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Cutting Edge: Persistence of Increased Mast Cell Numbers in Tissues Links Dermatitis to Enhanced Airway Disease in a Mouse Model of Atopy

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The development of chronic allergic dermatitis in early life has been associated with increased onset and severity of allergic asthma later in life. However, the mechanisms linking these two diseases are poorly understood. In this study, we report that the development of oxazolone-induced chronic allergic dermatitis, in a mouse model, caused enhanced OVA-induced allergic asthma after the resolution of the former disease. Our findings show that oxazolone-induced dermatitis caused a marked increase in tissue mast cells, which persisted long after the resolution of this disease. Subsequent OVA sensitization and airway challenge of mice that had recovered from dermatitis resulted in increased allergic airway hyperreactivity. The findings demonstrate that the accumulation of mast cells during dermatitis has the detrimental effect of increasing allergic airway hypersensitivity. Importantly, our findings also show that exposure to a given allergen can modify the immune response to an unrelated allergen. The Journal of Immunology, 2012, 188: 531–535.

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Molecular Immunology Section, Laboratory of Molecular Immunogenetics, National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health, Bethesda, MD 20892

1Current address: Department of Medicine, Meir Medical Center, Kfar Saba, Israel.

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Address correspondence and reprint requests to Dr. Juan Rivera, National Institute of Arthritis and Musculoskeletal and Skin Diseases, National Institutes of Health, Building 10, Room 13C103, Bethesda, MD 20892-1930. E-mail address: juan_rivera@nih.gov

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and staining were done at American Histolabs. Formalin overnight with rotation to ensure fixation. Embedding, sectioning, tissues were collected and placed in 10% neutral buffered formalin. Lungs staining of tissue sections. Engraftment was allowed for a minimum of 6 wk. After disease induction Scientific Respiratory Equipment). With increasing doses of aerosolized methacholine using flexiVent (Scireq trachea, and the animals then were ventilated mechanically and challenged mg/ml]. A 19-gauge blunt-end needle was inserted into the ketamine/xylazine mixture (1 ml ketamine [100 mg/ml], 0.5 ml xylazine [20 m]. Determined. Mice were anesthetized by i.p. administration of 300 mg DNP-human serum albumin. Measurement of body temperature was performed performed. Airway responses to methacholine were compared using a two-way ANOVA test. Data are presented as mean SEM. Statistical analysis was with Prism software (GraphPad Software).

Results and Discussion
Increased asthma in mice after recovery from oxazolone-induced dermatitis
AD-like disease was elicited by repeated exposures of the ear skin of mice to oxazolone. Disease course could be divided into three phases (Fig. 1A): 1) sensitization, which is a critical step in determining the intensity of subsequent inflammation; 2) acute inflammation manifested as continuously increasing ear swelling; 3) chronic inflammation, starting from approximately the fifth challenge onward in which ear thickness reaches a plateau. After the withdrawal of oxazolone treatment (Fig. 1A, arrow), ear swelling gradually subsided and stabilized by 20 d postwithdrawal. As shown in Fig. 1B, chronic airway hyperreactivity was induced subsequently using a protocol of OVA challenges without adjuvant. In this model, MCs have been shown to be key participants and can considerably intensify the inflammatory response to OVA (14). When OVA sensitization was initiated 5 wk after the last oxazolone challenge (Fig. 1B) airway hyperreactivity was more severe, with increased resistance (Fig. 1B, left panel) and, to a lesser but nonetheless significant extent, reduced compliance (Fig. 1B, right panel). Having ruled out a direct effect of oxazolone dermatitis on lung function (Supplemental Fig. 1A), we hypothesized that it may enhance airway disease by increasing sensitization to OVA. However, OVA-specific IgE was not increased in the postdermatitis state (Supplemental Fig. 1B), despite the diverse cytokines induced by oxazolone (Supplemental Fig. 2A–C), which included IL-4 that is required for full development of dermatitis (Supplemental Fig. 2B).

We reported previously (15) that, during the course of oxazolone-induced chronic AD in mice, MCs become activated, migrate from the skin to the draining lymph nodes and spleen, and expand in the tissues. In this setting, MCs were found to suppress inflammation during the late stages of disease by producing IL-2 and supporting regulatory T cell function at the site of inflammation. In humans, it is well known that MC numbers increase in the affected skin of individuals with AD (16). Thus, we postulated that the ex-
acerbation of post-AD airway disease, in our mouse model, might be caused by increased numbers of tissue MCs. We evaluated MC numbers in the spleens of mice with dermatitis and found that their numbers were increased (data not shown), which is consistent with prior findings (15). The increased numbers of MCs in tissues remained during convalescence and after the challenge with OVA (Fig. 2A, 2B). Our previous study (15) demonstrated that during dermatitis a significant proportion of splenic MCs produced IL-2. In contrast, 5 wk postdermatitis, splenic MCs were no longer producing IL-2 (Fig. 2C), suggesting that these cells were no longer activated or could be nonresponsive. To test the latter possibility, we conducted a systemic anaphylactic challenge of dermatitis-induced mice 5 wk after convalescence. As shown in Fig. 2D, an enhanced anaphylactic response was observed for dermatitis-induced mice relative to that of those treated with solvent alone, and this enhanced response was still present after 5 wk of convalescence. This demonstrated that MCs are not cleared readily from the tissues and remain fully capable of responding to a subsequent challenge. Moreover, examination of the spleens of mice challenged with oxazolone, allowed to convalesce, and subsequently challenged with OVA disclosed more MCs than in the spleens of mice challenged with OVA alone (Fig. 2E). This demonstrates that the development of dermatitis is the cause of the marked increase in tissue MCs seen in postdermatitis airway challenged mice.

Because we found previously (15) that MCs dampen chronic AD, we asked whether MCs can function as regulatory and effector cells in dermatitis and airway disease, respectively. MC-deficient (KitW<sup>sh/sh</sup>) and appropriate control C57BL/6 mice (colony established from F<sub>1</sub> wild-type progeny of a Kit<sup>W/+</sup> mating) were subjected to oxazolone-induced dermatitis. Control C57BL/6 mice demonstrated milder inflammation relative to that of Kit<sup>W<sub>sh/sh</sub></sup> mice, which is consistent with our prior results (15). In a separate experiment, induction of airway disease revealed increased airway hyperreactivity in control C57BL/6 mice when compared

**FIGURE 2.** Long-term persistence of increased MC numbers and enhanced systemic anaphylaxis in postdermatitis mice. A, Protocol scheme and measurement of MC numbers in BALB/c mice after 5 wk of postdermatitis convalescence and concomitant 9 wk of OVA treatment, as shown (n = 5). **p = 0.0039, ***p = 0.0006. B, Toluidine blue staining for MCs in the indicated tissues, 5 wk after the cessation of either vehicle (acetone) or oxazolone. Scale bars, 150 µm. C, Numbers of IL-2–producing (IL-2+) MCs in the spleens of mice with dermatitis (Oxaz) or after recovery (5 wk post-Oxaz). *p = 0.03. D, Passive systemic anaphylaxis in mice with oxazolone-induced dermatitis or after their recovery (postdermatitis). After challenge, body temperature was recorded using a s.c. probe (n = 5). ***p < 0.0001. E, Representative picture (left panel) of toluidine blue-stained MCs in the spleens of mice after sequential oxazolone dermatitis and OVA airway hyperreactivity induction, solvent (Ace) challenge only, or OVA airway hyperreactivity induction only. Quantification of MC numbers in spleens (n = 5). Scale bars, 150 µm. *p = 0.017, ***p < 0.0001.

**FIGURE 3.** Introduction of MCs into the skin results in a dual effect of protection from dermatitis and exacerbated asthma. A, C57BL/6 and Kit<sup>W<sub>sh/sh</sub></sup> mice were subjected to oxazolone challenges, and ear swelling responses were compared (n = 5) ***p < 0.0001. The graph shows the range of ear swelling (y-axis) with time (x-axis) previously shown (15) to be the point in the disease where MCs are involved. B, Concomitantly, OVA sensitization and challenge was started in littermates of each group, and lung function was assessed by a methacholine study (n = 5). **p = 0.0086, ***p < 0.0001. C, Kit<sup>W<sub>sh/sh</sub></sup> mice were injected i.d. with bone marrow-derived MCs. Six weeks later, mice were sensitized and subsequently challenged with oxazolone (n = 7). ***p < 0.0001. D, After 5 wk of recovery from dermatitis, sensitization to OVA was initiated in a manner similar to the experimental design depicted in Fig. 1B. At the end of asthma induction, lung functions were evaluated as in Fig. 3B (n = 5). **p = 0.0008, ***p < 0.0001. C<sub>dyn</sub>, compliance; R, resistance.
airways, spleens, cervical lymph nodes, and ear tissues were stained for MCs to demonstrate inflammatory infiltrate within peri-bronchiolar collagen. Large numbers in unchallenged i.d. reconstituted mice were: airways, N.D.; spleen, 1.5; cervical lymph node, 2186±34; ear, 27±6 (n = 5). C. Quantification of eosinophils in bronchoalveolar lavage (BAL) fluid of mice in (A, B) (n = 3). *p = 0.02. D. MCs in tracheal tissue of wild-type BALB/c mice, enumerated after toluidine blue staining under a light microscope (n = 5). *p = 0.016, **p = 0.0011.

FIGURE 4. MC distribution in tissues after oxazolone dermatitis and OVA-induced asthma in i.d. reconstituted KitW-sh/W-sh mice. A. Tissues were harvested from the indicated three groups of mice and embedded in paraffin after the OVA challenge. Lung samples were stained with Masson’s trichrome to vested from the indicated three groups of mice and embedded in paraffin after the OVA challenge. Lung samples were stained with Masson’s trichrome to

with that in KitW-sh/W-sh mice (Fig. 3B). This suggests that MCs, which dampen chronic AD (15), conversely promote the induction of OVA-mediated airway hyperresponsiveness. To formally demonstrate that this transition from regulatory to effector MCs could occur in the same mouse, we performed an adoptive (intradermal [i.d.]) transfer of MCs in KitW-sh/W-sh mice, and afterward we induced oxazolone dermatitis in these mice as well as in non-reconstituted KitW-sh/W-sh mice. Disease induction was followed by 5 wk of convalescence and subsequent OVA-induced airway hyperactivity. As shown in Fig. 3C, MC-reconstituted KitW-sh/W-sh mice showed reduced inflammation during the late stages of oxazolone-induced dermatitis when compared with that in their non-reconstituted counterparts. No protection was observed at early stages of disease. In contrast, OVA-induced airway hyperreactivity was increased markedly in MC-reconstituted KitW-sh/W-sh mice (Fig. 3D) when compared with that in non-reconstituted littermates. These findings demonstrate that, although MCs play a protective role in one disease, they are conversely able to promote the severity of another disease. The findings are consistent with the view that induction of a Th2 response in one disease may well predispose one to another disease, as reported previously for lyn−/− mice (10, 17). Examination of the tissues of MC-reconstituted KitW-sh/W-sh mice revealed that i.d. injected MCs not only engraffed the skin but also were found in cervical lymph nodes and the spleen (Fig. 4A, 4B), which is consistent with our previous findings (15). These dynamics were associated with increased inflammation, as judged by airway inflammation (Fig. 4A) and by increased numbers of eosinophils in the bronchoalveolar lavage fluid (Fig. 4C). Although some MCs could be found in the tracheae of wild-type mice (14) (Fig. 4D), we observed no MC engraftment in the lungs or large airways of MC-reconstituted mice (Fig. 4A, 4B) demonstrating that the dermatitis-induced effect on airway hyperreactivity is mediated distal to the site of inflammation.

In summary, the work presented herein provides a murine model for the atopic march with several characteristics of the syndrome in humans. First, accumulation of MCs during chronic allergic dermatitis was observed, which is consistent with reports in human disease (16). Although in our model of oxazolone-induced AD the accumulation of MCs was protective (15), these cells also were able to enhance anaphylaxis as reported in some humans with AD (1). Second, post-dermatitis mice developed more severe airway disease, which is consistent with the well described observations of increased incidence and severity of asthma after AD (18). Finally, exposure to one allergen caused increased responsiveness to another allergen, suggesting potential epigenetic regulation, which is consistent with a role for the epigenome in increasing susceptibility and/or severity of allergic disease (19). Thus, the atopic model described herein provides a mechanistic link between the dermatitis-driven MC expansion and the increased risk and/or severity of asthma. It appears that, although the expansion of MCs in AD is beneficial at late stages of this disease, the cost is an increased risk for the development or severity of airway hyperreactivity.

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Disclosures
The authors have no financial conflicts of interest.

References


Figure S1: Oxazolone dermatitis does not affect lung function and does not enhance OVA sensitization. (A) As depicted in the top panel, lung functions were evaluated in vehicle-treated, 5 week post-dermatitis convalescence and OVA-treated Balb/c mice (R=resistance; C\textsubscript{dyn}=compliance) (n=6). ***, p<0.0001; NS, not significant. (B) OVA specific IgE was measured by ELISA in mice whose lung functions are presented in Figure 1B (n=5). **, p=0.0016.
Figure S2: Dermatitis-induced IL-4 production does not enhance concomitant sensitization to OVA. (A) Ears were collected from acetone- and oxazolone-treated mice \((n=4)\), homogenized in 700 μl PBS and protease inhibitor and cytokines profiled by antibody arrays. (B) Comparison of ear swelling between wild type \(Il4^{+/+}\) and \(Il4^{-/-}\) mice during induction of oxazolone dermatitis \((n=5)\). ***, \(p<0.0001\). (C) Mice were subjected to treatment with OVA (9 weeks) and oxazolone (4 weeks) as depicted in the top panel. After 9 weeks, sera were collected from all mice and evaluated for total (bottom left) and OVA (bottom right) IgE \((n=6)\). **, \(p=0.0034\); ***, \(p<0.0001\).