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

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Receptor-mediated airway smooth muscle (ASM) contraction via G\textsubscript{aq}, and relaxation via G\textsubscript{as}, underlie the bronchospastic features of asthma and its treatment. Asthma models show increased ASM G\textsubscript{ai} expression, considered the basis for the proasthmatic phenotypes of enhanced bronchial hyperreactivity to contraction mediated by M\textsubscript{3}-muscarinic receptors and diminished relaxation mediated by β\textsubscript{2}-adrenergic receptors (β\textsubscript{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{ai2} or a G\textsubscript{ai2} peptide inhibitor in ASM. Unexpectedly, G\textsubscript{ai2} overexpression decreased contractility to methacholine, while G\textsubscript{ai2} inhibition enhanced contraction. These opposite phenotypes resulted from different crosstalk loci within the G\textsubscript{q} signaling network: decreased phospholipase C and increased PKC\textsubscript{α}, respectively. G\textsubscript{ai2} overexpression decreased β\textsubscript{2}AR-mediated airway relaxation, while G\textsubscript{ai2} inhibition increased this response, consistent with physiologically relevant coupling of this receptor to both G\textsubscript{s} and G\textsubscript{i}. IL-13 transgenic mice (a model of asthma), which developed increased ASM G\textsubscript{ai}, displayed marked increases in airway hyperresponsiveness when G\textsubscript{ai} function was inhibited. Increased G\textsubscript{ai} in asthma is therefore a double-edged sword: a compensatory event mitigating against bronchial hyperreactivity, but a mechanism that evokes β-agonist resistance. By selective intervention within these multipronged signaling modules, advantageous G\textsubscript{s}/G\textsubscript{q} activities could provide new asthma therapies.
Crosstalk between G\textsubscript{i} and G\textsubscript{q}/G\textsubscript{s} pathways in airway smooth muscle regulates bronchial contractility and relaxation


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Receptor-mediated airway smooth muscle (ASM) contraction via G\textsubscript{q/s} and relaxation via G\textsubscript{i3} underlie the bronchospastic features of asthma and its treatment. Asthma models show increased ASM G\textsubscript{i3} expression, considered the basis for the proasthmatic phenotypes of enhanced bronchial hyperreactivity to contraction mediated by M\textsubscript{3}-muscarinic receptors and diminished relaxation mediated by β\textsubscript{2}-adrenergic receptors (β\textsubscript{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{i3} or a G\textsubscript{i2} peptide inhibitor in ASM. Unexpectedly, G\textsubscript{i2} overexpression decreased contractility to methacholine, while G\textsubscript{i2} inhibition enhanced contraction. These opposite phenotypes resulted from different crosstalk loci within the G\textsubscript{i} signaling network: decreased phospholipase C and increased PKC\textsubscript{iti}, respectively. G\textsubscript{i2} overexpression decreased β\textsubscript{2}AR-mediated airway relaxation, while G\textsubscript{i2} inhibition increased this response, consistent with physiologically relevant coupling of this receptor to both G\textsubscript{s} and G\textsubscript{i3}. IL-13 transgenic mice (a model of asthma), which developed increased ASM G\textsubscript{i3} displayed marked increases in airway hyperresponsiveness when G\textsubscript{i3} function was inhibited. Increased G\textsubscript{i3} in asthma is therefore a double-edged sword: a compensatory event mitigating against bronchial hyperreactivity, but a mechanism that evokes β\textsubscript{2}-agonist resistance. By selective intervention within these multipronged signaling modules, advantageous G\textsubscript{s}/G\textsubscript{i} activities could provide new asthma therapies.

Introduction

Airway smooth muscle (ASM) contraction and relaxation are primarily regulated by G\textsubscript{i} protein–coupled receptors, the former mediated by receptors signaling to G\textsubscript{i3} and the latter by those that couple to G\textsubscript{i} (1, 2). Many inflammatory cascades in asthma evoke bronchoconstriction by promoting local increases of G\textsubscript{i} 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 β\textsubscript{2}-adrenergic receptor (β\textsubscript{2}AR) of ASM is the target of pharmacologically administered β-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{3}-muscarinic receptor promote disassociation of heterotrimeric G\textsubscript{s} into G\textsubscript{s} and G\textsubscript{i3} subunits, with the α subunit activating phospholipase C (PLC; which promotes inositol-3-phosphate and diacylglycerol production) and the latter activating PKC. Receptors such as the β\textsubscript{2}AR act via G\textsubscript{i3} to stimulate the effector adenylyl 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{i3} (inhibitory guanine nucleotide binding protein α subunits 2 and 3; G\textsubscript{i2} and G\textsubscript{i3}, 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 β-agonist isoproterenol. These events were temporally related to increased G\textsubscript{i3} protein expression, and these characteristics were attenuated by pertussis toxin (PTX), which inactivates G\textsubscript{i3}.

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{i3} expression. It remains unclear how the 2 proasthmatic phenotypes of hyperresponsiveness to bronchoconstriction and resistance to bronchodilatation, which are mediated by G\textsubscript{s} and G\textsubscript{i}-coupled receptors, respectively, could be influenced by the cellular expression levels of G\textsubscript{i3}. Recent studies in recombinant cells have shown, however, that β\textsubscript{2}AR, once phosphorylated by PKA, has the capacity to couple to G\textsubscript{i3} (7). Given that G\textsubscript{i3} inhibits adenylyl 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{i3} could amplify or modify in some other way this bifurcated cou-

Nonstandard abbreviations used: AR, adrenergic receptor; ASM, airway smooth muscle; G\textsubscript{s}/G\textsubscript{i3}/IP, G\textsubscript{s} inhibitory peptide expression; G\textsubscript{s}/G\textsubscript{i3} overexpression; GRK2, G protein–coupled receptor kinase 2; NTG, nontransgenic littermate; PLC, phospholipase C; PTX, pertussis toxin; SMP8, smooth muscle actin promoter 8.

Conflict of interest: The authors have declared that no conflict of interest exists.

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A mechanism by which $G_i$ expression alters receptor-$G_{q}$ signaling is not readily apparent; however, previously unrecognized crosstalk between signaling pathways in ASM presumed to be unrelated has now been documented (8). Of particular interest in crosstalk between signaling pathways in ASM presumed to be a compensatory event that may be a factor mitigating against one or both of the asthmatic phenotypes. To ascertain the role of increased $G_i$ to the phenotypes in light of the complex regulatory events within many diverse pathways that are undoubtedly underway in asthma. Similarly, it is unclear whether the increase in $G_i$ is participating in the pathologic process or is a compensatory event that may be a factor mitigating against one or both of the asthmatic phenotypes. To ascertain the role of isolated increased or decreased $G_i$ function on bronchoconstrictive and dilating signaling of $G$ protein–coupled receptors in the airway, transgenic mice were generated overexpressing $G_{a_2}$ ($G_{a_2}$-OE mice) and expressing a $G_{a_2}$ inhibitory peptide ($G_{a_2}$-IP mice) in ASM. We found that increased $G_i$ did not cause enhanced contraction, but rather decreased the contractile response, while $G_i$ inhibition evoked enhanced contraction. However, although these phenotypes are physiologically antithetic, their mechanistic basis was crosstalk with 2 different elements of the $G_i$ signaling pathway. In the IL-13 transgenic model of asthma and airway hyperresponsiveness, where we found increased $G_i$ in ASM, inhibition of $G_i$ resulted in even greater hyperresponsiveness. Thus the increase in $G_i$ appears to be a compensatory event aimed at attenuating bronchial hyperresponsiveness. We also found that $\beta_2$AR-mediated relaxation of ASM was substantially regulated by $G_i$ expression, which we propose is due to direct coupling of this receptor to $G_i$.

Results

$G_{a_2}$ is increased in a genetic model of asthma, and PTX alters airway responsiveness. To assess whether the findings by Grunstein and colleagues of increased $G_{a_2}$ in rabbit models of asthma (3) are true for another model, we examined the expression of $G_{a_2}$ 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 $G_{a_2}$ 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 asthma 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 $G_{i2}$-coupled $M_2$-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). While these findings potentially implicate $G_i$ function as an important element in airway contraction and relaxation, the use of systemic PTX is not specific for ASM and does not provide information as to the effects of increased $G_{a_2}$ expression, as is found in the aforementioned asthma models. These limitations led to the generation of transgenic mice $G_{a_2}$-OE (incorporating the full-length human $G_{a_2}$ cDNA) and $G_{a_2}$-IP (a “minigene” peptide consisting of the C-terminal portion of $G_{a_2}$) targeted to ASM.

Transgenic expression of $G_{a_2}$ and a $G_{a_2}$ competitive inhibitor. Transgenic mice were generated using smooth muscle actin promoter 8 (SMP8); the injected constructs consisted of the full-length cDNA for human $G_{a_2}$ or a cDNA encoding the carboxy terminus of human $G_{a_2}$ (58 amino acids), which also included a 5′ HA-tag (see Results).
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 G\(_{\alpha}\)i2 transgene by RT-PCR using human-specific G\(_{\alpha}\)i2 primers and for the G\(_{\alpha}\)i2-IP transgene using primers based on sequence from the 5’ HA-tag and human G\(_{\alpha}\)i2. As shown in Figure 3A, the human G\(_{\alpha}\)i2 transcript was identified only in ASM cells derived from G\(_{\alpha}\)i2-OE mice. Immunoblots using G\(_{\alpha}\)i2 antisera further showed overexpression of G\(_{\alpha}\)i2 protein by approximately 10-fold in the ASM cells derived from the full-gene overexpressors (Figure 3B; note that the G\(_{\alpha}\)i2-IP 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 G\(_{\alpha}\)i2-IP minigene, RT-PCR revealed the chimeric HA-G\(_{\alpha}\)i2-IP transcript in ASM cells only in the G\(_{\alpha}\)i2-IP–derived cell lines, not the NTG or G\(_{\alpha}\)i2-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 arterial blood pressure measured noninvasively by tail cuff readings over a period of 5 days did not differ among NTG, G\(_{\alpha}\)i2-OE, and G\(_{\alpha}\)i2-IP mice (125 ± 1 mmHg, 125 ± 3 mmHg, and 126 ± 5 mmHg, respectively; n = 10; data not shown).

**Effects of altering G\(_{\alpha}\)i by transgenesis on airway contractile and relaxation responses.** Baseline airway resistance did not differ among G\(_{\alpha}\)i2-OE, G\(_{\alpha}\)i2-IP, and NTG mice (0.53 ± 0.061 cm H\(_2\)O/ml/s, 0.58 ± 0.036 cm H\(_2\)O/ml/s, and 0.57 ± 0.041 cm H\(_2\)O/ml/s, respectively; n = 6–9; data not shown). However, G\(_{\alpha}\)i2-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 G\(_{\alpha}\)i expression and function to physiologic effect (contraction), G\(_{\alpha}\)i2-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).

**Figure 3**

G\(_{\alpha}\)i2-OE and G\(_{\alpha}\)i2-IP in ASM cells. (A) RT-PCRs from total RNA derived from primary ASM cell cultures from NTG (lanes 1, 2, 7, 8, 13, and 14), G\(_{\alpha}\)i2-IP (lanes 3, 4, 9, 10, 15, and 16), and G\(_{\alpha}\)i2-OE (lanes 5, 6, 11, 12, 17, and 18) mice were performed using transgene-specific primers. (B) Overexpression of G\(_{\alpha}\)i2 protein in ASM lysates from G\(_{\alpha}\)i2-OE cells. Note that the protein from G\(_{\alpha}\)i2-OE cells was underloaded by 10-fold compared with NTG cells, as shown by the GAPDH signals. (C) Histopathologic specimens from the lungs of the NTG and 2 representative transgenic lines. Shown are hematoxylin and eosin–stained (upper panels) and trichrome-stained (lower panels) representative sections. Original magnification, ×20.

**Figure 4**

G\(_{\alpha}\)i2-OE or G\(_{\alpha}\)i2-IP in mouse ASM alters responsiveness to M\(_3\)-muscarnic and β\(_2\)-AR agonists. (A) Intact, ventilated mice were administered the indicated doses of inhaled methacholine and airway resistance measured. The G\(_{\alpha}\)i2-IP mice had a greater response to methacholine than NTG mice, while G\(_{\alpha}\)i2-OE mice were less responsive than NTG. \(^1\)P < 0.005 versus NTG, ANOVA. (B) Mice were pretreated with vehicle or inhaled isoproterenol and then underwent the methacholine challenge. NTG mice showed the expected decrease in maximal contraction while the G\(_{\alpha}\)i2-OE mice showed no statistical difference in airway resistance with isoproterenol. The G\(_{\alpha}\)i2-IP mice had an enhanced response to isoproterenol. Results are from 6–8 independent experiments. \(^*\)P < 0.05; \(^\ddagger\)P < 0.01.

The contractile responses to methacholine observed in the \( \text{G}_{\alpha i2-IP} \) mice were consistent with those observed with PTX treatment (Figure 2A). The effects of \( \text{G}_{\alpha i} \) expression on \( \beta_2 \)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 \( \text{G}_{\alpha i2-IP} \) mice, a markedly enhanced \( \beta_2 \)AR function was observed, with very little bronchoconstriction in these mice when pretreated with isoproterenol. This effect of \( \text{G}_{\alpha i2-IP} \) 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 \( \text{G}_{\alpha i2-OE} \) mice there was an apparent small decrease in contraction in the presence of isoproterenol, but this did not reach statistical significance, suggesting impaired \( \beta_2 \)AR function. Thus, like the bronchoconstrictive response (where \( \text{G}_{\alpha i2} \) upregulation and downregulation had opposite effects), \( \text{G}_{\alpha i2} \) inhibition enhanced relaxation via \( \beta_2 \)AR, while \( \text{G}_{\alpha i2} \) overexpression decreased it.

We considered that the \( \beta_2 \)AR-mediated relaxation phenotype of \( \text{G}_{\alpha i2-OE} \) mice could be a result of altered expression of ASM \( \beta_2 \)AR or altered function of another receptor acting via \( \text{G}_{\alpha i} \). However, \( \beta_2 \)AR expression, as determined by quantitative \( ^{125}\text{I}-\text{cyanopindolol} \) binding, did not differ among NTG, \( \text{G}_{\alpha i2-OE} \), and \( \text{G}_{\alpha i2-IP} \) cells \((15 \pm 2.1 \text{ fmol/mg}, 19 \pm 3.8 \text{ fmol/mg}, \text{and } 20 \pm 2.9 \text{ fmol/mg}, \text{respectively};\)

Figure 5
\( \text{M}_2 \) muscarinic receptor activation does not alter the \( \text{G}_{\alpha i} \)-effect on \( \beta_2 \)AR-mediated smooth muscle relaxation. Shown are experiments where isolated tracheal rings were pretreated with 0.1 μM pilocarpine (pilo) or vehicle, contracted with 60 mM KCl, and then exposed to increasing concentrations of isoproterenol. The brackets clarify the effects of pilocarpine compared with vehicle, which were not significantly different, in the NTG and \( \text{G}_{\alpha i2-OE} \) groups \((n = 4 \text{ experiments})\).

Figure 6
Downstream modulation of signal transduction elements by altered \( \text{G}_{\alpha i} \) in ASM cells. (A) Western blots from 4 independent ASM cell lysates for each line. Symbols at right of blots denote significant increase (up arrows), significant decrease (down arrows), or no change (dashes) in protein expression from \( \text{G}_{\alpha i2-OE} \) and \( \text{G}_{\alpha i2-IP} \) derived cells (left and right symbols, respectively) compared with NTG cells. (B) Quantification of Western blot data, presented as mean ± SEM. \(* P < 0.05\); \# \( P < 0.01\); † \( P < 0.005\); ‡ \( P < 0.001\) versus NTG.

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 Gs-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 81% ± 4.0% (a 22% decrease; Figure 5).

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a number of models of asthma, and it has been proposed 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 Gαi function via a minigene. This resulted in increased contraction, which is the opposite phenotype to Gαi2-EO, 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 Gαi. Thus, the increase in Gαi 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 Gαi is a beneficial compensatory event, acting to limit the extent of hyperresponsiveness. To confirm this notion, the IL-13–ducible 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 M1-muscarinic receptor function. Although the M3 subtype is clearly the major muscarinic receptor that mediates airway contraction to muscarinic agonists, we recognize that the M4 subtype also contributes (16). This subtype, which is Gβ2 coupled, appears to promote contraction via decreasing CAMP and eliciting nonelective cation conductance (17). However, our results with the Gαi2-EO 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-EO and Gαi2-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 Gαi resulted in downregulation of PLCβ3, the effector for Gαi-coupled receptor activation. In contrast, PLCβ3 expression was unchanged in Gαi2-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 Gαi 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 Gαi 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 Gβ/γ-coupled receptor, can also couple to Gq (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 Gq 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 Gq, which has important physiologic consequences. The results with the Gαi2-EO mice revealed that increased Gq expression was associated with increased β2AR-Gq signaling, which competed with stimulation of β2AR-mediated relaxation via Gq. 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 Gαq 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

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**Figure 8**

Multiple roles of Gαi in regulating contraction and relaxation signaling in ASM. Increased (green arrows) or decreased (red arrows) expression or function of given parameters are indicated. Dotted lines denote pathways and critical mechanisms of action from increased Gαi; dashed lines denote pathways and critical mechanisms of action from decreased Gαi. AC, adenylyl cyclase; MβR, Mβ-muscarinic receptor.
desensitizes β2AR) 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, PKCs and PKCδ were downregulated in both mice.

The current work shows a complex, multifactorial interplay between Gα activation 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 Gαi2 observed in asthmatic-like airways (3–6) appears to serve a protective effect: the increase acts to attenuate bronchial hyperresponsiveness from Gαs-mediated receptor signaling. Given that virtually all bronchospastic mediators act via Gαi-coupled receptors (e.g., M3-muscarinic, LTI-cysteinyl leukotriene, and H1-hista- mine), it would appear that not only is the increase in Gαi beneficial in asthma, attempts to adjust these levels at or below normal will increase bronchial hyperreactivity and exacerbate asthma. On the other hand, the increase in Gαi impaired β-agonist bronchodilatation. This appears to be due to an enhancement of β2AR-Gαi coupling, which opposes β2AR-Gαi functional stimulation of adenyl cyclase. Furthermore, decreasing Gαi function acts to increase β2AR-mediated bronchodilatation, as would be expected based on this mechanism. Therefore, in the absence of β-agonist treatment the increase in Gαi in asthmatic mice different from Gαs acts to attenuate bronchospasm, but also limits the effectiveness of β-agonists in relieving bronchoconstriction. This multipronged set of regulatory events may indicate that pharmacologic or genetic methods to modulate Gαi could have limited clinical utility. However, there may be opportunities to exploit these relationships by manipulating other downstream effects of altered Gαi expression. For example, if decreasing Gαi expression and function could be accomplished while also inhibiting PKCα, then both the relaxation and the constrictive pathways would be affected in a manner that would be expected to be clinically beneficial for hyperresponsiveness and β-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 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 NotI/XhoI 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 on 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 cultured 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′-GGCCGGTTGTCTACAGCAACCAT-3′ and 5′-CTT-GCTCTGTGGGGCATGTACTC-5′). For Gαi2-IP, the 5′ primer was based on the HA-tag sequence (5′-TACCCATAGCGTGCCCAGACTA-3′ and 5′-CCACAGTCTCTTCAGGGTGTCTTG-5′). 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 β-agonist, isoproterenol (1.0 mg/ml) was delivered by aerosol, and then the constrictive 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). Tracheae 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 mN, 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-antimyocytic solution (Invitrogen). After additional surrounding tissue was removed, the tracheal segment was cut longitudinally and dissected into 2- to 3-mm squares. Segments from a single trachea were then placed into a sterile 60-mm dish. After adherence, Dulbecco’s modified Eagle’s medium supplemented with 20% FCS and 2x antibiotic-antimyocytic was added to cover the explants. Explanted trachea were subsequently removed when there was local confluency. Once the initial seed dish became confluent, cells were harvested by trypsinization and transferred 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% IGEPAL, 0.5% sodium deoxycholate, and 0.1% SDS in phosphate-buffered saline. The protease inhibitors benzamidine, soybean trypsin inhibitor, and aprotinin (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 the unsolubilized material and the supernatants aliquoted and frozen at -70°C. Proteins from whole tracheae were prepared in a similar manner, 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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