Asthma is a pulmonary disorder in which episodic dyspnea is caused by reversible bronchospasm (Steel and Holgate, 2001). Increased susceptibility to bronchospasm presumably results from qualitative and/or quantitative increases in the contractility of airway smooth muscle. Increased contractility could result from changes intrinsic to smooth muscle (increases in the number, size, and/or responsiveness of smooth muscle cells to stimuli that induce contraction) or from changes in other cell types such as neural cells, infiltrating inflammatory cells and epithelial cells that produce stimuli that promote smooth muscle contractility. In human asthmatics and animals with experimental allergic airway disease, the predisposition to bronchospasm is manifested as airway hyperresponsiveness (AHR; Steel and Holgate, 2001; Lewkowich and Wills-Karp, 2008), an increased sensitivity to agents such as acetylcholine and methacholine, which induce smooth muscle contraction in normal individuals.

Production of the cytokines IL-4 and IL-13 is increased in both human asthma and mouse asthma models, and Stat6 activation by the common IL-4/IL-13R drives most mouse model pathophysiology, including airway hyperresponsiveness (AHR). However, the precise cellular mechanisms through which IL-4Rα induces AHR remain unclear. Overzealous bronchial smooth muscle constriction is thought to underlie AHR in human asthma, but the smooth muscle contribution to AHR has never been directly assessed. Furthermore, differences in mouse versus human airway anatomy and observations that selective IL-13 stimulation of Stat6 in airway epithelium induces murine AHR raise questions about the importance of direct IL-4R effects on smooth muscle in murine asthma models and the relevance of these models to human asthma. Using transgenic mice in which smooth muscle is the only cell type that expresses or fails to express IL-4Rα, we demonstrate that direct smooth muscle activation by IL-4, IL-13, or allergen is sufficient but not necessary to induce AHR. Five genes known to promote smooth muscle migration, proliferation, and contractility are activated by IL-13 in smooth muscle in vivo. These observations demonstrate that IL-4Rα promotes AHR through multiple mechanisms and provide a model for testing smooth muscle–directed asthma therapeutics.

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expression in human asthmatic lungs (Huang et al., 1995; Kotsimbos et al., 1996; Humbert et al., 1997), the association of specific IL-4Rα alleles with risk for atopic asthma (Rosa-Rosa et al., 1999), and observations that inhalation of an IL-4R antagonist improves pulmonary function in human asthmatics (Wenzel et al., 2007) suggest that a similar pathophysiological process is involved in human asthma. However, it is not known whether IL-4 and IL-13 induce AHR through direct effects on airway smooth muscle. Although IL-13 increases smooth muscle contractility when added to cultures of airway smooth muscle cells (Shore and Moore, 2002; Shore, 2004b), airway smooth muscle isolated from human asthmatics is not consistently hypercontractile (Wills-Karp, 1997). Furthermore, IL-13 induces AHR in transgenic mice that only express Stat6 in pulmonary epithelial cells (Kuperman et al., 2002). These observations suggest that AHR might result from changes in the properties of airway epithelium such as increased swelling, permeability, rigidity, and mucus production that decrease airway diameter rather than from changes in smooth muscle. Alternatively, Stat6-mediated effects on epithelial cells could stimulate the production of mediators that affect airway smooth muscle.

Recent studies with mice that selectively lack IL-4Rα on smooth muscle are also consistent with the sufficiency of IL-4 or IL-13 effects on airway epithelium for induction of AHR. Intraperitoneal immunization with ovalbumin bound to alum, followed by ovalbumin inhalation, induced AHR, goblet cell hyperplasia, and airway eosinophilia, as well as Th2 cytokine and IgE secretion, which were similar in mice that expressed IL-4Rα normally or that selectively deleted IL-4Rα from smooth muscle cells, whereas similar immunization of mice totally deficient in IL-4Rα failed to induce any of these effects (Kirstein et al., 2010). The normal responsiveness of mice that selectively lacked smooth muscle IL-4Rα in this model was somewhat surprising, inasmuch as studies with the same mice demonstrated decreased Th2 cytokine expression and airway goblet cell hyperplasia after infection with the nematode parasite Nippostrongylus brasiliensis (Horsnell et al., 2007, 2011).

These results were consistent with some analyses of pulmonary function assays in rodents, which support the view that increased AHR in experimental models of allergic airway disease results predominantly from changes in epithelial rather than smooth muscle cells (Wagers et al., 2004); however, this view is not universal (Glaab et al., 2007). In fact, IL-4Rα-mediated effects on epithelial cells are not likely to totally account for increased AHR because allergen inhalation still induces AHR in mice in which the signaling IL-4R polypeptide, IL-4Rα, has been selectively deleted from epithelial cells (Kuperman et al., 2005). Collectively, the in vivo observations made with IL-4Rα and Stat6 transgenic mice suggest that IL-4R signaling induces AHR through direct effects on more than one cell type and leave open the possibility that AHR development is promoted by direct IL-4R signaling of smooth muscle cells. We have evaluated this possibility by examining the effects of IL-4, IL-13, and allergen immunization in transgenic mice that express IL-4Rα only in smooth muscle, as well as a second set of mice that have selectively deleted IL-4Rα from smooth muscle. Our results demonstrate that selective smooth muscle expression of IL-4R is sufficient for cytokine-dependent induction of AHR and that this occurs in the absence of pulmonary eosinophilia or goblet cell hyperplasia. Our results also identify molecular mechanisms by which IL-4Rα signaling may induce AHR by demonstrating that IL-13 inhalation by mice that express IL-4Rα in smooth muscle induces five genes already known to increase smooth muscle proliferation, migration, and contractility. Finally, we confirm that direct smooth muscle responsiveness to IL-4/IL-13 is not required for induction of AHR by demonstrating that AHR develops, along with airway eosinophilia and goblet cell hyperplasia, in IL-13−/− and allergen-inoculated mice that selectively lack IL-4Rα on smooth muscle. These observations demonstrate that direct effects of IL-4 and IL-13 on smooth muscle are sufficient but not necessary for induction of AHR, provide a tool that can be used to study how effects of these cytokines on smooth muscle influence AHR in human asthma, and identify novel smooth muscle–associated targets for asthma therapy.

RESULTS

Generation of mice that selectively express IL-4Rα on smooth muscle cells

To determine whether IL-4Rα signaling restricted to smooth muscle cells can induce responses characteristic of murine allergic airway disease, we produced mice that express a transgene for IL-4Rα controlled by the smooth muscle–specific promoter SMP8 (see Materials and methods) and bred these mice for more than eight generations to BALB/c IL-4Rα−/− defective mice (Mountford et al., 2001) to produce mice that expressed a single allele of the SMP8-IL-4Rα transgene and two null alleles for the normal IL-4Rα gene (IL-4Rα−/−/SMP8−IL-4Rα+/−). Four approaches were tried to determine whether IL-4Rα−/−/SMP8−IL-4Rα+/− mice express IL-4Rα only in smooth muscle. Staining tissue sections with a probe specific for IL-4Rα messenger RNA or with an anti–IL-4Rα mAb proved unsatisfactory because of a low signal to noise ratio. Instead, we prepared single cell suspensions of spleen cells, tracheal smooth muscle cells, lung macrophages, and tracheal epithelial cells from wild-type (IL-4Rα+/+) mice, IL-4Rα−/− mice, IL-4Rα−/−/SMP8−IL-4Rα−/− mice, and IL-4Rα−/−/SMP8−IL-4Rα−/− mice, stained these cells with TO-PRO-3 iodide (Invitrogen) to eliminate dead cells and with anti–IL-4Rα mAb, and analyzed IL-4Rα staining by flow cytometry. We observed greater staining of spleen cells and lung macrophages from IL-4Rα+/+ mice than IL-4Rα−/−/− mice, with approximately half as much staining by spleen cells from IL-4Rα+/+ mice (Fig. 1, A [top], B, and C). Spleen cells from IL-4Rα−/−/−/SMP8−IL-4Rα−/− mice stained similarly to spleen cells from IL-4Rα−/−/− mice (Fig. 1, A [top] and B). Tracheal smooth muscle cells from IL-4Rα−/−/− mice stained approximately twice as brightly as tracheal smooth muscle cells from either IL-4Rα+/+ or
IL-4Rα<sup>−/−</sup>/SMP8–IL-4Rα<sup>+/−</sup> mice, and these stained more brightly than tracheal smooth muscle cells from IL-4Rα<sup>−/−</sup> mice (Fig. 1A [middle] and D). Tracheal epithelial cells from IL-4Rα<sup>−/−</sup>/SMP8–IL-4Rα<sup>+/−</sup> mice stained no more brightly than tracheal epithelial cells from IL-4Rα<sup>−/−</sup> mice and less brightly than tracheal epithelial cells from IL-4Rα<sup>+/−</sup> mice (Fig. 1A, bottom). Thus, the SMP8–IL-4Rα transgene induces approximately the same amount of IL-4Rα expression as the normal IL-4Rα gene on smooth muscle cells and does not induce IL-4Rα expression on spleen cells or on pulmonary epithelial cells.

Because it was not possible to determine IL-4Rα expression on all cell types by immunofluorescence staining and flow cytometry, we investigated the specificity of the SMP8 promoter for smooth muscle by breeding SMP8-Cre mice with B6.129 × 1-Gt(ROSA)26.Sor<sup>tm1[EYFP]Crg/J</sup> mice (Rosa-YFP mice; Druckenbrod and Epstein, 2005), in which YFP is produced by cells that express Cre, and evaluating frozen sections of lung, intestine, and liver for YFP expression by fluorescence microscopy. YFP expression was restricted to smooth muscle cells in the lung (Fig. 1E), small intestine, and artery (Fig. S1).

Effects of inhaled IL-13 and IL-4 on mice that selectively express IL-4Rα on smooth muscle
IL-4Rα<sup>+/−</sup>, IL-4Rα<sup>−/−</sup>, and IL-4Rα<sup>−/−</sup>/SMP8–IL-4Rα<sup>+/−</sup> mice were inoculated intratracheally (i.t.) with IL-13 or saline (2–3 µg/day for 7 d) and tested for responsiveness to cholinergic stimulation by noninvasive barometric plethysmography, the invasive air pressure–time index (APTI) technique,

![Figure 1. Evaluation of IL-4Rα expression in IL-4Rα<sup>−/−</sup>/SMP8–IL-4Rα<sup>+/−</sup> mice.](image-url)
i.t. inoculation of all three mouse strains with IL-4C (a long-acting form of IL-4) also stimulated AHR in IL-4Rα−/−, IL-4Rα+/−, and IL-4Rα−/−/SMP8–IL-4Rα−/− mice but not IL-4Rα−/− mice (Fig. 3, A–C). However, in contrast to IL-13, IL-4C had a greater effect on airway responsiveness in the IL-4Rα−/−/SMP8–IL-4Rα−/− mice than in IL-4Rα+/− or even IL-4Rα+/+ mice. IL-4C inhalation induced some increase in airway responsiveness in IL-4Rα−/−/SMP8–IL-4Rα−/− mice in as little as 24 h, as determined by barometric plethysmography, although greater effects at higher doses of methacholine were seen after 3 d (Fig. 3 D). IL-4C resembled IL-13 more closely in that it induced BAL fluid eosinophilia (Fig. 3 E) and goblet cell hyperplasia (Fig. 3 F) only in the mice that expressed a wild-type IL-4Rα allele. None of the IL-4C– or IL-13–inoculated mice showed convincing airway smooth muscle hyperplasia or hypertrophy by histological examination (unpublished data).

Effects of allergen inhalation on mice that selectively express IL-4Rα on smooth muscle

To determine whether AHR could be induced by endogenously produced IL-4/IL-13 in IL-4Rα−/−/SMP8–IL-4Rα−/− mice, these mice as well as IL-4Rα+/− and IL-4Rα−/− mice were inoculated i.t. thrice weekly for 3 wk with dust mite allergen, which induces allergic airway disease in wild-type BALB/c mice without a requirement for systemic priming with allergen plus adjuvant (Johnson et al., 2004; Lewkowich et al., 2005). Dust mite inoculation induced AHR in IL-4Rα+/− mice but not in IL-4Rα−/− mice as measured by barometric plethysmography but was similar as measured by the two invasive techniques. IL-13 inhalation increased airway responsiveness in both IL-4Rα−/−/SMP8–IL-4Rα−/− and IL-4Rα+/− mice but had a greater effect in the IL-4Rα+/+ mice. This difference was observed with both the invasive and non-invasive techniques but was most apparent when the invasive techniques were used.

Figure 2. i.t. inoculation of IL-4Rα−/−/SMP8–IL-4Rα+/− mice with IL-13 induces AHR but not goblet cell hyperplasia or BAL fluid eosinophilia. (A–C) IL-4Rα+/+, IL-4Rα−/−, and IL-4Rα+/−/SMP8–IL-4Rα+/− mice were inoculated daily i.t. with saline or 2 or 3 µg IL-13 for a consecutive 7 d and tested for responsiveness to methacholine by barometric plethysmography (A; three experiments, pooled data, n = 11–13/group), flexiVent (B; one experiment, n = 4–7/group), and APTI (C; one experiment, n = 3–5/group). (D) Numbers of BAL neutrophils, lymphocytes, macrophages, and eosinophils (three experiments, pooled data, n = 11–12/group). (E) Lung sections were PAS stained and evaluated for percentage of PAS+ bronchial epithelial cells (one of three experiments with similar results shown, n = 4–5/group). Error bars indicate SEs. *, P < 0.05 for IL-13 versus saline treatment.
Because the failure of IL-4Rα−/−/SMP8–IL-4Rα+/- mice to develop AHR might result from a poor IL-4/IL-13 response to dust mite allergen inoculation also induced an IgE response in IL-4Rα−/−/SMP8–IL-4Rα+/- mice but not in IL-4Rα+/- or IL-4Rα+/-/SMP8–IL-4Rα+/- mice (Fig. 4 D), much greater eosinophil responses in IL-4Rα−/− mice than in IL-4Rα+/- or IL-4Rα+/-/SMP8–IL-4Rα+/- mice (Fig. 4 E), and goblet cell responses only in IL-4Rα−/− mice (Fig. 4 F).

Because the failure of IL-4Rα−/−/SMP8–IL-4Rα+/- mice to develop AHR, as demonstrated by the invasive techniques might result from a poor IL-4/IL-13 response to dust mite allergen by the IL-4Rα-deficient T cells in these mice (Fig. 4 G) rather than from the inability of their lung epithelial cells to respond to these cytokines, we performed an additional experiment in which the same mouse strains were injected with bronchial lymph node cells from dust mite–immunized wild-type BALB/c mice before i.t. inoculation of the recipients with dust mite allergen. This protocol induced the development of AHR in both IL-4Rα+/- and IL-4Rα−/−/SMP8–IL-4Rα+/- mice but not in IL-4Rα+/- mice, as determined by barometric plethysmography, flexiVent analysis, and APTI (Fig. 5, A and B). Both the IL-4Rα+/- and IL-4Rα−/−/SMP8–IL-4Rα+/- recipients of allergen-primed wild-type bronchial lymph node cells developed more BAL eosinophilia and goblet cell hyperplasia than mice that were not immunized but considerably less than allergen-inoculated IL-4Rα+/- mice (Fig. 5, C and D), whereas most IL-4Rα+/- mice and some IL-4Rα+/-/SMP8–IL-4Rα+/- mice developed increased serum IgE levels (Fig. 5 E).

IL-13 induction of pulmonary gene expression
These observations demonstrated that AHR can be induced through direct, in vivo effects of IL-4R signaling on smooth muscle and were consistent with previous in vitro evidence that IL-4R signaling can increase smooth muscle contractility (Laporte et al., 2001; Tliiba et al., 2003; Shore, 2004b; Akiho et al., 2005; Kellner et al., 2007; Bossé et al., 2008; Farghaly et al., 2008; Martin et al., 2008; Ohta et al., 2008; Woodruff, 2008). However, they offered no insight into the mechanisms through which IL-4R signaling induces these effects. To shed light on possible mechanisms, a comprehensive gene scan was performed to identify genes in lung whose expression was
increased or decreased by a factor >1.5 by IL-13 inhalation in IL-4Rα+/+ and IL-4Rα−/−/SMP8–IL-4Rα+/+ mice but not in IL-4Rα−/− deficient mice. Results (GEO DataSets accession no. GSE26476), confirmed by real-time PCR, revealed five genes, Timp1, Egln3, Myocd, Vcan, and Rab39b, whose expression was significantly increased in IL-4Rα−/−/SMP8–IL-4Rα+/+ mice by IL-13 inhalation and which were expressed at a greater level in IL-13–inoculated IL-4Rα−/−/SMP8–IL-4Rα+/+ mice than in IL-4Rα−/− mice (Fig. 6 A, top six panels). Expression of a sixth gene, Tafirs11, which was originally identified by our gene scan, was significantly greater in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/+ than IL-4Rα−/− mice but not significantly greater in IL-13–treated than in saline-treated IL-4Rα−/−/SMP8–IL-4Rα+/+ mice (P = 0.07). Remarkably, all of these genes were already known to be expressed in smooth muscle and to contribute to smooth muscle cell differentiation, proliferation, contractility, and/or migration (Table 1). An additional 12 genes were identified by gene scan to decrease lung expression in response to inhaled IL-13 in IL-4Rα−/−/SMP8–IL-4Rα+/+ but not in IL-4Rα−/− mice; however, this was not confirmed by real-time PCR (unpublished data). As expected, several genes known to be induced by IL-4R signaling in epithelial cells and macrophages were strongly induced by IL-13 inhalation in IL-4Rα−/− mice but not in IL-4Rα−/− or IL-4Rα−/−/SMP8–IL-4Rα+/+ mice (results are shown in Fig. 6 A for Ihlb and Spr2a; Arg, Muc5ac, Mnp12, Chi3l3, Retnlb, Chia, and Cka3 were also expressed at least 40-fold more in IL-4Rα−/− mice than in IL-4Rα−/−/SMP8–IL-4Rα+/+ mice that had inhaled IL-13). These observations suggest several potential mechanisms for induction of AHR by IL-4 and IL-13 and provide an independent confirmation of the smooth muscle specificity of IL-4Rα expression in IL-4Rα−/−/SMP8–IL-4Rα+/+ mice.

To determine whether any of the five genes that were induced by IL-13 in IL-4Rα−/−/SMP8–IL-4Rα+/+ mice are induced selectively in smooth muscle, we evaluated their expression along with expression of Tafirs11, Ihlb, and Spr2a in SMP8–Cre+/−/IL-4Rαlox−/− mice, which were designed to express IL-4Rα on all cell types except for smooth muscle (Fig. 1, A and D–F). As expected, IL-13 greatly up-regulated expression of Ihlb and Spr2a in these mice (Fig. 6 B). IL-13 also up-regulated expression of Tafirs11, Egln3, and Vcan in these mice, suggesting that these genes are up-regulated by IL-13 in nonsmooth muscle as well as smooth muscle cells. In contrast, Myocd and Rab39b were not up-regulated by
IL-13 in these mice, even though they were up-regulated by IL-13 in IL-4Rα+/− and IL-4Rα−/−/SMP8–IL-4Rα+/− mice (Figs. 6, A and B). This suggests that Myocd and Rab39b are selectively up-regulated by IL-13 in smooth muscle cells and makes them attractive potential therapeutic targets.

Expression of IL-4Rα by smooth muscle is not essential for induction of AHR by IL-13 or allergen

A previous study suggested that IL-4Rα expression by smooth muscle should not be essential for cytokine induction of AHR, by demonstrating that AHR develops in mice that overexpress IL-13 in their lungs and express Stat6, which is a transcription factor required for IL-4/IL-13–induced AHR, only in airway epithelium (Kuperman et al., 2002). This result was recently confirmed in a study that used the smooth muscle myosin heavy chain promoter rather than SMP8 to AHR, in addition to airway eosinophilia and goblet cell hyperplasia, was induced by inhalation of either IL-13 or dust mite allergen in IL–4Rα−/−/SMP8–Cre+/− versus IL–4Rα−/− and IL–4Rα+/− mice.

DISCUSSION

AHR, a hallmark of asthma and cause of asthma morbidity, is induced by IL–4 and IL–13 in mice and associated with the same cytokines in humans. Because IL–4/IL–13R expression is ubiquitous, AHR could, in theory, result from IL–4/IL–13 effects on almost any cell type. Stimulation of lymphocytes, macrophages, mast cells, basophils, or dendritic cells, for example, might induce production of vasoactive mediators that promote AHR through their effects on epithelial cells, neurons, or smooth muscle cells or induce production of chemokines that attract inflammatory cells whose activities induce AHR.
Although a previous study demonstrated that direct IL-13 activation of Stat6 in airway epithelial cells induces AHR in mice (Kuperman et al., 2002) and AHR has been reported to depend on the products of epithelial cell–expressed genes that are induced by IL-4/IL-13 (Howarth et al., 1995; Goto et al., 2000; Poynter et al., 2002; Zhu et al., 2004; Kawada et al., 2007), a study that demonstrated that AHR still develops in allergen-inoculated mice that have selectively deleted IL-4R α from airway epithelium (Kuperman et al., 2005) indicates that IL-4/IL-13 effects on other cell types must also be capable of inducing AHR. This justified consideration of smooth muscle, a cell type implicated in AHR by in vitro human and animal studies. These studies demonstrated that IL-13 increases the

![Figure 6](https://example.com/figure6.png)

**Figure 6.** IL-13–induced pulmonary smooth muscle gene expression. (A) Mice of the indicated genotype were inoculated i.t. with normal saline or 3 µg IL-13 for a consecutive 7 d. Lung RNA was prepared and analyzed in an initial experiment by gene scan to identify genes that were increased at least twofold in IL-13– versus saline-treated IL-4Rα+/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα+/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice and for genes that were expressed >10-fold more in IL-13–treated IL-4Rα+/− versus IL-4Rα−/− mice (gene scan performed with two separate groups of four mice each for each genotype and treatment). Results of the gene scan were verified by real-time PCR with the same RNA samples and with RNA prepared from lungs from two additional experiments. Total of 18–22 mice for each genotype/treatment group. To pool data from different experiments, the mean value for each gene in the IL-4Rα−/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice (gene scan performed with two separate groups of four mice each for each genotype and treatment). Results of the gene scan were verified by real-time PCR with the same RNA samples and with RNA prepared from lungs from two additional experiments. Total of 18–22 mice for each genotype/treatment group. To pool data from different experiments, the mean value for each gene in the IL-4Rα−/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice (gene scan performed with two separate groups of four mice each for each genotype and treatment). Results of the gene scan were verified by real-time PCR with the same RNA samples and with RNA prepared from lungs from two additional experiments. Total of 18–22 mice for each genotype/treatment group. To pool data from different experiments, the mean value for each gene in the IL-4Rα−/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice (gene scan performed with two separate groups of four mice each for each genotype and treatment). Results of the gene scan were verified by real-time PCR with the same RNA samples and with RNA prepared from lungs from two additional experiments. Total of 18–22 mice for each genotype/treatment group. To pool data from different experiments, the mean value for each gene in the IL-4Rα−/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice (gene scan performed with two separate groups of four mice each for each genotype and treatment). Results of the gene scan were verified by real-time PCR with the same RNA samples and with RNA prepared from lungs from two additional experiments. Total of 18–22 mice for each genotype/treatment group. To pool data from different experiments, the mean value for each gene in the IL-4Rα−/−/SMP8–IL-4Rα+/− mice and at least twofold in IL-13–treated IL-4Rα−/−/SMP8–IL-4Rα+/− versus IL-4Rα−/− mice
Table I. Pulmonary genes induced by i.t. IL-13 in IL-4Rα−/−/SMP8–IL-4Rαflox mice

| Gene       | Alternate name | Description                                                                 | Reference               |
|------------|----------------|------------------------------------------------------------------------------|-------------------------|
| Egln3      | EGL nine homologue 3 | A prolyl hydroxylase, involved in muscle differentiation, most highly expressed in muscle. | Fu et al., 2007         |
| Vcan       | Versican, chondroitin sulfate glycoprotein 2 (Cspg2) | A large chondroitin sulfate proteoglycan that is deposited in the airway smooth muscle layer in patients with asthma; promotes proliferation and migration of vascular smooth muscle cells. | Huang et al., 2006     |
| Myocd      | Myocardin     | The dominant driver of smooth muscle differentiation and the smooth muscle contractile phenotype | Pipes et al., 2006      |
| Rab39b     | Ras-related protein Rab 39B | A member of the RAS oncogene family; small molecular weight GTPases that control vesicular trafficking. Ras family signaling is associated with differentiation, proliferation, and hypertrophy. | Sugden, 2003           |
| Timp1      | Tissue inhibitor of metalloproteinase 1 | Expressed in dystrophic and regenerating muscle fibers, blocks extracellular matrix degradation. | Untergasser et al., 2005; Sun et al., 2006 |
| Tnfrsf11b  | TNF receptor superfamily, member 11b, osteoprotegerin (OPG) | Produced by smooth muscle cells; stimulates proliferation and migration of pulmonary artery smooth muscle cells in vitro. | Lawrie et al., 2008     |

**Figure 7.** IL-13 induces allergic airway disease in mice that selectively lack IL-4Rα in smooth muscle. (A, top) Mice of the indicated genotype were inoculated i.t. with saline or 3 µg IL-13 thrice weekly for 3 wk and then analyzed for AHR by barometric plethysmography (two pooled experiments, n = 6–14/group). (bottom) Mice were then inoculated with an additional dose of IL-13 and analyzed for AHR with a flexiVent apparatus (two pooled experiments, n = 6–14/group). (B) BAL cell numbers and differential counts (one experiment, n = 7–8/group). (C) Percentage of PAS+ bronchial epithelial cells (one experiment, n = 7–8/group). Error bars indicate SEs. Asterisks indicate a significant increase (*, P < 0.05) for IL-13 versus saline treatment.
affinity of intestinal smooth muscle for acetylcholine (Kellner et al., 2007), that IL-4 and IL-13 increase intestinal smooth muscle responses to nerve stimulation through a Stat6-dependent mechanism (Zhao et al., 2003), that IL-13 acts in vitro to increase airway smooth muscle contractility and proliferation and stimulate smooth muscle production of the chemokine eotaxin (Shore, 2007), that IL-4 and IL-13 increase intestinal smooth muscle responses to nerve stimulation through a Stat6-dependent mechanism (Zhao et al., 2003), that IL-13 acts in vitro to increase airway smooth muscle contractility and proliferation and stimulate smooth muscle production of the chemokine eotaxin (Shore, 2007), and that IL-13 induces calcium transients in cultured mouse airway smooth muscle cells and augments the calcium and contractile responses of these cells to leukotriene D4 (Eum et al., 2005). However, until now, there has been no evidence that direct effects of IL-4/IL-13 on smooth muscle contribute to AHR development in vivo.

Our results indicate that the direct effects of these cytokines on smooth muscle contribute to AHR and are likely to be biologically important. In contrast to IL-4Rα−/− deficient mice, transgenic mice that express IL-4R only on smooth muscle cells and at approximately the same level as mice that have a single allele of the wild-type IL-4Rα gene developed AHR after i.t. inoculation with IL-4 or IL-13. This was observed despite the lack of development of airway eosinophilia or goblet cell hyperplasia in the smooth muscle-only mice. Consistent results were observed after i.t. inoculation of dust mite allergen instead of IL-4 or IL-13. However, allergen administration induced less AHR in smooth muscle-only mice than in wild-type mice, probably because endogenous lymph node cells from wild-type mice before their own inoculation with allergen.

Our results also suggest that smooth muscle IL-4R signaling increases AHR by increasing the expression of several genes that likely act in parallel to promote smooth muscle differentiation, proliferation, migration, and contractility and to promote the accumulation of extracellular matrix, which enhances smooth muscle contractility (Table I). Although the extent to which these changes in gene expression affect smooth muscle protein expression and the exact mechanisms by which changes in the expression of these genes promote AHR remain unknown, our observations provide useful leads for further investigation as well as potential targets for asthma therapy. It is also likely that IL-4R signaling increases or decreases the expression of additional genes in smooth muscle but that these changes are not seen in a whole lung analysis because they are obscured by IL-4R−/− independent expression of the same genes in other cell types.

Although selective smooth muscle IL-4R expression is sufficient for AHR induction by allergen or cytokine inhalation, it is not required. This is consistent with the previous demonstration of AHR in transgenic mice that overexpress IL-13 in their lungs and express Stat6 only in airway epithelial cells (Kuperman et al., 2002). Most likely, AHR can be induced in mice either by airway narrowing caused by epithelial cell enlargement and mucus production, despite normal
smooth muscle contractility, or by increased smooth muscle contractility, despite normal airway diameter. Alternatively, it is possible that IL-4/IL-13 effects on airway epithelium indirectly increase smooth muscle contractility.

The significance of AHR in rodents and the best way to determine it has been debated (Finkelman, 2008). There are considerable differences between murine and human lung structure, and it is impossible to characterize maximal voluntary inhalations and exhalations in rodents (these are used to measure airway responsiveness in people). Noninvasive techniques performed with awake mice, such as barometric plethysmography, avoid changes in airway physiology that are induced by anesthesia and intubation but are indirect and can be influenced by upper airway inflammation and factors other than airway diameter and distensibility. Invasive techniques allow more direct measurement of airway characteristics, but the results they provide may be distorted by instrumentation and the use of anesthetics and paralytics. We approached the issues raised by these considerations by using three different techniques to measure responsiveness to cholinergic stimulation. Despite their differences, each technique demonstrated that exogenous and endogenously produced IL-4/IL-13 induce AHR in mice that express IL-4Rα only on smooth muscle but not in fully IL-4Rα-deficient mice.

This still leaves open the issue of whether our results with mouse models are applicable to human asthma. Although it is impossible to resolve this issue without performing human studies that are unethical and probably technically impossible, similar in vitro observations made with IL-4/IL-13-stimulated rodent and human smooth muscle cells (Shore, 2004a,b) make it seem likely that the in vivo mouse observations will also extend to humans. Indeed, the much greater airway diameter and distensibility. Invasive techniques performed with awake mice, such as barometric plethysmography, avoid changes in airway physiology that are induced by anesthesia and intubation but are indirect and can be influenced by upper airway inflammation and factors other than airway diameter and distensibility. Invasive techniques allow more direct measurement of airway characteristics, but the results they provide may be distorted by instrumentation and the use of anesthetics and paralytics. We approached the issues raised by these considerations by using three different techniques to measure responsiveness to cholinergic stimulation. Despite their differences, each technique demonstrated that exogenous and endogenously produced IL-4/IL-13 induce AHR in mice that express IL-4Rα only on smooth muscle but not in fully IL-4Rα-deficient mice.

Second, do IL-4/IL-13 effects on smooth muscle and epithelial cells total account for AHR induction by these cytokines, or might effects of these cytokines on other non-bone marrow–derived cell types (neurons, fibroblasts, and vascular endothelium) also contribute? Mice that express a floxed IL-4Rα gene and both smooth muscle– and epithelial cell–specific Cre are currently being bred to address this question.

MATERIALS AND METHODS

Mice. BALB/c female wild-type and IL-4Rα-deficient mice were purchased from Taconic. Rosa-YFP mice were purchased from the Jackson Laboratory (Druckenbrod and Epstein, 2005). SMP8-Cre transgenic mice on a mixed genetic background were a gift from T. Clemens and J. Fagin (University of Cincinnati, Cincinnati, OH). These mice were bred to Rosa-YFP mice so that Cre expression could be localized by fluorescence microscopy. SMP8-Cre mice were also bred to IL-4Rα−/− mice to generate IL-4Rα−/−/SMP8−/− mice, which were then bred to IL-4Rα−/− mice to generate SMP8-Cre−/−/IL-4Rα−/− mice, which selectively delete IL-4Rα in smooth muscle cells. Because these mice have a mixed genetic background, littermates that had an SMP8-Cre−/−/IL-4Rα−/− genotype (designated, for the sake of simplicity, as IL-4Rα−/− mice) were used as controls, as were mixed genetic background IL-4Rα−/− mice. A PCR approach was used for genotyping. All animal experiments were approved by the Cincinnati Children’s Hospital Medical Center Institutional Animal Care and Use Committee.

Immunological reagents. M1 (rat IgG2a anti–mouse IL-4Rα mAb; Beckmann et al., 1990) was originally obtained from K. Grabstein (Amgen) and was grown as ascites in Pristane-primed athymic nude mice and purified by ammonium sulfate fractionation and DE-52 cation exchange chromatography. GL117, a control rat IgG2a (anti–Eisenrichia coli β-galactosidase) was obtained from DNAx and purified in the same way. mAbs were labeled with biotin. Fluorochrome-labeled mAbs to CD4, B220, and CD45 were purified from CD4, B220, and CD45 were purchased from BD. Dust mite allergen was purchased from GREER.

Construction of an SMP8–IL-4Rα fusion gene. We constructed a fusion gene in which IL-4Rα cDNA was controlled by smooth muscle–α-actin regulatory sequences. IL-4Rα cDNA (Mosley et al., 1989; a gift from Amgen) had previously been placed upstream of the terminal SV40 T-antigen intron and polyA signal sequence in a pUC18-based plasmid controlled by the FABP promoter. The FABP promoter was excised by digestion with NdeI followed by a partial BanHI digest, which produced a 5.8-kb promoterless fragment containing IL-4Rα cDNA upstream of the SV40 T-intron and polyA signal in a pUC18 backbone. A 3.6-kb NdeI–BamHI fragment was obtained from DNAx and purified in the same way. mAbs were labeled with biotin. Fluorochrome-labeled mAbs to CD4, B220, and CD45 were purchased from BD. Dust mite allergen was purchased from GREER.

Two other issues raised by our observations remain unresolved and are attractive subjects for future study. First, why do IL-4 and IL-13 differ in their relative effects on airway responsiveness in IL-4Rα−/− versus IL-4Rα−/−/SMP8−/−IL-4Rα−/− mice? One possible explanation is that IL-4 but not IL-13 stimulates NK and T cells to produce IFN-γ and IL-10 (Finkelman et al., 2005; Morris et al., 2006; unpublished data), cytokines which can suppress airway responsiveness. Failure of IL-4 to induce these cytokines in IL-4Rα−/−/SMP8−/−IL-4Rα−/− mice might account for the greater IL-4 stimulation of AHR in IL-4Rα−/−/SMP8−/−IL-4Rα−/− mice than IL-4Rα−/− or wild-type mice. The failure of IL-13 to induce IFN-γ or IL-10 expression would account for the greater effect of IL-13 on AHR in wild-type mice, in which it directly affects epithelial and inflammatory cells, than on IL-4Rα−/−/SMP8−/−IL-4Rα−/− mice, in which it only directly affects smooth muscle.
Determination of airway responsiveness to methacholine. For determination of responsiveness to methacholine by barometric plethysmography, mice were placed, unrestrained, in cylindrical Plexiglas plethysmography chambers that were connected to a nebulized control aerosol delivery system and a Max II apparatus for analyzing barometric plethysmography (Buxco Research Systems). Baseline measurements of enhanced pause (Penh; Hamelmann et al., 1997) were made over a 5-min period. Mice were then challenged for 3 min by inhalation of aerosolized β-methacholine in PBS produced with a nebulizer (model 5500D-030; DeVilbiss Healthcare), starting at a methacholine concentration of 0.8 mg/ml. Penh measurements were made for 5 min, starting 2 min after completion of exposure to the aerosolized methacholine, and average Penh values for the 5-min period were calculated. The procedure was then serially repeated with methacholine at concentrations of 1.6, 3.2, 6.4, 12.8, and 25.6 mg/ml. Airway responsiveness of anesthetized, intubated mice to acetylcholine by the APTI technique was performed as previously described (Gavett et al., 1994). Airway responsiveness of anesthetized, intubated mice to methacholine was also performed with a flexiVent apparatus (SCIREQ). Mice were anesthetized with xylazine and Na pentobarbital. Their tracheas were then cannulated with an 18-gauge needle, and mice were ventilated at 150 breaths/min, 3.0-cm water positive end expiratory pressure. Mice were paralyzed with pancuronium bromide (Sigma-Aldrich) and allowed to stabilize on the ventilator for 2 min. Two total lung capacity perturbations were performed for airway recruitment before baseline measurement and subsequent methacholine challenges were performed. Dynamic resistance (R) was determined by fitting the data to a single compartment model of airway mechanics where \( P_{\text{R}} = RV + EV + P_{\text{d}} \) (\( P_{\text{d}} \), tracheal pressure; \( V \), volume; and \( P_{\text{d}} \), constant). Resistance measurements were made using a 1.25-s, 2.5-Hz volume driven oscillation applied to the airways by a computer-controlled piston (Snapshot perturbation). Methacholine was aerosolized for 10 s followed by 10 s of ventilation with an ultrasonic nebulizer (Aeroneb; Aerogen), and 20 Snapshot perturbations were performed. The procedure was repeated for 0, 6.25, 25, and 100 mg/ml concentrations of methacholine. The maximum R value with a coefficient of determination of 0.9 or greater (as determined by the flexiVent software) was used to determine the dose–response curve.

Lung histology. After BAL, lungs were inflated by injecting 1 ml of zinc formalin fixative through the catheter used to perform BAL. Lungs were then removed and fixed in the same solution. Lung sections were stained with periodic acid-Schiff (PAS) and examined microscopically.

Evaluation of goblet cell hyperplasia. Lung sections stained with PAS were evaluated blindly. Three bronchioles containing 90–130 epithelial cells were identified on each section. PAS+ (goblet) cells and total epithelial cell nuclei per bronchiole section were counted, and the ratio was converted into a percentage.

Preparation of suspensions of tracheal smooth muscle cells. Tracheas excised from mice were rinsed in antibiotic-supplemented HBSS. Connective tissue was removed under a dissecting microscope. Tracheas were then flushed with 0.02% EDTA and cut longitudinally. The tracheal interior was scraped with a round scalpel blade, and the trachea was transferred to a Petri dish containing 2 ml HBSS and 20 µl each of Liberase Blendzyme 1 and 4 (Roche). Tissue was incubated for 20 min at 37°C in an atmosphere that contained 5% CO₂. Dissociated tissue was further cleaned, and tracheal rings were separated into smaller tissue fragments. Three tissue fragments of 2–3 mm³ were transfused, intima side down, to collagen IV-coated Petri dishes (BD). The plates were pretreated with smooth muscle basal medium containing growth supplements human epithelial growth factor, insulin, human fibroblast growth factor B, FBS, and GA-1000 (Lonza). Additional media was added to the plate to just cover the tissue. The plates were incubated at 37°C, 5% CO₂ for 4 d undisturbed to allow the tissue to become established to the collagen. Enough media was added for the first 10–14 d to just keep the tissue covered. After 10–14 d of incubation and observing growth of new smooth muscle cells, media was gently pipetted off and replaced with enough new media to just cover the tissue. Media was replaced every 4 d thereafter. Cells were lifted from the plate and stained after 2–3 wk of growth.

Preparation of suspensions of tracheal epithelial cells. Epithelial cells were isolated from mouse tracheas by enzymatic digestion with 0.1% Pronase (Roche).
Detached cells were suspended in bronchial epithelial cell growth medium (Lonza) and plated on Transwell plates (Corning) that had been coated with collagen type 1 (BD) at 1 mg/ml. Cultures were grown at 37°C in a 5% CO₂-containing atmosphere until the cells became confluent. Cells were then dissociated from the plates with Liberase (Roche) and analyzed for surface IL-4Rα expression by flow cytometry.

**Fluorescence microscopy.** Frozen sections of lung and jejunum were prepared, mounted with Vectashield mounting medium with DAPI, and examined for background and YFP fluorescence with a microscope (Axioskop; Carl Zeiss) equipped with filters for YFP (EX 513 and EM 527). Photographs were taken with a color camera (MRC 5; Carl Zeiss) and processed with Axiosvision software version 4.3 (Carl Zeiss) and Photoshop CS (Adobe).

**Gene expression experiments.** Gene expression of homogenized whole lung was determined by a gene scan approach, as previously described (Lewis et al., 2009; GEO Datasets accession no. GSE26476). Gene scan results were confirmed by real-time PCR, as previously described (Finkelman et al., 2005). Using primers purchased from QIAGEN, IL-13–responsive genes were considered to be induced predominantly or entirely in smooth muscle cells if they were (a) expressed less in IL-13–inoculated SMP8-Cre+/−/IL-4Rα−/− mice than in IL-13–inoculated IL-4Rα−/− mice and (b) expressed no more in IL-13–inoculated SMP8-Cre−/−/IL-4Rα−/− mice than in saline-inoculated SMP8-Cre−/−/IL-4Rα−/− mice and/or were expressed no more in IL-13–inoculated SMP8-Cre−/−/IL-4Rα−/− mice than in IL-13–inoculated IL-4Rα−/− mice.

**Statistics.** Data were analyzed with a one-tailed Student’s t test to test hypotheses that cytokine or allergen treatment increased AHR or did not increase goblet cell hyperplasia or airway eosinophilia in IL-4Rα−/−/SMP8−IL-4Rα−/− mice or induced all three effects in SMP8-Cre/IL-4Rα−/− mice. A one-tailed Student’s t test was also used to test the hypothesis that IL-13 inhalation increased the expression in IL-4Rα−/−/SMP8−IL-4Rα−/− mice but not in SMP8-Cre/IL-4Rα−/− mice of six genes that had previously been identified by a gene scan. IL-4Rα−/− and IL-4Rα−/− were used as positive or negative controls, respectively. Values for P < 0.05 were considered significant. Figures show means ± SEs.

**Online supplemental material.** Fig. S1 demonstrates that the SMP8-Cre transgene is expressed only in smooth muscle in arteries and intestine. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20100023/DC1.

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