript, Ullah et al. (40) reported that numbers of DCs in the airway following intranasal instillation of HDM were lower in RAGE^{-/-} mice compared with RAGE^{+/+} mice, suggesting the importance of RAGE expression on DC for sensitization. However, they did not compare RAGE^{-/-} DCs with RAGE^{+/+} DCs for the ability to trigger airway inflammation. In the present study, using OVA as an allergen, we demonstrated that RAGE^{-/-} DCs were able to induce allergic airway inflammation comparable to RAGE^{+/+} DCs, which is consistent with the previous study showing APC function of RAGE^{-/-} DCs (29). Although the allergens used were different, at least in our model, OVA-pulsed DCs did not require RAGE expression for allergic inflammation, confirming the importance of RAGE expression on structural cells but not hematopoietic cells.

Moser et al. (29) have reported that RAGE was required for in vivo CD4 T cell proliferation using RAGE^{-/-} OT-II cells. They have also recently shown that RAGE deficiency resulted in reduction of IL-5 and IFN- γ and enhancement of IL-17 production from OT-II cells following OVA challenge, which was associated with lower accumulation of OT-II cells in the airway (1). In the present study, we have demonstrated lower IL-5 and IL-13 production from spleen and PBLN cells of RAGE^{-/-} mice, suggesting a requirement for RAGE for systemic Th2 sensitization in vivo. We also saw lower Th2 cytokine levels in BAL fluid, but did not see differences in numbers of Th1, Th2, and Th17 cells in the airways between RAGE^{-/-} and RAGE^{+/+} mice. Direct comparison of their studies and the present study is difficult because of differences in experimental protocols. Using chimeric mice, we have clearly shown the critical role of RAGE expression on radio-resistant structural cells, but not T cells, for the development of allergic airway inflammation and Th2 cytokine secretion in the airway. We have also shown the importance of RAGE expression on structural cells in elastase-induced airway inflammation and emphysematous change in mice (42).

RAGE^{-/-} mice, even in a naive state, showed significantly higher MCh-induced AHR compared with RAGE^{+/+} mice. Using a different strain of RAGE^{-/-} mice, Milutinovic and colleagues (27) reported no significant differences in AHR, although RAGE^{-/-} mice trended to higher AHR compared with wild-type mice. We further demonstrated the expression of RAGE on radio-resistant lung structural cells as perhaps the major contributor to the increased AHR in naive mice. Interestingly, levels of IL-33 in the lungs of RAGE^{-/-} mice were significantly higher than in RAGE^{+/+} mice. We demonstrated that blockade of ST2 attenuated innate AHR in RAGE^{-/-} mice. Thus absence of RAGE appears linked to increased

IL-33 levels in the lung, perhaps from EC, which might, at least in part, have contributed to the development of increased AHR in nonsensitized and nonchallenged RAGE^{-/-} mice. The mechanism(s) whereby the absence of RAGE leads to increased IL-33 levels in the lungs is not currently defined.

In summary, we demonstrated that RAGE played a critical role in airway inflammation, activation of Th2 cells, and the accumulation of ILC2 in the airways. Furthermore, we characterized the importance of RAGE expression on structural cells in the development of airway inflammation. In contrast, absence of RAGE on structural cells enhanced innate AHR. Our data suggest that manipulation of these contrasting roles of RAGE on structural cells for allergic airway inflammation vs. AHR may be beneficial for controlling asthmatic responses.

ACKNOWLEDGMENTS

We thank Diana Nabighian (National Jewish Health) for assistance in preparation of the manuscript.

GRANTS

This work was supported by Japan Society for Promotion of Science KAKENHI Grant 24591463 (to N. Miyahara).

DISCLOSURES

No conflicts of interest, financial or otherwise are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: A.T., N.M., K.W., E.K., U.F., and Y.Y. performed experiments; A.T., N.M., K.W., U.F., M.K., Y.Y., and H.Y. analyzed data; A.T., N.M., K.W., Y.T., M.K., E.W.G., M.T., and A.K. interpreted results of experiments; A.T., N.M., K.W., and U.F. prepared figures; A.T., N.M., and E.W.G. drafted manuscript; A.T., N.M., K.W., E.K., U.F., Y.T., M.K., Y.Y., E.W.G., H.Y., M.T., and A.K. approved final version of manuscript; N.M. and H.Y. conception and design of research; N.M., K.W., E.K., Y.T., M.K., Y.Y., E.W.G., H.Y., M.T., and A.K. edited and revised manuscript.

REFERENCES

1. Akirav EM, Henegariu O, Preston-Hurlburt P, Schmidt AM, Clynes R, Herold KC. The receptor for advanced glycation end products (RAGE) affects T cell differentiation in OVA induced asthma. *PLoS One* 9: e95678, 2014.
2. Barlow JL, Peel S, Fox J, Panova V, Hardman CS, Camelo A, Bucks C, Wu X, Kane CM, Neill DR, Flynn RJ, Sayers I, Hall IP, McKenzie AN. IL-33 is more potent than IL-25 in provoking IL-13-producing nuocytes (type 2 innate lymphoid cells) and airway contraction. *J Allergy Clin Immunol* 132: 933–941, 2013.
3. Bates JH, Rincin M, Irvin CG. Animal models of asthma. *Am J Physiol Lung Cell Mol Physiol* 297: L401–L410, 2009.
4. Bochner BS, Busse WW. Allergy and asthma. *J Allergy Clin Immunol* 115: 953–959, 2005.
5. Bouffie C, Rochman M, Zust CB, Stucke EM, Kartashov A, Fulkerson PC, Barski A, Rothenberg ME. IL-33 markedly activates murine eosinophils by an NF- κ B-dependent mechanism differentially dependent upon an IL-4-driven autoinflammatory loop. *J Immunol* 191: 4317–4325, 2013.
6. Chen ZG, Zhang TT, Li HT, Chen FH, Zou XL, Ji JZ, Chen H. Neutralization of TSLP inhibits airway remodeling in a murine model of allergic asthma induced by chronic exposure to house dust mite. *PLoS One* 8: e51268, 2013.
7. Cohn L, Woodruff PG. Update in asthma 2013. *Am J Respir Crit Care Med* 189: 1487–1493, 2014.
8. Deckers J, Branco Madeira F, Hammad H. Innate immune cells in asthma. *Trends Immunol* 34: 540–547, 2013.
9. Dumitriu IE, Baruah P, Valentinis B, Voll RE, Herrmann M, Nawroth PP, Arnold B, Bianchi ME, Manfredi AA, Rovere-Querini P. Release of high mobility group box 1 by dendritic cells controls T cell activation via the receptor for advanced glycation end products. *J Immunol* 174: 7506–7515, 2005.

10. Fritz G. RAGE: a single receptor fits multiple ligands. *Trends Biochem Sci* 36: 625–632, 2011.
11. Fuchimoto Y, Kanehiro A, Miyahara N, Koga H, Ikeda G, Waseda K, Tanimoto Y, Ueha S, Kataoka M, Gelfand EW, Tanimoto M. Requirement for chemokine receptor 5 in the development of allergen-induced airway hyperresponsiveness and inflammation. *Am J Respir Cell Mol Biol* 45: 1248–1255, 2011.
12. Georas SN, Rezaee F. Epithelial barrier function: at the frontline of asthma immunology and allergic airway inflammation. *J Allergy Clin Immunol* 134: 509–520, 2014.
13. Gold MJ, Antignano F, Halim TY, Hirota JA, Blanchet MR, Zaph C, Takei F, McNagny KM. Group 2 innate lymphoid cells facilitate sensitization to local, but not systemic, TH2-inducing allergen exposures. *J Allergy Clin Immunol* 133: 1142–1148, 2014.
14. Halim TY, Steer CA, Matha L, Gold MJ, Martinez-Gonzalez I, McNagny KM, McKenzie AN, Takei F. Group 2 innate lymphoid cells are critical for the initiation of adaptive T helper 2 cell-mediated allergic lung inflammation. *Immunity* 40: 425–435, 2014.
15. Hamada N, Maeyama T, Kawaguchi T, Yoshimi M, Fukumoto J, Yamada M, Yamada S, Kuwano K, Nakanishi Y. The role of high mobility group box1 in pulmonary fibrosis. *Am J Respir Cell Mol Biol* 39: 440–447, 2008.
16. Ikeda G, Miyahara N, Koga H, Fuchimoto Y, Waseda K, Kurimoto E, Taniguchi A, Tanimoto Y, Kataoka M, Tanimoto M, Kanehiro A. Effect of a cysteinyl leukotriene receptor antagonist on experimental emphysema and asthma combined with emphysema. *Am J Respir Cell Mol Biol* 50: 18–29, 2014.
17. Jerums G, Panagiotopoulos S, Forbes J, Osicka T, Cooper M. Evolving concepts in advanced glycation, diabetic nephropathy, and diabetic vascular disease. *Arch Biochem Biophys* 419: 55–62, 2003.
18. Kabata H, Moro K, Fukunaga K, Suzuki Y, Miyata J, Masaki K, Betsuyaku T, Koyasu S, Asano K. Thymic stromal lymphopoietin induces corticosteroid resistance in natural helper cells during airway inflammation. *Nat Commun* 4: 2675, 2013.
19. Kearley J, Silver JS, Sanden C, Liu Z, Berlin AA, White N, Mori M, Pham TH, Ward CK, Criner GJ, Marchetti N, Mustelin T, Erjefalt JS, Kolbeck R, Humbles AA. Cigarette smoke silences innate lymphoid cell function and facilitates an exacerbated type I interleukin-33-dependent response to infection. *Immunity* 42: 566–579, 2015.
20. Koga H, Miyahara N, Fuchimoto Y, Ikeda G, Waseda K, Ono K, Tanimoto Y, Kataoka M, Gelfand EW, Tanimoto M, Kanehiro A. Inhibition of neutrophil elastase attenuates airway hyperresponsiveness and inflammation in a mouse model of secondary allergen challenge: neutrophil elastase inhibition attenuates allergic airway responses. *Respir Res* 14: 8, 2013.
21. Kondo Y, Yoshimoto T, Yasuda K, Futatsugi-Yumikura S, Morimoto M, Hayashi N, Hoshino T, Fujimoto J, Nakanishi K. Administration of IL-33 induces airway hyperresponsiveness and goblet cell hyperplasia in the lungs in the absence of adaptive immune system. *Int Immunol* 20: 791–800, 2008.
22. Kurimoto E, Miyahara N, Kanehiro A, Waseda K, Taniguchi A, Ikeda G, Koga H, Nishimori H, Tanimoto Y, Kataoka M, Iwakura Y, Gelfand EW, Tanimoto M. IL-17A is essential to the development of elastase-induced pulmonary inflammation and emphysema in mice. *Respir Res* 14: 5, 2013.
23. Lambrecht BN, Hammad H. The airway epithelium in asthma. *Nat Med* 18: 684–692, 2012.
24. Lambrecht BN, Hammad H. Innate immune cells to the help. *Immunity* 40: 313–314, 2014.
25. Llop-Guevara A, Chu DK, Walker TD, Goncharova S, Fattouh R, Silver JS, Moore CL, Xie JL, O'Byrne PM, Coyle AJ, Kolbeck R, Humbles AA, Stampfli MR, Jordana M. A GM-CSF/IL-33 pathway facilitates allergic airway responses to sub-threshold house dust mite exposure. *PLoS One* 9: e88714, 2014.
26. Mangalmurti NS, Friedman JL, Wang LC, Stolz D, Muthukumaran G, Siegel DL, Schmidt AM, Lee JS, Albelda SM. The receptor for advanced glycation end products mediates lung endothelial activation by RBCs. *Am J Physiol Lung Cell Mol Physiol* 304: L250–L263, 2013.
27. Milutinovic PS, Alcorn JF, Englert JM, Crum LT, Oury TD. The receptor for advanced glycation end products is a central mediator of asthma pathogenesis. *Am J Pathol* 181: 1215–1225, 2012.
28. Miyahara N, Ohnishi H, Matsuda H, Miyahara S, Takeda K, Koya T, Matsubara S, Okamoto M, Dakhama A, Haribabu B, Gelfand EW. Leukotriene B4 receptor 1 expression on dendritic cells is required for the development of Th2 responses and allergen-induced airway hyperresponsiveness. *J Immunol* 181: 1170–1178, 2008.
29. Moser B, Desai DD, Downie MP, Chen Y, Yan SF, Herold K, Schmidt AM, Clynes R. Receptor for advanced glycation end products expression on T cells contributes to antigen-specific cellular expansion in vivo. *J Immunol* 179: 8051–8058, 2007.
30. Myint KM, Yamamoto Y, Doi T, Kato I, Harashima A, Yonekura H, Watanabe T, Shinohara H, Takeuchi M, Tsuneyama K, Hashimoto N, Asano M, Takasawa S, Okamoto H, Yamamoto H. RAGE control of diabetic nephropathy in a mouse model: effects of RAGE gene disruption and administration of low-molecular weight heparin. *Diabetes* 55: 2510–2522, 2006.
31. Robinson DS, Hamid Q, Ying S, Tsicopoulos A, Barkans J, Bentley AM, Corrigan C, Durham SR, Kay AB. Predominant TH2-like bronchoalveolar T-lymphocyte population in atopic asthma. *N Engl J Med* 326: 298–304, 1992.
32. Scanlon ST, McKenzie AN. The messenger between worlds: the regulation of innate and adaptive type-2 immunity by innate lymphoid cells. *Clin Exp Allergy* 45: 9–20, 2015.
33. Sims GP, Rowe DC, Rietdijk ST, Herbst R, Coyle AJ. HMGB1 and RAGE in inflammation and cancer. *Annu Rev Immunol* 28: 367–388, 2010.
34. Sparvero LJ, Asafu-Adjei D, Kang R, Tang D, Amin N, Im J, Rutledge R, Lin B, Amoscato AA, Zeh HJ, Lotze MT. RAGE (receptor for advanced glycation endproducts), RAGE ligands, and their role in cancer and inflammation. *J Transl Med* 7: 17, 2009.
35. Steinman RM, Kaplan G, Witmer MD, Cohn ZA. Identification of a novel cell type in peripheral lymphoid organs of mice. V. Purification of spleen dendritic cells, new surface markers, and maintenance in vitro. *J Exp Med* 149: 1–16, 1979.
36. Stern DM, Yan SD, Yan SF, Schmidt AM. Receptor for advanced glycation endproducts (RAGE) and the complications of diabetes. *Ageing Res Rev* 1: 1–15, 2002.
37. Sukkar MB, Ullah MA, Gan WJ, Wark PA, Chung KF, Hughes JM, Armour CL, Phipps S. RAGE: a new frontier in chronic airways disease. *Br J Pharmacol* 167: 1161–1176, 2012.
38. Sukkar MB, Wood LG, Tooze M, Simpson JL, McDonald VM, Gibson PG, Wark PA. Soluble RAGE is deficient in neutrophilic asthma and COPD. *Eur Respir J* 39: 721–729, 2012.
39. Suzukawa M, Morita H, Nambu A, Arae K, Shimura E, Shibui A, Yamaguchi S, Suzukawa K, Nakanishi W, Oboki K, Kajiura N, Ohno T, Ishii A, Korner H, Cua DJ, Suto H, Yoshimoto T, Iwakura Y, Yamasoba T, Ohta K, Sudo K, Saito H, Okumura K, Broide DH, Matsumoto K, Nakae S. Epithelial cell-derived IL-25, but not Th17 cell-derived IL-17 or IL-17F, is crucial for murine asthma. *J Immunol* 189: 3641–3652, 2012.
40. Ullah MA, Loh Z, Gan WJ, Zhang V, Yang H, Li JH, Yamamoto Y, Schmidt AM, Armour CL, Hughes JM, Phipps S, Sukkar MB. Receptor for advanced glycation end products and its ligand high-mobility group box-1 mediate allergic airway sensitization and airway inflammation. *J Allergy Clin Immunol* 134: 440–450, 2014.
41. Waseda K, Miyahara N, Kanehiro A, Ikeda G, Koga H, Fuchimoto Y, Kurimoto E, Tanimoto Y, Kataoka M, Tanimoto M, Gelfand EW. Blocking the leukotriene B4 receptor 1 inhibits late-phase airway responses in established disease. *Am J Respir Cell Mol Biol* 45: 851–857, 2011.
42. Waseda K, Miyahara N, Taniguchi A, Kurimoto E, Ikeda G, Koga H, Fujii U, Yamamoto Y, Gelfand EW, Yamamoto H, Tanimoto M, Kanehiro A. Emphysema requires the receptor for advanced glycation end products triggering on structural cells. *Am J Respir Cell Mol Biol* 52: 482–491, 2015.
43. Yao W, Zhang Y, Jabeen R, Nguyen ET, Wilkes DS, Tepper RS, Kaplan MH, Zhou B. Interleukin-9 is required for allergic airway inflammation mediated by the cytokine TSLP. *Immunity* 38: 360–372, 2013.
44. Yao XJ, Huang KW, Li Y, Zhang Q, Wang JJ, Wang W, Liu J, Lv Z, An YQ, Ding YZ, Corrigan CJ, Sun YC, Ying S. Direct comparison of the dynamics of IL-25- and 'allergen'-induced airways inflammation, remodelling and hypersensitivity in a murine asthma model. *Clin Exp Allergy* 44: 765–777, 2014.
45. Zhang H, Tasaka S, Shiraiishi Y, Fukunaga K, Yamada W, Seki H, Ogawa Y, Miyamoto K, Nakano Y, Hasegawa N, Miyasho T, Maruyama I, Ishizaka A. Role of soluble receptor for advanced glycation end products on endotoxin-induced lung injury. *Am J Respir Crit Care Med* 178: 356–362, 2008.