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The Enhancement or Prevention of Airway Hyperresponsiveness during Reinfection with Respiratory Syncytial Virus Is Critically Dependent on the Age at First Infection and IL-13 Production

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Respiratory syncytial virus (RSV) infection in early life is suspected to play a role in the development of postbronchiolitis wheezing and asthma. Reinfection is common at all ages, but factors that determine the development of altered airway function after reinfection are not well understood. This study was conducted in a mouse model to define the role of age in determining the consequences on airway function after reinfection. Mice were infected shortly after birth or at weaning and were reinfected 5 wk later, followed by assessment of airway function, airway inflammation, and lung histopathology. Infection of mice at weaning elicited a protective airway response upon reinfection. In this age group, reinfection resulted in increased airway inflammation, but without development of airway hyperresponsiveness (AHR) or eosinophilia and decreased IL-13 levels. By contrast, neonatal infection failed to protect the airways and resulted in enhanced AHR after reinfection. This secondary response was associated with the development of airway eosinophilia, increased IL-13 levels, and mucus hyperproduction. Both CD4- and CD8-positive T cells were a source of IL-13 in the lung, and inhibition of IL-13 abolished AHR and mucus production in these mice. Inoculation of UV-inactivated virus failed to elicit these divergent responses to reinfection, emphasizing the requirement for active lung infection during initial exposure. Thus, neonatal RSV infection predisposes to the development of airway eosinophilia and enhanced AHR via an IL-13-dependent mechanism during reinfection, whereas infection at a later age protects against the development of these altered airway responses after reinfection. The Journal of Immunology, 2005, 175: 1876–1883.

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4 Abbreviations used in this paper: RSV, respiratory syncytial virus; AHR, airway hyperresponsiveness; BALF, bronchoalveolar lavage fluid; BM, basement membrane; cIg, control Ig; MBP, major basic protein; MCh, methacholine; PAS, periodic acid-Schiff; uvRSV, UV-inactivated RSV.

first infected with purified RSV shortly after birth (at <1 wk of age) or at weaning (at 3 wk of age), then reinfect ed 5 wk later, after complete resolution of AHR and airway inflammation. Airway function, airway inflammation, and cytokine production were assessed after both primary and secondary infections. The results were compared with those obtained at the same time after primary infection of age-matched animals and demonstrated the important influence of age at first infection on the response to reinfection.

Materials and Methods

Animals

BALB/c mice were obtained from The Jackson Laboratory. Mice were bred and maintained under pathogen-free conditions at the Biological Resource Center, National Jewish Medical and Research Center. Mice were used under an experimental protocol approved by the institutional animal care and use committee.

Virus preparation

Strain A2 of human RSV (catalogue no. VR-1302) was obtained from American Type Culture Collection. Stocks of purified RSV were prepared under endotoxin-free conditions and were assessed to be free of endotoxin contamination using a Limulus amebocyte lysate-based Pyrogen Plus Gel Clot assay with a sensitivity of 0.06 endotoxin units/ml (BioWhittaker; catalogue no. N283-06). The virus was propagated in monolayers of HEP-2 cells (American Type Culture Collection; catalogue no. CCL-23) grown in MEM (Invitrogen Life Technologies) supplemented with 5% FBS. At maximum cytopathic effect, the cells were harvested and disrupted by sonication in the same culture medium. The suspension was clarified by centrifugation at 10,000 × g for 15 min at 10°C, and the resulting supernatant was layered on top of a sucrose gradient (30% in 50 mM Tris-buffered normal saline solution containing 1 mM EDTA, pH 7.5) and additionally centrifuged at 100,000 × g for 2 h at 10°C. The pellet containing purified virus was resuspended in 10 mM PBS (pH 7.4) containing 15% sucrose and stored at aliquots at −70°C. Viral titers were determined by standard plaque assay combined with immunostaining for RSV using a biotinylated goat anti-human RSV Ab (Accurate Chemical & Scientific) and an avidin-biotin peroxidase detection system (DakoCytomation). Uninfected HEP-2 cell cultures were similarly processed to obtain a control, virus-free, sham preparation.

Experimental design

At the indicated ages, mice were inoculated intranasally with 10⁵ PFU of purified RSV, resuspended in 10 μl (for <1-wk-old mice) or 20 μl (for mice aged ≥3 wk of age) of endotoxin-free PBS. Age-matched control mice were inoculated with the virus-free, sham preparation or UV light (UV)-inactivated RSV. Full inactivation of RSV, as assessed by viral titers and IL-13 levels. The murine IL-13Rα1 (provided by Dr. D. D. Donaldson, Wyeth Pharmaceuticals, Kenilworth, NJ) and MBP were detected by flow cytometry with gating on the CD3-positive cell population using CellQuest software on a FACSCalibur (BD Biosciences). Staining was analyzed by quantitative analyses, the data were normalized to the perimeter of the basal lamina as previously described.

Detection of IL-13 in lung T cells

Intracellular IL-13 was detected by immunofluorescent staining of lung CD4 and CD8 T cells, as previously described. Briefly, lung T cells were isolated by collagenase digestion of lung tissue, followed by separation of mononuclear cells by density gradient centrifugation (Organon Teknika). Lung mononuclear cells were stimulated in culture for 4 h with PMA (5 ng/ml) and ionomycin (500 ng/ml) in the presence of brefeldin A (10 μg/ml). After staining for cell surface markers with CyChrome-conjugated anti-CD3 (Caltag Laboratories) and FITC-conjugated anti-CD4 or anti-CD8 Abs (BD Pharmingen), cells were washed, fixed in paraffinol-dehydrate (4% in PBS), and permeabilized with saponin (0.1% in PBS). After incubation with non-specific goat serum to block non-specific background staining, the permeabilized cells were incubated for 30 min with a biotinylated goat anti-mouse IL-13 Ab or a similarly conjugated isotope-matching control Ab (R&D Systems). Cells were washed and stained for 30 min with PE-conjugated streptavidin (BD Pharmingen). Staining was analyzed by flow cytometry with gating on the CD3-positive cell population using CellQuest software on a FACSCalibur (BD Biosciences).

Statistical analysis

Data are expressed as the mean ± SEM of six to eight mice in each group. Statistical significance at a level of p < 0.05 was determined by ANOVA using the StatView 4.5 statistical analysis software package (Abacus Concepts). Differences between the groups were determined by multiple comparisons using Fisher’s protected least significant difference test.

Results

Age-related differences in airway responsiveness to primary RSV infection

To examine whether the age at first infection determines the extent of airway responsiveness to a primary RSV infection, mice were first infected shortly after birth (<1 wk of age) or at weaning (3 wk of age). Airway function and airway inflammation were assessed on day 6 after infection. Without infection, baseline resistance was significantly higher in the youngest mice (mean ± SEM, 2.25 ± 0.08 cm H₂O/ml · s⁻¹), reflecting smaller airway size, compared with weanling mice (mean ± SEM, 1.24 ± 0.05 cm H₂O/ml · s⁻¹; p < 0.01). Similar to sham-inoculated mice, mice inoculated with UV-inactivated virus (uvRSV) exhibited normal airway responsiveness to inhaled MCh in both age groups (Fig. 1A and B). After RSV infection, the baseline resistance was not altered in any of the age groups (2.36 ± 0.08 cm H₂O/ml · s⁻¹ for the youngest mice and 1.36 ± 0.06 cm H₂O/ml · s⁻¹ for weanling mice). However, RSV infection resulted in the development of AHR in response to inhaled MCh in both age groups.

After primary infection, the numbers of lymphocytes recovered in BALF were significantly increased for both age groups compared with either sham-inoculated or uvRSV-inoculated, age-matched control groups (Fig. 1C and D). The extent of the lymphocytic response, however, was lower in the youngest group. In
tissue, RSV infection resulted in the development of a characteristic peribronchial and perivascular airway tissue infiltration predominantly by mononuclear cells (Fig. 2). Compared with mice infected at weaning, mice infected at <1 wk of age showed more mucus-producing cells in the airways (Fig. 2) and mild, but significant, airway tissue eosinophilia (Table I).

Cytokine levels were measured and compared between the two age groups. IFN-γ levels were higher in the BALF of RSV-infected weanling mice, but were barely detected in the BALF of RSV-infected newborn mice (Fig. 3A). By contrast, IL-13 levels were significantly higher in lung tissue homogenates of RSV-infected newborn mice compared with RSV-infected weanling mice (Fig. 3B). The levels of IL-4 and IL-5 were at the limit of the assay detection and were not different between the two age groups.

Virus replication and clearance were examined in the lungs of both age groups by measuring the amounts of replicating virus recovered from the lungs at different time points after inoculation. No replicating virus was recovered from the lungs of uvRSV-inoculated mice (data not shown), and no significant differences were detected between the two age groups in lung viral titers measured on day 1, 3, or 6 after RSV infection, indicating similar rates of viral replication and clearance for both age groups (Fig. 3C).

RSV infection at weaning protects mice against the development of AHR on reinfection

To define the pattern of airway response to a secondary RSV infection in mice initially infected at weaning and after full recovery, when no significant AHR or airway inflammation could be detected after the primary infection (data not shown), these mice were reinfected 5 wk later (at 8 wk of age). Airway function and airway inflammation were assessed in these animals on day 6 after the secondary infection, and the results were compared with those obtained in age-matched animals after primary infection with RSV (at 8 wk of age) with or without prior inoculation of uvRSV at weaning.

Compared with mice infected only once, at 8 wk of age (Fig. 4A) or at 3 wk of age (Fig. 2), mice that were initially infected at weaning and reinfected 5 wk later developed increased mononuclear airway tissue inflammation after secondary RSV infection (Fig. 4C). Mucus production and tissue-infiltrating eosinophil numbers, however, were not altered after secondary infection in these animals (Table I). In parallel, the numbers of lymphocytes recovered in BALF after reinfection at 8 wk were also increased compared with the numbers of lymphocytes recovered after a primary infection at either 3 or 8 wk of age (Fig. 4D). By contrast, inoculation of uvRSV at weaning did not alter the inflammatory response to subsequent infection with live RSV at 8 wk of age (Fig. 4, B and D). Most surprisingly, in contrast to age-matched control animals that developed significant AHR after a primary RSV infection at 8 wk of age, AHR was completely abolished in the reinfected animals despite the intense inflammatory response that developed in the lungs (Fig. 4E). In parallel, the peak viral titers were significantly reduced in the lungs of these animals (Fig. 4F).

After secondary RSV infection, the levels of IFN-γ detected in BALF were higher than those measured after a primary infection, but the peak response was shifted to an earlier time point after reinfection (Fig. 4G). By contrast, the amounts of IL-13 measured in lung tissue homogenates were significantly reduced after reinfection of mice that were initially infected at weaning (Fig. 4H).

Neonatal RSV infection predisposes mice to the development of eosinophilic airway inflammation and enhanced AHR after reinfection

To determine whether early age at infection predisposes to more severe alterations in airway responsiveness on RSV reinfection, mice were infected shortly after birth (<1 wk of age) and reinfected 5 wk later, when no significant AHR or airway inflammation could be detected after complete recovery from the primary infection (data not shown). Airway function and airway inflammation were assessed in these animals on day 6 after the secondary infection, and the results were compared with those obtained in age-matched animals that received a primary RSV infection (at 6 wk of age) with or without inoculation of uvRSV during the neonatal period (<1 wk of age).

Compared with mice infected only once, either at 6 wk of age (Fig. 5, A and D) or at <1 wk of age (Fig. 2), mice initially infected at <1 wk of age and reinfected 5 wk later developed an
additional increase in airway tissue inflammation (Fig. 5C) associated with markedly enhanced mucus production and pronounced airway tissue eosinophilia (Fig. 5F and Table I) after the secondary RSV infection. The numbers of lymphocytes recovered in the BALF of these animals were significantly increased after secondary RSV infection compared with those recovered after a primary infection in the age-matched group (Fig. 5G). Such altered responses, however, were not observed in animals that were first inoculated as neonates with uvRSV and subsequently infected with RSV 5 wk later (Fig. 5, B, E, and G). Unlike the primary infection, where only rare eosinophils were recovered in the BALF, the secondary infection induced significant airway eosinophilia, as shown by a markedly increased proportion and numbers of eosinophils in the BALF. Interestingly, in contrast to the absence of AHR after secondary infection in mice initially infected at weaning, AHR was not only observed, but was further increased after reinfection in mice that were initially infected early in postnatal life (Fig. 5H). However, despite the enhanced AHR and lung histopathology, the amounts of replicating virus recovered from the lungs of these mice were not different from those in age-matched control animals, which received a single RSV infection with or without previous inoculation with uvRSV (Fig. 5I).

Although IFN-γ was barely detected in BALF of mice that were infected only once, at <1 wk of age, the amounts of IFN-γ measured in BALF after reinfection at 6 wk of age were comparable to those measured after either a primary or a secondary infection in weanling mice (Fig. 5J). In parallel, the amounts of IL-13 detected in lung tissue homogenates were further increased after reinfection of mice that were initially infected at <1 wk of age (Fig. 5K).

Analysis of airway tissue-infiltrating T cells for intracellular IL-13 content by immunostaining and flow cytometry revealed that both CD4-positive and CD8-positive T cells expressed IL-13 (Fig. 6B). Of note, treatment of these mice during the secondary RSV infection with a recombinant murine IL-13Rα2-human IgG fusion protein (IL-13i) completely abolished AHR (Fig. 7A), indicating a central role for IL-13 in the altered airway response to secondary RSV infection in mice initially infected early in life. Inhibition of IL-13 also attenuated airway eosinophilia, without altering mononuclear cell infiltration, in both BALF (Fig. 7B) and airway tissue. The number (mean ± SEM) of airway tissue-infiltrating, MBP-positive cells was significantly lower in mice treated with IL-13i (5.8 ± 1.4/mm BM) than in mice treated with control Ig (clg; 18.3 ± 3.4/mm BM; p < 0.05). Furthermore, IL-13 inhibition completely abolished mucus hyperproduction in the airways of these animals (Fig. 7D). The number of PAS-positive goblet cells was dramatically reduced from 117 ± 13.2 cells/mm BM in clg-treated animals to 16.4 ± 4.1 cells/mm BM in IL-13i-treated animals (p < 0.05).

Discussion

The objective of this study was to define the role of age in the development of altered airway function after reinfection with RSV.
Because recurrent RSV infection is frequent at all ages in humans, but the peak incidence for primary and secondary RSV-related lower respiratory tract disease is in infancy (9, 16), we hypothesized that the development of altered airway function during reinfection with RSV is determined in an age-dependent manner, at the time of initial infection. As demonstrated in the present study, neonatal RSV infection predisposes mice to develop more severe airway disease on reinfection. This amplified and altered response to reinfection is characterized by the development of significant AHR associated with marked airway eosinophilia. By contrast, primary infection at weaning elicited a protective airway response to reinfection characterized by an increased inflammatory response, predominantly lymphocytic, but without development of AHR and airway eosinophilia. However, these divergent responses to reinfection were not elicited if the mice were initially inoculated with uvRSV, clearly demonstrating the requirement for active lung viral infection during initial exposures. Most remarkably, viral clearance was achieved at similar rates, and AHR developed to the same extent in both age groups, after the primary infection. The most distinctive differences between the two ages in terms of response to primary RSV infection were lower IFN-γ, but increased IL-13, levels in the lungs of neonatally infected animals. However, after reinfection, greater amounts of IFN-γ were detected in BALF and were comparable in both age groups. By contrast, after reinfection, the levels of IL-13 were further increased in mice initially infected as neonates, but were virtually undetectable in mice initially infected at weaning. From these data it is clear that the consequences of reinfection are established very early in life. Thus, if infected early in life, the host might not be able to mount the appropriate response that would protect against the consequences of reinfection.

In general, recurrent RSV infection results in milder symptoms, usually restricted to the upper respiratory tract in young children and adults (24, 25), but in some cases more severe symptoms involving the lower respiratory tract can develop after secondary RSV infection, resulting in recurrent wheezing in younger children. A recent prospective study evaluated RSV-specific T cell responses in the peripheral blood of 55 infants hospitalized for RSV bronchiolitis and found that the lymphoproliferative responses to RSV stimulation in vitro were similar during both acute and convalescent phases of bronchiolitis and were not enhanced after a subsequent episode of natural RSV infection during...
the second winter season (26). These observations led the investigators to conclude that RSV-specific T cell responses do not provide protection against reinfection and to speculate that RSV-specific T cells may fail to expand in vivo after reinfection. However, it is possible that these cells could be compartmentalized to specific locations in the lung and respond more vigorously in situ upon secondary RSV infection, as demonstrated in previous experimental animal studies (27, 28). A recent study conducted in mice suggested that the extent of the BALF inflammatory response to reinfection in adulthood is determined by the age at first infection (29). They showed that the pattern of inflammatory (lymphocytic) response to reinfection in adulthood differs depending on the age at first infection with RSV, and that neonatal infection primes the host to develop a Th2-biased response. Our data not only extend these findings, but additionally demonstrate that the enhancement of AHR during reinfection requires IL-13, is associated with airway eosinophilia and mucus hyperproduction, and is determined in an age-dependent manner at the time of initial infection with RSV. This is contrasted with the protective response against development of AHR and the absence of airway eosinophilia and mucus production despite the marked BAL and lung lymphocytic accumulation elicited on reinfection of mice initially infected at weaning.

In both humans and animal models, the Th2 cytokine IL-13 has been identified as a central mediator of AHR (18, 30). IL-13 is also a major regulator of mucus production in the airways (31), and to some degree it contributes to the development of airway eosinophilia (32). The role of IL-13 in RSV-mediated airway disease is to some extent controversial. IL-13 production is increased along with that of other Th2 cytokines in the lungs of mice previously primed with formalin-inactivated RSV and subsequently infected with live virus (33). Unlike formalin-inactivated RSV, the secreted form of the attachment G glycoprotein of RSV appears to preferentially prime the animals to develop high levels of IL-5 and IL-13 and pulmonary eosinophilia, even in the complete absence of IL-4 (34). Given the marked increases in IL-13 production detected in the present study, especially in mice reinfected after primary infection as neonates, we determined the cellular source of this cytokine and defined its role in the development of mucus production, airway eosinophilia, and AHR in this group. Intracellular staining of isolated
lung T cells revealed that both CD4 and CD8 T cells were a source of IL-13, and the frequency of these cells was significantly increased after reinfection of the youngest mice. Furthermore, treatment of these animals with murine IL-13Rα2-human IgG fusion protein during secondary RSV infection completely abolished the development of AHR and mucus production and significantly inhibited airway eosinophilia. In contrast to our earlier studies of the role of IL-13 in primary RSV infection (20), these data clearly identified IL-13 as a central mediator involved in the development of AHR after reinfection of mice initially infected as neonates.

The role of IFN-γ in RSV-mediated airway disease is not clear. Several clinical studies have described an imbalance in Th1/Th2 cytokine expression with a predominant Th2-like response. This has been generally attributed to deficient IFN-γ production, associated with lower respiratory tract disease in infants and young children with documented RSV infection (35–38). More recently, a prospective study examined type 1 and type 2 cytokine responses in high-risk infants (at least one atopic parent with asthma) to their first natural RSV infection and related the response to the onset of disease (39). In particular, the levels of IFN-γ measured in nasal lavage samples taken at the first signs of symptoms were significantly lower in infants who developed lower respiratory tract disease (bronchiolitis) than in those who developed upper respiratory symptoms alone. When PBMC were stimulated in vitro, deficient IFN-γ production could also be demonstrated in infants with more severe symptoms, corroborating the results obtained in vivo. IFN-γ production is restricted to T cells and NK cells. Although produced in large amounts in the lungs of RSV-infected adult mice, IFN-γ did not appear to be involved in the development of AHR (40). The present study provides additional evidence that IFN-γ is not involved in the development of AHR. In particular, AHR was completely abolished after reinfection despite high levels of IFN-γ in the lungs of mice that were initially infected at weaning. Similarly, IFN-γ was not apparently protective, because mice infected at <1 wk of age and reinfeected 5 wk later developed enhanced AHR despite high levels of IFN-γ. As demonstrated by the inhibition studies, IL-13 appears to be a major regulator of AHR and mucus hyperproduction after reinfection.

It is well known that immune responses change with advancing age. In general, the responses are compared at widely different ages; in the mouse aged is defined as older than 6 mo in some studies. In contrast, it appears that significant differences in terms of the consequences of re-exposure are established very early in life. Thus, in an allergen challenge model, the age at initial sensitization was critical in dictating the degree of airway (eosinophilic) inflammation, the profile of cytokine production, and AHR on subsequent allergen challenge (41). In an analogous fashion, the present study demonstrates that the age at first RSV infection, even within the narrow window of primary infection at 1 wk vs primary infection at 3 wk, is sufficient to establish the consequences of reinfection. It is not entirely clear what the underlying mechanisms are. It is possible, at least in part, that a neonatal deficiency in IFN-γ production during primary infection, perhaps due to immaturity of the host immune response rather than the result of an aberrant response to viral infection, allows for the development of an unopposed, Th2-biased response that persists and can be re-stimulated during subsequent infection by RSV. However, it is unlikely that simple differences in the levels of IFN-γ dictate or account for this narrow window of susceptibility. IL-13 does emerge as a major regulator, at least of the enhanced response to reinfection of young mice. When extrapolated to the human situation and exposures in the neonate/young infant, these studies highlight the importance of developing preventative or delaying strategies, so that the consequences of initial RSV infection may be mitigated by the age at which they occur.

![FIGURE 6](http://www.jimmunol.org)  
**FIGURE 6.** Cellular source of IL-13 production in the lung after the secondary infection in mice initially infected as neonates (same groups as described in Fig. 5). T cells were isolated from collagenase-digested lung tissue and simultaneously stained for surface expression of CD3 and CD4 or CD8, followed by intracellular staining for IL-13 and analysis of expression by flow cytometry. A, Representative flow cytometry panels showing IL-13-expressing lung T cells in the three groups of mice. B, Proportion (mean ± SEM) of IL-13-expressing lung T cells. Both CD4-positive and CD8-positive lung T cells expressed IL-13, and the proportions of these cells were further increased after the secondary infection compared with primary infection. *, Significant difference compared with sham group (p < 0.05); §, significant difference compared with RSV(6wk) (p < 0.05).

![FIGURE 7](http://www.jimmunol.org)  
**FIGURE 7.** Role of IL-13 in the development of enhanced AHR, airway inflammation, and mucus production during secondary RSV infection. Mice were initially infected as neonates and treated with IL-13i (RSV(1wk)/RSV(6wk) + IL-13; n = 6) or control Ig (RSV(1wk)/RSV(6wk) + cIg; n = 6) during reinfection. Airway responsiveness to inhaled MCh (A), bronchoalveolar lavage cellularity (B), and lung histopathology (C and D) were assessed on day 6 after the secondary infection. Neutralization of IL-13 resulted in significant inhibition of AHR (A) and airway eosinophilia in both bronchoalveolar lavage (B) and tissue (see text), and abolished mucus hyperproduction in the airways (D, arrows) without altering mononuclear airway inflammation in bronchoalveolar lavage (B) or tissue (C and D, arrowheads). Scale bars = 50 μm. *, Significant difference compared with sham group (p < 0.05); §, significant difference compared with cIg-treated group (p < 0.05).