Histamine-releasing factor has a proinflammatory role in mouse models of asthma and allergy

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IgE-mediated activation of mast cells and basophils underlies allergic diseases such as asthma. Histamine-releasing factor (HRF; also known as translationally controlled tumor protein [TCTP] and fortilin) has been implicated in late-phase allergic reactions (LPRs) and chronic allergic inflammation, but its functions during asthma are not well understood. Here, we identified a subset of IgE and IgG antibodies as HRF-interacting molecules in vitro. HRF was able to dimerize and bind to Igs via interactions of its N-terminal and internal regions with the Fab region of Igs. Therefore, HRF together with HRF-reactive IgE was able to activate mast cells in vitro. In mouse models of asthma and allergy, Ig-interacting HRF peptides that were shown to block HRF/Ig interactions in vitro inhibited IgE/HRF-induced mast cell activation and in vivo cutaneous anaphylaxis and airway inflammation. Intranasally administered HRF recruited inflammatory immune cells to the lung in naive mice in a mast cell– and Fc receptor–dependent manner. These results indicate that HRF has a proinflammatory role in asthma and skin immediate hypersensitivity, leading us to suggest HRF as a potential therapeutic target.

Introduction

Mast cells and basophils are key effector cells for IgE-dependent allergic inflammatory reactions (1). Upon activation, these cells secrete preformed proinflammatory chemical mediators (e.g., histamine, proteases, proteoglycans, and nucleotides) as well as de novo synthesized lipids (e.g., leukotrienes and prostaglandins) and polypeptides (e.g., cytokines and chemokines). These substances lead to the development of allergic inflammation.

Since Thueson et al. first described an activity from cultured peripheral blood mononuclear cells that induced the release of histamine from basophils (2), histamine-releasing activities have been studied for more than 30 years (3). In addition to several cytokines and chemokines with this activity, an unrelated protein termed histamine-releasing factor (HRF) was purified and molecularly cloned in 1995 (4). HRF, also known as translationally controlled tumor protein (TCTP) and fortilin, is a highly conserved protein with both intracellular and extracellular functions (4–8). HRF is secreted by macrophages and other cell types and can stimulate histamine release and IL-4 and IL-13 production from IgE-sensitized basophils and mast cells (9). HRF-like activities were found in nasal, skin blister, and bronchoalveolar lavage (BAL) fluids during late-phase allergic reactions (LPRs), implicating HRF in the LPR and chronic allergic inflammation (10–12). However, definitive evidence for the role of HRF in allergic reactions has been elusive (8, 9, 13).

Confounding the research, HRF has a wide range of intracellular functions, including cell cycle progression, proliferation, survival, and malignant transformation of a variety of cell types (8). HRF is ubiquitously expressed in all tested eukaryotic cells; its expression is active in mitotically active tissues (14, 15) and subject to both transcriptional and translational control (16). In tumor cells, HRF is highly expressed and downregulated upon tumor reversion (17). It is involved in the elongation step of protein synthesis by interacting with both eEF1A (a small GTPase) and eEF1Bβ (a guanine nucleotide exchange factor) (18–20). Drosophila and human HRFs act as the guanine nucleotide exchange factor for the Ras superfamily GTPase, Rheb, which regulates the TSC1-TSC2-mTOR pathway (21, 22). These studies implicate this protein in the regulation of growth and proliferation as well as in the control of organ size. HRF interacts with Mcl-1 (23, 24) and Bcl-xL (25), antiapoptotic members of the Bcl-2 family, and antagonizes apoptosis by inserting into the mitochondrial membrane and inhibiting Bax dimerization (26). HRF also interacts with p53 tumor suppressor and suppresses p53-mediated apoptosis (27). Other HRF-interacting molecules include tubulin (28), NEMO (29) and vitamin D_3 receptor (30). Phosphorylation of HRF by the protein kinase Plk decreases the microtubule-stabilizing activity of HRF (31).

The extracellular function of HRF is considered a cytokine-like activity toward IgE-primed mast cells and basophils (9). Despite considerable efforts, researchers have failed to identify an HRF receptor. Unfortunately, HRF knockout mice are embryonic lethal (32, 33) and cannot provide meaningful information on HRF function. Because of the lack of reagents that can distinguish between HRF's intracellular and extracellular functions, it is particularly dif-

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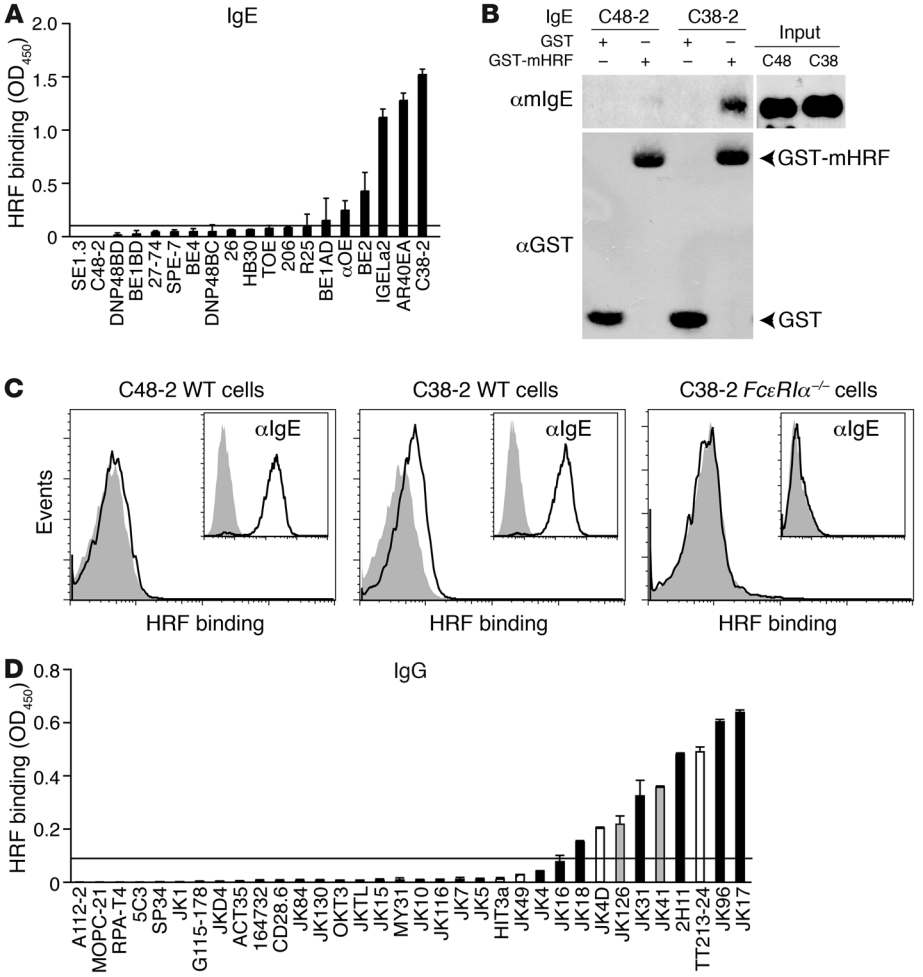

Figure 1

A subset of IgE and IgG molecules binds HRF. (**A**) IgE molecules were incubated in GST-mHRF–coated wells. HRF-bound IgE was quantified by ELISA, as detected by color development with HRP. OD_{450} values with GST-mHRF subtracted from those with GST control are shown. $OD_{450} \leq 0.1$ was used as an arbitrary cutoff value. Data represent at least 3 experiments. (**B**) IgEs were incubated with GST- or GST-mHRF–agarose beads. Bead-bound IgEs were pulled down. IgE and GST proteins were detected by immunoblotting. Lanes were run on the same gel but were noncontiguous (white lines). Representative of 2 experiments. (**C**) BMMCs preincubated with (black line) or without (gray shading) the indicated IgE (see Supplemental Table 3) were incubated with mHRF-His_6, and bound mHRF-His_6 was detected with rabbit anti-His tag antibody and Alexa Fluor 647–conjugated anti-rabbit IgG. HRF binding was detected by flow cytometry. Insets show IgE binding: the same cells were incubated with FITC-labeled anti-mouse IgE. Representative of 2 experiments. (**D**) HRF-bound IgGs were detected by ELISA. Representative of 3 experiments. HRF binding was independent of IgG isotype, as the tested IgG1, IgG2a, and IgG2b molecules contained both HRF-reactive and -nonreactive molecules. The K_D values for HRF binding were 0.685 μM (JK17), 2.78 μM (JK31), and 5.78 μM (JK96). Black bars, IgG1; white bars, IgG2a; gray bars, IgG2b.

ficult to dissect extracellular functions in complex in vivo settings. In this study, we sought to identify HRF-interacting molecules and inhibitors of interactions of HRF with HRF-reactive molecules.

Results

HRF binds to Fab fragments of a subset of IgE and IgG antibodies. Despite a previous study implying that IgE does not interact with HRF (34), we reexamined this possibility first by using an ELISA and a panel of IgE mAbs. As shown in Figure 1A, immobilized N-terminally glutathione S-transferase–tagged (GST-tagged) mouse HRF protein (referred to herein as GST-mHRF) bound C38-2 and 5 other IgE mAbs. In contrast, C48-2 and 12 other IgE mAbs failed to bind GST-mHRF. Similar results were obtained when C-terminally hexahistidine-tagged mHRF (referred to herein as mHRF-His_6) was used as a capturing agent (Supplemental Figure 1; supplemental material available online with this article; doi:10.1172/JCI59072DS1). Interaction of C38-2 and IGELa2 IgE mAbs with mHRF was also demonstrated by affinity pulldown (Figure 1B and data not shown). HRF bound to mouse bone marrow–derived mast cells (BMMCs) preincubated with the HRF-reactive C38-2 IgE, but not the HRF-nonreactive C48-2 IgE, in flow cytometry experiments (Figure 1C). However, we observed no HRF binding to C38-2 IgE–incubated *FcεRIα*$^{-/-}$ BMMCs, which lack expression of the high-affinity IgE receptor FcεRI. We also found that 9 of the 34 tested IgG mAbs bound to mHRF (Figure 1D). HRF binding was independent of IgG isotype or antigen specificity. For example, the HRF-binding IgG molecules JK31 and JK96, and the non-HRF binding IgG molecule JK116 all recognize the same viral antigen.

Importantly, an Fab, but not Fc, fragment of an HRF-binding IgG molecule bound mHRF (Figure 2, A and B), and the IgE-HRF (or IgG-HRF) interaction was inhibited by an Fab, but not Fc, fragment (Figure 2, C–F). Consistent with this, the interaction between the OVA-specific αOE IgE and mHRF was inhibited by OVA (Supplemental Figure 2A), and those between the trinitrophenyl-specific (TNP-specific) IGELa2 or C38-2 IgE and mHRF were inhibited by TNP-glycine (Supplemental Figure 2, C and E). However, the IGELa2-mHRF and C38-2–mHRF interactions were not inhibited by TNP–glutamic acid (Supplemental Figure 2, C and E), and the C38-2–mHRF interaction was not inhibited by TNP-lysine, whereas the IGELa2-mHRF interaction was inhibited by TNP-lysine. These results suggest that the mHRF-binding site in IgE overlaps at least in part with the antigen-binding sites. Collectively, these results suggest that a considerable proportion of antibodies in immunized mice interact with HRF. In addition, 1 of the 5 tested human IgEs (i.e., HE-1) bound GST-mHRF (data not shown).

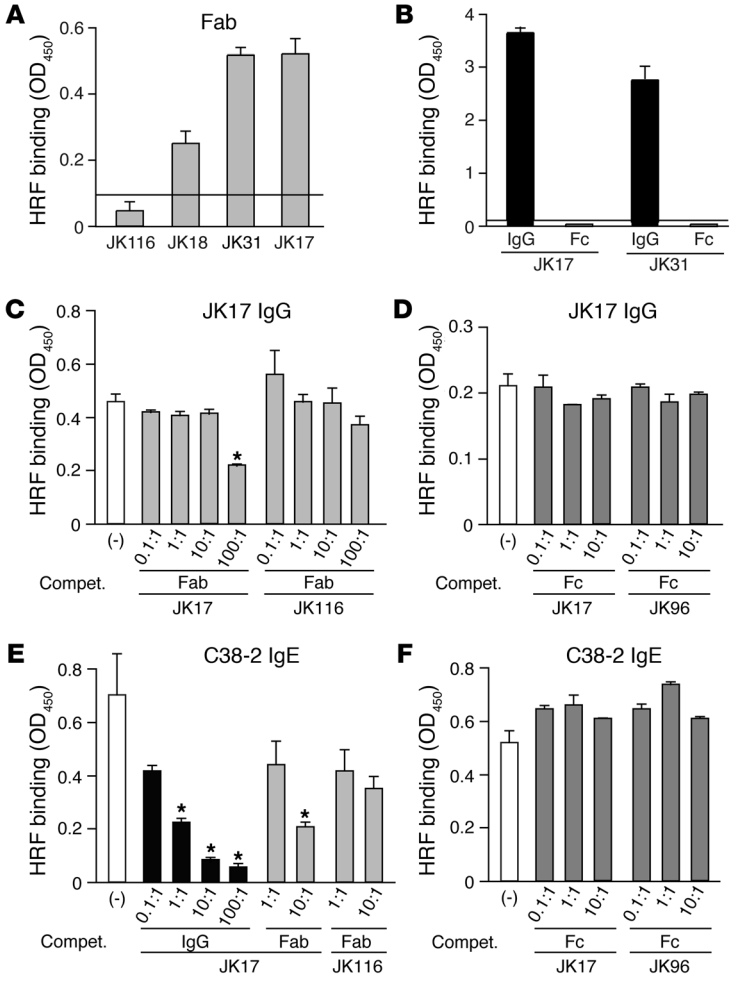

Figure 2
HRF-reactive Igs binds HRF via their Fab region. (**A** and **B**) Fab, but not Fc, fragments bound to HRF. GST-mHRF was coated onto a 96-well ELISA plate. After blocking with 10% FCS, the plate was incubated with whole molecules (IgG) or with Fab or Fc fragments of the indicated IgGs. HRF-bound Fab was detected by incubation with HRP-conjugated goat anti-mouse κ chain antibody. HRF-bound Fc or IgG was detected with HRP-conjugated anti-IgG. (**C** and **D**) Competition by Fab, but not Fc, fragments for JK17 IgG binding to HRF. GST-mHRF was incubated with JK17 IgG in the presence or absence of Fab or Fc fragments at different molar ratios. Bound JK17 IgG was detected with HRP-conjugated anti-κ (**C**) or biotin-conjugated anti-IgG1 followed by streptavidin-HRP (**D**). (**E** and **F**) Competition by Fab, but not Fc, fragments for C38-2 IgE binding to HRF. GST-mHRF was incubated with C38-2 IgE in the presence or absence of Fab or Fc fragments at different molar ratios. Bound IgE was detected with biotin-conjugated anti-mouse IgE followed by streptavidin-HRP. *$P < 0.05$. All data are representative of 2 experiments.

Peptides corresponding to the Ig-binding sites within HRF inhibit HRF-Ig interactions. We next mapped the Ig-binding sites within HRF. IgE and IgG binding assays using a panel of truncated GST-mHRF proteins gave similar binding patterns (Figure 3, A and B, and Supplemental Figure 3). A major Ig-binding site was mapped to the N-terminal 19-residue peptide (N19), as GST-tagged N19 (referred to herein as GST-N19), but not GST fusion proteins containing shorter N-terminal fragments, bound Igs. Another binding site was mapped to internal residues 79–142 (Figure 3, A and B). Further fine mapping localized the latter binding site to the H3 region (residues 107–135, termed GST-H3; Figure 3D and data not shown).

Intracellular HRF might contribute to allergic inflammation by controlling cell cycle progression, proliferation, and survival of immune and structural cells (8, 21, 32). Therefore, it is essential to find an inhibitor of HRF-Ig interactions to dissect HRF's extracellular functions, separate from HRF's intracellular functions. We tested whether the Ig-interacting HRF sequences might serve as specific inhibitors of HRF binding to Igs. Indeed, GST-N19 inhibited IgE binding to mHRF with potency similar to full-length GST-mHRF (Figure 3C). However, shorter mHRF peptides tested (residues 1–6, 1–12, 1–16, 5–19, and 9–19) or a scrambled peptide (KYI-N16) did not inhibit HRF-IgE binding (Supplemental Figure 4). Control experiments showed that GST-N19 did not affect growth properties that fall under the control of intracellular functions of HRF (8): treatment of various cells with 3.6 or 36 μM GST-N19 did not affect their viability or proliferation (Supplemental Figure 5, A–D), nor did it affect apoptosis induced by growth factor withdrawal in BMMCs or by H_2O_2 in CHO-K1 cells (Supplemental Figure 5, E and F). These concentrations of HRF were higher than what has previously been shown to stimulate basophils (1.6–5 μM; ref. 35). Importantly, GST-N19 did not enter BMMCs (Figure 4A). A synthetic N19 peptide also inhibited IgE binding to mHRF and did not alter the growth or survival of various cells (Supplemental Figure 6). Similar to GST-N19, GST-H3 also inhibited IgE binding to mHRF (Figure 3D); GST-H3 neither affected cell growth or apoptosis nor entered the cells (Supplemental Figure 7 and data not shown). These results indicated that the HRF N19 and H3 peptides can be used to probe extracellular functions of HRF in vitro and in vivo.

N19 and H3 peptides block mast cell activation. Analysis of purified recombinant mHRF-His_6 on reducing and nonreducing SDS-PAGE yielded direct evidence for disulfide-linked dimerization of HRF (Supplemental Figure 8A). Both monomeric and dimeric forms of HRF could bind to IgE (data not shown). Consistent with this, monomeric mHRF mutant 2CA, with 2 cysteine residues at positions 28 and 172 substituted with alanine, also bound Igs (Supplemental Figure 9, A and B). The dimerizing ability of HRF with 2 Ig-binding sites suggests the potential of HRF to crosslink Ig-bound Fc receptors (Supplemental Figure 8B). This notion was supported by activation of mast cells by

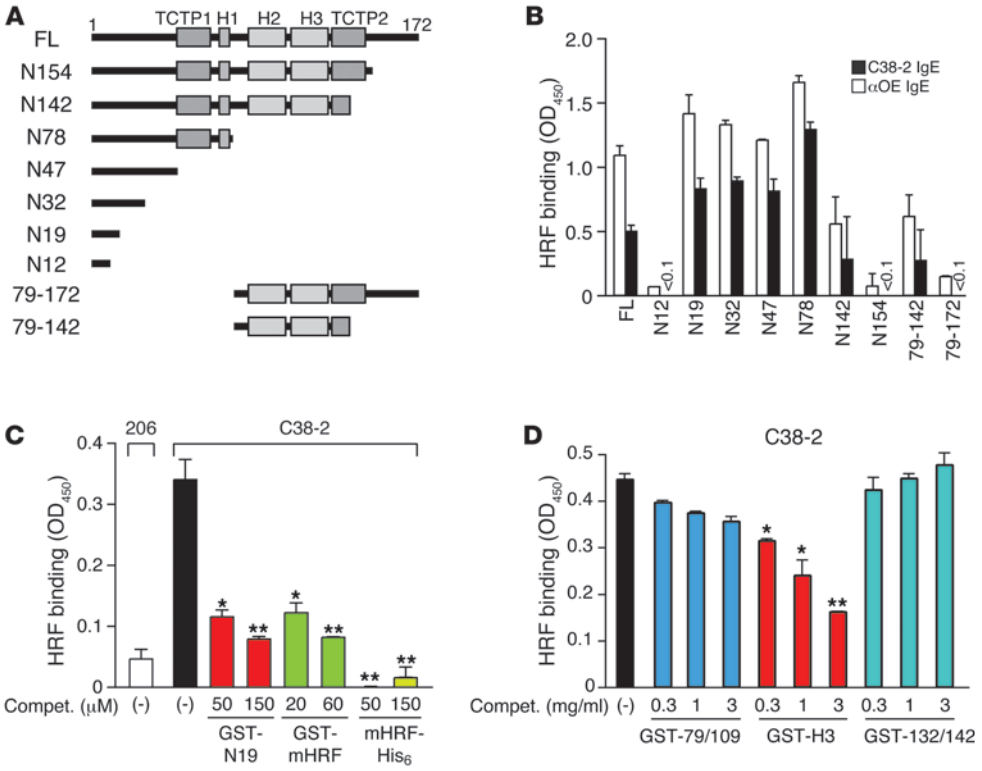

Figure 3
Mapping IgE-binding sites within HRF and inhibition of HRF-IgE interactions by the HRF-derived N19 and H3 peptides. (**A**) Scheme of full-length (FL) and truncated forms of GST-mHRF used for binding assays. Domain structures such as TCTP1–TCTP2 and H1–H3 are shown. (**B**) IgE-binding site mapping. C38-2 (5 μg/ml) and αOE (20 μg/ml) IgE molecules were incubated in wells coated with GST-mHRF. Bound Igs were detected by ELISA. <0.1, value too small to display. (**C**) Inhibition of HRF-Ig interactions by N19. IgE molecules were incubated in GST-mHRF–coated wells in the presence or absence of the indicated concentrations of competitors. After incubation, bound IgE was detected by ELISA. (**D**) Inhibition of HRF-Ig interactions by GST-H3. $^*P < 0.05$, $^{**}P < 0.01$. Data are representative of 2 (**B**), 5 (**C**), or 3 (**D**) experiments.

cotreatment with mHRF and HRF-reactive, but not HRF-nonreactive, IgEs, as evidenced by histamine release and cytokine production from BMMCs (Figure 4, B and C) and by β-hexosaminidase release from peritoneal mast cells (C38-2 IgE, 17.8% ± 4.6% release; C48-2 IgE, 2.4% ± 0.1% release; $P < 0.0001$). These reactions were inhibited by GST-N19 and GST-H3 (Figure 4, D and E, and data not shown). Consistent with mast cell activation, tyrosine phosphorylation of several proteins was observed in C38-2 IgE/HRF-treated cells (data not shown).

HRF inhibitors suppress passive cutaneous anaphylaxis. Acute passive cutaneous anaphylaxis (PCA) reactions induced by antigen in IgE-sensitized mice are mediated mainly by histamine released from activated mast cells (36). LPRs in the skin are mediated in part by mast cell–derived TNF-α (37, 38) and IL-33 (39). Strikingly, when HRF was injected i.d. 24 hours after IgE injection, both acute reactions and LPRs were induced by HRF-reactive, but not HRF-nonreactive, IgE (Figure 5, A and B). The HRF-reactive C38-2 IgE induced increased vascular permeability after HRF injection (Figure 5A). Interestingly, the LPRs induced by HRF, as measured by increased ear swelling at 6 hours, were as high as those induced by antigen (Figure 5B). Both acute reactions and LPRs induced by IgE/HRF were prevented by pretreatment with GST-N19 (Figure 5C and data not shown) and appeared to be mast cell mediated, as the reactions were abolished in mast cell–deficient $Kit^{W-sh/W-sh}$ mice (40) and restored in $Kit^{W-sh/W-sh}$ mice engrafted with WT BMMCs (Figure 5A). Furthermore, loss of FcεRI abolished PCA responses (Figure 5D). Control experiments showed little effect of GST or GST-N19 alone on ear thickness (data not shown). Therefore, HRF and HRF-reactive IgE can induce anaphylactic responses in a mast cell– and FcεRI-dependent manner. Interestingly, PCA reactions were not induced by IgE/2CA mutant (Supplemental Figure 9, C and D), and IgE/HRF-induced PCA reactions were inhibited by 2CA mutant (Supplemental Figure 9E), which suggests that the dimeric form of HRF is responsible for the bioactivity of HRF.

We next tested whether HRF contributes to IgE/antigen-induced PCA reactions. Antigen was injected to the ears of IgE-sensitized mice, with GST-N19 or GST pretreatment. GST-N19 significantly reduced PCA acute reactions and LPRs in mice sensitized with HRF-reactive IgE (Figure 5E and data not shown). However, PCA induced by an HRF-nonreactive IgE was insensitive to GST-N19 treatment. Similar results were observed using GST-H3 in place of GST-N19, and GST-N19 plus GST-H3 had a stronger PCA-suppressive effect than GST-N19 or GST-H3 alone (Supplemental Figure 10). These results suggest that HRF is required for maximal IgE/antigen-induced PCA reactions. Consistent with this, HRF was dramatically increased in the dermis during LPRs (Supplemental Figure 11).

HRF inhibitors suppress mast cell–dependent airway inflammation. Asthma is a chronic lung disease characterized by airway inflammation, airway hyperresponsiveness (AHR), and reversible airway obstruction (41). We used a mast cell–dependent, OVA-induced airway inflammation model (42). In addition to the increased HRF levels in lungs and blood (Figure 6A), immunofluorescence microscopy showed increased levels of HRF staining in nonpermeabilized lung tissues (Supplemental Figure 12A), which indicates that HRF is secreted into lung tissues in OVA-challenged mice. Levels of HRF-reactive IgG were also increased in plasma and BAL fluids of these mice (Supplemental Figure 12B). Pretreatment with GST-N19 before the OVA challenges abrogated airway inflammation, as evidenced by reduced eosinophils and neutrophils in BAL fluids (Figure 6B) and by reduced inflammatory cells and goblet cell hyperplasia in the lung (Figure 6C). Production of IL-13 (the cytokine essential for AHR, eosinophilia, and mucus production; refs. 43–45) and IL-5 (the cytokine critical for eosinophilia and

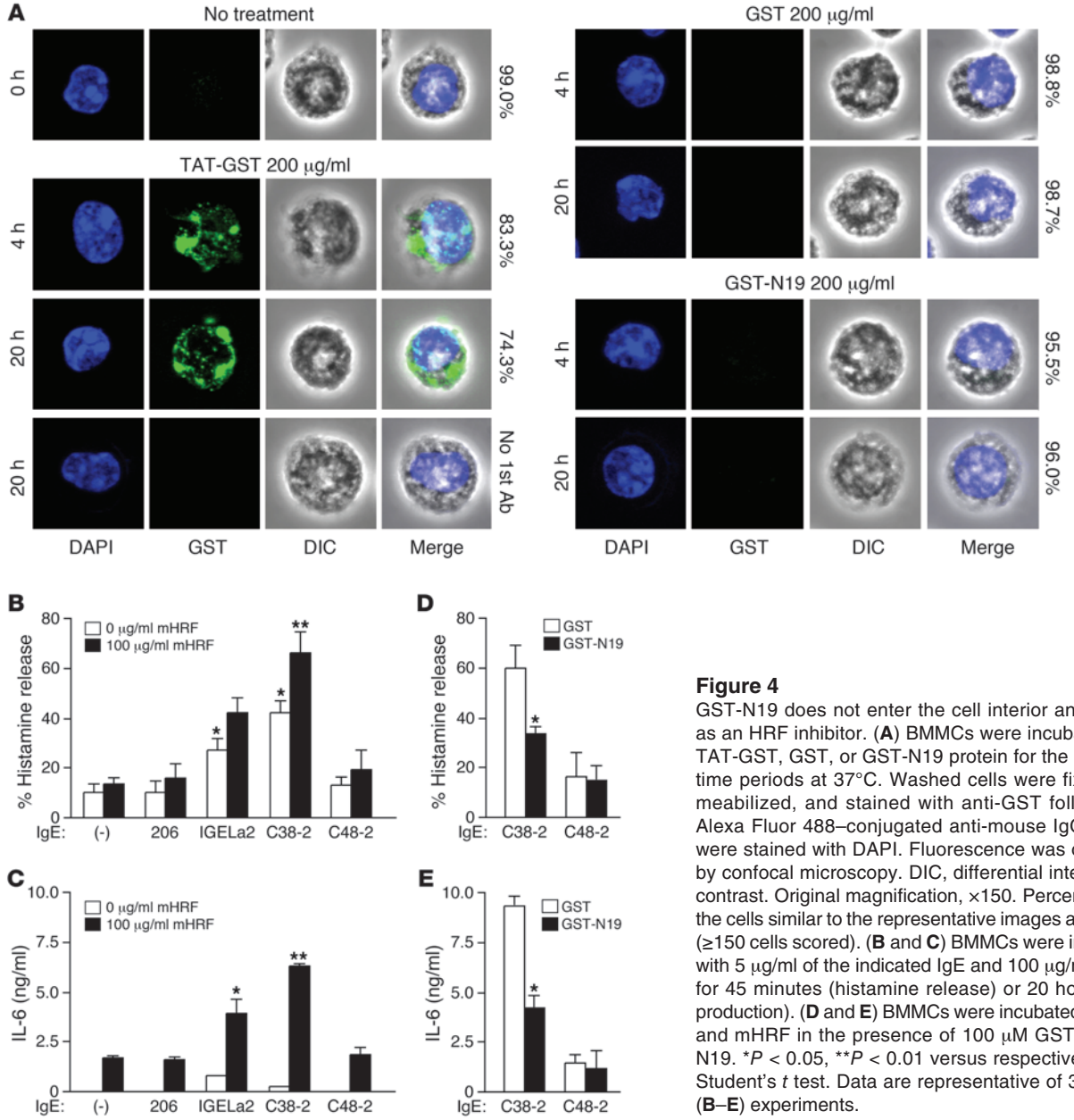

Figure 4
GST-N19 does not enter the cell interior and serves as an HRF inhibitor. (**A**) BMMCs were incubated with TAT-GST, GST, or GST-N19 protein for the indicated time periods at 37°C. Washed cells were fixed, permeabilized, and stained with anti-GST followed by Alexa Fluor 488–conjugated anti-mouse IgG. Nuclei were stained with DAPI. Fluorescence was observed by confocal microscopy. DIC, differential interference contrast. Original magnification, ×150. Percentages of the cells similar to the representative images are shown (≥150 cells scored). (**B** and **C**) BMMCs were incubated with 5 μg/ml of the indicated IgE and 100 μg/ml mHRF for 45 minutes (histamine release) or 20 hours (IL-6 production). (**D** and **E**) BMMCs were incubated with IgE and mHRF in the presence of 100 μM GST or GST-N19. *$P < 0.05$, **$P < 0.01$ versus respective control, Student's *t* test. Data are representative of 3 (**A**) or 2 (**B**–**E**) experiments.

AHR; ref. 46) in lung tissues was drastically decreased in GST-N19–treated mice (Figure 6D). Consistent with these observations, GST-N19 treatment inhibited AHR ($P < 0.05$ vs. GST at 48 mg/ml methacholine, Bonferroni correction; Figure 6E). Circulating systemic HRF was reduced by GST-N19 (Supplemental Figure 12C), probably reflecting an antiinflammatory effect of GST-N19. In contrast, HRF-reactive plasma IgG levels and OVA-specific IgE, IgG1, and IgG2a levels were not affected by GST-N19 (Supplemental Figure 12B and data not shown). Administration of a synthetic N19 peptide or GST-H3 abrogated airway inflammation with similar potency to that of GST-N19 (Supplemental Figure 13 and data not shown).

We confirmed the efficacy of GST-N19 in a second model of asthma: partially IgE-dependent airway inflammation induced by *Aspergillus fumigatus* allergens (47). HRF inhibition resulted in substantial reduction of allergic airway inflammation and inflammatory cells in BAL fluids (Supplemental Figure 14). Interestingly, HRF inhibition failed to reduce airway inflammation in a mast cell–independent OVA-alum model (ref. 48 and Supplemental Figure 15).

HRF-induced airway inflammation is dependent on Fc receptors. Airway inflammation in the above experiments involves a complex interplay of various cells (41, 49, 50). To gain mechanistic insights into how HRF promotes lung inflammation, we used a simpler in vivo model. Administration i.n. of WT, but not 2CA mutant, reduced/carboxymethylated or boiled mHRF to WT naive mice induced weak but consistent lung inflammation, as shown by increased eosinophils, neutrophils, and macrophages/monocytes in BAL fluids (Figure 7A and data not shown). However, no or little HRF-induced lung inflammation was seen in B cell–deficient (μ*MT*), mast cell–deficient ($Kit^{W-sh/W-sh}$), or $FcR\gamma^{-/-}$ mice (Figure 7, A and B).

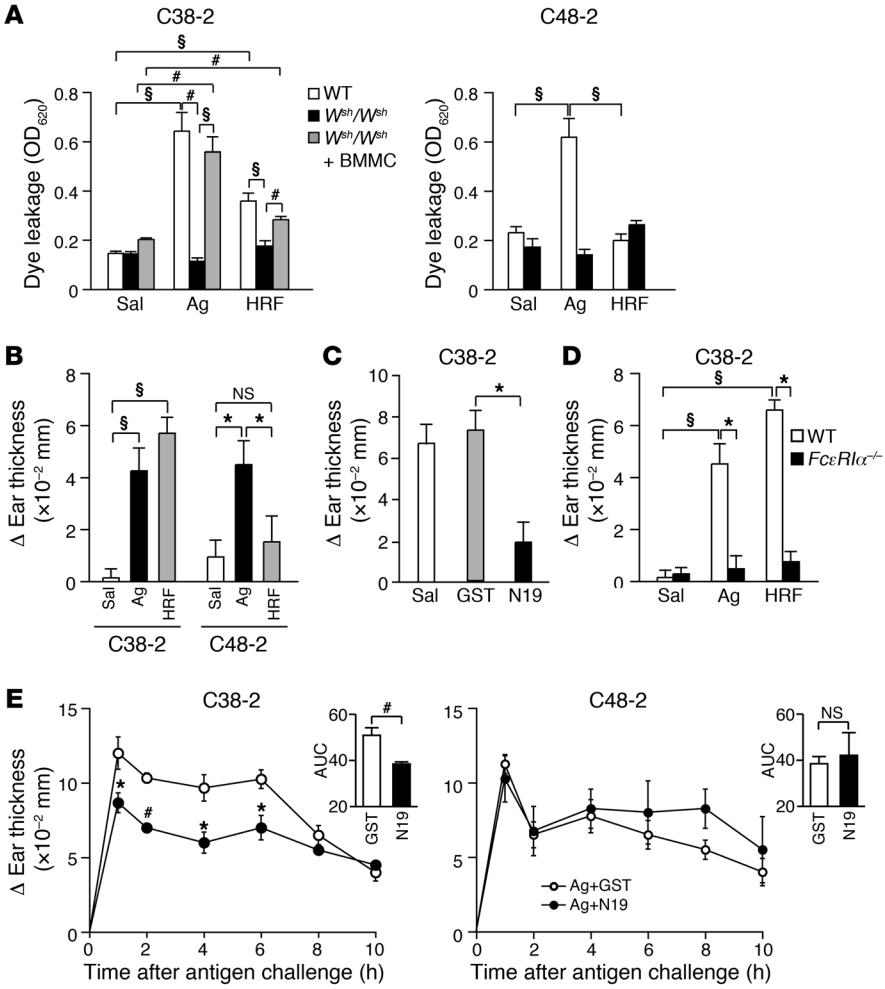

Figure 5
HRF promotes PCA reactions in mice sensitized with HRF-reactive IgE. (**A**) IgE/HRF-induced acute PCA reactions. Mice were sensitized with the indicated IgEs. 24 hours later, Evans blue and mHRF-His_6 were injected in IgE-sensitized mice. After 30 minutes, dye leakage from the ears was measured. For controls, saline (Sal) and TNP_{26}-BSA (Ag) were injected in sensitized ears. *Kit*$^{W-sh/W-sh}$ mice were used before or 6 weeks after engraftment of WT BMMCs by i.d. injection. Toluidine blue staining confirmed that the engrafted mice had numbers of mast cells similar to those of WT mice. (**B**–**D**) IgE/HRF-induced PCA LPRs. mHRF-His_6 was injected in IgE-sensitized ears, and LPR was analyzed by measurement of ear thickness at 6 hours. For controls, saline and TNP_{26}-BSA were injected. (**C**) C38-2 IgE–sensitized mice were pretreated with saline, GST, or GST-N19 (N19) before injection with mHRF-His_6. (**D**) LPR in *FcεRIα*$^{-/-}$ mice. (**E**) Inhibition of IgE/antigen-induced PCA reactions by GST-N19. WT mice were sensitized overnight with the indicated IgEs. Left ears were injected with GST and right ears were injected with GST-N19, then TNP_{26}-BSA was injected in both ears. Ear thickness was measured. Insets show area under curve (AUC). $^{*}P < 0.05$, $^{\#}P < 0.01$, $^{\S}P < 0.001$. 3–6 mice were used for each cohort. Data are representative of 2 (**A**–**D**) or 3 (**E**) experiments.

FcRγ is shared by multiple Fc receptors, including FcεRI, FcγRI, FcγRIII, and FcγRIV (51, 52). Among the Igs and Fc receptors, IgE and FcεRI were the predominant contributors to the effects of HRF, as HRF-induced lung inflammation was almost abrogated in naive *FcεRIα*$^{-/-}$ mice (Figure 7A). Since FcεRI is expressed on mast cells and basophils in mice (53), these results were consistent with the effectiveness of N19 and H3 peptides in mast cell–dependent asthma models (Figure 6 and data not shown).

Importantly, the absence of inflammatory cell responses to HRF in μ*MT* or *FcRγ*$^{-/-}$ mice corroborated our finding that HRF bound Igs (Figure 1). To further evaluate the target range of HRF, we performed global gene expression analysis. Expression of 196 genes was up- or downregulated more than 3-fold by HRF in the lungs of naive WT mice, with 90 genes up- or downregulated more than 5-fold (Figure 7C). Upregulated genes included those encoding Th1-, Th2-, and Th17-associated cytokines and various chemokines, potentially accounting for the recruitment of monocytes/macrophages, neutrophils, eosinophils, and other immune cells (Supplemental Figure 16). Expression of some Th1 and Th2 cytokines were confirmed by real-time PCR analysis (data not shown). Other upregulated genes included the previously reported genes in mouse asthma models, such as *Agr2*, *Ccl8*, *Ccl11*, *Fcgr2b*, *Scin*, *Serpina3g*, *Serpina3n*, and *Timp1*. However, only a small fraction of these genes (39 of 196) fluctuated more than 3-fold in *FcεRIα*$^{-/-}$ mice; furthermore, fewer genes (11 of 196) were changed in *FcRγ*$^{-/-}$ mice (Figure 7C). These results suggest that HRF executes its action largely, if not exclusively, by engaging IgE- and IgG-bound Fc receptors and promotes airway inflammation.

Discussion

Despite considerable efforts in the last 15 years since the cloning of HRF (4), the receptor for HRF has not been identified. Using functional assays on RBL-2H3 rat mast cells expressing human FcεRI, Wantke et al. indirectly suggested that human recombinant HRF does not bind to IgE (34). However, we clearly demonstrated that a subset of IgE and IgG can interact with HRF. Our study differs from that of Wantke et al., as theirs used human FcεRI-expressing RBL-2H3 cells, which in our hands were difficult to activate. Importantly, we used more than a dozen IgE mAbs in an ELISA-based binding assay, compared with 2 types of polyclonal IgE used in the prior study. Furthermore, HRF binding of some IgE mAbs was confirmed by affinity pulldown and flow cytometry.

HRF interacts with the Fab, but not Fc, region of Igs. Experiments with OVA antigen and monovalent haptens suggested that the mHRF-binding site in IgE overlaps at least in part with the antigen-binding sites. Inspection of amino acid sequences of V regions of a limited number of IgE and IgG molecules indicates that HRF-reactive IgEs and IgGs contain unique V_k sequences

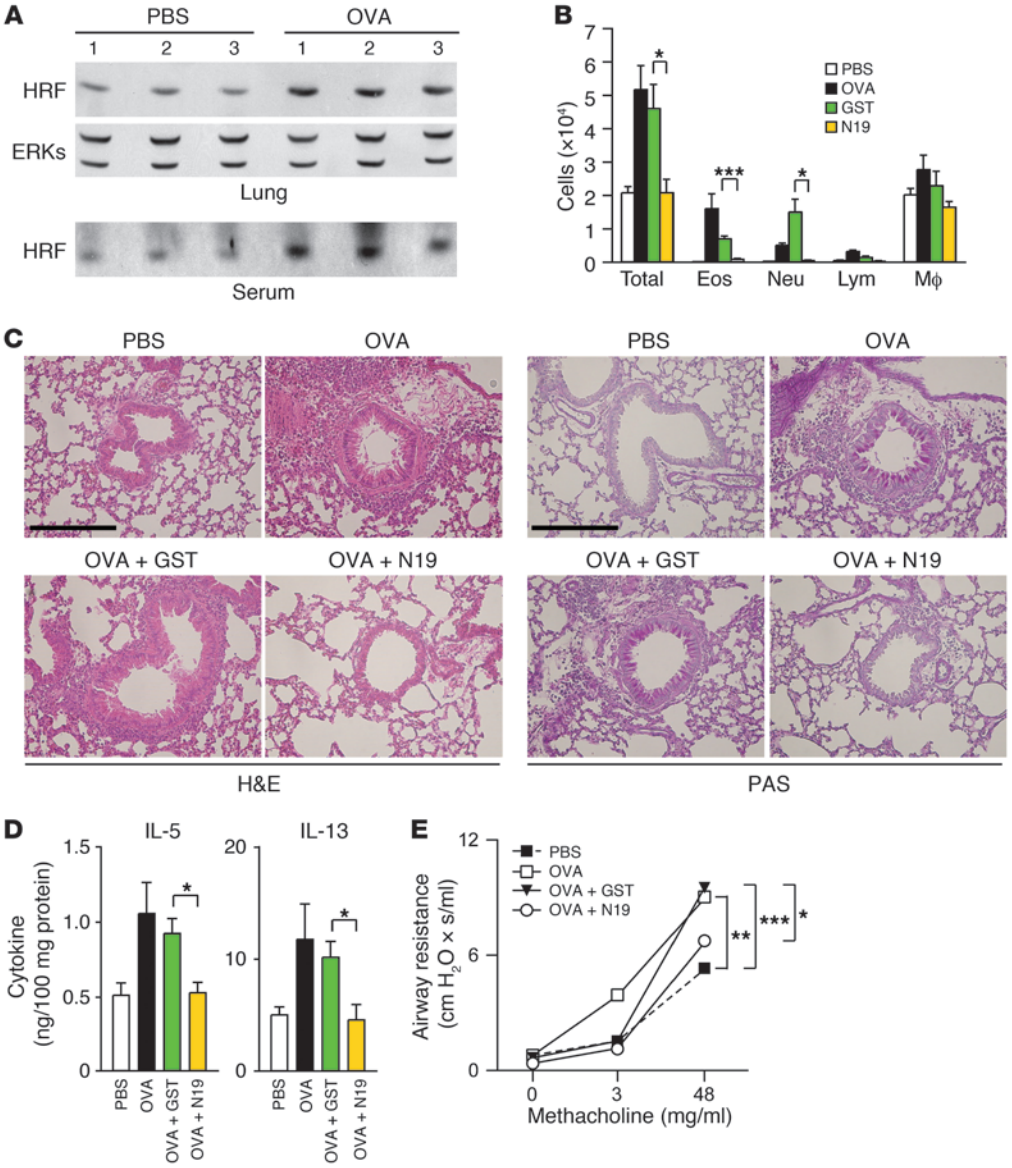

Figure 6
GST-N19 blocks mast cell–dependent airway inflammation. C57BL/6 mice were sensitized with OVA (10 μg) and i.n. challenged with OVA (20 μg) or PBS. Some mice were i.n. pretreated with GST or GST-N19 (400 μg) before every OVA challenge. 24 hours after the last challenge, mice were subjected to invasive lung function testing, and BAL fluids and lung tissues were collected. (**A**) Increased HRF amounts in the lung and sera of OVA-sensitized and -challenged mice. SDS-PAGE was performed on lung homogenates and serum samples, and HRF amounts of 3 mice were evaluated by immunoblotting. ERK1/2 expression was used as a loading control. (**B**) Total and specific immune cell numbers in BAL fluids. Eos, eosinophils; Neu, neutrophils; Lym, lymphocytes; Mϕ, macrophages and monocytes. (**C**) H&E and periodic acid-Schiff (PAS) staining of lung tissues. Scale bars: 200 μm. (**D**) IL-5 and IL-13 in lung homogenates were measured by ELISA. (**E**) Airway resistance was measured using FlexiVent. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$. 3–6 mice were used for each cohort. All data are representative of 3 experiments.

(8–30 and 2–137, respectively; Supplemental Table 1). In contrast, these IgEs and IgGs use different V_H family members. The Ig-binding N19 peptide forms 2 antiparallel β-sheets (positions 3–5 and 14–15), which, together with the C-terminal β-sheet, form the 3-stranded sheet B (54, 55). The structure consisting of sheet B, the 4-stranded sheet A, and the small helix is similar to that of the human protein Mss4, which binds to Rab proteins and is proposed to be a guanine nucleotide-free chaperone (56). The other Ig-interacting H3 domain is a long α-helix packed against part of sheet A. Our observations collectively suggest that 2 sites of HRF interact with V regions specifically. However, data on hapten inhibition of HRF-Ig interactions cannot rule out the possibility that HRF-Ig binding is enacted by relatively nonspecific ionic or other interactions of different parts of Igs.

As shown by others (57, 58), our bacterially expressed mHRF preparations can form a dimer. HRF has 2 Ig-binding sites at the N19 and H3 peptide regions. Our present biochemical analyses suggested that an HRF dimer can aggregate 2 or 4 FcεRI complexes preloaded with IgE (Supplemental Figure 8B). As a dimer is the minimal FcεRI complex required for cell activation (59), mHRF along with HRF-reactive IgE could induce mast cell activation. Consistent with these in vitro data, FcεRI-dependent PCA-like skin inflammation and lung inflammation were induced by WT mHRF, but not the monomeric 2CA mutant mHRF.

The progress in HRF research has been hindered by the lack of identification of an HRF receptor and the lack of tools to distinguish its extracellular from intracellular HRF functions. The peptides N19 and H3 corresponding to the Ig-interacting sites within mHRF turned out to be specific inhibitors that interfered with the interactions between extracellular HRF and IgE, but had no effect on HRF's intracellular functions. The biologic activities of these peptides were shown by their suppression of in vitro mast cell activation and in vivo mast cell–dependent inflammation, i.e., PCA and airway inflammation. It should be emphasized that these peptides used as GST fusion proteins did not affect HRF's intracellular functions, as they were not taken up intracellulary.

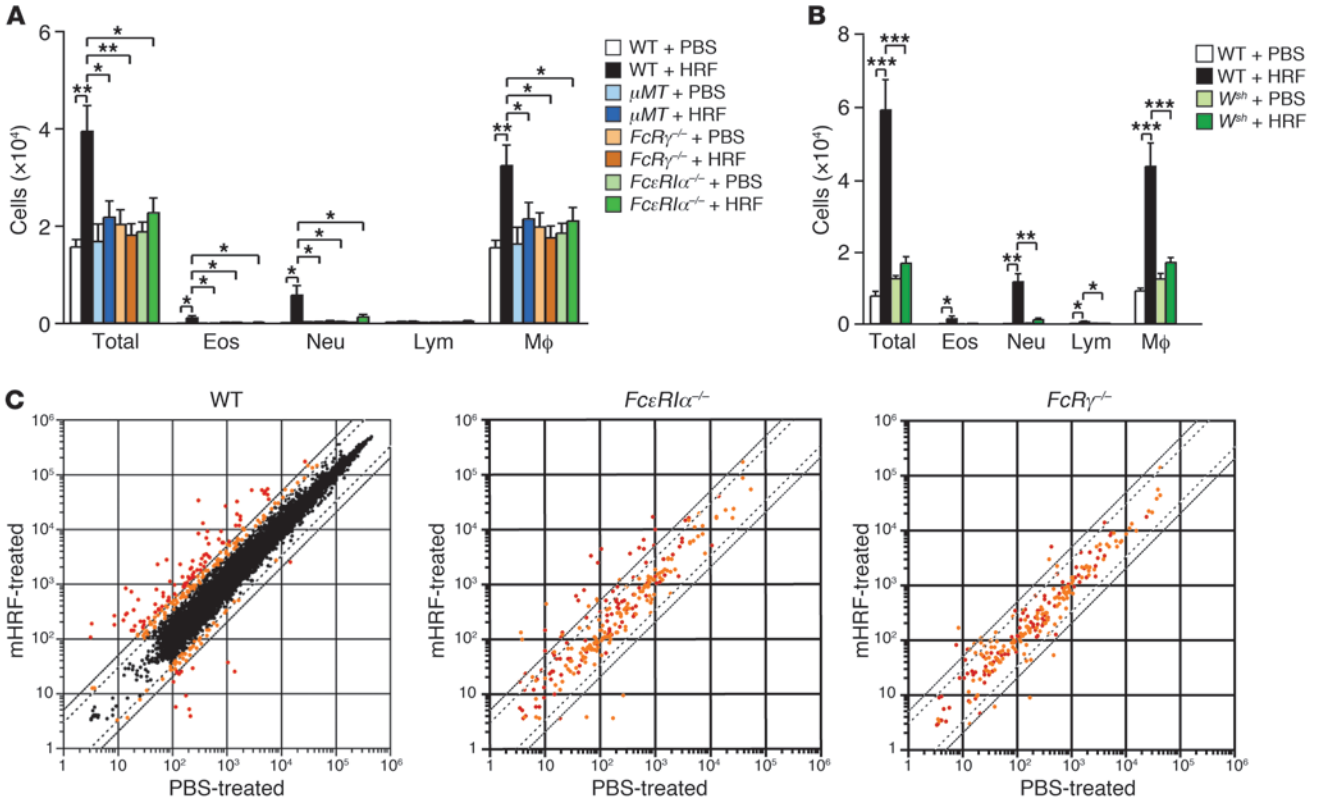

Figure 7

Lung inflammation is induced by HRF in naive mice in an Fc receptor–dependent manner. Naive WT C57BL/6 and mutant mice were treated i.n. with 40 μg mHRF-His_6 3 times every third day. PBS served as a negative control. (**A** and **B**) HRF-induced lung inflammation required B and mast cells as well as FcεRI (and probably Fcγ receptors). BAL procedures were conducted 24 hours after the last HRF administration. Differential cell counting was performed on cytospin preparations stained with May-Giemsa. (**C**) Genes whose expression was up- or downregulated by HRF. Black symbols, ≤3-fold change; orange symbols, 3- to 5-fold change; red symbols, >5-fold change. Genes whose expression fluctuated ≤3-fold in WT, *FcεRIα*$^{-/-}$, and *FcRγ*$^{-/-}$ mice are not shown in the plots for the mutant mice. Dashed and solid lines indicate 3- and 5-fold differences, respectively, in gene expression. **P* < 0.05, ***P* < 0.01, ****P* < 0.001, Student's *t* test. Each cohort consisted of 3–5 mice. All data are representative of 5 (WT) and 2 (mutant) experiments.

A synthetic N19 peptide also did not affect the intracellular functions. Kim et al. have shown that N10 of HRF can work as a protein translocation domain (PTD) when fused with some proteins at their N termini (60). Protein internalization by this PTD was characterized by the high dose requirement (8–32 μM) and slow kinetics compared with that of TAT, an HIV-encoded peptide (61). However, we found that the PTD function of N10 peptide in conjunction with GST (both N10-GST and GST-N10) was very weak compared with TAT-GST, particularly when N10 was fused at the C-terminus of GST (compare Supplemental Figure 7 and Figure 4A). More importantly, we clearly showed that GST-N19 and GST-H3 did not enter the mast cell or other cells.

A recent study shows that an N-terminal deletion mutant of rat HRF (Del-N11) exhibits a stronger dimerizing propensity and a stronger cytokine activity than the full-length HRF (58), consistent with our results indicating that the dimer is the biologically active form of HRF. The same study also shows that Del-N11 HRF, but not full-length HRF, induces airway inflammation, when the HRF protein is used to i.p. sensitize and then to i.n. challenge mice. Although these results are interesting, HRF was used as an antigen, similar to OVA in the acute airway inflammation experiments. Thus, the results do not necessarily represent the cytokine activity of HRF. Consistent with this interpretation, Del-N11 HRF fails to induce the recruitment of monocytes and macrophages in the acute airway inflammation experiments, which is very different from our data on airway inflammation induced by mHRF in naive mice.

Inhibition or amelioration of PCA and airway inflammation by N19 or H3 blockade of HRF-Ig interactions demonstrated that HRF plays a critical role in promoting antigen-induced inflammation. Consistent with our data, transgenic mice expressing HRF in a lung Clara cell–specific manner exhibit increased numbers of macrophages in BAL fluids in naive mice and increased airway inflammation in OVA-sensitized and OVA-challenged mice (62). However, the effect of HRF overexpression in this transgenic study could not be ascribed solely to the function of the secreted HRF molecule; the effect of the transgene could be due to the intracellular effect of HRF as well. Given our present data on the crucial role of HRF in asthma models, as well as the previous data of HRF-like activity in asthma and other allergic conditions, further studies of HRF and the utility of N19 and H3 inhibition of HRF are warranted in preclinical and clinical settings.

Airway inflammation by HRF in naive mice may be mediated predominantly by FcεRI expressed on mast cells, but not basophils, as there are normal numbers of basophils in *Kit*$^{W-sh/W-sh}$ mice

(63). However, Fcγ receptors may also contribute to this inflammation. Abrogation of HRF-induced airway inflammation and gene modulation in naive *FcεRIα*$^{-/-}$ and *FcRγ*$^{-/-}$ mice support the notion that IgE and IgG are the long-sought receptors for HRF in the lung. Based on the profile of up- or downregulated genes, we propose the following scenario: HRF crosslinks FcεRI-bound IgE (and Fcγ receptor–bound IgG) on mast cells in naive mice and activates the cells; activated mast cells secrete various proinflammatory mediators; these mediators then initiate inflammation by directly or indirectly recruiting various inflammatory cells. In addition, a similar HRF-mediated mechanism promotes the amplification of allergen-induced inflammation by activating mast cells and basophils, in which FcεRI complexes are occupied suboptimally with allergen-specific IgE (or, rather, occupied with nonspecific IgEs) to respond to allergen. Potentially at odds with the above scenario, sera and BAL fluids from naive mice contain HRF, which does not appear to induce inflammation under homeostatic conditions. Thus, there seem to be mechanisms to suppress inflammation potentially inducible by endogenous HRF. The endogenous amount of HRF might be lower than the threshold for HRF to induce inflammation. Alternatively, there might be endogenous inhibitors that inhibit HRF's extracellular functions. These possibilities are worthy of investigation.

In summary, our study demonstrated that the bioactive HRF (i.e., dimers and oligomers) interacted with some IgE molecules and could crosslink that IgE-bound FcεRI. FcεRI aggregates activated mast cells in vitro. Inhibitors that prevent HRF-Ig interactions suppressed IgE/antigen-induced skin hypersensitivity and allergen-induced mast cell–dependent airway inflammation. Thus, we conclude that HRF promotes allergic inflammation in the skin and lung.

Methods

Mice. C57BL/6 and Balb/c mice were purchased from the Jackson Laboratory. *FcεRIα*$^{-/-}$, *FcRγ*$^{-/-}$, and *μMT* mice were also used.

Preparation of recombinant mHRF. mHRF cDNAs were amplified by RT-PCR using the primers listed in Supplemental Table 2. GST fusion proteins were purified using glutathione-agarose (Sigma-Aldrich). mHRF-His_6 expressed by pET-24a(+) plasmid was purified using ProBond resin (Invitrogen). All recombinants were further purified by Sephacryl S-100 and dialyzed against PBS. mHRF-His_6 preparations contained less than 0.05 pg/μg protein of endotoxin, as measured by Limulus amebocyte lysate test.

ELISA. 96-well ELISA plates were coated overnight with GST, GST-mHRF, or mHRF-His_6 (each at 10 μg/ml in 0.1 M carbonate buffer [pH 9.5]). The plates were washed and blocked with 10% FCS or 1% BSA. Next, mouse IgE and IgG molecules (10 μg/ml), plasma (1:100–1:200 dilution), and BAL fluids (1:10 dilution) were incubated in the coated wells, after which bound IgE was detected by incubation with biotinylated anti-mouse IgE followed with HRP-conjugated streptavidin. Bound IgG was detected by incubation with HRP-conjugated anti-mouse IgG. Color was developed using TMB substrate (BD Biosciences), and absorbance at 450 nm was measured. Sources of IgE and IgG are listed in Supplemental Table 3.

Affinity pulldown of IgE with GST-mHRF. IgE mAbs (3 μg) in 100 μl of 1% Triton X-100/PBS were incubated with 10 μg of GST- or GST-mHRF–agarose beads. Bead-bound IgEs were pulled down by centrifugation. IgE and GST proteins eluted with SDS sample buffer were detected by immunoblotting with anti-mouse IgE antibody and anti-GST mAb, respectively.

Binding affinity measurement by quartz crystal microbalance method. A quartz crystal microbalance–based (QCM-based) assay was performed using Affinix Q4 apparatus (Initium Co. Ltd.) as described previously (64).

Mast cells. BMMCs were generated by culturing bone marrow cells in IL-3 (65). Peritoneal mast cells purified using anti–c-Kit Positive Selection kit (StemCell Technologies) were also used.

Growth and apoptosis of cultured cells. CHO-K1, Jurkat, and Caco-2 cells were cultured in the absence or presence of GST or GST-N19 for 4 days, and live cells were counted. Apoptosis was induced by IL-3 depletion in BMMCs for 4 days and by 800 nM H_2O_2 in CHO-K1 cells for 2 days, and live cells were counted.

Microscopic localization of GST-N19 and other GST fusion proteins. BMMCs were incubated at 37°C with 20 or 200 μg/ml of GST or GST fusion proterin for 0–24 hours. Washed cells were settled on glass slides. After fixation, cells were permeabilized with ice-cold methanol, then stained with anti-GST followed by Alexa Fluor 488–conjugated anti-mouse IgG. ProLong Gold antifade with DAPI (Invitrogen) was used to mount the slides. Fluorescence was observed with a FLUOVIEW FV10i confocal laser scanning microscope (Olympus).

Degranulation. Mast cells were sensitized overnight with IgE. The cells were stimulated with TNP_{26}-BSA or mHRF-His_6 for 45 minutes. The amount of histamine or β-hexosaminidase in supernatants was measured.

PCA. Mice were sensitized by i.d. injection of IgE into the ear with 0.5 μg of IgE mAb. 24 hours later, Evans blue dye (i.v.) and mHRF-His_6 (10 μg, i.d.) were sequentially injected. Dye extravasated 30 minutes after mHRF challenge was measured by extracting ears in formamide. Engraftment of *Kit*$^{W-sh/W-sh}$ mice with BMMCs was performed 6 weeks before the experiments (66). In some experiments in which mice were stimulated without Evans blue, ear thickness was measured.

Asthma models. In the first model (42), C57BL/6 mice were sensitized with i.p. injection of OVA (10 μg) at days 0, 7, 14, 21, 28, and 35. At days 40, 43, and 46, mice were i.n. challenged with OVA (20 μg). Some mice were i.n. pretreated with 40–400 μg of GST or GST-N19 before every OVA challenge. In some experiments, 20 μg of synthetic N19 peptide or vehicle (2% DMSO) was used for pretreatment. 24 hours after the last challenge, lung function was tested using FlexiVent system (SCIREQ). Mice were sacrificed, and BAL fluids as well as blood and lung tissues were collected. Cells in BAL fluids were enumerated after staining with May-Giemsa. Paraffin-embedded lung tissues were stained with H&E and periodic acid-Schiff. Cytokines in lung homogenates were quantified by ELISA.

In the second model of asthma (47), BALB/c mice were i.n. treated with *Aspergillus fumigatus* allergen (50 μl; Greer Laboratories) or PBS 3 times per week for 3 weeks. Some mice were i.n. pretreated with GST or GST-N19 (200 μg/50 μl) beginning at the second week for 30 minutes before each immunization. 24 hours after the last challenge, mice were sacrificed.

In the third model (48), C57BL/6 mice were i.p. immunized with OVA in the presence of alum on days 0 and 12. Mice were i.n. administered with OVA (20 μg/20 μl) on days 24, 26, and 28. Some mice were i.n. pretreated with GST or GST-N19 (400 μg/20 μl) before each OVA challenge. 24 hours after the last challenge, mice were sacrificed.

Oligonucleotide microarray. Total RNA was extracted from lungs using RNeasy Total RNA Mini Kit (Qiagen). A microarray analysis was performed using 200 ng of total RNA from each sample and SurePrint G3 Mouse Gene Expression 8x60K arrays (Agilent Technologies) according to the manufacturer's instructions. The microarray data have been deposited in Gene Expression Omnibus (GEO; accession no. GSE34133; http://www.ncbi.nlm.nih.gov/geo/query/acc.cgi?acc=GSE34133). Data analysis was performed with GeneSpring software (version GX 10.3). Because the expression levels of housekeeping genes (*GAPDH* and *β-actin*) did not differ among all samples, specific normalization was not performed. To eliminate genes containing only a background signal, genes were selected only if the raw values of "Expression" were more than 100. In addition, we focused on probes with reliable annotations (https://earray.chem.agilent.com/earray/) in the present study. A total of 16,374 genes met these criteria and were subjected to further analysis.

Statistics. Bonferroni correction was used for AHR analysis. Other statistical analyses were performed by 2-tailed Student's *t* test. Data shown indicate mean ± SEM. A *P* value less than 0.05 was considered significant.

Study approval. Animal experiments were approved by the Animal Care and Use Committee of the La Jolla Institute for Allergy and Immunology.

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