

Cooperation between Mast Cells and Neurons Is Essential for Antigen-Mediated Bronchoconstriction¹

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Mast cells are important sentinels guarding the interface between the environment and the body: a breach in the integrity of this interface can lead to the release of a plethora of mediators that engage the foreign agent, recruit leukocytes, and initiate adaptive physiological changes in the organism. While these capabilities make mast cells critical players in immune defense, it also makes them important contributors to the pathogenesis of diseases such as asthma. Mast cell mediators induce dramatic changes in smooth muscle physiology, and the expression of receptors for these factors by smooth muscle suggests that they act directly to initiate constriction. Contrary to this view, we show herein that mast cell-mediated bronchoconstriction is observed only in animals with intact innervation of the lung and that serotonin release alone is required for this action. While ablation of sensory neurons does not limit bronchoconstriction, constriction after Ag challenge is absent in mice in which the cholinergic pathways are compromised. Linking mast cell function to the cholinergic system likely provides an important means of modulating the function of these resident immune cells to physiology of the lung, but may also provide a safeguard against life-threatening anaphylaxis during mast cell degranulation. *The Journal of Immunology*, 2009, 182: 7430–7439.

Immunoglobulin E-dependent mast cell activation is the central mechanism underlying immediate allergic reaction (1). Cross-linking of IgE bound by Fc receptors on mast cells leads to release of preformed mediators stored in the mast cell granules, as well as production of lipid mediators and up-regulation of cytokine synthesis (1). These mediators can profoundly influence the physiology of the organism, and thus systemic release of mast cell mediators can result in life-threatening anaphylaxis. Mast cells can also contribute to chronic inflammatory diseases, including asthma, where activation by environmental allergens contributes to inflammation and reversible airway constriction, a hallmark of this disease. Consistent with a role for mast cells in this aspect of asthma, an increase in airway mast cells has been reported in asthmatic patients compared with healthy individuals (2).

The mechanisms through which mast cell mediators contribute to the airway obstruction are not yet completely understood. However, airway smooth muscle (ASM)³ expresses many receptors for mediators produced by mast cells (3). Thus, in the simplest model,

mast cell mediators, including cysteinyl leukotrienes, histamine, and serotonin (5-HT) act directly on smooth muscle, triggering increases in intracellular Ca^{2+} followed by assembly of the contractile apparatus. Direct ability of several mast cell mediators to elicit Ca^{2+} flux in muscle cells and constriction of tracheal rings further support this model (4–6).

In a number of organ systems, close interaction of mast cells with both sensory and parasympathetic neurons has been demonstrated, suggesting that mast cells may induce bronchoconstriction by altering the activity of the neuronal pathways that function to determine ASM tone. For example, histamine released by mast cells is reported to stimulate parasympathetic neurons in the guinea pig heart (7), while Ag challenge in sensitized rats results in the activation of afferent nerve fibers in the gut mediated by both histamine and serotonin (8). Consistent with this, mucosal mast cell mediators from patients with irritable bowel syndrome were reported to excite rat nociceptive visceral sensory nerves (9). Additionally, a number of studies suggest that this relationship is also present in other organs including the lung. For example, it has been reported that substance P-containing nerves in the rat trachea interact with mast cells to cause Ag-specific, and dependent, changes in lung solute clearance and epithelial chloride ion secretion (10–12).

In humans, the cholinergic parasympathetic nervous system represents the predominant bronchoconstrictor pathway in the airways. Efferent cholinergic nerve fibers run through the vagus nerve and synapse in small ganglia within the airway wall. These nerve fibers release acetylcholine (ACh), which binds nicotinic ACh receptors (nAChRs) on the parasympathetic ganglion, which activates postganglionic fibers innervating ASM and submucosal glands. These postganglionic fibers release ACh, which binds to muscarinic ACh receptors (mAChRs) directly on ASM. The activity of the parasympathetic pathway is modulated by sensory neurons present throughout the airway. Supporting a role for the mast cell interaction with the autonomic nervous system, mast

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³ Abbreviations used in this paper: ASM, airway smooth muscle; ACh, acetylcholine; BALF, bronchoalveolar lavage fluid; B6, C57BL/6; 5LO, 5-lipoxygenase; FOT, forced oscillatory technique; G, tissue damping; H, tissue elastance; LT, leukotriene; MCh, methacholine; mAChR, muscarinic acetylcholine receptor; nAChR, nicotinic acetylcholine receptor; PAR2, protease-activated receptor 2; PCPA, 4-chloro-DL-phenylalanine; R_{aw} , airway resistance; R_L , lung resistance; Wsh/Wsh, C57BL/6 Kit^{W-sh}/Kit^{W-sh} .

cells have been shown to be closely associated with airway nerves (13), and receptors for many mast cell mediators, including histamine and serotonin, are expressed by neurons (14–16). In the studies detailed herein we demonstrate that in allergic mice, Ag challenge induces constriction of the central airways, and this constriction is dependent not only on mast cells but also on an intact parasympathetic system.

Materials and Methods

Experimental animals

All studies were conducted in accordance with the National Institutes of Health "Guide for the Care and Use of Laboratory Animals" and were approved by the Institutional Animal Care and Use Committee guidelines of the University of North Carolina at Chapel Hill. Mast cell-deficient C57BL/6 *Ki^{W-sh}/Ki^{W-sh}*, protease-activated receptor 2 (PAR2)^{−/−} mice (17) and their wild-type C57BL/6J controls were purchased from The Jackson Laboratory. M₁ and M₃ mAChR-deficient mice and their controls were bred as previously described (18, 19). The generation of congenic 5-HTT-deficient mice has been previously described (20). All experiments were conducted using 8- to 12-wk-old mice, with the exception of the 5-HTT mice. Both control and experimental animals were 6 mo of age.

Airway measurements in intubated mice

Mechanical ventilation and airway measurements were conducted as previously described (21). After baseline measurements, serotonin (6.25 μ g/ml; Sigma-Aldrich) was administered i.v. through a jugular catheter in increasing doses (0.3, 0.6, and 1.2 μ g/ml). Single doses of DNP (250 μ l, 5 mg/ml; Sigma-Aldrich) or OVA (50 μ l, 10 mg/ml, grade V; Sigma-Aldrich) were also delivered i.v. through a jugular catheter. After administration, airway mechanics were determined using the forced oscillatory technique (FOT) every 10 s for 3 min. The resultant pressure and flow data were fit to a constant phase model as previously described (22). Similar to other studies assessing FOT, we confined our analysis to airway resistance (R_{aw} ; Newtonian resistance), which assesses the flow resistance of the conducting airways, and G (tissue damping), which reflects tissue resistance in the peripheral airways (23). Total lung resistance (R_L) was calculated from the FOT data by adding tissue resistance (R_t) to R_{aw} as previously described (23, 24). R_t is given as $R_t(f) = G/(2\pi f)^\alpha$, where f is the frequency in Hz and $\alpha = (2/\pi)\tan^{-1}(H/G)$, with H indicating tissue elastance. All data are represented as percentage baseline R_L , R_{aw} , or G .

To determine the contribution of various receptors in airway responses, mice received a pretreatment i.p. injection of pharmacological antagonist before exogenous administration of mediators or Ag. To assess the role of mAChRs and nAChRs to airway responses, mice received a pretreatment i.p. injection of atropine sulfate (10 μ M/kg; American Pharmaceutical Partners) or mecamylamine (4 mg/kg; Sigma-Aldrich), respectively. Methiothepin (2 mg/kg, i.p.), ketanserin (12 mg/kg, i.p.), and ondansetron (1 mg/kg, i.p.) were administered to block serotonin receptors. Methiothepin is a nonspecific antagonist, whereas ketanserin and ondansetron are specific antagonists for 5-HT_{2A} and 5-HT₃ receptors, respectively.

Anaphylaxis protocols

IgE-dependent passive anaphylaxis. Mice were sensitized with 20 μ g of mouse monoclonal anti-DNP IgE (1.0 mg/ml; Sigma-Aldrich; 200 μ l of total volume in saline) or an equal volume PBS i.v. through the tail vein. Approximately 19–24 h after anti-DNP IgE injection, mice were anesthetized, catheterized, tracheostomized, and mechanically ventilated as described above. Immediately following the baseline measurements, 0.25 ml of 5 mg/ml DNP (or an equal volume of PBS) was injected into the jugular, and airway parameters were measured every 10 s for 3 min immediately following anaphylaxis induction. Bar graphs represent the area under the curve.

Active systemic anaphylaxis to OVA. Mice received a single i.p. injection of 0.2 ml of sterile 0.9% NaCl containing 20 μ g of OVA emulsified in 2.25 mg of aluminum hydroxide gel (Sigma-Aldrich). Eighteen to 21 days after OVA immunization, mice were anesthetized, placed on a ventilator, challenged with a single i.v. infusion (via a jugular catheter) of 500 μ g of OVA in 50 μ l of sterile 0.9% NaCl, and airway measurements were taken every 10 s for 3 min (25). Control mice were challenged with an equal volume of sterile 0.9% NaCl. Bar graphs represent the area under the curve.

Acute anaphylaxis to OVA following induction of allergic airway disease. Mice were sensitized by i.p. injection of 20 μ g of OVA emulsified in 2.25 mg of aluminum hydroxide gel in a total volume of 200 μ l on days 1 and 14. Mice were challenged (45 min) via the airways with OVA (1% in

saline) for 5 days (days 21–25) using an ultrasonic nebulizer (DeVilbiss Health Care). On day 26 mice were anesthetized, placed on a ventilator, challenged with a single i.v. infusion (via a jugular catheter) of 500 μ g of OVA in 50 μ l of sterile 0.9% NaCl. Airway measurements were taken every 10 s for 3 min. Bar graphs represent the area under the curve.

After airway measurements, mice were sacrificed and 0.5–1.0 ml of blood was collected by cardiac puncture. Following coagulation, serum was collected. Total IgE levels in the serum were measured by ELISA (R&D Systems). Bronchoalveolar lavage was performed successively with 1.0 ml of sterile HBSS five times. The recovered bronchoalveolar lavage fluid (BALF) was centrifuged to remove cells. Histamine levels were measured in the cell-free supernatant by ELISA (Beckman Coulter).

Inhibition of serotonin with 4-chloro-DL-phenylalanine (PCPA)

Mice received a single i.p. injection of 0.2 ml of sterile 0.9% NaCl containing 20 μ g of OVA emulsified in 2.25 mg of aluminum hydroxide gel. Eighteen to 21 days after OVA immunization, mice were treated with PCPA (150 mg/kg, i.p.; 25 mg/ml in 1 N HCl) and immediately challenged with 250 μ g of OVA in 50 μ l of sterile 0.9% NaCl (i.v.) to deplete serotonin stored in mast cells. Twenty-four hours later, mice received a second treatment of PCPA (150 mg/kg, i.p.) and were then anesthetized, placed on a ventilator, and challenged with a single i.v. infusion (via a jugular catheter) of 500 μ g of OVA in 50 μ l of sterile 0.9% NaCl, and airway measurements taken every 10 s for 3 min. Control mice were challenged with an equal volume of sterile 0.9% NaCl.

After airway measurements, mice were sacrificed and 0.5–1.0 ml of blood was collected by cardiac puncture with a syringe containing 20 μ l of 100 U/ml heparin. The blood was then centrifuged at 12,000 rpm for 5 min to collect plasma. Serotonin levels were measured in the plasma by ELISA (Beckman Coulter).

Sensory ablation

Adults. Capsaicin was administered to ablate sensory neurons as previously described (26, 27). For pretreatment, mice received a s.c. dose of 25 mg/kg capsaicin at 0 h and a second s.c. dose of 75 mg/kg capsaicin at 24 h (5 and 15 mg/ml capsaicin dissolved in 1:1:8 ethanol/Tween 80/saline, respectively). To minimize the respiratory effects associated with capsaicin injection, animals were first anesthetized with avertin (250 mg/kg, i.p.) and then treated with 10 mg/kg theophylline (s.c., 5 mg/ml in distilled water; Sigma-Aldrich) and 0.1 mg/kg terbutaline (i.p., 0.05 mg/ml in saline; Sigma Chemical). Airway assessment was conducted 10–12 days after the final capsaicin treatment.

Neonates. Pups were injected with 50 mg/kg capsaicin (15 mg/ml, s.c.) at day 2 to 3 after birth to degrade sensory neurons. Animals were aged to 8 wk before conducting studies.

To check for effectiveness of the treatment, a drop of 0.1 mg/ml capsaicin was instilled into one eye of each mouse and wiping movements were counted as previously described (28, 29). For substance P measurements, lungs were lavaged with 0.4 ml of chilled PBS containing 500 kallikrein inhibitor U/ml aprotinin (Sigma-Aldrich). Substance P was measured from BALF by ELISA (R&D systems).

Vagotomy

A surgical vagotomy was conducted to assess the contribution of intact parasympathetic innervation as previously described (30). Briefly, the right and left vagus nerves running parallel to the trachea were isolated and a piece of surgical string was passed underneath to facilitate cutting during mechanical ventilation. In experimental animals, basal lung mechanics were established before severing of both vagus nerves. After vagotomy, baseline was then reassessed before i.v. challenge. Control animals received a sham operation that involved simply lifting and releasing of the surgical string along with the nerve fibers.

Statistical analysis

Data are represented as means $\pm$ SEM. ANOVA followed by Tukey-Kramer honestly significant difference for multiple comparisons was performed on complex data sets. Statistical significance for single data points was assessed by Student's two-tailed t test. A p value of <0.05 was considered statistically significant.

Results

Change in airway resistance during anaphylaxis is dependent on mast cells, primarily those located in the central airways

We first determined the contribution of mast cells to changes in airway mechanics. Previous studies have shown that in the mouse,

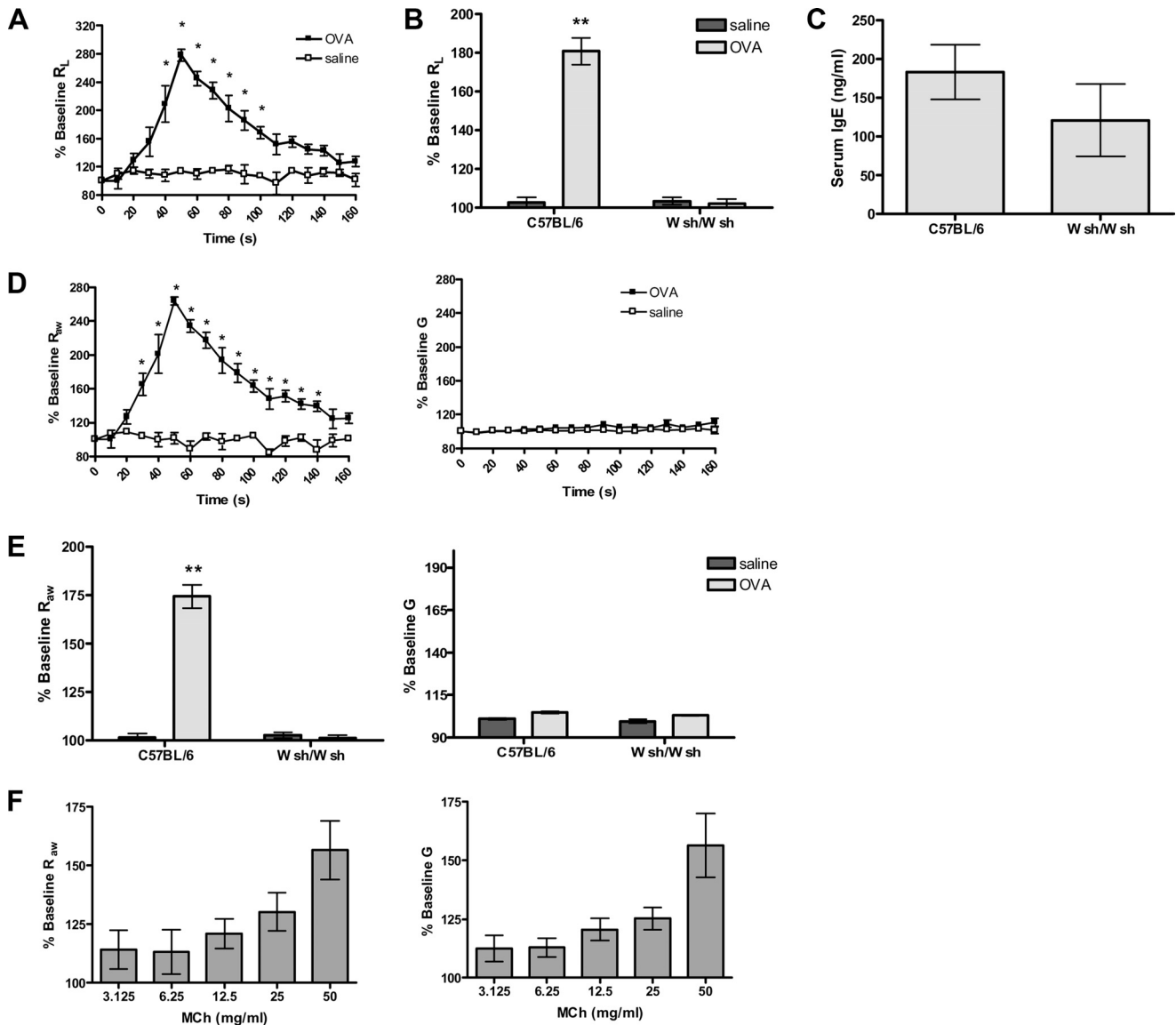


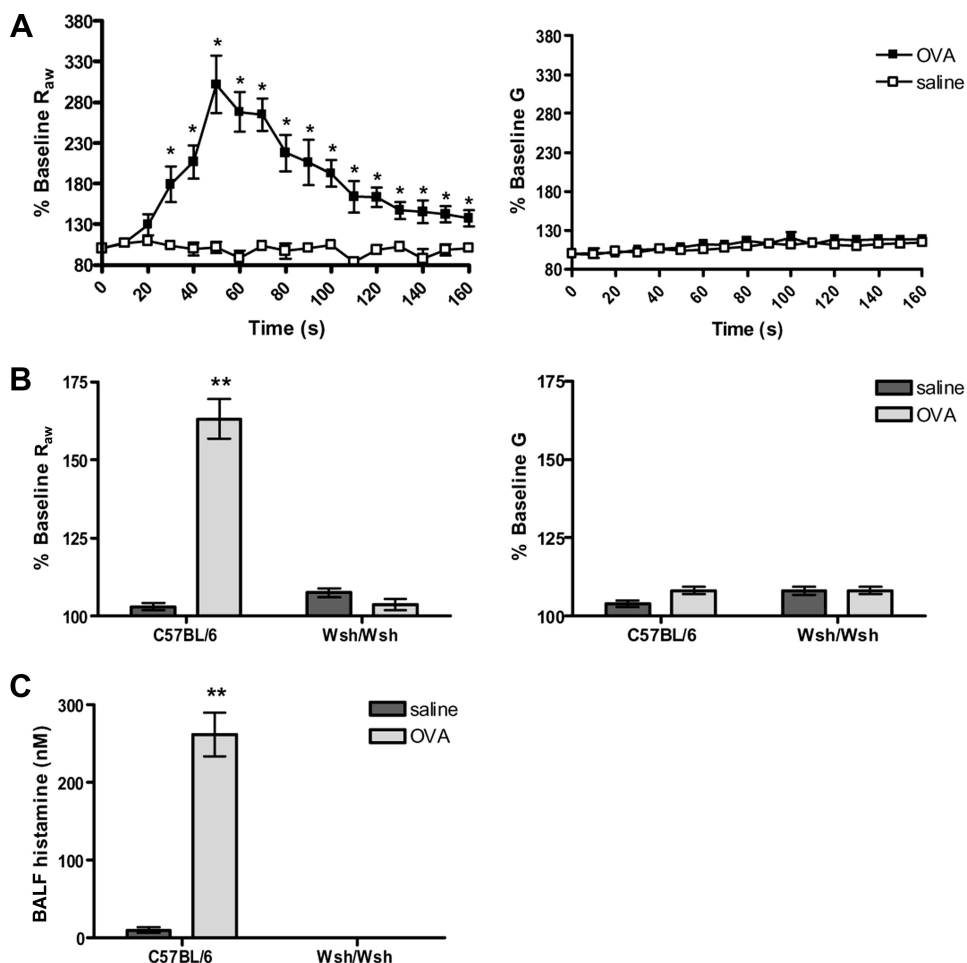
FIGURE 1. Changes in airway physiology of wild-type and mast cell-deficient mice in response to OVA and MCh. **A**, OVA challenge in sensitized mice ($n = 5$) induced an immediate increase in R_L that gradually returned to baseline. Control animals ($n = 4$) sensitized with OVA but challenged with saline had no change in R_L over baseline (*, $p < 0.05$ compared with OVA/saline). **B**, Increases in R_L are dependent on mast cells, as there was no response in mast cell-deficient Wsh/Wsh mice ($n = 8$) after Ag challenge (**, $p < 0.001$ compared with all other groups). **C**, IgE levels were comparable between wild-type ($n = 7$) and mast cell-deficient ($n = 7$) mice sensitized and challenged with OVA. **D**, FOT measurement of airway mechanics after Ag challenge. OVA challenge in sensitized mice ($n = 5$) resulted in a significant increase in R_{aw} but no change in G compared with controls ($n = 4$) (*, $p < 0.05$ compared with saline). **E**, Increases in R_{aw} in sensitized mice are dependent on mast cells. Sensitized Wsh/Wsh mice ($n = 8$) had no response to Ag challenge (**, $p < 0.001$ compared with all other groups). **F**, Aerosol MCh challenge in B6 mice ($n = 13$) results in a dose-dependent increase in both R_{aw} and G .

Ag treatment following sensitization results in rapid decrease in lung conductance (G_L) (25), which is the inverse of lung resistance (R_L). Similarly, we found that sensitization of wild-type C57BL/6 (B6) mice with OVA plus adjuvant, followed by exposure to Ag, resulted in a rapid and dramatic increase in R_L (Fig. 1A). Similar immunization and challenge of C57BL/6 *Kit^{W-sh}/Kit^{W-sh}* (Wsh/Wsh) mice, which lack mast cells, failed to induce changes in lung mechanics, indicating that this response was dependent on the normal development of this cell population (Fig. 1B). To verify that the difference in R_L was not due to a reduction in overall IgE production in the mast cell-deficient animals, we compared total serum IgE levels in the B6 and Wsh/Wsh congenic pairs (Fig. 1C). There was no difference in IgE production between the two groups.

Mast cells are located throughout the airways, including the trachea, bronchus, and sporadically in the parenchyma (31), yet it is

unclear whether all of these cells contribute to changes in lung physiology during anaphylaxis. To examine this point more closely, we monitored changes in airway mechanics after sensitization and exposure to OVA using FOT. Interestingly, using this method we found that the changes in lung mechanics were largely limited to a parameter termed “airway resistance” or R_{aw} , which a number of theoretical and experimental studies suggest is sensitive primarily to changes in the central airways (32). As can be seen in Fig. 1D, Ag induced a significant and robust change in R_{aw} in B6 mice previously sensitized to OVA plus adjuvant and little to no change in G , a parameter termed “tissue damping” that is associated with changes in the distal lung. In contrast, no change in R_{aw} was observed in mast cell-deficient Wsh/Wsh mice after Ag challenge or in mice treated with vehicle (Fig. 1E). To further verify these findings, we examined changes in airway mechanics in a

FIGURE 2. Anaphylactic bronchoconstriction in wild-type and mast cell-deficient mice with allergic lung disease. **A**, Allergic lung disease was induced by sensitization and repeated aerosol with OVA. B6 mice with inflamed airways ($n = 5$) exhibited a significant increase in R_{aw} after Ag challenge but no change in G (*, $p < 0.05$ compared with saline). Saline-challenged controls ($n = 3$) had no response. **B**, Mast cell-deficient Wsh/Wsh mice with an inflamed airway ($n = 7$) failed to respond to Ag challenge (**, $p < 0.001$ compared with all other groups). **C**, Histamine levels in B6 mice with inflamed airways were significantly increased after Ag injection ($n = 6$) compared with levels after saline injection ($n = 3$) (**, $p < 0.001$ compared with saline). Histamine was undetectable in Wsh/Wsh mice ($n = 7$).



mouse model of passive anaphylaxis. Mice received i.v. monoclonal anti-DNP IgE, and 24 h later, after establishment of baseline lung mechanics, mast cell degranulation was induced by i.v. delivery of Ag (DNP). DNP induced similar increases in R_{aw} as those seen during active anaphylaxis to OVA (data not shown). Unlike Ag-induced constriction, airway constriction induced with methacholine (MCh), a stable acetylcholine analog, resulted in both changes in R_{aw} and G consistent with both changes in the central and distal airways in response to this neurotransmitter (Fig. 1F). Similar responses to both Ag and MCh challenge were also observed in the BALB/c and 129/SvEv strains (data not shown). This suggests that although the ability of MCh to induce airflow obstruction is distributed throughout the lung, mast cell degranulation results in only central airway constriction, despite the presence of these cells in peripheral airways.

We next asked whether this is also the case in mice with inflamed airways, particularly in those with allergic lung disease. To address this question we induced allergic lung disease in B6 and Wsh/Wsh mice by sensitization and challenge with OVA using an immunization protocol previously shown to induce similar levels of inflammation in both lines (33). As expected, the absence of mast cells in the Wsh/Wsh mice did not significantly alter any of the disease parameters including IgE production, cellularity of the BALF, mucus cell hyperplasia, or the induction of the Th2 pathway (supplemental Fig. S1).⁴ Twenty-four hours after the last OVA challenge, changes in airway resistance in response to Ag were measured using FOT, monitoring both R_{aw} and G changes in

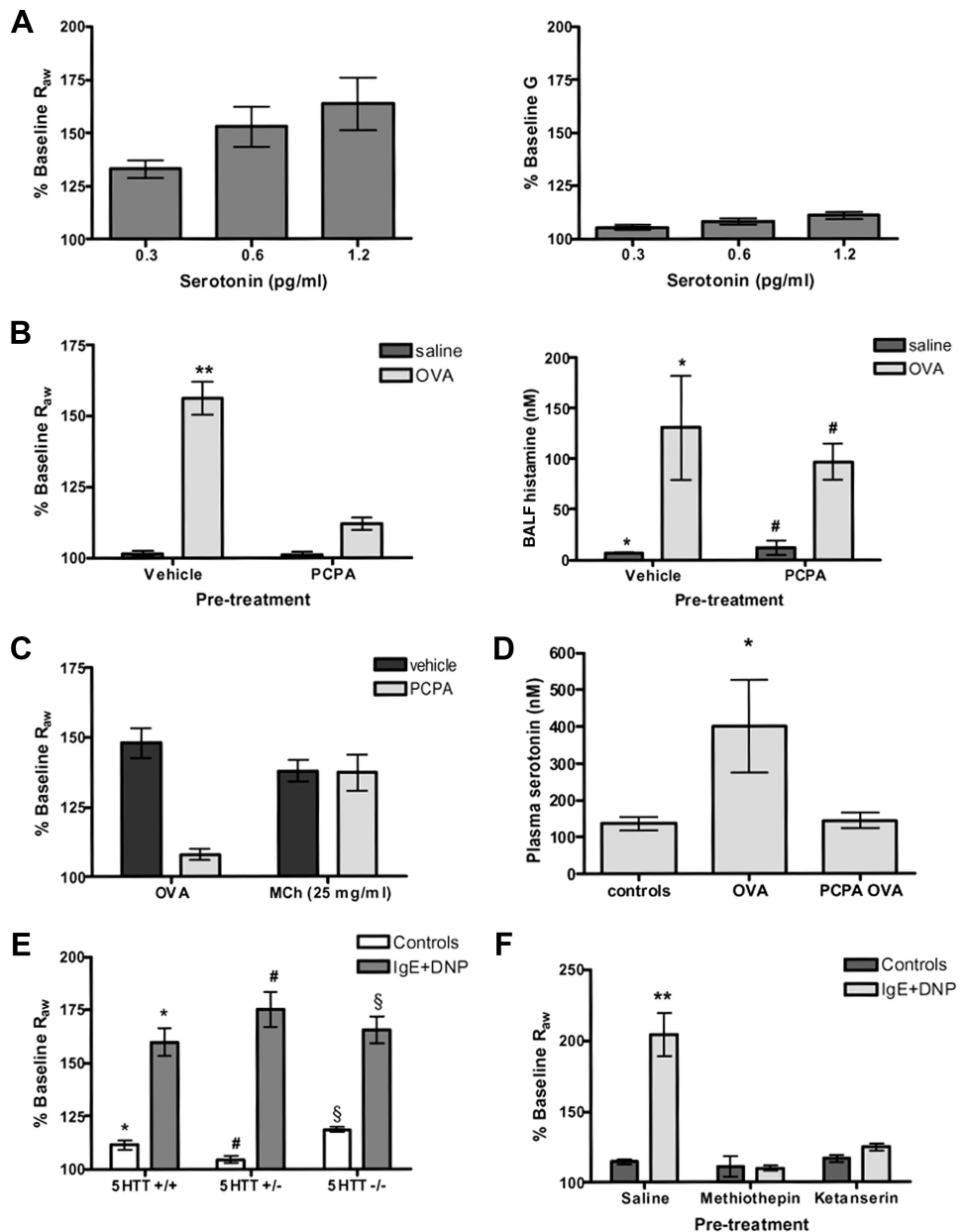
lung mechanics in the OVA-treated mice. Despite robust inflammation in the central and distal lung, changes in airway mechanics were limited to parameters associated with the central airways. A significant increase in R_{aw} was observed; however, no significant increase in G was observed after infusion of Ag into mice with inflamed lungs (Fig. 2A). Similar to actively sensitized animals, the increase in R_{aw} after OVA challenge in mice with allergic airway disease was dependent on mast cells; Wsh/Wsh mice failed to respond to Ag challenge (Fig. 2B). As would be expected given the absence of mast cells in the Wsh/Wsh mice, no histamine was detected in the Wsh/Wsh animals, while this mediator could easily be detected in the BALF from B6 mice following Ag challenge (Fig. 2C). Similar to the naive airway, Ag-induced constriction appears to be located within the central airways.

Mast cell release of serotonin alone mediates airway constriction during anaphylaxis

To address the contribution of the various mast cell mediators to allergen-induced bronchoconstriction, we took advantage of a number of pharmacological and genetic tools to examine the impact of loss of various pathways on the changes in R_{aw} during anaphylaxis (supplemental Fig. S2). Anaphylaxis results in a measurable increase of leukotriene (LT) C_4 in the BALF (34). To examine the contribution of LTC $_4$ to anaphylactic bronchoconstriction, we utilized animals lacking the enzyme 5-lipoxygenase (5LO), which is required for the synthesis of all leukotrienes. The inability of the mast cells to produce this lipid mediator did not alter bronchoconstriction after induction of passive anaphylaxis in 5LO $^{-/-}$ mice (Fig. S2C). Although PGD $_2$ has been shown to be

⁴ The online version of this article contains supplemental material.

FIGURE 3. Changes in airway physiology in response to serotonin and after inhibition of serotonergic pathways. **A**, Similar to Ag exposure, exogenous i.v. serotonin induces dose-dependent increases in R_{aw} , but no change in G ($n = 13$). **B**, Vehicle-treated mice ($n = 10$) sensitized and challenged with OVA had a significant increase in R_{aw} . Pretreatment with PCPA (150 mg/kg, $n = 15$) abolished anaphylactic airway constriction in actively sensitized mice challenged with OVA (**, $p < 0.001$ compared with all other groups). PCPA treatment had no effect on the ability of mast cells to degranulate; histamine levels were the same in both groups of OVA-treated animals ($n = 10$ –15/group). **C**, PCPA treatment had no effect on the ability of the airway smooth muscle to constrict to aerosolized MCh administered after Ag challenge ($n = 3$). **D**, PCPA treatment significantly attenuated plasma serotonin levels in OVA-challenged animals ($n = 4$ –6/group) (*, $p < 0.05$ compared with all other groups). **E**, Passively sensitized serotonin transporter (5-HTT)-deficient ($n = 4$) and heterozygous mice ($n = 5$) challenged with DNP had a significant increase in R_{aw} compared with controls ($n = 2$ /group). This response was similar to that of WT animals ($n = 5$) (*, $p < 0.001$; #, $p < 0.001$; §, $p < 0.001$). **F**, Blockade of serotonin receptors with methiothepin (2 mg/kg, $n = 5$) or ketanserin (12 mg/kg, $n = 5$) abolished airway constriction after Ag challenge in passively sensitized animals (**, $p < 0.001$ compared with all other groups).



synthesized and released during IgE-dependent activation of mouse bone marrow-derived mast cells (35), no attenuation of airway resistance was noted in mice in which the production of prostaglandins was inhibited by treatment with the nonsteroidal anti-inflammatory drug indomethacin (Fig. S2B). Similarly, antagonists which block the H1 and H2 histamine receptors did not significantly alter anaphylactic bronchoconstriction (Fig. S2A). The most abundant mediator found in human mucosal mast cells, tryptase, has the ability to activate PAR2 receptors, which can mediate airway constriction under some experimental conditions (36). To determine whether this pathway was involved in bronchoconstriction associated with anaphylaxis, we examined this response in PAR2^{-/-} mice (17); no difference in R_{aw} was noted between the mutant and control animals (Fig. S2D).

Mast cells express the enzyme required for the production of serotonin (37), and previous studies have indicated that serotonin can mediate changes in lung resistance (38). We therefore first asked whether the change in airway mechanics mediated by serotonin were also limited to the central airways. As can be seen in

Fig. 3A, exogenous serotonin induced a dose-dependent increase in R_{aw} with little change in G , a pattern that is similarly observed after mast cell degranulation. To address the role of serotonin in mast cell-mediated bronchoconstriction more directly, we examined the impact of PCPA on airway resistance. PCPA inhibits the activity of tryptophan hydroxylase, an enzyme that carries out the essential step in the synthesis of serotonin. Mice were sensitized with OVA and 3 wk later treated with either vehicle or PCPA before the induction of anaphylaxis by injection of Ag. Ag exposure resulted in a robust increase in airway resistance in the vehicle-treated animals. In contrast, airway resistance was abolished in mice treated with PCPA, despite the normal degranulation of mast cells in these animals; histamine levels in the BALF collected immediately after induction of anaphylaxis were not significantly different between the two groups (Fig. 3B). Furthermore, no difference was observed between the PCPA and control animals in the ability of their airways to respond to MCh (Fig. 3C). As expected, anaphylaxis resulted in a measurable increase in plasma serotonin levels, but this increase was not observed in the PCPA-treated

mice (Fig. 3D). Thus, the protection of the PCPA-treated mice from bronchoconstriction was due to attenuated serotonin release and not to alterations in either smooth muscle function or the responsiveness of mast cells to Ag.

To rule out a possible role for platelet-derived serotonin in this model, we examined the response to IgE and Ag in mice lacking the serotonin transporter. While mast cells express tryptophan hydroxylase and thus can produce serotonin, platelets acquire this mediator via the serotonin transporter as they pass through the intestinal circulation. Thus, platelets from mice and rats lacking the transporter also lack serotonin (39, 40). 5-HTT-deficient mice demonstrate wild-type levels of constriction after Ag challenge (Fig. 3E), indicating that platelet-derived serotonin is not critical for this response. Serotonin-dependent constriction was also observed in BALB/c mice (supplemental Fig. S3), which are commonly thought of as prototypical Th2 responders.

If bronchoconstriction is mediated by mast cell-derived serotonin, it would follow that agents that block serotonin receptors would also attenuate changes in R_{aw} . Serotonin-induced increases in R_{aw} were abolished by both the nonspecific antagonist methiothepin and the 5-HT_{2A}-specific antagonist ketanserin, whereas the 5-HT₃-specific antagonist ondansetron failed to attenuate this increase in airway mechanics (data not shown). Both methiothepin and ketanserin abolished allergic airway constriction in passively sensitized mice (Fig. 3F). Taken together, these studies indicate that while mast cells release many mediators that may modulate the inflammatory response, serotonin alone mediates the changes in airway resistance during anaphylaxis through its action on 5-HT_{2A} receptors.

Intact sensory innervation is not required for mast cell-mediated bronchoconstriction

Our observation that the ability of mast cells to mediate bronchoconstriction was sensitive to the location of these cells in the lung, and our observation that serotonin alone mediated this response, suggested to us that the mast cell-mediated constriction may result from indirect stimulation of sensory neurons, triggering a bronchial reflex. To test this hypothesis we examined the ability of IgE and Ag to induce constriction in mice in which sensory neurons had been ablated by treatment with capsaicin. Ablation of sensory C-fibers with capsaicin in both adults and neonates failed to significantly decrease R_{aw} after Ag challenge in passively sensitized mice (Fig. 4, A and B), suggesting that capsaicin-sensitive C-fibers do not play a primary role in allergic airway constriction. Substance P, the primary neurotransmitter stored in C-fibers, was measured to evaluate the efficacy of capsaicin treatment. Ag challenge in passively sensitized mice increased substance P levels in the BALF, but such levels were attenuated in mice pretreated with capsaicin (Fig. 4C), verifying that the capsaicin treatment ablated substance P containing C-fibers in these animals.

Vagotomy abolishes anaphylactic airway constriction in both the naive and allergic airway

The tone of ASM is largely dependent on parasympathetic innervation, which travels in the vagus nerve. Mast cells have been observed close to the vagus nerve and parasympathetic ganglia in other organisms and tissues (7, 13, 41), raising the possibility of cooperation between mast cells and these cholinergic fibers in bronchoconstriction. To test this hypothesis, we examined mast cell-mediated bronchoconstriction in mice in which the cholinergic pathways were disabled using a number of approaches.

Blockade of nAChRs with the nonspecific nicotinic antagonist mecamylamine, before Ag challenge, abolished Ag-induced increases in R_{aw} in passively sensitized mice (Fig. 5A). Postgangli-

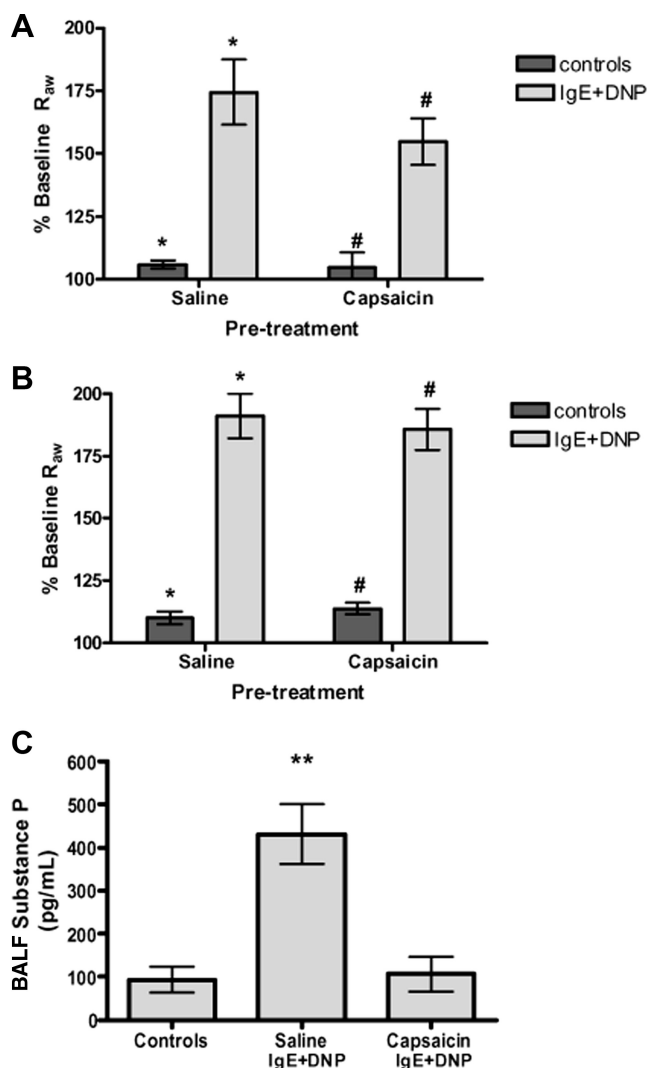


FIGURE 4. Anaphylactic bronchoconstriction following ablation of sensory C-fibers with capsaicin. **A**, Sensory ablation with capsaicin (25–75 mg/kg) in adults ($n = 6$) had no significant effect on airway constriction after Ag challenge in passively sensitized mice (*, $p < 0.001$; #, $p < 0.01$). **B**, Degradation of C-fibers with capsaicin (50 mg/kg) in newborn mice ($n = 7$) had no effect on airway parameters after Ag challenge in passively sensitized mice (*, $p < 0.001$; #, $p < 0.001$). **C**, Ag challenge in passively sensitized mice ($n = 10$) increased substance P content in the BALF. Neonatal treatment of capsaicin ($n = 5$) reduced BALF substance P after Ag challenge to levels seen in control animals ($n = 3$) (**, $p < 0.05$ compared with all other groups).

onic fibers release ACh, which binds mAChRs expressed by smooth muscle cells to initiate contraction. Blockade of mAChRs with the nonspecific muscarinic antagonist atropine resulted in complete absence of airway constriction after Ag challenge in both B6 (Fig. 5B) and BALB/c mice (supplemental Fig. S4). To further define the muscarinic receptors required for mast cell-mediated bronchoconstriction, we examined a series of mouse lines deficient in M₁ or M₃ mAChRs. Complete attenuation of R_{aw} was only observed in the mice lacking the M₃ mAChR (Fig. 5C), which has been shown to be expressed by airway smooth muscle (3).

The observation that disruption of both nicotinic and muscarinic neuronal transmission inhibits anaphylactic changes in airway mechanics suggests that an intact parasympathetic pathway is required for this mast cell function. If this is the case, we would expect that severing the incoming neural fibers would eliminate

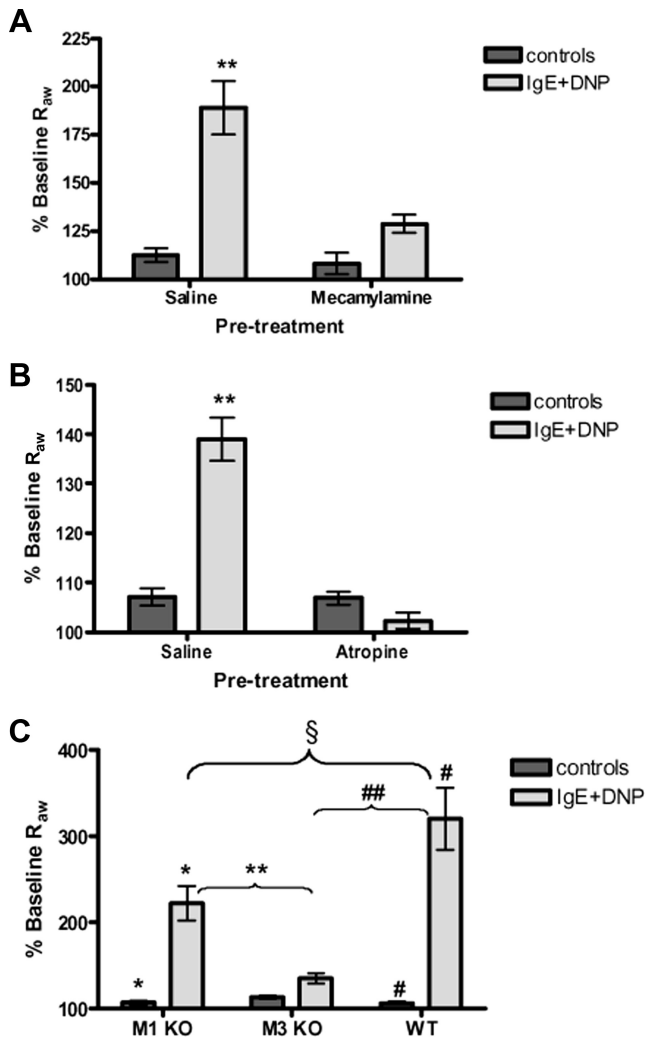


FIGURE 5. Ag-induced bronchoconstriction following cholinergic inhibition. *A*, Blockade of cholinergic nAChRs with mecamylamine (4 mg/kg, $n = 8$) abolished airway constriction following Ag challenge in passively sensitized wild-type mice (**, $p < 0.001$ compared with all other groups). *B*, Blockade of mAChRs with atropine (10 μ M/kg, $n = 6$) resulted in complete loss of airway constriction after Ag challenge in passively sensitized mice (**, $p < 0.01$ compared with all other groups). *C*, In passively sensitized animals, loss of the M_3 receptor ($n = 6$) resulted in abolishment of anaphylactic airway constriction, whereas M_1 receptor deficiency ($n = 6$) resulted in a significant attenuation, but not complete loss of the response to Ag (*, $p < 0.001$; **, $p < 0.01$; #, $p < 0.001$; ##, $p < 0.001$ §, $p < 0.01$).

IgE/Ag-mediated bronchoconstriction. To test this hypothesis, mice were treated with either IgE or saline and the following day the vagus nerve was severed before treatment with Ag. Control groups in which the nerve was isolated but not severed were also prepared. Vagotomy abolished Ag-mediated airway constriction in both B6 (Fig. 6A) and BALB/c mice (supplemental Fig. S4). We next determined whether severing the vagus nerve altered the ability or extent of mast cell degranulation in the airways by measuring histamine levels in the BALF immediately after measurement of airway parameters. No difference in histamine levels was seen following vagotomy (Fig. 6B). To verify that the vagotomy did not alter fundamental properties of the ASM, we confirmed that this surgical procedure did not alter the response of the mice to MCh (supplemental Fig. S5).

Inflammation results in the recruitment of cells to the lung. This raises the possibility that, in such an environment, mast cells may

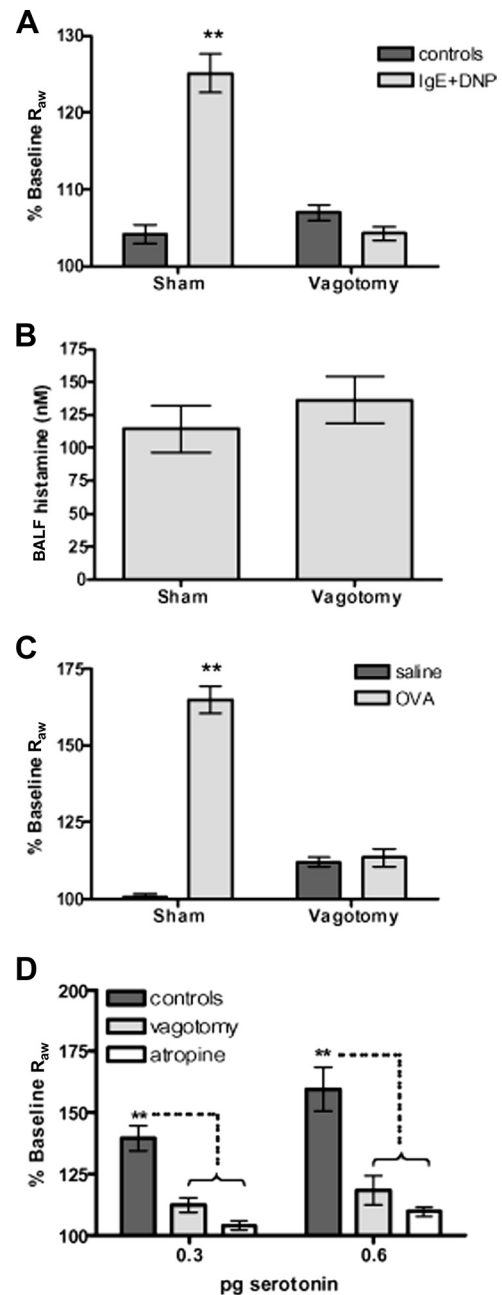


FIGURE 6. Vagotomy attenuates Ag and serotonin-induced changes in airway resistance. *A*, Passively sensitized and challenged wild-type mice after dissection of the vagus nerve ($n = 18$) or a surgical sham ($n = 28$). Ag-challenged mice showed a significant increase in R_{aw} that was abolished in vagotomized animals (**, $p < 0.001$ compared with all other groups). *B*, Histamine levels in the BALF were measured after induction of passive anaphylaxis. Vagotomy did not affect the levels of histamine in the BALF ($n = 5$ /group). *C*, Changes in R_{aw} were abolished after vagotomy in OVA-challenged sensitized mice ($n = 7$ –14/group) with allergic lung disease (**, $p < 0.001$ compared with all other groups). *D*, Serotonin was delivered i.v. following either vagal dissection or pretreatment with atropine. Exogenous serotonin ($n = 11$) resulted in a dose-dependent increase in R_{aw} that was sensitive to both vagotomy ($n = 5$) and atropine ($n = 6$) (**, $p < 0.01$).

bring about changes in airway caliber in response to Ag independent of parasympathetic pathways. To test this, we induced allergic lung disease in mice and examined the impact of vagotomy on these animals. Again, vagotomy abolished increases in R_{aw} following Ag challenge (Fig. 6C).

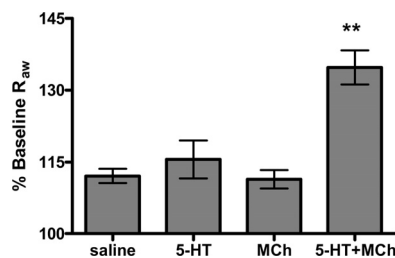


FIGURE 7. Increased airway resistance in mice treated with nonprovoking doses of both serotonin and MCh. B6 mice exhibited increased sensitivity to serotonin when coupled with exposure to a nonprovoking dose of MCh. Low levels of either i.v. serotonin (0.075 μ g, $n = 3$) or aerosolized MCh (6 mg/ml, $n = 3$) does not result in a significant increase in R_{aw} compared with saline challenge. A significant increase in R_{aw} was detected after nonprovoking doses of serotonin and MCh were delivered together ($n = 3$) (**, $p < 0.001$ compared with all other groups).

If serotonin released by mast cells collaborates with signals derived from the parasympathetic pathways, one would expect constriction of the airways to exogenous serotonin to show similar sensitivity to changes in the activity of this system. Supporting the role of serotonin in neural-mediated anaphylaxis, administration of exogenous serotonin exhibited dose-dependent central airway constriction that was sensitive to both vagotomy and atropine (Fig. 6D). Additionally, pretreatment with a nonprovoking dose of serotonin resulted in an additive effect on bronchoconstriction to a nonprovoking dose of MCh (Fig. 7). Collectively, these studies support a model in which mast cell-derived serotonin collaborates with cholinergic pathways of the lung to bring about changes in airway patency during anaphylaxis.

Discussion

We show herein that IgE-mediated degranulation of mast cells leads to an increase in the release of mast cell-specific mediators in the mouse lung accompanied by changes in airway mechanics. These changes in airway mechanics are dependent on both mast cell release of serotonin and intact cholinergic innervation of the lung. Similar to previous studies (42) we show that there was a dramatic increase in total R_L following Ag challenge, similar in magnitude to that generally achieved with 2 μ g of i.v. MCh (data not shown). More recently it has become possible to evaluate changes in airway mechanics using FOT. Using the input impedance of prime waves of various amplitudes, fit to the constant phase model of the lung, airflow obstruction following anaphylaxis can be distinguished between the central and peripheral airways (23, 32). Using this method we found that while MCh affects parameters associated with changes in mechanics of both the central and peripheral airways, changes observed after mast cell degranulation were surprisingly limited to the central airways despite the fact that these cells can be found throughout the lung, including within the distal airways and lung parenchyma (31). A number of different explanations are possible for this observation. First, while mast cells are found throughout the lung in B6 mice, a larger concentration is localized within close proximity of bronchial smooth muscle while few are found in the alveolar spaces and within the lung parenchyma (31). While Ag exposure may lead to degranulation of cells in the distal lung, the distribution of the receptor(s) sensitive to mast cell mediators may also be biased toward smooth muscle of the central airways. Alternate explanations are also possible. For example, it is possible that cholinergic innervation is more abundant in the central airways, or that the mast cell localization with respect to these neurons differs at different levels of the airways. However, our observation that inhaled

serotonin leads to changes in lung mechanics similar to that observed upon mast cell degranulation suggests that the distribution of serotonin receptors plays a role in limiting the response to the larger airways. This finding differs from studies conducted on precision cut lung slices prepared from rats in which constriction of airways was observed in both the distal and proximal airways (43). In this study Ag challenge of passively sensitized lung slices resulted in both stronger and faster constriction of the small airways when compared with the large conducting airways. Similarly, serotonin-provoked responses were also greater in the peripheral airways. Additionally, passively sensitized lung slices from humans have also been reported to have an increased response to Ag with decreasing airway size (44). The difference in these findings underscores the continuing importance of verification of ex vivo findings in an animal model. Alternately, this may reflect differences between species in the anatomical distribution of mast cells, ASM, airway receptors, or a combination thereof, and it may also indicate that while bronchoconstriction in mice is restricted to central airways this may not be representative of all species.

Mast cells produce a number of mediators that have been shown, both in vitro and in vivo, to mediate airway constriction, including LTC₄/LTD₄, PGD₂, tryptase, and histamine. Direct testing using mice lacking 5LO indicated that leukotrienes are not required for IgE/Ag-mediated airway constriction, at least in this species. Likewise, inhibition of endogenous prostaglandin production using the nonsteroidal anti-inflammatory drug indomethacin failed to inhibit Ag-induced increases in R_{aw} , ruling out the involvement of PGD₂ in this response. Furthermore, mice lacking PAR2 responded similarly to wild-type animals, indicating that, in the mouse, activation of PAR2 receptors by tryptase is not essential for airway constriction in this model. Also, we did not find evidence supporting a role for mast cell-derived histamine in this response, despite the ability of inhaled histamine to induce an increase in airway resistance in humans (45) and to modestly increase R_{aw} in some mouse strains (data not shown). In contrast, both inhibition of serotonin synthesis and blockage of the serotonin 5-HT_{2A} receptor completely abolished the change in airway mechanics after Ag challenge. This finding is consistent with a number of previous studies using mice, in which pharmacological agents were shown to attenuate changes in airway mechanics. For example, Eum et al. reported that pretreatment of Ag-challenged mice with the nonspecific serotonin receptor antagonist methysergide significantly attenuated anaphylactic bronchoconstriction (42). 5-HT₂ receptor-specific antagonists have also been shown to attenuate serotonin-induced increases in pulmonary mechanics (46).

Serotonin has been reported to activate human airway smooth muscle ex vivo (47). However, unlike LTC₄ and histamine, serotonin inhalation does not lead to increased airway constriction, even in asthmatics (48). Furthermore, until recently, it was thought that human mast cells, unlike the rodent counterpart, could not produce serotonin. Careful study of these cells has revealed both the expression of tryptophan hydroxylase and the localization of serotonin (37); however, these findings are limited to cells derived ex vivo and levels were quite small relative to the amounts stored in rodent mast cell granules. Despite the differing expression between human and mouse mast cells, a reevaluation of potential roles for this pathway in human mast cells is warranted. For example, it is possible that localized release of this mediator in close apposition to nerves or ASM can produce a significant change in the activity of the parasympathetic pathway, and that this activity is not easily mimicked by delivery to the epithelial surface.

The vagus nerve contains both the incoming parasympathetic efferents and the sensory nerves originating from the lung, and thus the loss of response in mice after vagotomy is consistent with a

model in which mast cells release mediators that stimulate sensory neurons. Sensory neuron activation can lead to both local release of mediators and a bronchial reflex resulting in increased activity of the parasympathetic pathway, a response lost in the vagotomized mice. The serotonin 5-HT₃ receptor is known to be involved in activation and depolarization of sensory neurons in several species, including the mouse (15). It is possible that serotonin released by mast cells activates sensory neurons to elicit a bronchial reflex. Past studies in various species have suggested the involvement of sensory neurons in the allergic response. For example, degranulation of purified human lung mast cells enhanced the excitability of rabbit visceral sensory C-fibers in vitro (49). Furthermore, antigenic stimulation of sensitized guinea pig bronchi caused increased sensitivity of sensory nerve endings (50). Consistent with this, Yu et al. showed that mast cell degranulation enhanced the excitability of guinea pig esophageal C-fibers to mechanical and chemical stimulation (51). In the rat, capsaicin-sensitive neurons interact with mast cells to influence lung solute clearance and chloride ion secretion in the trachea (10–12). Our observation does not support this mechanism, as pretreatment of the mice with capsaicin had little impact on mast cell-mediated airway constriction while, as expected, release of substance P by these neurons was all but eliminated. Consistent with this, pretreatment of mice with the 5-HT₃ receptor-specific antagonist ondansetron did not attenuate serotonin-induced increases in airway mechanics (data not shown). While it is unlikely that substance P is involved in this reaction, as animals were treated both as adults and as neonates, the involvement of this neurotransmitter cannot be completely discounted, as effects of specific NK receptor antagonists were not evaluated.

A number of lines of evidence presented herein support a critical role for parasympathetic neurons in mast cell-mediated bronchoconstriction. This includes the loss of the Ag-induced contractile response in vagotomized mice, the ability of antagonists of both nAChRs and mAChRs to block the response, and the inability of IgE and Ag to trigger bronchoconstriction in mice lacking the M₃ receptor. In recent years, studies have suggested that the cholinergic contractile response to serotonin depends on a non-neuronal source of ACh, specifically, serotonin released from the epithelium (46). This hypothesis was based largely on in vitro studies of mouse isolated trachea challenged with exogenous serotonin. They showed that serotonin-induced contractions of tracheal smooth muscle was sensitive to epithelial removal but not to inhibition of neural pathways, and that these contractions were dependent on the release of ACh. Our studies do not support this hypothesis, as it would predict that severing the vagus nerve would have no effect on the ability of serotonin to induce bronchoconstriction. Our data show that in vivo, airway constriction from both exogenous serotonin and mast cell-derived serotonin is sensitive to vagotomy.

A number of models for mast cell interaction with the cholinergic neural pathway are possible. First it is possible that mast cells increase transmission at the preganglionic terminal, either by increasing ACh release or by augmenting the activity of nAChRs. Second, mast cell mediators could amplify the release of ACh from postganglionic nerve terminals. Finally, activation of serotonin receptors on ASM may lead to smooth muscle contraction only when ACh, which is released at low levels constitutively by the parasympathetic fibers, occupies M₃ receptors present on ASM. A number of studies support the models in which Ag challenge induces an increase in release of ACh. Ex vivo studies have measured an increase in ACh levels after stimulation with Ag in both mouse and canine tracheal rings (52, 53). Drugs that decrease ACh metabolism increased bronchoconstriction after either Ag or 5-HT challenge (42). However, our finding that only the 5-HT_{2A} receptor antagonist attenuates this response, coupled with evidence that

supports the localization of this receptor to ASM (54) and not cholinergic fibers, supports the latter model in which the impact of engagement of the 5-HT_{2A} receptors is dependent on M₃ receptors present on ASM. The need for this “second signal” is not clear. Serotonin alone can shorten smooth muscle in vitro and in ex vivo lung slices (54, 55), and therefore the observation that in the mouse its ability to alter smooth muscle activity in vivo is regulated by parasympathetic pathways is somewhat surprising. However, it is interesting to speculate that this relationship represents one of a number of “checks and balances” designed to safeguard the patency of the airways, limiting the activity of smooth muscle modulators stored by mast cells, while at the same time allowing mast cells to safeguard the airway against infectious agents by rapid deployment of their arsenals of inflammatory mediators.

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Disclosures

The authors have no financial conflicts of interest.

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Supplemental Methods

Experimental animals. PAR2^{-/-} mice and wild-type C57BL/6 and BALB/c mice were purchased from Jackson Laboratory. Mice deficient in 5-lipoxygenase (5LO^{-/-}) were generated as previously described.(1) All experiments were carried out using 8-12 week old mice.

Cell counts. Cells present in the BAL were determined using a hemocytometer. A differential cell count was conducted on a cytospin prepared from 150 µl of BAL fluid and stained with Diff-Quik solution (Sigma Chemical).

Histology. For histopathologic examination, lungs were fixed by inflation (20 cm pressure) and immersion in 10% formalin. To evaluate airway eosinophilia, fixed lung slices were subjected to hematoxylin and eosin (H & E) staining. H&E stained lung slices were digitally imaged midway along the length of the main axial airway, as well as, at both ends of the same airway. Each of the three images was then divided into 4 quadrants and the levels of inflammation in each quadrant were semi quantitatively assessed based on a score of 0 (no inflammation) to 3 (severe inflammation). Scores from all quadrants for each of the 3 pictures representing 1 airway were then averaged together to represent the average H&E score of that airway.(2) To assess goblet cell hyperplasia, serial sections of the left lobes of the lungs that yield maximum longitudinal visualization of the intrapulmonary main axial airway were analyzed following Alcian-blue/periodic acid-schiff reaction (PAS) staining. To avoid bias for a certain region, and to consistently view the identical region in all slides, a 2-mm length of airway, located midway along the length of the main axial airway, was digitally imaged. Using ImageJ software (NIH, National Technical Information Service, Springfield, VA), the area and

length of the PAS/AB-stained region in the sections were measured and the data expressed as the mean volume density ($V_s = \text{nl/mm}^2$ basal lamina + SEM of PAS/Abstained material within the epithelium) as previously described.(3)

MCh treatment in vagotomized mice. Anesthetized, paralyzed, vagotomized, mechanically ventilated mice were treated with i.v. MCh (20 $\mu\text{g/ml}$, Sigma Chemical) administered through a jugular catheter in increasing doses (50 μl , 100 μl , and 200 μl) or an aerosolized dose response of MCh (12.5-50 mg/ml) delivered via a nebulizer through a side port in the ventilator circuit for 30 s at a rate of 200 breaths/min with a tidal volume of 0.15 ml. Immediately following the aerosol challenge, the nebulizer was isolated from the inspiratory circuit and the original mechanical ventilation was resumed.

Inhibition of PGD_2 . To assess the role of prostaglandins in IgE-dependent anaphylactic airway constriction, mice were pretreated with 10 mg/kg indomethacin (1 mg/ml , i.p., Sigma Chemical) 1 hour prior to airway measurements. To determine the efficacy of prostaglandin depletion, levels of PGD_2 were measured by EIA (Assay designs) from harvested gut samples.

Antagonism of histamine receptors. To determine the contribution of HR_1 and HR_2 to airway responses, passively sensitized mice received a pre-treatment i.p. injection of pyrilamine (40 mg/kg , Sigma Chemical) or cimetidine (25 mg/kg , Sigma Chemical), respectively.

Supplemental References

1. Goulet, J. L., J. N. Snouwaert, A. M. Latour, T. M. Coffman, and B. H. Koller. 1994. Altered inflammatory responses in leukotriene-deficient mice. *Proc Natl Acad Sci U S A* 91:12852-12856.
2. Kelly-Welch, A. E., M. E. Melo, E. Smith, A. Q. Ford, C. Haudenschild, N. Noben-Trauth, and A. D. Keegan. 2004. Complex role of the IL-4 receptor alpha in a murine model of airway inflammation: expression of the IL-4 receptor alpha on nonlymphoid cells of bone marrow origin contributes to severity of inflammation. *J Immunol* 172:4545-4555.
3. Cressman, V. L., E. M. Hicks, W. K. Funkhouser, D. C. Backlund, and B. H. Koller. 1998. The relationship of chronic mucin secretion to airway disease in normal and CFTR-deficient mice. *Am J Respir Cell Mol Biol* 19:853-866.

Supplemental Figure Legends

Figure S1 Airway inflammation in B6 and Wsh/Wsh mice with allergic lung disease. (A) There was no significant difference in serum IgE levels in wild-type ($n=8$) and mast cell deficient mice ($n=6$). (B) The resulting cell profile was the same for the wild-type ($n=6$) and mast cell deficient mice ($n=8$), with the majority of the cells ($>80\%$) being eosinophils. (C) IL-13 levels were used to represent the amount of inflammation present in the airways. There was no significant difference in IL-13 between the wild-type ($n=8$) and mast cell deficient mice ($n=9$). (D) The average H&E score was semi quantitatively measured for each main axial airway, and did not differ between the C57BL/6 ($n=9$) and C57BL/6 *Kit^{W-sh}/Kit^{W-sh}* ($n=9$) mice. (E) There was no significant difference in mucus levels in the wild-type ($n=8$) and mast cell-deficient ($n=8$) mice.

Figure S2 Pharmacological and genetic inhibition of mast cell mediator pathways during passive anaphylaxis. (A) C57BL/6 mice were pretreated with either pyrilamine (40 mg/kg) or cimetidine (25 mg/kg) to block histamine H1 and H2 receptors, respectively. Antagonism of histamine receptors had no effect on anaphylactic airway constriction in passively sensitized mice. Saline- controls, $n=3$; IgE+DNP, $n=13$. Pyrilamine- controls, $n=3$; IgE+DNP, $n=10$. Cimetidine- controls, $n=3$; IgE+DNP, $n=13$ (* $P<0.001$, # $P<0.01$, † $P<0.001$). (B) Pretreatment of passively sensitized C57BL/6 mice with indomethacin (10 mg/kg), to deplete endogenous prostaglandin production, had no effect on R_{aw} after antigen challenge. Saline- controls, $n=3$; IgE+DNP+saline, $n=6$. Indomethacin- controls, $n=3$; IgE+DNP+indomethacin, $n=7$ (* $P<0.001$, # $P<0.001$). (C)

Passively sensitized leukotriene deficient (5LO^{-/-}) mice and their wild-type C57BL/6 controls showed no difference in R_{aw} after antigen challenge. 5LO^{+/+} - controls, *n*=3; IgE+DNP, *n*=6. 5LO^{-/-} - controls, *n*=3; IgE+DNP, *n*=6 (**P*<0.001, #*P*<0.001). **(D)** Antigen induced airway constriction was equivalent in wild-type and PAR2^{-/-} passively sensitized mice. PAR2^{+/+} - Controls, *n*=4; IgE+DNP, *n*=6. PAR2^{-/-} - Controls, *n*=5; IgE+DNP, *n*=4 (**P*<0.001; #*P*<0.001).

Figure S3 Serotonin mediates antigen-induced central airway constriction in BALB/c mice. Vehicle treated mice sensitized with OVA and challenged with either PBS (Controls, *n*=2) or OVA (OVA, *n*=5). OVA challenged mice had a significant increase in R_{aw}. Pretreatment with 150 mg/kg PCPA (OVA+PCPA, *n*=4) abolished anaphylactic airway constriction in actively sensitized mice challenged with OVA (***P*<0.001 compared to all other groups).

Figure S4 Antigen-induced bronchoconstriction following vagotomy and atropine in BALB/c mice. Passively sensitized and challenged wild-type BALB/c mice after dissection of the vagus nerve or pretreatment with atropine. Antigen challenged mice (*n*=6) showed a significant increase in R_{aw} compared to controls (*n*=3). Airway constriction was abolished in vagotomized animals (*n*=5). Blockade of mAChRs with atropine (10 µM/kg, *n*=6) resulted in complete loss of central airway constriction after antigen challenge in passively sensitized mice. No significant change in G was observed. (***P*<0.001 compared to all other groups).

Figure S5 Airway mechanics in response to MCh challenge after vagotomy. (A)

Vagotomy also did not significantly affect the response to iv MCh. MCh, $n=3$;

MCh+vagotomy, $n=3$. **(B)** Constriction of airway smooth muscle following aerosolized

MCh was not altered following dissection of the vagus nerve. MCh, $n=7$;

MCh+vagotomy, $n=7$.

Supplemental Figures

Figure S1

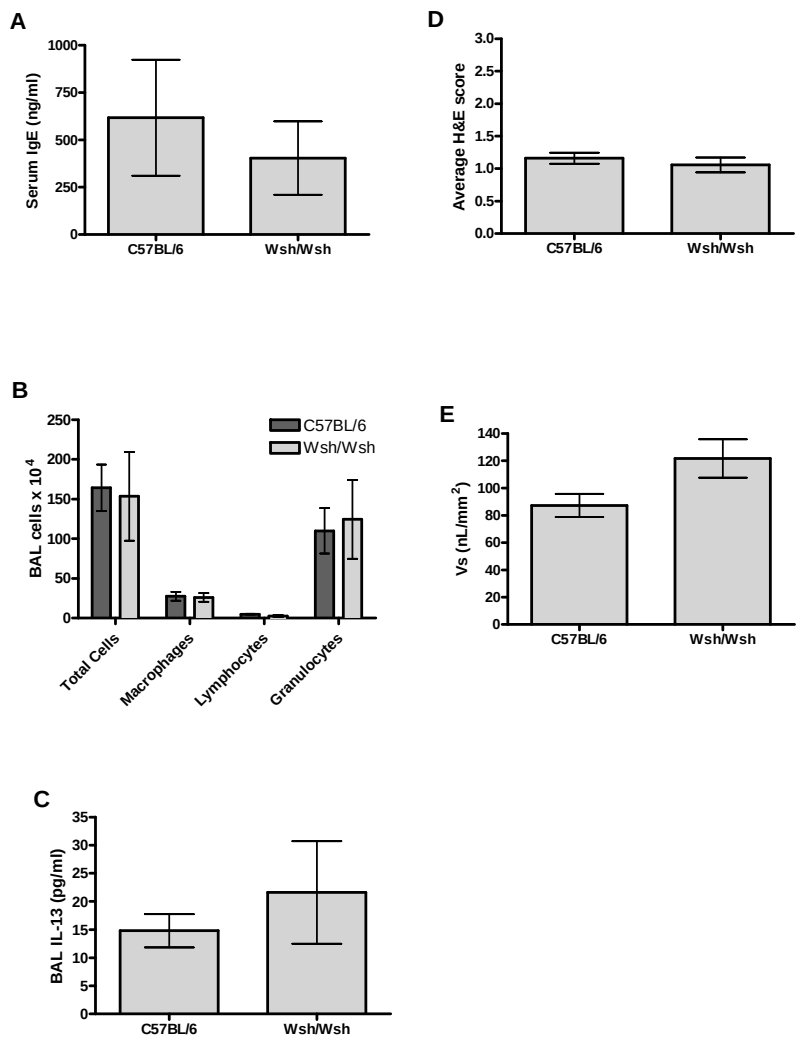


Figure S2

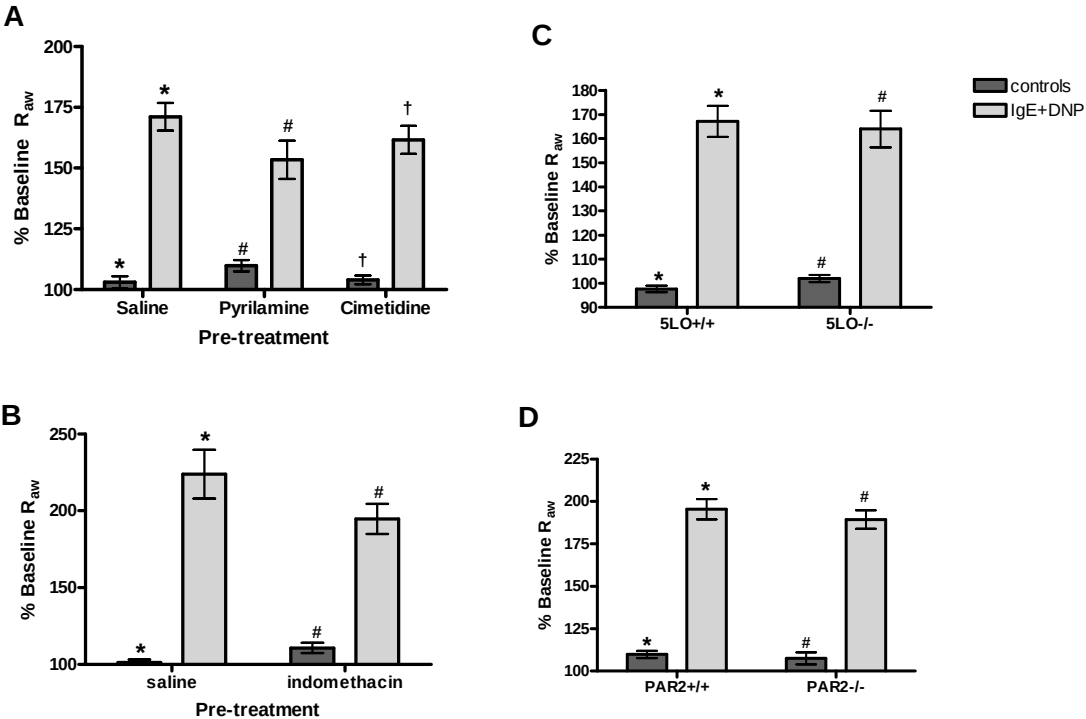


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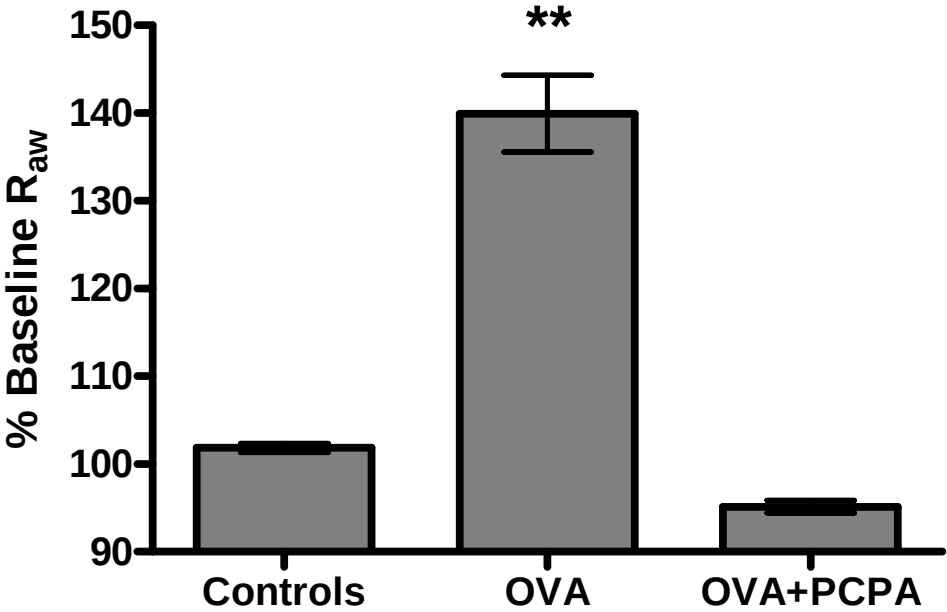


Figure S4

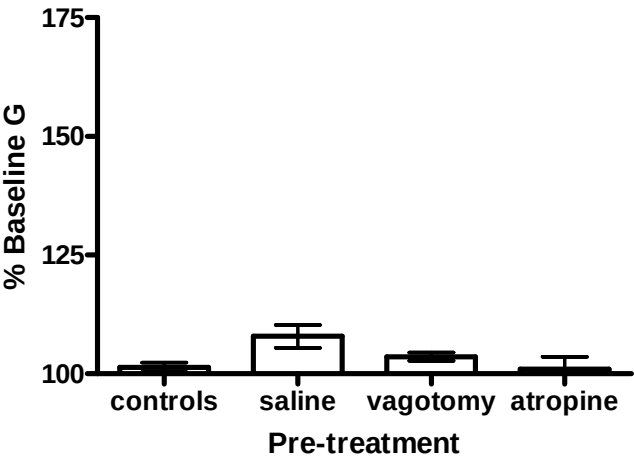
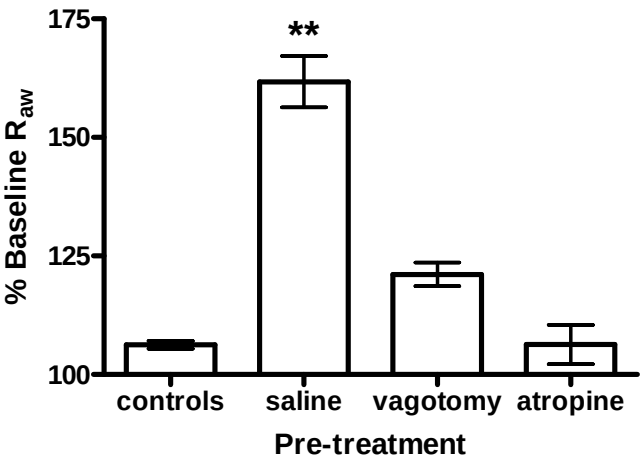


Figure S5

