Crosstalk between \( G_i \) and \( G_q/G_s \) pathways in airway smooth muscle regulates bronchial contractility and relaxation

Dennis W. McGraw, ... , Marc E. Rothenberg, Stephen B. Liggett


Receptor-mediated airway smooth muscle (ASM) contraction via \( G_{qi} \), and relaxation via \( G_{qs} \), underlie the bronchospastic features of asthma and its treatment. Asthma models show increased ASM \( G_{qi} \) expression, considered the basis for the proasthmatic phenotypes of enhanced bronchial hyperreactivity to contraction mediated by \( M_3 \)-muscarinic receptors and diminished relaxation mediated by \( \beta_2 \)-adrenergic receptors (\( \beta_2 \)ARs). A causal effect between \( G_i \) expression and phenotype has not been established, nor have mechanisms whereby \( G_i \) modulates \( G_q/G_s \) signaling. To delineate isolated effects of altered \( G_i \), transgenic mice were generated overexpressing \( G_{qi2} \) or a \( G_{qi2} \) peptide inhibitor in ASM. Unexpectedly, \( G_{qi2} \) overexpression decreased contractility to methacholine, while \( G_{qi2} \) inhibition enhanced contraction. These opposite phenotypes resulted from different crosstalk loci within the \( G_q \) signaling network: decreased phospholipase C and increased PKCa, respectively. \( G_{qi2} \) overexpression decreased \( \beta_2 \)AR-mediated airway relaxation, while \( G_{qi2} \) inhibition increased this response, consistent with physiologically relevant coupling of this receptor to both \( G_s \) and \( G_i \). IL-13 transgenic mice (a model of asthma), which developed increased ASM \( G_{qi} \), displayed marked increases in airway hyperresponsiveness when \( G_{qi} \) function was inhibited. Increased \( G_{qi} \) in asthma is therefore a double-edged sword: a compensatory event mitigating against bronchial hyperreactivity, but a mechanism that evokes \( \beta \)-agonist resistance. By selective intervention within these multipronged signaling modules, advantageous \( G_s/G_q \) activities could provide new asthma therapies.

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Crosstalk between G\textsubscript{i} and G\textsubscript{q}/G\textsubscript{s} pathways in airway smooth muscle regulates bronchial contractility and relaxation

Dennis W. McGraw,\textsuperscript{1} Jean M. Elwing,\textsuperscript{1} Kevin M. Fogel,\textsuperscript{1} Wayne C.H. Wang,\textsuperscript{2} Clare B. Glinka,\textsuperscript{2} Kathryn A. Mihlbachler,\textsuperscript{2} Marc E. Rothenberg,\textsuperscript{3} and Stephen B. Liggett\textsuperscript{2}

\textsuperscript{1}Pulmonary Division, Department of Medicine, University of Cincinnati College of Medicine, Cincinnati, Ohio, USA. \textsuperscript{2}Cardiopulmonary Genomics Program, Department of Medicine, University of Maryland School of Medicine, Baltimore, Maryland, USA. \textsuperscript{3}Division of Allergy and Immunology, Department of Pediatrics, Cincinnati Children’s Hospital Medical Center, Cincinnati, Ohio, USA.

Receptor-mediated airway smooth muscle (ASM) contraction via G\textsubscript{o,3} and relaxation via G\textsubscript{i,3} underlie the bronchospastic features of asthma and its treatment. Asthma models show increased ASM G\textsubscript{i,2} expression, considered the basis for the proasthmatic phenotypes of enhanced bronchial hyperreactivity to contraction mediated by M\textsubscript{1}-muscarinic receptors and diminished relaxation mediated by \(\beta_2\)-adrenergic receptors (\(\beta_2\)ARs). A causal effect between G\textsubscript{i} expression and phenotype has not been established, nor have mechanisms whereby G\textsubscript{i} modulates G\textsubscript{q}/G\textsubscript{s} signaling. To delineate isolated effects of altered G\textsubscript{i}, transgenic mice were generated overexpressing G\textsubscript{i,2} or a G\textsubscript{i,2} peptide inhibitor in ASM. Unexpectedly, G\textsubscript{i,2} overexpression decreased contractility to methacholine, while G\textsubscript{i,2} inhibition enhanced contraction. These opposite phenotypes resulted from different crosstalk loci within the G\textsubscript{q} signaling network: decreased phospholipase C and increased PKC\(\alpha\), respectively. G\textsubscript{i,2} overexpression decreased \(\beta_2\)AR-mediated airway relaxation, while G\textsubscript{i,2} inhibition increased this response, consistent with physiologically relevant coupling of this receptor to both G\textsubscript{i} and G\textsubscript{s}. IL-13 transgenic mice (a model of asthma), which developed increased ASM G\textsubscript{i,2} displayed marked increases in airway hyperresponsiveness when G\textsubscript{i,2} function was inhibited. Increased G\textsubscript{i,2} in asthma is therefore a double-edged sword: a compensatory event mitigating against bronchial hyperreactivity, but a mechanism that evokes \(\beta\)-agonist resistance. By selective intervention within these multipronged signaling modules, advantageous G\textsubscript{i}/G\textsubscript{q} activities could provide new asthma therapies.

Introduction

Airway smooth muscle (ASM) contraction and relaxation are primarily regulated by G protein–coupled receptors, the former mediated by receptors signaling to G\textsubscript{i} and the latter by those that couple to G\textsubscript{s} (1, 2). Many inflammatory cascades in asthma evoke bronchoconstriction by promoting local increases of G\textsubscript{s} receptor agonists such as acetylcholine, cysteinyl leukotrienes, prostaglandins, and histamine, which activate their cognate receptors expressed on ASM. There appear to be fewer G\textsubscript{i}-coupled receptors that act via endogenous agonists to counteract bronchoconstriction, but the \(\beta_2\)-adrenergic receptor (\(\beta_2\)AR) of ASM is the target of pharmacologically administered \(\beta\)-agonists and is typically highly effective in relaxing constricted airways. The molecular events and critical transduction elements for these 2 classes of receptors are well recognized. Agonist binding to receptors such as the M\textsubscript{1}-muscarinic receptor promote dissociation of heterotrimeric G\textsubscript{s} into G\textsubscript{q} and G\textsubscript{b}, subdivisions, with the \(G\beta\gamma\) subunit activating phospholipase C (PLC; which promotes inositol-3-phosphate and diacylglycerol production) and the latter activating PKC. Receptors such as the \(\beta_2\)AR act via G\textsubscript{i,2} to stimulate the effector adenyl cyclase, resulting in cAMP production and activation of PKA. Substantial interest has revolved around how these pathways might be modified in asthma, because there may be nodal points which are critical for the pathogenesis of bronchospasm, or may be particularly amenable for pharmacologic intervention. A number of studies have shown, somewhat surprisingly, that a third major class of G proteins, G\textsubscript{q} (inhibitory guanine nucleotide binding protein \(\alpha\) subunits 2 and 3; G\textsubscript{i,2} and G\textsubscript{i,3}, respectively), is increased in ASM in animal models of asthma. Early studies by Grunstein and colleagues (3) showed that rabbit tracheal smooth muscle that was passively sensitized with serum from atopic asthmatics had enhanced ex vivo contraction to acetylcholine and decreased relaxation to the \(\beta\)-agonist isoproterenol. These events were temporally related to increased G\textsubscript{i,2} protein expression, and these characteristics were attenuated by pertussis toxin (PTX), which inactivates G\textsubscript{i,2}.

Other studies have shown that cytokine exposure (4, 5) and rhinovirus infection (6) give this same physiologic phenotype, which is accompanied by a several-fold increase in ASM G\textsubscript{i,2} expression. It remains unclear how the 2 proasthmatic phenotypes of hyper responsiveness to bronchoconstriction and resistance to bronchodilatation, which are mediated by G\textsubscript{i,2} and G\textsubscript{s}-coupled receptors, respectively, could be influenced by the cellular expression levels of G\textsubscript{s}. Recent studies in recombinant cells have shown, however, that \(\beta_2\)AR, once phosphorylated by PKA, has the capacity to couple to G\textsubscript{i} (7). Given that G\textsubscript{i,2} inhibits adenyl cyclase, this dual coupling may serve to attenuate the cAMP response. However, the magnitude of the physiologic effect in the airway of this coupling “switch” is not known, nor is it clear whether modest changes in G\textsubscript{i,2} could amplify or modify in some other way this bifurcated cou-

Nonstandard abbreviations used: AR, \(\beta_2\)-adrenergic receptor; ASM, airway smooth muscle; G\textsubscript{o,3}IP, G\textsubscript{o,3} inhibitory peptide expression; G\textsubscript{i,2}OE, G\textsubscript{i,2} overexpression; GRK2, G protein–coupled receptor kinase 2; NTG, nontransgenic littermate; PLC\(\gamma\), phospholipase C; PTX, pertussis toxin; SMP8, smooth muscle actin promoter 8.

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Research Article

Induction of IL-13 in mouse airways increases \( G_{\alpha_i} \) expression. Three-week-old bitransgenic mice generated to have doxycycline-inducible expression of IL-13 targeted to the airways by the CC10 promoter were fed normal food (−Dox) or doxycycline-impregnated food (+Dox) for 3 weeks. Tracheae were homogenized, and membrane preparations were subjected to Western blots performed with \( G_{\alpha_i} \) and GAPDH antibodies. Induction of IL-13 increased \( G_{\alpha_i} \) expression by approximately 8-fold.

Results

\( G_{\alpha_i} \) is increased in a genetic model of asthma, and PTX alters airway responsiveness. To assess whether the findings by Grunstein and colleagues of increased \( G_{\alpha_i} \) in rabbit models of asthma (3) are true for another model, we examined the expression of \( G_{\alpha_i} \) in tracheae from the inducible IL-13–overexpressing mouse (9). In these mice IL-13 is targeted to the airway by the Clara cell secretory protein (CCSP) promoter, with induction by 3 weeks of doxycycline administration; they develop inflammation, bronchial hyperresponsiveness, to methacholine, fibrosis, and airspace enlargement (9, 10). Figure 1 shows that tracheal expression of \( G_{\alpha_i} \) assessed by Western blot increased approximately 8-fold upon IL-13 induction in these transgenic mice. These data pointed toward increased \( G_i \) as a common feature of asthmatic-like airways from passive sensitization with asthmatic serum (3), cytokines (4, 5), and rhinovirus exposure (6) as well as increased IL-13 production. However, these prior studies do not indicate whether isolated changes in \( G_i \) levels influence airway contraction or relaxation responses, nor do they implicate the increase in \( G_i \) in these models as a mechanism that underlies altered airway signaling or address whether the increase represents a compensatory event. We thus proceeded with screening studies using in vivo PTX, which ablates \( G_i \) coupling by ADP-ribosylation of the \( \alpha \) subunit. Wild-type mice were treated with i.p. PTX or with vehicle, and 18 hours later airway resistance was measured in the intact, ventilated mouse using previously described methods (8, 11). Unexpectedly, PTX treatment increased the contractile response to methacholine (mediated by the \( G_i \)-coupled M1-muscarinic receptor) as shown by both an increased maximal response and a left-shifted dose-response curve (Figure 2A). To assess \( \beta_2 \)-AR-mediated relaxation, mice were pretreated with aerosolized isoproterenol prior to methacholine challenge. With PTX treatment, \( \beta_2 \)-AR signaling appeared to be enhanced, in that there was little contraction to methacholine under these conditions (Figure 2B).

Figure 1

Induction of IL-13 in mouse airways increases \( G_{\alpha_i} \) expression. Three-week-old bitransgenic mice generated to have doxycycline-inducible expression of IL-13 targeted to the airways by the CC10 promoter were fed normal food (−Dox) or doxycycline-impregnated food (+Dox) for 3 weeks. Tracheae were homogenized, and membrane preparations were subjected to Western blots performed with \( G_{\alpha_i} \) and GAPDH antibodies. Induction of IL-13 increased \( G_{\alpha_i} \) expression by approximately 8-fold.

Figure 2

PTX alters airway contraction and relaxation responses. FVB/N NTG mice were treated with vehicle (veh) or i.p. PTX for 18 hours. Airway resistance and the response to inhaled methacholine (mch) was determined in intact ventilated mice (see Methods). Studies were performed without (A) or with (B) pretreatment with inhaled isoproterenol (Iso). Results are from 5 independent experiments. \( *P < 0.01 \) versus vehicle.
Methods). Mice were screened for the transgene by PCRs using genomic DNA derived from digested tails. Transgenic mice had a normal body weight and habitus, and their viability was the same as nontransgenic littermate (NTG) mice. To ascertain whether the transgenes were expressed in the cell type of interest, we prepared RNA from cultures of primary ASM cells that were established from tracheal explants of heterozygous F2 and F3 mice. We detected mRNA for the Gαi2 transgene by RT-PCR using human-specific Gαi2 primers and for the Gαi2-IP transgene using primers based on sequence from the 5’ HA-tag and human Gαi2. As shown in Figure 3A, the human Gαi2 transcript was identified only in ASM cells derived from Gαi2-OE mice. Immunoblots using Gαi2 antisera further showed overexpression of Gαi2 protein by approximately 10-fold in the ASM cells derived from the full-gene overexpressors (Figure 3B; note that the Gαi2-OE protein was underloaded to obtain a reasonable visual comparison with the NTG signal). Although we were not able to reproducibly detect protein expression of the Gαi2-IP minigene, RT-PCR revealed the chimeric HA–Gαi2-IP transcript in ASM cells only in the Gαi2-IP–derived cell lines, not the NTG or Gαi2-OE lines. Formalin-fixed sections of the lungs revealed no microscopic evidence of increased ASM mass, basement membrane thickening, inflammation, fibrosis, or parenchymal distortion in either transgenic line. Figure 3C shows representative sections that include both airway and parenchyma. Mean systolic blood pressure measured noninvasively by tail cuff readings over a period of 5 days did not differ among NTG, Gαi2-OE, and Gαi2-IP mice (125 ± 1 mmHg, 125 ± 3 mmHg, and 126 ± 5 mmHg, respectively; n = 10; data not shown).

Effects of altering Gαi by transgenesis on airway contractile and relaxation responses. Baseline airway resistance did not differ among Gαi2-OE, Gαi2-IP, and NTG mice (0.53 ± 0.061 cm H2O/ml/s, 0.58 ± 0.036 cm H2O/ml/s, and 0.57 ± 0.041 cm H2O/ml/s, respectively; n = 6–9; data not shown). However, Gαi2-OE mice exhibited a depressed contractile response (P < 0.005) to methacholine, primarily due to a 50% decrease in the maximal response compared to the maximal response observed in NTG mice (Figure 4A). Consistent with an antithetic relationship of Gαi expression and function to physiologic effect (contraction), Gαi2-IP mice had a greater response to methacholine (P < 0.005), with the maximal response being 50% greater than that of NTG mice (Figure 4A).
The contractile responses to methacholine observed in the G\textsubscript{ai2}-IP mice were consistent with those observed with PTX treatment (Figure 2A). The effects of G\textsubscript{i} expression on β\textsubscript{2}AR-mediated relaxation responses were assessed by pretreatment of mice with aerosolized isoproterenol, followed by methacholine challenge. As shown in Figure 4B, in NTG mice this caused the expected approximately 40% decrease in maximal bronchoconstriction due to methacholine. For the G\textsubscript{ai2}-IP mice, a markedly enhanced β\textsubscript{2}AR function was observed, with very little bronchoconstriction by methacholine in these mice when pretreated with isoproterenol. This effect of G\textsubscript{ai2}-IP amounted to an approximate 80% decrease in resistance compared with methacholine treatment alone in these mice (P < 0.01), and indeed resistance after isoproterenol was also less than in NTG mice under the same conditions (P < 0.05). In the G\textsubscript{ai2}-OE mice there was an apparent small decrease in contraction in the presence of isoproterenol, but this did not reach statistical significance, suggesting impaired β\textsubscript{2}AR function. Thus, like the bronchoconstrictive response (where G\textsubscript{ai2} upregulation and downregulation had opposite effects), G\textsubscript{ai2} inhibition enhanced relaxation via β\textsubscript{2}AR, while G\textsubscript{ai2} overexpression decreased it.

We considered that the β\textsubscript{2}AR-mediated relaxation phenotype of G\textsubscript{ai2}-OE mice could be a result of altered expression of ASM β\textsubscript{2}AR or altered function of another receptor acting via G\textsubscript{i}. However, β\textsubscript{2}AR expression, as determined by quantitative 125I-cyanopindolol binding, did not differ among NTG, G\textsubscript{ai2}-OE, and G\textsubscript{ai2}-IP cells (15 ± 2.1 fmol/mg, 19 ± 3.8 fmol/mg, and 20 ± 2.9 fmol/mg, respectively; Figure 5).
α excised tracheal rings were studied ex vivo to measure relaxation as the Mα comparable to that observed with NTG rings: from 67% ± 3.3% to results are consistent with our physiologic studies showing that Potential crosstalk between Gα and PLC, and PKC isoforms. Gαi downregulation of downstream mediators of contraction and relaxation was shown. These results are consistent with the increased Gαi expression in the Gαi2OE cells, which displayed a significant increase in Gαi2 compared with doxycycline-only mice. Interestingly, Gαi was modestly decreased (about 30%) in both Gα2-IP and Gα2-IP mice, which does not explain the discordant signaling, and G protein–coupled receptor kinase 2 (GRK2) was decreased by approximately 40% in Gα2OE cells. However, this decrease would be expected to enhance β2AR function, instead of the decreased function we observed with Gα2OE. Our findings are consistent with β2AR coupling to Gs with attenuation of β2AR stimulation of adenylyl cyclase. Indeed, the primary signal that has been used to assess β2AR-Gi coupling is p44/p42 activation (7), which was markedly enhanced (about 3-fold; P < 0.001) in the Gα2-IP cells (Figure 6B).

Increased Gαi in a mouse asthma model is a beneficial compensatory event attenuating airway hyperresponsiveness. The physiologic consequences of transgenic overexpression of Gαi revealed a decrease, rather than the expected increase, in airway constriction to methacholine. In addition, the molecular events that we defined as a consequence of increased Gαi were consistent with this phenotype. This suggested that the increase in Gαi that has been observed in several animal models of asthma is a compensatory event, acting to attenuate bronchial hyperresponsiveness. To test this, we used the inducible IL-13 mice, which displayed a significant increase in Gαi upon IL-13 induction (Figure 1). These mice are known to be hyperresponsive, which is a key aspect of their phenotype (10), but the question remains as to whether inactivating Gαi would further increase airway contractility in these mice, thus revealing the partial protective effect against hyperresponsiveness provided by increased Gαi. The IL-13 mice were given normal chow or chow with doxycycline for 3 weeks, and then some mice were treated with PTX i.p. and studied 18 hours later. As shown in Figure 7, IL-13 induction increased methacholine-promoted airway constriction. Treatment with PTX further enhanced contraction, amounting to a 2-fold increase compared with doxycycline-only mice. These data are consistent with the aforementioned concept that the increase in Gαi that occurs in this animal model of asthma (and others as well) acts in a compensatory manner to limit airway hyperresponsiveness. The β-agonist isoproterenol afforded protection against bronchoconstriction in the noninduced IL-13 mice. Interestingly, β-agonist provided no protection in the IL-13–induced mouse, where extensive airway constriction due to methacholine was observed, consistent with depressed βAR function. However, there was a nonsignificant trend toward less constriction in the presence of isoproterenol with PTX treatment, which supports improved βAR function.

Discussion
The aim of these studies was to ascertain the relevance of altered Gαi expression on airway contraction and relaxation. As introduced earlier, a several-fold increase in Gα2i has been found in

Figure 7
The increase in Gαi in IL-13 mice limits airway hyperresponsiveness. Shown are experiments where the IL-13 doxycycline-inducible mice were studied in the absence or presence of induction with doxycycline. The latter were treated with i.p. PTX or vehicle. Airway resistance was measured using the ventilated mouse model, at a single concentration of aerosolized methacholine (10 mg/ml). After resistance returned to baseline, mice were treated with the same concentration of methacholine with isoproterenol. PTX enhanced methacholine-promoted airway constriction (compare black versus shaded bars under methacholine). These results are consistent with the increased Gαi found in these mice after IL-13 induction acting to attenuate hyperresponsive- ness. Results are from independent experiments with 2–3 mice in each group. *P < 0.05.

n = 4; data not shown). We thus considered the potential for enhanced function of a classic receptor-Gi–coupled pathway (such as the M1-muscarinic pathway) that might antagonize Gi-coupled relaxation at adenylyl cyclase. To address this potential mechanism, excised tracheal rings were studied ex vivo to measure relaxation responses during KCl contraction. Rings were treated with vehicle or the M2-muscarinic receptor agonist pilocarpine (0.1 μM) and then contracted continuously with 60 mM KCl. Relaxation was then ascertained in response to increasing concentrations of isoproterenol. As expected, with NTG rings, pilocarpine modestly blunted isoproterenol-mediated relaxation from 51% ± 5.0% to 62% ± 5.0% of maximal contraction (a 20% decrease; Figure 5). However, there was no accentuation of this effect in the Gαi2OE rings, with pilocarpine reducing isoproterenol-mediated relaxation by an amount comparable to that observed with NTG rings: from 67% ± 3.3% to 81% ± 4.0% (a 22% decrease; Figure 5).

Gαi2 expression regulates multiple downstream signaling elements. Potential crosstalk between Gαi2 expression and function and relevant downstream mediators of contraction and relaxation was assessed by Western blot analyses from primary ASM cells derived from NTG, Gαi2-IP, and Gαi2OE mice (Figure 6). Of particular interest — because of the counterintuitive effects on contraction — was expression of elements involved in airway constriction: Gαq, PLC, and PKC isoforms. Gαq levels were not altered in either transgenic. However, its effector, PLCβ3, was downregulated by more than 50% (P < 0.005) in the Gαi2OE cells but was not different in the Gα2IP cells compared with NTG cells (Figure 6B). These results are consistent with our physiologic studies showing that the Gαi2OE mice were hyporesponsive to methacholine. However, this does not explain the hyperresponsiveness observed in Gα2IP mice, which indicates that while the phenotypes of the Gα2OE and Gα2-IP mice are oppositional, the mechanisms by which these responses are attained are different and potentially multifactorial. PKCα was upregulated by approximately 50% (P < 0.01) in Gα2-IP cells but unchanged in Gα2OE cells (Figure 6B). Given that PKCα has been demonstrated to sensitize smooth muscle to contraction (12–15), this upregulation in the Gα2-IP cells is consistent with the hyperresponsive contractile phenotype. Less is known about the other PKC isoforms in regards to G protein–coupled receptor-mediated smooth muscle contraction. We noted that expression of PKCb1 was not altered, while PKCc and PKCd were downregulated by approximately 20% in cells from both lines of mice. In terms of the β2AR response, we found no pattern of regulation of downstream signaling elements that was consistent with the 2 phenotypes. Gαs was modestly decreased (about 30%) in both Gα2OE and Gα2-IP cells, which does not explain the discordant signaling, and G protein–coupled receptor kinase 2 (GRK2) was decreased by approximately 40% in Gα2OE cells. However, this decrease would be expected to enhance β2AR function, instead of the decreased function we observed with Gα2OE. Our findings are consistent with β2AR coupling to Gs with attenuation of β2AR stimulation of adenylyl cyclase. Indeed, the primary signal that has been used to assess β2AR-Gi coupling is p44/p42 activation (7), which was markedly enhanced (about 3-fold; P < 0.001) in the Gα2-IP cells (Figure 6B).

The increase in Gαi in IL-13 mice limits airway hyperresponsiveness. Shown are experiments where the IL-13 doxycycline-inducible mice were studied in the absence or presence of induction with doxycycline. The latter were treated with i.p. PTX or vehicle. Airway resistance was measured using the ventilated mouse model, at a single concentration of aerosolized methacholine (10 mg/ml). After resistance returned to baseline, mice were treated with the same concentration of methacholine with isoproterenol. PTX enhanced methacholine-promoted airway constriction (compare black versus shaded bars under methacholine). These results are consistent with the increased Gαi found in these mice after IL-13 induction acting to attenuate hyperresponsive- ness. Results are from independent experiments with 2–3 mice in each group. *P < 0.05.
a number of models of asthma, and it has been suggested that both bronchial hyperresponsiveness to contraction and impaired β2AR-mediated relaxation can be attributed to this increase (3–6). Undoubtedly, there are expression changes in many signaling elements in these asthma models, and thus a causal relationship between Gαi expression and the above phenotypes cannot be established, nor can the specific effects of altered Gαi expression, in isolation, be ascertained. In the current work we show that increased Gαi2 resulted in decreased contractile responsiveness, which contradicts the aforementioned proposed paradigm. Furthermore, as a complementary and independent approach, we examined the effect of lowering Gai function via a minigene. This resulted in increased contraction, which is the opposite phenotype to Gαi2-OE, and thus supports the notion that up- or downregulation of Gαi levels has opposing effects on contraction. The phenotype of the PTX-treated mice is additional confirmation of the Gαi2-IP results, and also indicates that the effect of the minigene was not because of its interaction with receptor-Gq signaling, since PTX ADP-ribosylates Gai. Thus, the increase in Gai observed in animal models of asthma and/or bronchial hyperresponsiveness is clearly not the cause of contractile hyperresponsiveness: it actually decreased the methacholine response. Indeed, it appears that an increase in Gai is a beneficial compensatory event, acting to limit the extent of hyperresponsiveness. To confirm this notion, the IL-13-inducible mice, which have airway hyperresponsiveness and increased Gαi2, were treated with PTX and displayed further enhancement of bronchoconstriction due to methacholine.

The effects of altering Gαi expression and function on methacholine-promoted bronchoconstriction are not readily explained by alterations in muscarinic receptor–G protein interactions (i.e., at the receptor–G protein interface). The M1-muscarinic receptor couples to Gαi and there is no evidence of promiscuous coupling of this receptor to Gβ. Nor can the phenotype be attributed to altered M2-muscarinic receptor function. Although the M3 subtype is clearly the major muscarinic receptor that mediates airway contraction to muscarinic agonists, we recognize that the M2 subtype also contributes (16). This subtype, which is Gβ coupled, appears to promote contraction via decreasing CAMP and eliciting nonselective cation conductance (17). However, our results with the Gαi2-OE mice cannot be explained by enhanced M2-receptor function, because in these mice we found a decreased bronchoconstrictive response to methacholine, and when M2-Gαi coupling would be expected to be diminished with the Gαi2-IP minigene, we observed enhanced contraction. Rather, the mechanisms for the phenotypes appear to be due to crosstalk between Gαi and downstream mediators of contraction. While the phenotypes of the Gαi2-OE and Gαa2-IP mice are opposites, the mechanism for these phenotypes does not appear to be caused by regulation of a single transduction element. Instead, 2 elements that are closely linked in receptor-Gq signaling, PLCβ3 and PKCα, are each independently regulated. Increased Gαq resulted in downregulation of PLCβ3, the effector for Gq-coupled receptor activation. In contrast, PLCβ3 expression was unchanged in Gαa2-IP ASM, but PKCα, whose activation is a consequence of PLC activation, was upregulated. In a positive feedback loop, PKCα sensitizes smooth muscle to receptor-mediated contraction via Gq receptors. This effect has been particularly well documented in vascular smooth muscle, where PKC increases the myofilament force sensitivity to intracellular Ca2+ concentration (12–15). Interestingly, increased Gαq has been reported in many animal models of cardiac hypertrophy and heart failure (18–20) as well as in human heart failure (21). Taken together with the various animal models of asthma, an increase in Gαq may be a generalized response to cellular hypertrophy, which in asthma contributes to the increased ASM mass (22). Although Gαq is not increased in hearts overexpressing β2AR, coupling of β2AR to Gαq appears to provide protection against β2AR-mediated cardiomyopathy (23).

The β2AR-mediated relaxation phenotype is consistent with the recent recognition that this receptor, a classic Gαi-coupled receptor, can also couple to Gβ (7). What has remained unknown is the physiologic relevance of β2AR-Gq coupling and whether changes in Gq expression can modulate a physiologic effect (as opposed to Gα being in such excess that its expression is not rate limiting). It has not been entirely clear whether β2AR-Gq coupling serves to substantially modulate Gq-mediated bronchodilatation or whether it is more relevant to non-cAMP-dependent signaling, such as p44/p42 MAP kinase activation. We show here that inhibition of β2AR-Gq coupling via the minigene markedly enhanced β2AR-mediated ASM relaxation. This is consistent with the concept that even with normal levels of Gq, β2AR actively couples to Gβi, which has important physiologic consequences. The results with the Gαi2-OE mice revealed that increased Gαi expression was associated with increased β2AR-Gq signaling, which competed with stimulation of β2AR-mediated relaxation via Gαi. This indicates that increasing expression levels by pathologic processes, or by pharmacologic means, will have an impact on the airway relaxation response. Several downstream signaling elements potentially related to β2AR signaling were regulated by overexpression of Gαi2 or expression of the Gαi2-IP minigene. However, these changes were inversely related to the observed gain, or loss, of β2AR function. For example, GRK2 (which phosphorylates and
desensitizes β2-AR) was downregulated in Gαi2-OE smooth muscle. However, if anything this would cause an increase in β2AR function, rather than the decreased function that was observed in these mice. Similarly, p44/p42 MAP kinase phosphorylates GRK2 and impairs its function (24). The former kinase was markedly activated in the Gαi2-OE smooth muscle cells, but β2AR function was impaired, as opposed to enhanced, in these mice. Gαi2 was decreased approximately 30% in both Gαi2-OE and Gαi2-IP cells, and thus this change is unlikely to represent a major factor given the opposite β2AR phenotypes in the 2 mice. Similarly, PKCθ and PKCβ were downregulated in both mice.

The current work shows a complex, multifactorial interplay between Gα, expression and contraction and relaxation signaling via G protein-coupled receptors in the airway (Figure 8). From the standpoint of the pathogenesis of bronchospasm, the increase in Gαi observed in asthmatic-like airways (3–6) appears to serve a protective effect: the increase acts to attenuate bronchial hyperresponsiveness from Gαi in asthma, asthma, attempts to adjust these levels at or below normal will increase bronchial hyperreactivity and exacerbate asthma. On the other hand, the increase in Gαs impaired β2-agonist bronchodilatation. This appears to be due to an enhancement of β2AR-Gαs coupling, which opposes β2AR-Gαs functional stimulation of adenylyl cyclase. Furthermore, decreasing Gαs function acts to increase β2AR-mediated bronchodilatation, as would be expected based on this mechanism. Therefore, in the absence of β2-agonist treatment the increase in Gαs in asthma acts to attenuate bronchospasm, but also limits the effectiveness of β2-agonists in relieving bronchoconstriction. This multipronged set of regulatory events may indicate that pharmacologic or genetic methods to modulate Gαs could have limited clinical utility. However, there may be opportunities to exploit these relationships by manipulating other downstream effects of altered Gα expression. For example, if decreasing Gα expression and function could be accomplished while also inhibiting PKCθ, then both the relaxation and the contractive pathways would be affected in a manner that would be expected to be clinically beneficial for hyperresponsiveness and β2-agonist efficacy (Figure 8).

Methods

Transgenic mice. These studies were approved by the Institutional Animal Care and Use Committees of the University of Cincinnati College of Medicine and the University of Maryland School of Medicine. Gαi2-OE and Gαi2-IP in mice were targeted to ASM using a construct based on the mouse SMP8 and the SV40 polyadenylation region as previously described (25). Briefly, for the Gαi2-OE construct, the full-length human Gαi2 cDNA was subcloned into the Neo/XbaI sites between the SMP8 promoter and the SV40 polyadenylation site of the construct. For Gαi2-IP, PCR techniques were used to create a cDNA encoding the influenza HA tag (YPYDVPDYA) in-frame with the last 58 amino acids of human Gαi2, which was cloned into the same sites as above in the SMP8 construct. For transgenic generation, the final constructs were excised with NotI, purified, and microinjected into fertilized zygotes from superovulated FVB/N mice. Surviving zygotes were implanted into pseudopregnant females. Offspring were screened for the presence of transgenes using PCRs of genomic DNA from tail clips, with the 3′ primer being in the SV40 polyadenylation region. Hemizygous mice from generations 4–6 that were 8–10 weeks of age were used for all studies. FVB/N littermates that were negative by transgene screening were used as the NTG controls. Transgene mRNA expression from cultivated ASM cell total RNA was confirmed by RT-PCR using an oligo-dT primer for reverse transcription. For the PCR, primers were designed that were specific for the human, versus mouse, Gαi2 (5′-GGCGGTGTCTACGACACCAT-3′ and 5′-CTTGCTCGTGGGATGTACTAC-3′). For Gαi2-IP, the 5′ primer was based on the HA-tag sequence (5′-TACCCATACGTCGCCAGATCT-3′ and 5′-CCACATCCTTACGGTTGCTTTG-3′). The dosycycline-inducible IL-13 bitransgenic mice were generated as previously described (9). IL-13 induction was initiated in 3-week-old mice by addition of doxycycline (625 mg/kg) in their chow for 3 weeks (9).

Airway physiology. Invasive assessment of respiratory mechanics was performed using an intact, intubated, anesthetized mouse model similar to that previously reported (8, 11). Briefly, mice were anesthetized with approximately 60 mg/kg pentobarbital, after which the trachea was cannulated with an 18-gauge metal needle. Mice were then mechanically ventilated using a computer-controlled rodent ventilator (flexiVent version 4.01; SCIREQ) to deliver a tidal volume of 10 ml/kg (approximately 250 μl/breath) at a rate of 150 breaths per minute, with positive end-expiratory pressure of 2.5 cm H2O. Dynamic lung resistance was determined by fitting a linear first-order single-compartment model of airway mechanics to measurements of airway pressure, volume, and air flow made during application of single sinusoidal perturbation with an amplitude of 150 μl at 2.5 Hz for approximately 1.2 seconds using software provided by the manufacturer (flexiVent version 4.01; SCIREQ). Then mean of 2 measurements of resistance made prior to administration of methacholine was established as baseline. Increasing concentrations of methacholine were subsequently delivered to the airway by transiently diverting the inspiratory limb of the ventilator through the reservoir of an ultrasonic nebulizer for 30 seconds. Resistance was measured at 30-second intervals for 5 minutes after each dose, and the maximum resistance value following each dose was used to establish the dose-response curves. In studies to assess the relaxation effects of inhaled β2-agonist, isoproterenol (1.0 mg/ml) was delivered by aerosol, and then the contractive response to varying doses of methacholine was determined as described above. In some studies, mice were pretreated with PTX (100 μg/kg body weight i.p.) injected 18 hours before being studied. Data were fit by nonlinear curve fitting (Prism version 4.0; GraphPad). Since full dose-response sigmoid-like curves cannot be attained in vivo, ANOVA was used to compare the response data across all doses rather than a simpler model that relies on extrapolated values to obtain and compare the maximal responses.

Tracheal ring studies. Studies of mouse tracheal ring contractility were performed as reported previously in detail (26). Tracheas were excised and cut into rings of 5 mm in length. They were mounted on stainless steel wires connected to isometric force transducers and maintained at 37°C in a physiologic saline solution (118 mM NaCl, 11 mM glucose, 4.73 mM KCl, 1.2 mM MgCl2, 0.026 mM EDTA, 1.2 mM KH2PO4, 2.5 mM CaCl2, 25 mM NaH2CO3, pH 7.40) with bubbled 95% O2 and 5% CO2. Rings were stretched to a tension of 5 μN, which we have previously determined to be an optimal passive tension for maximizing active force (25). Following a 30-minute equilibration period, rings were contracted with 60 mM KCl, and the maximal response over the next 5 minutes was recorded. With KCl remaining in the bath, the relaxation response to isoproterenol was determined by perfusing rings with the indicated concentrations of isoproterenol (Figure 5), and the isometric force was continuously measured over the ensuing 5 minutes. In some studies, rings were incubated with 0.1 μM pilocarpine for 30 minutes at 37°C prior to, and during, KCl and isoproterenol treatments. Airway smooth muscle culture. Primary cultures of murine ASM cells were established from tracheal explants of NTG, Gαi2-OE, and Gαi2-IP mice as previously reported (25). The trachea between the larynx and main stem bronchi was removed and placed on a dish containing Hanks’ balanced...
saline solution supplemented with a 2x concentration of antibiotic-antimycotic solution (Invitrogen). After additional surrounding tissue was removed, the trabecular segment was cut longitudinally and dissected into 2- to 3-mm squares. Segments from a single trachea were then placed into intima-side-down in a sterile 60-mm dish. After adherence, Dulbecco’s modified Eagle’s medium supplemented with 20% FCS and 2x antibiotic-antimycotic was added to cover the explants. Explanted trachea were subsequently removed when there was local confluence. Once the initial seed dish became confluent, cells were harvested by trypsinization and passed into 75-cm² flasks. As previously described (25), over 90% of these cells were smooth muscle cells, as determined by immunohistochemistry performed with an antibody raised against smooth muscle α-actin. Cells were studied at passages 5–8.

Western blots. Primary ASM cells in monolayers were washed 3 times with PBS and lysed in a solubilization buffer containing 1% IGE-PAL, 0.5% sodium deoxycholate, and 0.1% SDS in phosphate-buffered saline. The protease inhibitors benzamidine, soybean trypsin inhibitor, and aprotonin (all at 5 µg/ml) were included in this and all subsequent steps. Lysates were passed 3 times through a 21-gauge needle and then rotated at 4°C for 1 hour in microfuge tubes. The tubes were then centrifuged to pellet unsolubilized material and the supernatants aliquoted and frozen at -70°C. Proteins from whole tracheae were prepared in a similar manner, but were first homogenized with a polytron. Equal amounts of protein (typically 15 µg) were loaded in all lanes. Western blots were performed using standard enhanced chemiluminescence techniques as previously described in detail (8, 27), with signals from the membranes acquired with a Fuji LAS-3000 charged-coupled acquisition system. Quantification of the immunoreactive bands was performed with software from the manufacturer (ImageGauge version 4.22; Fuji). Membranes were stripped and reprobed for GAPDH; these signals were used to control for minor variations in protein loading or transfer.

Statistics. All curve fitting was by nonlinear regression techniques using Prism software (version 4.0; GraphPad). Data are presented as mean ± SEM. Comparisons were by 2-tailed paired or unpaired Student’s t tests unless otherwise indicated, with significance considered at P < 0.05.

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Address correspondence to: Stephen B. Liggert, 20 Penn Street, HSF-II, Room S-114, Baltimore, Maryland 21201-1075, USA. Phone: (410) 706-6256; Fax: (410) 706-6262; E-mail: sligg001@umaryland.edu.