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Secondhand Smoke Induces Allergic Sensitization in Mice

Robert Rumold,* Minna Jyrala †, and David Diaz-Sanchez2*

Epidemiological studies have suggested increased prevalence of atopy in children of maternal smokers. Although secondhand smoke or environmental tobacco smoke (ETS) has been shown to augment allergic responses, its role in atopic sensitization is still controversial. We studied whether ETS could initiate a Th2 response and thus induce primary allergic sensitization. Mice were exposed for 10 consecutive days to either 1% aerosolized OVA, ETS (5 cigarettes), or both ETS and OVA. C57BL/6 mice receiving both ETS and OVA developed OVA-specific IgE and IgG1, 12, 14, and 25 days after the initial exposure, whereas those receiving OVA alone did not. Thirty days after the initial challenge (20 days after its completion), mice were re-exposed to OVA. Bronchoalveolar lavage performed 24 h later revealed an influx of eosinophils in the group initially challenged with both ETS and OVA, but not in those exposed to ETS alone or OVA alone. Increases in IL-5, GM-CSF, and IL-2 were observed in bronchoalveolar lavage from this OVA/ETS-exposed group, whereas IFN-γ levels were significantly inhibited. These results suggest that ETS can induce allergic sensitization to a normally harmless Ag, and they may explain why secondhand smoke is a major risk factor for the development of allergy in children. The Journal of Immunology, 2001, 167: 4765–4770.

The worldwide prevalence and severity of allergic disease is increasing in the general population (1–3). Although this increase is probably the result of several factors, epidemiological studies have implicated both a decrease in childhood infections and an increase in environmental pollution as risk factors (reviewed in Ref. 4). Maternal smoking is often associated with allergic disease and increased skin test reactivity, serum IgE, and prevalence of eosinophilia in children. (5–9) However, other studies have failed to see such an association (10) and experimental data supporting these claims is scant. Although the role of pollutants in allergic inflammation has been extensively studied in many animal models, few studies have used these models to study the association between environmental tobacco smoke (ETS) (3) (commonly referred to as "secondhand smoke") and allergy/asthma. Seymour et al. (11) have shown that ETS can exacerbate allergic responses in mice previously sensitized i.p. to OVA before airway OVA exposure; i.e., that ETS can enhance secondary responses. However, a role of ETS in atopic sensitization is still unresolved.

In this study we investigated whether ETS can induce sensitization to OVA (i.e., induce a primary response). In most murine models, repeated aerosolized exposure to protein Ag normally induces tolerance. Although some studies have shown that certain exposure regimes can sensitize mice, in the absence of an adjuvant, to aerosolized OVA (normally an innocuous Ag), no eosinophilia or cytokine changes are observed in these animals. (12) Additionally, increases in Ab responses only occur in IgE high-responder strains of mice (e.g., BALB/c). Sensitization of IgE low-responder strains of mice (e.g., C57BL/6), without prior i.p. immunization, normally requires modulation of the immune system such as over-expression of GM-CSF (13).

We and others (4, 14) have previously shown the potential of particulate pollutants to alter immune function. Thus, the model airborne pollutant, diesel exhaust particles, can induce allergic sensitization in murine models (15–18) and in the human upper airways. (19) In this study we show that ETS can induce sensitization to OVA in both high and low IgE-responder strains of mice via the airway in a manner highly relevant to normal exposures. We demonstrate that not only did ETS induce Ag-specific IgE and IgG1 responses, but also it could promote cytokine changes and airway eosinophilia.

Materials and Methods

Animals

Female BALB/c and C57BL/6 mice were purchased from The Jackson Laboratory (Bar Harbor, ME) and were housed in the UCLA vivarium under specific pathogen-free conditions. The study was approved by the Chancellor’s Animal Research Committee in adherence to guidelines set forth by the National Institutes of Health. Mice were 6–8 wk of age at the onset of each experiment. Additionally, study animals were fed an egg-free chow to preclude them from any environmental exposure to OVA.

Ag and ETS exposure

OVA (Grade V; Sigma-Aldrich, St. Louis, MO) exposure was used as the Ag in this study. Exposure was to a nebulized 1% (w/v) solution of OVA dissolved in PBS for 20 min following a 15-min chamber equilibration. Nebulization was achieved by the Schuco 2000 (Allied Health Care Products, St. Louis, MO) with a flow rate of 6 L/min at the nebulizer cup yielding particle sizes within 0.5–4.0 μm. A control group was exposed to saline alone with no OVA in an identical fashion.

ETS exposure was achieved from the side-stream smoke from 1R4F cigarettes (University of Kentucky Tobacco and Health Research Institute, Lexington, KY). ETS is composed primarily (95%) of side-stream smoke (emitted from the burning zone) and also (4%) smolder stream smoke (emitted from the puffing zone) (20). The reference-filtered cigarette is known to contain 9.2 mg of tar and 0.8 mg of nicotine. (21) It was stored under specific pathogen-free conditions. The study was approved by the Chancellor’s Animal Research Committee in adherence to guidelines set forth by the National Institutes of Health. Mice were 6–8 wk of age at the onset of each experiment. Additionally, study animals were fed an egg-free chow to preclude them from any environmental exposure to OVA.

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3 Abbreviations used in this paper: ETS, environmental tobacco smoke; BAL, bronchoalveolar lavage; DEP, diesel exhaust particles; PAH, polyaromatic hydrocarbons.
in a sealed plastic bag at 4°C to hold proper moisture levels in the ciga-
rettes. Fifteen minutes before use, they were immediately brought to room
temperature and used in an RM G1 Borgwaldt smoking machine (Ham-
burg, Germany) set at one inhalation/exhalation cycle is of a 5-s duration) to
comform to Federal Trade Commission guide-
lines for generation of side-stream smoke. No mainstream smoke entered
the system. ETS was mixed with saline administered as before through a
nebulizer delivering an airflow of 6 L/min. This acted as a pressurizing
agent carrying ETS into and out of the exposure chamber, and it diluted
fatty anoxic concentrations of CO. Mice were challenged with the smoke
from 5 cigarettes administered over the duration of 1 h.

Both ETS and OVA exposures were performed in a sealed system plexi-
glas exposure chamber (Ejay International, Glendora, CA) with an internal
exposure area of 18 x 9 x 9 in. Chambers were cleaned between expos-
ures to each agent to ensure no accidental contamination.

**Exposure protocol**

Groups of six BALB/c or C57BL/6 mice were used. Mice received expo-
sures as detailed above to either: saline, 1% OVA for 20 min, 1 h ETS, or
1 h ETS followed by 1% OVA for 20 min. This procedure was repeated for
10 consecutive days. It is important to note that mice receiving either ETS
alone or ETS plus OVA were placed together in the same chamber and
were challenged simultaneously to ensure identical ETS exposure to both
groups. Similarly, the second and fourth groups received simultaneous
OVA exposure.

Thirty days after the initial challenge (20 days after its completion),
mice were re-exposed to 1% OVA for 20 min. Bronchoalveolar lavage
(BAL) was performed 24 h later by standard methods as previously de-
dcribed. (22)

**Collection of BAL and blood**

Bleeds were performed from the periobital sinus of the eye under me-
thoracotomy anesthesia (Pitman-Moore, Mundelein, IL) before the initial
exposure (day 1) and at several times subsequent to that. Sera were stored
at -70°C until ready for use. BAL was spun at 300 x g for 20 min, and the
supernatant was used for cytokine determination (see below). A total
BAL cell count was performed using a hemacytometer. Cells were
fixed onto slides following cytocentrifugation, and differential staining was
then performed by Wright-Giemsa staining (Dade Behring, Newark, DE). Two
hundred cells were counted under a microscope by two different investi-
gators and the absolute numbers of each cell type were calculated.

**Cytokine and Ig determination**

Cytokine levels were determined in BAL fluid. Specifically, IL-2, IL-4,
IL-5, IFN-γ, and GM-CSF were detected using commercial ELISA kits
consisting of paired Abs and standards (BD PharMingen, San Diego, CA)
per the manufacturer’s instructions. Cytokine levels were measured from
standard curves generated from serial dilutions of the reference standard
provided with each kit. The threshold of detection for IL-2 was 10 pg/ml
IL-4 was 4.1 pg/ml, IL-5 was 15 pg/ml, IFN-γ was 5 pg/ml, and GM-CSF
was 7 pg/ml.

Both total IgE and IgGl were assayed by sandwich ELISA in the pe-
ripheral blood sera of the mice. Briefly, 96-well ELISA plates (Corning
Glass, Corning, NY) were coated overnight with 5 µg/ml Fc region, iso-
type-specific Abs (anti-IgGl and anti-IgE; BD Pharmingen). After wash-
ing and blocking with 1% BSA-PBS, sera samples were placed in wells
overnight. The sera was removed from the plate and washed. Biotinylated,
Fc-specific detecting Abs were added to the corresponding wells in ques-
tion after being diluted 1/500 in a PBS-Tween buffer containing 0.1%
bovine γ globulin and 0.5% BSA plus streptavidin alkaline phosphatase at
1/500. The detection mixture was allowed an incubation of 4 h at room
temperature before detection with PNPP (10 mg/ml). The resultant color
was read at 405 nm on a microplate reader (DPC Cirrus, Randolph, NJ).

**Statistical analysis**

The Statview II computer package (Abacus Concepts, Berkeley, CA) for
the Macintosh was used for all analysis. Comparisons of Ig levels at dif-
ferent times within a group were calculated using a paired t test. Compar-
isons of Ig and cytokine levels between groups were analyzed using the
Mann-Whitney U test.

**Results**

**Allergic Ab induction by OVA plus ETS**

ETS induced sensitization to OVA in our murine model. When the low (C57BL/6)
IgE-responder mice were exposed to aerosolized OVA alone for 10 days, no OVA-specific IgE was observed at any of the time points studied. In contrast, in the group exposed to ETS
plus OVA for 10 days, Ag-specific IgE was apparent 12 days (day 12) after the initial exposure (mean = 318 ± 108 U/ml) and
persisted until day 25 (Fig. 1A). Exposure to OVA alone did result in a
significant increase on day 12 in the high responder BALB/c
strain (Fig. 1B) compared with baseline, but this response was
transient and levels were back to baseline by day 25. BALB/c mice
exposed to both ETS/OVA made significantly higher OVA-IgE
levels than those receiving OVA alone at day 18, and this response
was still significantly above baseline levels at day 30. ETS also
synergized with OVA to significantly elevate total serum IgE in
the low responder C57BL/6 strain (Fig. 1C). Mice exposed to OVA
or OVA alone did not exhibit any change in IgE levels, nor did the
control group that was exposed to saline. In contrast, total IgE
levels in the ETS/OVA groups were significantly elevated from
baseline and were higher than in OVA-exposed animals at days 12,
18, and 25. There was no difference in total IgE levels between BALB/c mice exposed to either OVA alone or ETS/OVA (Fig. 1D).

In mice, IgGl is also an “anaphylactic Ab.” Similar to IgE lev-
els, OVA-IgGl could not be detected at any time in sera from C57BL/6 mice who had received aerosolized OVA alone. How-
ever, by day 12, OVA-IgGl could be detected in mice receiving
both ETS and OVA (Fig. 2A), and it remained elevated up to 30 days after initial exposure. OVA alone did induce OVA-IgGl re-
sponses in BALB/c mice, but this response was significantly
greater in the OVA/ETS group at all time points after day 12 (Fig.
2C). In contrast, ETS did not enhance production of a Th1-driven
isotype, so that in both strains of mice, OVA-IgG1 levels were
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significantly higher in the OVA/ETS group than in the saline
control group that was exposed to saline. In contrast, total IgE
levels in the ETS/OVA groups were significantly elevated from
baseline and were higher than in OVA-exposed animals at days 12,
18, and 25. There was no difference in total IgE levels between BALB/c mice exposed to either OVA alone or ETS/OVA (Fig. 1D).

**Induction of eosinophilia upon rechallenge of ETS and OVA sensitized mice**

The ability of ETS to induce eosinophilia was investigated in high-
and low-responder mice. Mice were exposed to OVA, ETS, or
both for 10 days as before, and then 20 days later (30 days after
initial exposure), the mice were re-exposed to 1% OVA for 20
min. BAL fluid obtained 24 h after re-exposure was assessed for
airway eosinophilia (Fig. 3). Confirming previous studies (12, 23),
BALB/c mice exposed to OVA alone showed no significant
changes in the cellular profile. Total eosinophil, neutrophil,
and mononuclear cell counts were similar in mice groups exposed to
saline, OVA, or ETS alone. However, exposure to the combination
of OVA/ETS resulted in significant eosinophilia following OVA
re-exposure (5.98 x 105 cells/ml vs 0 cells/ml saline control
group, p < 0.01). This increase in eosinophil cell numbers was
accompanied by an increase in total cell numbers in this OVA/ETS
group. Similarly, in the C57BL/6 strain, only in the BAL from
those mice previously exposed to both OVA/ETS was an accumu-
lation of eosinophils detected. Unlike the BALB/c strain, this
group was also characterized by significant increases in neutrophil
as well as total cell numbers, but this was less marked than the eosinophil response.

**Cytokine induction by ETS**

Airway eosinophilia and allergic Ab responses are normally associated with a Th2 cytokine milieu (24, 25). We therefore studied whether ETS exposure could cause a change in the cytokine profile in BAL obtained from C57BL/6 mice following re-exposure to OVA (Table I). In saline-exposed animals, re-exposure to OVA did not result in changes to any of the cytokines measured (IL-2, IL-4, IL-5, GM-CSF, or IFN-γ). Previous exposure to aerosolized OVA resulted in elevated IFN-γ BAL levels upon OVA re-exposure, but no change was seen in other cytokines. In contrast, increases in IL-5, GM-CSF, and IL-2 were observed in BAL from mice with prior exposure to OVA/ETS. In addition, this group also had significantly reduced levels of IFN-γ as compared with the OVA alone exposed group. It is noteworthy that in the ETS alone-exposed animals, compared with the saline control group, significantly increased levels of GM-CSF and IL-2 could be detected.

**Discussion**

The ability of ETS, also known as secondhand smoke, to increase the risk of middle ear effusion, bronchitis, and pneumonia in children is widely accepted (20). Several studies on the epidemiology of the allergic response in children have also implicated ETS in the exacerbation of allergic disease (5–9, 26) and asthma (10). ETS is thought to be especially harmful to children with asthma. The EPA estimates that for between 200,000 and one million asthmatic children, exposure to ETS worsens their condition. (27) ETS can be linked to severity of asthma symptoms, increased prevalence of asthma, increased frequency of medication use, and increased emergency room visits by asthmatic children. (28–31)

The role of ETS in atopic sensitization is more controversial. Our studies aimed to study the association between tobacco smoke and allergic sensitization by direct experimentation. The production of specific allergic Abs against inhaled protein allergens is the hallmark of the sensitization phase of allergic airway disease (allergic rhinitis and asthma); subsequent seasonal exposure leads to a secondary immune response. Many studies have demonstrated elevated IgE levels in active mild smokers (32–35). Studies investigating passive smoke exposure have shown differing results. Among others, Wagner et al. (5) have described a significant increase in serum IgE levels in children of smoking parents. Weiss et al. (6) described a 2.2-fold increased risk of being atopic (as defined by the presence of at least one positive skin test) when maternal smoking occurred. Ronchetti et al. (7) reported both increased skin test reactivity, serum IgE, and increased prevalence of eosinophilia in 9-year-old children of smoking parents. In contrast, other studies have failed to find such a link. Ownby and McCullough (36) found no increase in either total or allergen-specific IgE in children aged 1–19 years exposed to parental smoking. Although Osaka et al. (8) reported an increase in mite-specific IgE levels in Japanese children of smoking parents, Ozasa et al. (9)
found a negative association between Japanese cedar pollen-specific IgE and passive smoking in the same population.

In this study we show that ETS can augment primary sensitization to an innocuous protein. Our studies demonstrate that ETS can initiate de novo responses. Previous reports have studied the ability of ETS to augment pre-established Th2 responses. Seymour et al. (11) sensitized BALB/c mice to OVA and then exposed them to ETS or ambient air. Using this murine model of allergy, this showed that ETS had an adjuvant effect on IgE production and eosinophil numbers in the blood. Moreover, IL-4 and IL-10 was significantly higher in aerosolized allergen-sensitized mice exposed to ETS when compared with those exposed to ambient air. Raised serum IgE levels were found in rats exposed to tobacco smoke twice daily 5 days a week for 8 wk, however, it is unclear whether exposure was limited to only sidestream smoke in these experiments.

Aside from the evidence cited above, the effect of ETS on atopy can be inferred from experiments using other substances. Tobacco smoke contains ~6000 known chemical components, as well as nitrogen dioxide and sulfuric acid (20). Some of these components such as lead acetate, mercuric chloride, nickel sulfate, and tungsten have been shown to increase allergenicity in animal models. We have previously shown that, experimentally, diesel exhaust particles (DEP), a model environmental pollutant, can induce allergic sensitization in a human nasal model. DEP shares many characteristics with tobacco smoke including having a particulate phase and the presence of many similar polyaromatic hydrocarbons (PAH). Of note are the prototypical PAHs benzo(a)pyrene (which is particularly high in sidestream smoke) and phenanthrene, which can also induce IgE and Th2 cytokine responses in mice and in vitro.

The mechanism by which ETS induce primary sensitization has yet to be established. One possibility is that ETS may be improving
Ag presentation either by causing structural modifications to the allergen itself, or by absorption of allergen, thereby causing a more persistent allergen exposure. Allergen adsorption has been observed in vitro after mixing of DEP with the allergen Lol p1. (17) However, it is unlikely that this is the case in these experiments, where ETS and allergen were administered separately. Of course, it is still possible that absorption/modification occurs in the airways themselves. It is more plausible to believe that ETS is altering the environment to one more conducive to allergic sensitization by increasing induction of adhesion molecules, cytokine cascades, or proinflammatory cells. PAHs have been demonstrated to enhance MHC-II gene expression in murine macrophages and to up-regulate CD80 (B7-1) protein (14). In addition, they can affect production of inflammatory cytokines such as GM-CSF, IL-1, and TNF-α (4).

Under normal circumstances, the lungs can be viewed as sites of immunological homeostasis in which repeated aerosolized exposure to protein Ag induces a T cell-mediated immunological tolerance (13, 37). In this study, in the low responder C57BL/6 strain mice; however, this was not accompanied by eosinophilia. In contrast, mice exposed to both OVA and ETS developed eosinophilia had significantly less IFN-γ and had an increase in the Th2 cytokine IL-5. Thus, in our model we have shown that ETS disrupts the initial lung homeostatic mechanism via the airway in a manner highly relevant to normal exposure to permit allergic sensitization characterized by formation of allergic Abs, eosinophilia, and a Th2 cytokine response.

In conclusion, this work demonstrating the potential of ETS to interact with allergen and augments allergic sensitization provides experimental evidence to support studies that suggest that maternal smoking as a risk factor in the development of atopy. Because the prevalence of parental smoking in the U.S. is estimated to be from 40 to 60%, (38, 39), these results may have serious public health implications.

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