Airway Exposure Levels of Lipopolysaccharide Determine Type 1 versus Type 2 Experimental Asthma


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Airway Exposure Levels of Lipopolysaccharide Determine Type 1 versus Type 2 Experimental Asthma

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Allergic asthma is characterized by airway inflammation initiated by adaptive immune responses to aeroallergens. Recent data suggest that severe asthma may be a different form of asthma rather than an increase in asthma symptoms and that innate immune responses to LPS can modulate adaptive immune responses to allergens. In this study, we evaluated the hypothesis that airway exposure to different doses of LPS induces different form of asthma. Our study showed that neutrophilic inflammation and IFN-γ expression were higher in induced sputum from severe asthma patients than from mild to moderate asthmatics. Animal experiments indicated that allergen sensitization with low-dose LPS (0.1 μg) induced type 2 asthma phenotypes, i.e., airway hyperresponsiveness, eosinophilic inflammation, and allergen-specific IgE up-regulation. In contrast, allergen sensitization with high-dose LPS (10 μg) induced asthma phenotypes, i.e., airway hyperresponsiveness and noneosinophilic inflammation that were not developed in IFN-γ-deficient mice, but unaffected in the absence of IL-4. During the allergen sensitization period, TNF-α expression was found to be enhanced by both low- and high-dose LPS, whereas IL-12 expression was only enhanced by high-dose LPS. Interestingly, the asthma phenotypes induced by low-dose LPS, but not by high-dose LPS, were completely inhibited in TNF-α receptor-deficient mice, whereas the asthma phenotypes induced by high-dose LPS were abolished in the homozygous null mutation of the STAT4 gene. These findings suggest that airway exposure levels of LPS induces different forms of asthma that are type 1 and type 2 asthma phenotypes by high and low LPS levels, respectively. The Journal of Immunology, 2007, 178: 5375-5382.

Asthma is characterized as a chronic inflammatory disorder of the airways associated with reversible airway obstruction and airway hyperresponsiveness (AHR) (1, 2). In terms of the immunological pathogenesis of asthma, Th2 responses to aeroallergens are considered to play a central role in the initiation and orchestration of inflammatory responses in asthmatic airways (3, 4). The Th2 hypothesis of asthma pathogenesis was first suggested by Mosmann in 1989, who had earlier discovered the presence of two distinct subtypes of Th cells in mice: Th1 and Th2 (5, 6). The Th2 hypothesis states that asthma is caused by an increase in Th2 response in combination with a decrease in Th1 response. Although a wealth of animal data supports the Th2 hypothesis, studies in humans, however, have found that both Th1 and Th2 cytokines are elevated in the blood and airways of asthma patients (7, 8).

It is clear that the default immune response to the inhalation of inert proteins (allergens) is nonresponsiveness, i.e., “tolerance” (9, 10). Because inhaled allergens are ubiquitous in nature, it remains unclear why some individuals develop adaptive immune responses to allergens while others do not. In this context, respiratory infections have been associated with asthma in both the preventative and facilitative sense (11, 12), and LPS, a cell wall component of Gram-negative bacteria ubiquitously encountered in the environment and in household dust allergens, including house dust mites, is known to induce the production of IFN-γ and IL-12 (9, 13) and has been suggested to enhance Th1 priming and reduce Th2 cell priming to allergens (14, 15). Interestingly, a recent study indicated that low (0.1 μg) and high (100 μg) levels of inhaled LPS in a mouse model of allergic sensitization induces Th2 and Th1 responses to allergens, respectively (16), suggesting that airway allergen sensitization by LPS induces asthma that is differentially regulated according to LPS levels present at the time of exposure to aeroallergens. However, the exact mechanisms by which LPS induces polarized Th1 vs Th2 responses to allergens are not completely understood.

In this study, we evaluated the hypothesis that allergen sensitization with different doses of LPS induces differential adaptive
Table I. Characteristics of adult asthma patients according to severity

<table>
<thead>
<tr>
<th></th>
<th>Mild</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>53.6 ± 12.7</td>
<td>55.6 ± 11.3</td>
<td>58.8 ± 10.6</td>
</tr>
<tr>
<td>Sex</td>
<td>15/41</td>
<td>35/64</td>
<td>7/20</td>
</tr>
<tr>
<td>FEV1</td>
<td>98.8 ± 11.9</td>
<td>88.3 ± 15.6</td>
<td>76.4 ± 24.3</td>
</tr>
<tr>
<td>FEV1/FVC</td>
<td>96.7 ± 7.18</td>
<td>94.3 ± 8.23</td>
<td>87.7 ± 15.1</td>
</tr>
<tr>
<td>FVC (% predicted)</td>
<td>101.8 ± 14.2</td>
<td>94.1 ± 14.3</td>
<td>85.3 ± 17.7</td>
</tr>
</tbody>
</table>

a: Data are expressed as mean ± SEM unless otherwise indicated.

b: Sex, asthma symptoms; FVC, forced vital capacity.

c: Value of p < 0.05 vs mild and moderate severity by ANOVA linearity testing.

### Materials and Methods

#### Patients

One hundred eighty-two adult asthma patients (Table I) with reversible airway obstruction (percent increase of forced expiratory volume at 1 s (FEV1) >12%) and an absolute FEV1 increase of >400 ml after the use of asthma medications and without any remarkable lung abnormalities were enrolled in this study. Patients provided sputum samples at their initial visits and underwent spirometry and methacholine bronchial challenge tests under well-controlled conditions, as previously described (17). Asthma severity was classified as mild, moderate, or severe after at least 3 months of regular antiasthma medications, according to the Global Initiative for Asthma (GINA) guidelines concerning symptom and medication scores (18). All study protocols were approved by the ethics committee of Seoul National University Hospital, Korea.

#### Mice

IL-4-, IFN-γ-, TNFR1-deficient, and wild-type (WT) control mice on a C57BL/6 background, and STAT4-deficient and WT control mice on a BALB/c background were purchased from The Jackson Laboratory. The generation and breeding of null mutant and WT control mice were performed in specific pathogen-free conditions as previously described (19). Animal study protocols were approved by the Institutional Animal Care and Use Committee of Seoul National University, Korea.

#### A protocol for mouse models of asthma

LPS-depleted OVA was prepared as previously described (16) (Fig. 1). To generate a mouse model of LPS-enhanced asthma, 6-week-old mice were sensitized intranasally four times with 75 μg of OVA on days 0, 1, 2, and 7 with or without different doses of LPS (Sigma-Aldrich), and then challenged four times intranasally with 50 μg of OVA on days 14, 15, 21, and 22. The innate immune effects of LPS on the allergen sensitization were evaluated after allergen sensitization on days 0, 1, and 2. To evaluate asthma phenotypes, methacholine AHR (pulmonary function test (PFT)) and lung inflammation were evaluated on days 23 and 24, respectively.

#### Measurement of methacholine AHR

Methacholine AHR in asthma patients was expressed as slope of dose-response curve (DRS) of methacholine challenge which was defined by the percentage of fall of FEV1 divided by log (total dose of applied methacholine, milligrams per milliliter).

Pulmonary function testing in mice was assessed in conscious, unrestrained mice by noninvasive whole body plethysmography (Allmedicus). Measurements were performed as previously described (20). Briefly, mice were placed in a plethysmograph chamber and exposed to an aerosol of PBS (basal readings) and then to methacholine at 6.25, 12.5, 25, and 50 mg/ml. Aerosols were generated using an ultrasonic nebulizer and drawn through the chamber for 3 min. Enhanced pause (Penh) readings were taken for 3 min and averaged. We previously confirmed a direct correlation between Penh and airway resistance in response to methacholine challenge (20).

#### Evaluations of lung inflammation

Lung and bronchoalveolar lavage (BAL) samples were obtained and histological evaluations were performed as previously described (20). Briefly, mice were anesthetized and their trachea were isolated by blunt dissection. A small caliber tube was inserted and secured in the airway. Two successive volumes of 0.75 ml of PBS were instilled and gently aspirated and these two volumes were pooled. Each BAL sample was centrifuged and the supernatants were stored at −70°C until use. The total numbers of inflammatory cells were counted after dilution of cell pellets with 50 μl of PBS. After Diff-Quick staining (Dade Behring) of BAL pellets in a cytosin preparation, types of inflammatory cells were determined by counting 300 cells, which were classified as macrophages, lymphocytes, neutrophils, or eosinophils. The lung was perfused with cold PBS through the right ventricle until the pulmonary vasculature was clean. The whole lung was inflated with fixatives for histology. H&E stains were used on lung sections after pressure fixation with Streck solution (Streck Laboratories). The same microscopic magnification was used for all sample slides for comparison.

#### Evaluations of immunologic parameters

mRNA was quantified in the induced sputum samples of asthma patients and BAL protein and OVA-specific IgG2a and IgE levels in BAL and serum samples obtained during animal experiments were determined as previously described (19). For FACs analysis, single-cell suspensions from lungs were prepared as previously described (19). Briefly, cells isolated from lung tissues and BAL fluids were washed three times with PBS containing 1% BSA, counted, and distributed into staining tubes (1×10⁶ cells/tube) for cell surface marker analysis. They were then stained with FITC-conjugated anti-CD11c, anti-CD11b, anti-CD3, and anti-CD8 (all conjugated Abs were purchased from BD Biosciences). Intracellular cytokine staining was performed using Abs against PE-conjugated anti-IL-4, anti-IL-10, anti-IL-12, and anti-IFN-γ (BD Biosciences). Cells were analyzed using a FACs Calibur unit (BD Biosciences), and results were processed using CellQuest software (BD Biosciences).

#### Statistical analysis

Significant differences among groups were assessed using the Student t test, ANOVA, or a Wilcoxon rank sum test. For multiple comparisons, ANOVA was initially used and if significant differences were found individual two-tailed unpaired t or Wilcoxon rank sum tests between pairs of groups were used.

#### Results

Association between sputum neutrophils and disease severity in asthma patients and enhanced IFN-γ mRNA expression in these patients

A total of 182 adult asthmatic patients were enrolled in this study as shown in Table I. We defined asthma severity based on symptom and...
medication scores over a period of at least 3 mo during which anti-
asthma medications were used and found that a reduced baseline lung
function was positively associated with disease severity (Table I).
However, methacholine AHR was not found to be associated with
asthma severity, although showed a tendency to be increased in mild
asthmatics compared with other groups (Fig. 2A). Interestingly, we
found that the neutrophil percentage in all sputum inflammatory cells
was positively associated with asthma severity, but that sputum eo-
sinophil percentage was not (Fig. 2B). Moreover, our data indicate
that sputum IFN-γ mRNA expression was significantly higher in se-
vere asthma patients than in mild-to-moderate patients, although IL-4
mRNA expressions were similar in the two groups. *, p < 0.05 vs mild-to-moderate asthmatics by Student’s t test.

Airway allergen sensitization with LPS induces enhanced AHR
and lung inflammation

To test the notion that innate immune responses induced by LPS
modulate adaptive immune responses to inhaled proteins, C57BL/6 WT mice were sensitized intranasally with LPS-depleted
OVA in combination with 0.1, 1, 10, or 100 μg of LPS at days 0,
1, 2, and 7, and then challenged intranasally with OVA alone 7
days after the final allergen sensitization as shown in Fig. 1.
Methacholine AHR following allergen (OVA) challenge was more
enhanced in mice sensitized with OVA plus LPS, independent of
LPS dose, than in those sensitized with OVA or PBS alone (Fig.
3A). In terms of lung inflammation (Fig. 3B), we also found that
total inflammatory cell counts in BAL fluids after allergen chal-
lenge were enhanced in mice sensitized with OVA plus LPS in a
dose-dependent manner. However, mice sensitized with OVA
alone showed no enhanced BAL cellularity after OVA challenge
and had total BAL cell counts equivalent to PBS-sensitized mice.
BAL neutrophil counts were greater in mice sensitized with OVA
plus high-dose (10 or 100 μg) LPS than in those sensitized with OVA
plus low-dose (0.1 μg) LPS, whereas BAL eosinophil counts were
higher in mice sensitized with OVA plus low-dose LPS than in those sensitized with OVA
plus high-dose LPS. With respect to allergen-specific Ab production (Fig. 3C), serum OVA-specific IgE and IgG2a levels after subsequent OVA chal-
lenge: OVA-specific IgE production was enhanced by LPS, independently of LPS dose, whereas OVA-specific IgG2a was more enhanced by high
doses (10 and 100 μg) LPS, *, p < 0.05 vs OVA group.

FIGURE 2. AHR and lung inflammation according to asthma severity
in patients. A, AHR values, expressed as slopes of DRS to methacholine
in which lower values mean higher AHR, were similar for patients with mild,
moderate, and severe asthma. Statistical analysis was performed by
ANOVA linearity testing. B, Eosinophil and neutrophil numbers in induced
sputum: sputum neutrophil numbers were found to be positively associated
with asthma severity, whereas eosinophil numbers were not. *, p < 0.05 by
ANOVA linearity testing. C, Sputum IL-4 and IFN-γ mRNA expressions:
IFN-γ was markedly more enhanced in severe asthmatics than in mild-to-
moderate asthmatics, although IL-4 mRNA expressions were similar in the
two groups. *, p < 0.05 vs mild-to-moderate asthmatics by Student’s t test.

FIGURE 3. AHR and lung inflammation induced by allergen sensitiza-
tion with LPS. A–C, One experiment representative of five identical runs is
shown. A, AHR after allergen challenge: PFT was measured by unre-
strained noninvasive whole body plethysmography, and airway obstruc-
tions are expressed as Penh. Allergen sensitization by LPS, regardless of
LPS dose, enhanced AHR induced by allergen challenge. B, BAL cellu-
larity after allergen challenge: total bar heights represent total and individ-
ual inflammatory cell numbers in BAL. LPS enhanced BAL cellularity in a
dose-dependent manner. Low (0.1 μg) and high doses (10 and 100 μg)
of LPS enhanced eosinophil and neutrophil numbers in BAL, respectively.
*, p < 0.05 vs OVA and PBS groups; **, p < 0.05 vs the other groups. C, Serum OVA-specific IgE and IgG2a levels after subsequent OVA chal-
lenge: OVA-specific IgE production was enhanced by LPS, independently
of LPS dose, whereas OVA-specific IgG2a was more enhanced by high
doses (10 and 100 μg) LPS, *, p < 0.05 vs OVA group.
Differential expressions of TNF-α and IL-12 by LPS doses during allergen sensitization period

During the sensitization period, we found that TNF-α levels in BAL fluids were significantly higher in C57BL/6 WT mice sensitized with OVA plus LPS, regardless of LPS dose, than in those sensitized with OVA or PBS alone (Fig. 4A). Meanwhile, BAL TGF-β1 levels were found to be enhanced in mice sensitized with OVA alone vs PBS alone; however, the enhanced TGF-β1 production was inhibited by the additions of LPS, independent of LPS dose (data not shown). Interestingly, BAL IL-12p40 levels 6 or 24 h after 3 days of allergen sensitization were found to be significantly higher in mice sensitized with OVA plus high-dose (1, 10, or 100 μg) LPS than in those sensitized with OVA plus low-dose (0.1 μg) LPS or OVA alone (Fig. 4B).

TNF-α receptor-mediated pathway plays a key role in the development of Th2 response in the low-dose LPS model

We hypothesized that adaptive immune responses enhanced by LPS are dependent on the TNF-α receptor-mediated pathway. To test this, we applied the above-described mouse asthma models to TNFR1-deficient and same-aged WT control mice (C57BL/6 background). In this experiment, low and high doses of LPS were defined as 0.1 and 10 μg, respectively, which are levels of contamination consistent with house dust allergens (13). AHR induced by allergen challenge did not develop in TNFR1−/− mice sensitized with OVA plus low-dose LPS, but developed in TNFR1−/− mice sensitized with OVA plus high-dose LPS when compared with WT mice sensitized in the same manner (Fig. 5A). Moreover, BAL cellularity was significantly lower in TNFR1-deficient mice sensitized with OVA plus low-dose LPS, but similar in these mice when sensitized with OVA plus high-dose LPS, when compared with WT mice sensitized in the same manner (Fig. 5B). In terms of the role of the TNF-α receptor-mediated pathway on Ab production, our data show that OVA-specific IgE production enhanced by low-dose LPS in WT mice was not observed in TNFR1-deficient mice, whereas OVA-specific IgE production enhanced by high-dose LPS was similar in TNFR1-deficient and WT mice (Fig. 5C). In addition, IL-4 secretion enhanced by low-dose LPS was not observed in TNFR1-deficient mice, but IL-4 secretion was similar in TNFR1-deficient and WT mice sensitized with allergen plus high-dose LPS (Fig. 5D).

IFN-γ plays a key role in the development of AHR and noneosinophilic lung inflammation in the high-dose LPS mouse model

Based on our data showing that AHR and lung inflammation enhanced by high-dose LPS were accompanied by enhanced allergen-specific IgE and IgG2a productions after OVA challenge, we evaluated the roles of Th1 and Th2 cytokines in the development of the asthma phenotypes enhanced by high-dose LPS. To test this, the high-dose (10 μg) LPS-enhanced asthma model was applied to IFN-γ− and IL-4−/− deficient and same-aged WT control mice (C57BL/6 background). AHR induced by allergen challenge did not develop in IFN-γ−/− mice, but developed in IL-4−/− mice, sensitized with OVA plus high-dose LPS relative to WT mice sensitized in the same manner (Fig. 6A). In terms of the role of IL-4 and IFN-γ on the development of lung inflammation (Fig. 6B), airway infiltration of macrophages, lymphocytes, and neutrophils after allergen challenge did not develop in IFN-γ−/− mice sensitized with OVA plus high-dose LPS relative to WT mice sensitized in the same manner. Eosinophil infiltration, however, was aggravated in IFN-γ−/− mice sensitized with OVA plus high-dose LPS vs the WT. In contrast, BAL cellularity enhanced by high-dose LPS was not affected in the absence of IL-4.

In terms of the role of IL-4 and IFN-γ on Ab production (Fig. 6C), the levels of serum OVA-specific IgE were significantly lower in both IL-4 and IFN-γ-deficient mice sensitized in OVA plus high-dose LPS than in WT mice sensitized in the same manner. In contrast, OVA-specific IgG2a production was significantly lower in IFN-γ-deficient mice, but aggravated in IL-4-deficient
mice, sensitized with OVA plus high-dose LPS when compared with WT mice sensitized in the same manner. Moreover, we found that the enhanced production of Th1-related cytokines, namely IL-12 and IFN-γ-inducible protein 10 (IP-10), after allergen challenge in WT mice did not occur in IFN-γ−/− mice, whereas IgG2a was inhibited in the absence of IFN-γ, but aggravated in the absence of IL-4−/−. In contrast, TGF-β1 production was enhanced in IFN-γ−/− mice, but not in IL-4−/− mice, sensitized with OVA plus LPS.

**AHR and lung inflammation in the high-dose LPS asthma model are developed mainly via the STAT4-signaling pathway**

IL-12 is known to be potent Th1 skewing cytokines that are mainly mediated by the STAT4-signaling pathway (14). Based on our finding that high-dose LPS enhances IL-12 production during allergen sensitization (Fig. 4B), we hypothesized that the STAT4-signaling pathway might play an essential role in the development of asthma phenotypes enhanced by high-dose LPS. To test this, we applied the high-dose LPS mouse asthma model to STAT4-deficient and same aged WT control BALB/c mice. AHR induced by allergen challenge was not enhanced in STAT4−/− mice sensitized with OVA plus high-dose LPS (10 μg), but enhanced in WT mice sensitized in the same manner (Fig. 7A). Moreover, lung inflammation enhanced by high-dose LPS was significantly inhibited in STAT4-deficient mice (Fig. 7B). We also found that OVA-specific IgG2a production enhanced by high-dose LPS was significantly inhibited in STAT4-deficient mice (Fig. 7C). BAL cells were examined by intracellular cytokine analysis for the ability to produce IFN-γ and showed that airway infiltration by IFN-γ-producing cells, which were only CD8+ cells but not CD8− cells, after allergen challenge was significantly lower in STAT4-deficient mice sensitized with OVA plus high-dose LPS than in WT mice sensitized in the same manner (Fig. 7D). In addition, we
found that OVA-specific IgE production enhanced by high-dose LPS was completely inhibited in STAT4-deficient mice, and that this inhibition was positively associated with the down-regulation of IL-4 production in the absence of a STAT4-signaling pathway (Fig. 7, C and E).

**Discussion**

Our understanding of the pathogenesis of asthma has changed drastically over time, and it has been proposed that immune deviation toward Th1 response can protect against asthma, because Th1 cells antagonize the functions of Th2 cells (21, 22). The “Th2 asthma hypothesis” is based on the assumption that IgE and eosinophils play crucial roles in the pathogenesis of asthma; Th2 cytokines are believed to regulate IgE synthesis and eosinophil numbers and activity are thought play a major role in driving its pathogenesis (23, 24). Mouse models of asthma based on sensitization with i.p. administered OVA in alum support this concept by demonstrating that Th2 cytokines are major contributors to its pathogenesis (3, 4), although these observations are not consistent with findings from other studies (25–27). In particular, an abundance of human data raises questions concerning any concept that IFN-γ levels are reduced in asthma. Corrigan and Kay (28) demonstrated increased circulating blood levels of IFN-γ in patients with acute severe asthma and Magnan et al. (7) also showed that the numbers of IFN-γ⁺ cells in whole bloods are correlated with asthma severity and AHR. In addition, our data showed that IFN-γ mRNA expression in sputum was positively associated with asthma severity. Moreover, therapeutic interventions based on the Th2 hypothesis have indicated that directing the T cell response from Th2 or to Th1 does not affect asthma properties in humans (29, 30); several studies have reported that glucocorticoids, the most potent anti-inflammatory drugs available for the treatment of asthma, guide the differentiation of Th cells toward the Th2 phenotype (31). In addition, our data indicated that airway sensitization with high-dose LPS induced asthma phenotypes, such as AHR and lung inflammation, and that these were accompanied by the up-regulation of allergen-specific IgG2a, which is induced by IFN-γ. AHR and lung inflammation (except eosinophil infiltration) enhanced by high-dose LPS were found to be completely inhibited in the absence of IFN-γ. Taken together, these findings suggest that the Th2 hypothesis provides an oversimplified description of the pathogenesis of asthma and that IFN-γ plays a key role in the development of some asthma subtypes.

Advances in medical research methodologies, such as bronchoscopy and studies on induced sputum in severe asthma, have demonstrated that noneosinophilic and even eosinophilic forms of
severe asthma are associated with airway neutrophilia (32, 33). Our study also found that sputum neutrophils, and not eosinophils, are positively associated with disease severity in asthma patients, and that in a mouse model, BAL neutrophils were induced by LPS in a dose-dependent manner. A previous transgenic mouse experiment clearly demonstrated that high levels of IFN-γ in airways induce noneosinophilic (or neutrophilic) lung inflammation (34), and a separate study showed that IFN-γ inhibits allergen-induced eosinophil recruitment into mouse lung tissue (21). It is well-known that TGF-β1 is a key mediator in the development of eosinophilic inflammation and tissue fibrosis induced by Th2 cytokines (35) and our present data show that TGF-β1 production and eosinophilic inflammation after an allergen challenge are more enhanced in IFN-γ-deficient mice sensitized with high-dose LPS. Moreover, by placing a focus on the presence or absence of eosinophils in patients with severe asthma, Wenzel et al. (36) found that subbasement membrane thickening and TGF-β1-producing cell numbers in airways were higher in patients with severe eosinophilic asthma than with noneosinophilic asthma. Taken together, these findings suggest that IFN-γ plays an essential role in the development of noneosinophilic severe asthma and that IFN-γ is a key negative regulator of the development of eosinophilic inflammation during the pathogenesis of asthma.

It has been well-documented that IL-12 is produced by the innate arm of the immune system and it is an important regulator of Th1 cell development (37–39). Our study showed that LPS dose dependently enhanced IL-12 expression during allergen sensitization. In addition, because it is accepted that the biological effects of Th1-polarizing cytokines, such as IL-12 and IL-18, depend strongly on the STAT4-signaling pathway (40), we hypothesized that Th1 response enhanced by high-dose LPS is dependent on this pathway. Indeed, we have shown that AHR and lung inflammation enhanced by high-dose LPS were completely inhibited in STAT4-deficient mice. Our data also indicate that the inhibition of asthma phenotypes in STAT4-deficient mice is positively associated with the down-regulations of IFN-γ and IL-12 after allergen challenge. These findings suggest that the STAT4-signaling pathway mediates a positive feedback loop between IL-12 and IFN-γ during Th1 recall in response to inhaled allergens.

It is well-known that the default immune response to inert inhaled proteins is the development of immune tolerance (9, 10) and this study also showed that AHR and lung inflammation are not induced by airway sensitization with allergen alone. Eisenbarth et al. (16) showed that TNF-α cotreatment with inhaled allergens restores Th2 response. Our present data also indicate that allergen sensitization with low-dose LPS induces the Th2 asthma phenotypes associated with the up-regulation of TNF-α production during allergen sensitization. Based on these findings, we hypothesized that the TNF-α receptor-mediated pathway plays a critical role in the development of Th2 response to allergens. Indeed, our study found that AHR and lung inflammation with IL-4 up-regulation and allergen-specific IgE production (as enhanced by low-dose LPS) were completely inhibited in TNFR1-deficient mice. In contrast, our data showed that Th1 asthma phenotypes induced by high-dose LPS were not affected by the absence of TNF-α receptor-mediated pathway. Taken together, these findings suggest that TNF-α secretion induced by low-dose LPS is a key upstream molecule of Th2 polarization.

Our data support a model of sensitization to inert inhaled proteins that requires LPS. LPS is ubiquitously present in the environment and it has even been detected in house dust (41). We are therefore constantly exposed to at least low levels of environmental LPS and it is well-known that house dust LPS is associated with asthma severity in both adults and children (13, 42). The “hygiene hypothesis” states that the rising incidence of allergic asthma is causally related to reducing infectious burden in Westernized countries (11). A growing amount of evidence, however, supports a positive correlation between infectious burden and the development of allergic asthma (43–45). It has been reported that LPS concentrations in house dust fall in the range of 0.59–41.04 ng/mg (46). We can speculate that the LPS levels and genetic susceptibility to LPS may determine type 1 vs type 2 adaptive immune responses to inhaled aeroallergens in subjects exposed to house dust allergens contaminated with LPS during early life. This study demonstrated that airway allergen sensitization by differential doses of LPS induces different forms of asthma that are type 1 and type 2 asthma phenotypes by high and low doses of LPS, respectively.

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**Disclosures**

The authors have no financial conflict of interest.

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