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Chitinase 3-like 1 Regulates Cellular and Tissue Responses via IL-13 Receptor $\alpha 2$

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SUMMARY

Members of the 18 glycosyl hydrolase (GH 18) gene family have been conserved over species and time and are dysregulated in inflammatory, infectious, remodeling, and neoplastic disorders. This is particularly striking for the prototypic chitinase-like protein chitinase 3-like 1 (Chi311), which plays a critical role in antipathogen responses where it augments bacterial killing while stimulating disease tolerance by controlling cell death, inflammation, and remodeling. However, receptors that mediate the effects of GH 18 moieties have not been defined. Here, we demonstrate that Chi311 binds to interleukin-13 receptor $\alpha 2$ (IL-13R $\alpha 2$) and that Chi311, IL-13R $\alpha 2$, and IL-13 are in a multimeric complex. We also demonstrate that Chi311 activates macrophage mitogen-activated protein kinase, protein kinase B/AKT, and Wnt/ β -catenin signaling and regulates oxidant injury, apoptosis, pyroptosis, inflammasome activation, antibacterial responses, melanoma metastasis, and TGF- $\beta 1$ production via IL-13R $\alpha 2$ -dependent mechanisms. Thus, IL-13R $\alpha 2$ is a GH 18 receptor that plays a critical role in Chi311 effector responses.

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SUPPLEMENTAL INFORMATION

Supplemental Information contains Extended Experimental Procedures, five figures, and two tables and can be found with this article online at <http://dx.doi.org/10.1016/j.celrep.2013.07.032>.

INTRODUCTION

The 18 glycosyl hydrolase (GH 18) gene family contains true chitinases (Cs) that degrade chitin polysaccharides and chitinase-like proteins (CLPs) that bind to but do not degrade chitin (Lee et al., 2011). They are members of an ancient gene family that exists in species as diverse as plants and humans and has evolved during speciation, with a particularly impressive increase in CLPs coinciding with the appearance of mammals (Aerts et al., 2008; Funkhouser and Aronson, 2007). This retention over species and evolutionary time has led to the belief that these moieties play essential roles in biology. Recent studies have confirmed this speculation (Dela Cruz et al., 2012; Lee et al., 2009, 2011; Lee and Elias, 2010; Sohn et al., 2010). This is particularly true for the prototypic CLP chitinase 3-like-1 (Chi311, also called YKL-40 in humans and BRP-39 in mice), which has been shown by our laboratory and others to play major roles in antipathogen, antigen-induced, oxidant-induced, inflammation, repair and remodeling responses by regulating a variety of essential biologic processes including oxidant injury apoptosis, pyroptosis, inflammasome activation, Th1/Th2 inflammatory balance, M2 macrophage differentiation, transforming growth factor β 1 (TGF- β 1) elaboration, dendritic cell accumulation and activation, and mitogen-activated protein kinase (MAPK) and Akt signaling (Areshkov et al., 2012; Chen et al., 2011a; Dela Cruz et al., 2012; Kim et al., 2012; Lee et al., 2009; Sohn et al., 2010). The potential importance of YKL-40/Chi311/BRP-39-induced responses can also be seen in the large number of diseases in which Chi311/YKL-40 excess has been documented and the observation that the degree of Chi311/YKL-40 dysregulation often correlates with the severity and natural history of these disorders (reviewed in Coffman, 2008; Lee et al., 2011). Surprisingly, the mechanisms via which the GH 18 moieties mediate their biologic effects are poorly understood. Importantly the possibility that GH 18 proteins mediate their biologic effects via a ligand-receptor paradigm has not been addressed, and moieties that bind to and signal in response to any of these regulators have not been defined.

To address the possibility that YKL-40/Chi311/BRP-39, which does not have known enzymatic activity, mediates its effects via identifiable receptors, we used yeast two-hybrid binding and colocalization assays to define YKL-40/Chi311/BRP-39 binding-partner interactions and assessments of signaling, gene expression, and *in vivo* phenotype generation to evaluate the consequences of these interactions. These studies demonstrate that YKL-40/Chi311/BRP-39 binds to interleukin-13 receptor α 2 (IL-13R α 2). They also demonstrate that YKL-40/Chi311/BRP-39, IL-13R α 2, and IL-13 are in a multimeric complex. Lastly, they demonstrate that YKL-40 activates MAPK, Akt, and Wnt/ β -catenin signaling pathways and regulates apoptosis, pyroptosis, inflammasome activation, oxidant injury, antibacterial responses, melanoma metastasis, and TGF- β 1 elaboration via IL-13R α 2-dependent mechanisms.

RESULTS

Chi311/YKL-40/BRP-39 Binding to IL-13R α 2

To define the binding partners of Chi311/YKL-40, yeast two-hybrid analysis was undertaken using Chi311/YKL-40 as bait. A number of clones gave positive results in these assays. One of the most intriguing encoded IL-13R α 2 (Figure S1A). Further documentation of the

interaction between YKL-40 and IL-13R α 2 was obtained with coimmunoprecipitation (coIP), colocalization, and Biacore assays. In the former, A549 cells were transfected with both of these moieties and subjected to immunoprecipitation (IP) with antibodies to one moiety, and the precipitate was then analyzed via western blotting using antibodies to the other moiety. In these experiments, the two moieties always traveled together with IP using antibodies against YKL-40 always precipitating IL-13R α 2 and vice versa (Figure 1A). Immunohistochemical evaluations of lungs from IL-13 transgenic (Tg) mice (in which Chi311/BRP-39 and IL-13R α 2 are both strongly induced) demonstrated that Chi311/BRP-39 and IL-13R α 2 frequently colocalize in these tissues (Figure 1B). The major site of this colocalization was in F4/80+ macrophages (Figures 1B and S1B). Interestingly, there were macrophage populations in which colocalization occurred and populations in which Chi311 was noted and IL-13R α 2 could not be detected (Figure 1B). Colocalization in some alveolar type II cells was also appreciated (Figures 1B and S1C). To identify the sites in the cell of this colocalization, we employed fluorescence-activated cell sorting (FACS) evaluations of nonpermeabilized cells and immunohistochemistry (IHC) of tissue sections and stained both with anti-Chi311 and anti-iL-13R α 2. These studies clearly demonstrate that Chi311 and IL-13R α 2 can be seen together on the surface and in the cytoplasm of the cell (Figures 1C and S1D). The Biacore assays also demonstrated that Chi311/YKL-40 and IL-13R α 2 bind to one another. At pH 7.4, the binding was quite avid, with a K_d of 23 ± 14 pM (Figure 1D). The k_{off} was approximately 10^{-5} s^{-1} and the k_{on} was $3.39 \pm 1.54 \times 10^5 \text{ M}^{-1} \text{ s}^{-1}$. These studies demonstrate that YKL-40 specifically binds to IL-13R α 2 with high affinity.

Localization of Chi311/YKL-40-IL-13R α 2 Binding

Deletion mapping was next employed to define the regions in Chi311/YKL-40 and IL-13R α 2 that are required for their interactions in the yeast two-hybrid assay. These studies demonstrated that the region of YKL-40 between amino acids 22 and 357 contained the elements that were required to bind to full-length IL-13R α 2 (Figure 1E). This region is called the catalytic domain (CD) of GH 18 moieties and contains the chitin binding motif (CBM) but does not contain its signal peptide (SP) or the C-terminal peptide (Figure 1E). Interestingly, the CBM was necessary, but not sufficient, for YKL-30/Chi311-IL-13R α 2 binding (Figure 1E). These studies also demonstrated that the extracellular domain (ECD) of YKL-40 contained elements that were required for binding to full-length Chi311/YKL-40 (Figure 1E). The transmembrane and intracellular motifs of IL-13R α 2 did not play a critical role in this interaction (Figure 1F). The four sites of N-linked glycosylation within the ECD were also able to be mutated without abrogating IL-13R α 2 ECD-Chi311/YKL-40 binding (Figure 1F). These studies demonstrate that Chi311/YKL-40/IL-13R α 2 binding is dependent on the CD and the CBM of the former and the ECD, but not the sites of N-glycosylation in the latter.

Interactions with Soluble IL-13R α 2

An ECD-containing soluble version of this receptor has been described elsewhere (Chen et al., 2008, 2009). We thus speculated that Chi311/YKL-40 would also bind to soluble IL-13R α 2 (sIL-13R α 2). To test this hypothesis, we did coIP experiments using bronchoalveolar lavage (BAL) fluids from IL-13 Tg mice. These studies demonstrated that Chi311/BRP-39 also binds to sIL-13R α 2 (Figure S1E).

Role of IL-13R α 2 in Chi311/YKL-40/BRP-39 Signaling

To define the role(s) of IL-13R α 2 in Chi311/YKL-40/BRP-39-induced intracellular signaling, we compared the effects of Chi311/YKL-40/BRP-39 on MAPK, extracellular signal-regulated protein kinase (ERK) 1/2, AKT, and Wnt/ β -catenin activation in human THP-1 cells treated with IL-13R α 2 small interfering RNA (siRNA) or scrambled controls and peritoneal macrophages from wild-type (WT) and IL-13R α 2 null mice. As can be seen in Figure 2A, ERK activation, AKT activation, and the induction of nuclear β -catenin and *c-fos* were seen in THP-1 cells 30 min to 2 hr after the addition of recombinant (r) Chi311/YKL-40. These effects were dose dependent, with the activation of ERK and AKT being seen with doses of rYKL-40 as low as 0.1–0.3 μ g/ml and the induction of nuclear β -catenin and *c-fos* being seen with doses as low as 0.3–0.5 μ g/ml (Figure 2B). They were also at least partially IL-13R α 2 dependent, because siRNA that decreased the levels of IL-13R α 2 messenger RNA (mRNA) by greater than 70% (Figures S2A and S2B) significantly decreased each of these activation events (Figure 2C). In accord with these findings, rChi311/BRP-39 activated ERK and AKT signaling and induced nuclear β -catenin and *c-fos* accumulation in peritoneal macrophages from WT mice, and these inductive events were significantly decreased in cells from IL-13R α 2 null animals (Figure 2D). These effects were at least partially Chi311/YKL-40/BRP-39 specific because the related GH 18 moiety, acidic mammalian chitinase (AMCase), did not signal in a similar manner via IL-13R α 2 (Figure S2C). Interestingly, Chi311/YKL-40/BRP-39 signaling was also significantly decreased in experiments in which soluble IL-13R α 2 was added to the cell culture system (Figures 2E and S2D). These studies demonstrate that Chi311/YKL-40/BRP-39 activates ERK and AKT signaling and induces β -catenin nuclear translocation and *c-fos* accumulation via an IL-13R α 2-dependent mechanism(s) in mice and humans and that this signaling is regulated by sIL-13R α 2.

Given that the intracellular domain of IL-13R α 2 only contains a 17-amino-acid structure that lacks protein binding motifs, studies were undertaken to define the role of this domain in Chi311/YKL-40/BRP-39 signaling events. To address this question, we compared the signaling induced by Chi311/YKL-40/BRP-39 in macrophages from IL-13R α 2 null mice that were transfected with WT (full-length) IL-13R α 2 constructs or truncated constructs that lacked the intracellular domain. These studies demonstrate that the intracellular domain of IL-13R α 2 is not required for Chi311 activation of MAPK or AKT (Figure 2F). Interestingly, this segment was required for Chi311 activation of the Wnt/ β -catenin pathway (Figure S2E). These studies demonstrate that the intracellular domain of IL-13R α 2 has different roles in Chi311-induced MAPK and AKT versus Wnt/ β -catenin signaling.

Interactions of IL-13, IL-13R α 2, and Chi311/YKL-40/BRP-39

Because IL-13 also binds to IL-13R α 2, we used coIP, signaling, and Biacore experiments to define the interactions of IL-13, Chi311/YKL-40/BRP-39, and IL-13R α 2. These studies demonstrated that IL-13 and Chi311/YKL-40/BRP-39 do not bind to one another (data not shown). They did, however, demonstrate that Chi311, IL-13R α 2, and IL-13 colocalize in tissue sections (Figure 3A) and participate in a multimeric complex, because the immunoprecipitation of any one of the three always immunoprecipitated the other two (Figure 3B). In keeping with this finding, studies that demonstrated that IL-13 can activate

MAPK (Cho et al., 2006; Lee et al., 2006) and studies that demonstrated that IL-13 stimulates heparin binding-epidermal growth factor (HB-EGF) via an IL-13R α 2-dependent mechanism (Allahverdian et al., 2008) demonstrated that IL-13 also activates macrophage MAPK and AKT via IL-13R α 2- and Chi311-dependent pathways (Figure S3A and S3B). IL-13 did not compete with Chi311/YKL-40/BRP-39 for IL-13R α 2 binding or signaling (Figure 3C). Similarly, Chi311/YKL-40/BRP-39 did not compete with IL-13 for IL-13R α 2 binding or signaling (Figure 3D). IL-13 was also a powerful activator of STAT6, Chi311/YKL-40 did not activate STAT6, Chi311 did not inhibit IL-13-induced phosphorylation of STAT6, and IL-13 did not inhibit Chi311/YKL-40 activation of MAPK, AKT, or Wnt/ β -catenin signaling (Figure 3E). Structure-function evaluations also demonstrated that deletion of amino acids corresponding to site II (IL-13R α 2^{dS2}) and site III (IL-13R α 2^{dS3}) of IL-13R α 2, the reported IL-13 binding sites in IL-13R α 2 (Lupardus et al., 2010), abrogates IL-13 binding without abrogating Chi311 binding (Figure 3F). These studies demonstrate that IL-13, Chi311/YKL-40, and IL-13R α 2 participate in a multimeric complex. They also demonstrate that Chi311/YKL-40 and IL-13 do not compete with one another for IL-13R α 2 binding, do not abrogate each other's signaling, and do not bind to identical locations on IL-13R α 2.

Role of IL-13R α 2 in Oxidant-Induced Cell Death Responses

Previous studies from our laboratory demonstrated that Chi311/YKL-40/BRP-39 inhibits oxidant-induced lung injury and epithelial cell apoptosis (Sohn et al., 2010). To determine if IL-13R α 2 plays a role in these responses, we compared the epithelial cell death and pulmonary injury responses in WT, IL-13R α 2 null, YKL-40 Tg, and YKL-40 Tg/IL-13R α 2^{-/-} mice exposed to room air or 100% O₂ for 48 hr. Hyperoxia induced epithelial apoptosis/DNA injury, alveolar-capillary protein leak, and caspase-3 and caspase-8 activation in lungs from WT mice (Figures 4A, 4B, and S4A; data not shown). Hyperoxia-induced epithelial TUNEL responses and alveolar protein leak were exaggerated in lungs from Chi311/BRP-39 null mice and a phenocopy was seen in IL-13R α 2^{-/-} animals (Figures 4A and 4B). Transgenic YKL-40 ameliorated the hyperoxia-induced responses in WT mice and rescued the exaggerated responses in Chi311 null animals (Figures 4A and 4B). Importantly, the protective effects of YKL-40 were significantly decreased in Tg mice that lacked IL-13R α 2 (Figures 4A and 4B). In accord with these in vivo findings, epithelial cells treated with H₂O₂ in vitro manifest increased levels of apoptosis and necrosis and these responses were exaggerated in cells that lacked Chi311/YKL-40 or IL-13R α 2 (Figures 4C and S4B). The addition of rChi311/YKL-40 to these cultures markedly decreased the cell death responses in WT cells and rescued the exaggerated responses in Chi311/BRP-39 null mice but did not cause comparable cytoprotection in cells that lacked IL-13R α 2 (Figures 4C and S4B). These responses were not H₂O₂ or lung epithelial cell specific because similar responses were seen with FasL-treated lung epithelial cells and H₂O₂-treated kidney epithelial cells (Figures S4C and S4D). They were also at least partially mediated by the ability of Chi311/YKL-40/BRP-39 to activate AKT, because selective AKT inhibitors abrogated the antiapoptotic effects of Chi311/YKL-40/BRP-39 (Figure S4E; data not shown). Similarly, exposure of murine peritoneal macrophages from WT mice to H₂O₂ induced TUNEL staining and lactate dehydrogenase (LDH) release, and these responses were further exaggerated in cells from Chi311/BRP-39 null animals (Figures 4D and 4E). A

phenocopy was seen in cells from IL-13R α 2 null mice, which also manifest exaggerated levels of TUNEL staining and LDH release after H₂O₂ treatment (Figures 4D and 4E). Once again, the TUNEL staining and LDH release from macrophages from WT and Chi311/BRP-39 null mice were significantly ameliorated by treatment with rChi311/BRP-39. In contrast, rChi311/YKL-40 did not cause a similar degree of cytoprotection in cells that lacked IL-13R α 2 (Figures 4D and 4E). When viewed in combination, these studies demonstrate that oxidant-induced injury and cell death responses are similarly increased in vivo and in vitro in lungs, epithelial cells, and macrophages from Chi311/BRP-39 null and IL-13R α 2 null mice. They also demonstrate that transgenic and recombinant Chi311/YKL-40 rescue these exaggerated responses via IL-13R α 2-dependent mechanisms.

Role of IL-13R α 2 in Pyroptosis

Because previous studies from our laboratory demonstrated that Chi311/YKL-40/BRP-39 controls *Streptococcus pneumoniae* (*SP*)-induced macrophage pyroptosis, *SP*-induced cell survival, LDH release, and caspase-1 activation were evaluated in cells from WT, Chi311/BRP-39 null, and IL-13R α 2 null mice. Incubation with *SP* increased TUNEL staining and LDH release from cells from WT mice, and this response was further exaggerated in cells from Chi311/BRP-39 null animals (Figures 5A and 5B). These responses in cells from WT mice were not associated with significant increases in caspase-1 activity (Figure 5C). However, increased caspase-1 was seen in *SP*-infected cells from Chi311/BRP-39 null mice (Figure 5C). A phenocopy was seen in cells from IL-13R α 2 null mice, which also manifest exaggerated levels of TUNEL staining, LDH release, and caspase-1 activation after *SP* infection (Figures 5A–5C). Importantly, the exaggerated TUNEL staining, LDH release, and caspase-1 activation in Chi311/BRP-39 null mice were significantly rescued by treatment with rChi311/BRP-39. In contrast, rBRP-39/YKL-40 did not comparably rescue the exaggerated cell death phenotype and caspase-1 activation in IL-13R α 2 null cells (Figures 5A–5C). In accord with these studies, the defects in bacterial killing that were seen in macrophages from Chi311/BRP-39 null mice (Dela Cruz et al., 2012) were phenocopied in macrophages from IL-13R α 2 null mice (Figure 5D), and the former was rescued with rChi311 while the latter was not significantly altered by this recombinant protein (Figure 5D). When viewed in combination, these studies demonstrate that *SP*-induced pyroptosis is increased in a similar manner in macrophages from Chi311/BRP-39 null and IL-13R α 2 null mice and that rChi311/BRP-39 rescues this exaggerated phenotype via an IL-13R α 2-dependent mechanism.

Role of IL-13R α 2 in Inflammasome Activation

Studies were also undertaken to define the role(s) of IL-13R α 2 in the regulation of inflammasome activation by Chi311/YKL-40/BRP-39. In these experiments, incubation of macrophages from WT mice with *SP* stimulated the production of IL-1 β and the accumulation of IL-1 β mRNA (Figure S5A). Under these circumstances, a significant increase in pro-IL-1 β and a more modest increase in the levels of mature IL-1 β could also be appreciated in cells and supernatants from these cultures (Figures 6A–6D). Both of these responses were exaggerated in cells from Chi311/BRP-39 null mice (Figures 6A–6D). Enhanced levels of pro-IL-1 β were also seen in cells from *SP*-treated IL-13R α 2 null mice (Figures 6A–6D). In keeping with the increased levels of caspase-1 activity in these cells,

increased levels of cell-associated and supernatant mature IL-1 β were also seen in cultures of *SP*-treated IL-13R α 2 null cells (Figures 6B and 6D). Importantly the exaggerated mature IL-1 β responses in Chi311/BRP-39 null mice were ameliorated by treatment with rChi311/BRP-39. In contrast, rChi311/BRP-39 did not rescue the exaggerated inflammasome activation in IL-13R α 2 null cells (Figures 6C and 6D). These studies demonstrate that Chi311/YKL-40/BRP-39 inhibits *SP*-induced inflammasome activation via an IL-13R α 2-dependent mechanism.

Role of IL-13R α 2 in *SP* Infection In Vivo

Previous studies from our laboratory demonstrated that Chi311/BRP-39 plays a critical role in antipneumococcal responses where it augments bacterial killing by inhibiting macrophage pyroptosis and inhibits inflammasome activation (Dela Cruz et al., 2012). In keeping with the in vitro observations noted above, studies were undertaken to define the roles of IL-13R α 2 in in vivo anti-*SP* responses. *SP* infection caused a brisk neutrophil-rich inflammatory response that was associated with significant induction of BAL IL-1 β (Figures S5B and S5C). These responses and pyroptosis-associated caspase-1 activation were exaggerated and bacterial clearance was decreased in Chi311/BRP-39 null mice (Figures 6E and 6F). The *SP*-induced responses in IL-13R α 2 null mice were very similar to those in the Chi311/BRP-39 null mice with enhanced BAL and tissue inflammation, IL-1 β production, caspase-1 activity, and bacterial accumulation (Figures S5B, S5C, 6E, and 6F). Importantly, rChi311/YKL-40 successfully ameliorated the exaggerated responses in Chi311/BRP-39 null mice but did not have similar corrective effects in mice that lacked IL-13R α 2 (Figures S5B, S5C, 6E, and 6F). These studies demonstrate that IL-13R α 2 plays an important role in Chi311/YKL-40/BRP-39 regulation of pulmonary antibacterial responses in vivo.

Role of IL-13R α 2 in Chi311/YKL-40 Stimulation of Melanoma Metastasis and TGF- β 1 Production In Vivo

Recent studies have demonstrated that pulmonary melanoma metastasis is mediated via an IL-13R α 2-dependent mechanism that requires the production of TGF- β 1 (Fichtner-Feigl et al., 2008b; Strober et al., 2009). As a consequence, studies were undertaken to determine if Chi311/YKL-40/BRP-39 plays a role in this response and if it does so via IL-13R α 2. To accomplish this, we compared the B16-F10 melanoma cell-induced metastasis and TGF- β 1 elaboration in WT mice, YKL-40 Tg mice, and IL-13R α 2 null mice. Melanoma cell administration caused impressive levels of metastasis in lungs from WT mice, and this metastatic response was markedly increased in Tg mice in which YKL-40 was selectively targeted to the lung (Figures 7A and 7B). In accord with the studies of Strober et al. (Fichtner-Feigl et al., 2008b; Strober et al., 2009), these meta-static responses were associated with modest increases in the levels of TGF- β 1 in WT mice and significantly enhanced levels of total and activated TGF- β 1 in melanoma-challenged YKL-40 Tg animals (Figures 7C and 7D). Importantly, the metastatic responses in the WT and Tg mice and the levels of TGF- β 1 production were both significantly decreased in mice with null mutations of IL-13R α 2 (Figures 7A–7D). When viewed in combination, these studies demonstrate that endogenous Chi311/BRP-39 and transgenic Chi311/YKL-40 regulate pulmonary melanoma metastasis and the TGF- β 1 elaboration that underlies these responses. They also

demonstrate that the effects of Chi311/YKL-40/BRP-39 in this setting are mediated, at least in part, by IL-13R α 2.

DISCUSSION

IL-13R α 2 was described as a high-affinity receptor for IL-13 that is distinct from the IL-13R α 1-IL-4R α receptor dimer that IL-13 shares with IL-4 (Lupardus et al., 2010; Strober et al., 2009). It was initially believed to be a decoy receptor because it only contains a 17-amino-acid cytoplasmic domain that lacks a conserved box 1 region that plays a critical role in signal transduction (Konstantinidis et al., 2008) and early studies highlighted its ability to diminish IL-13 responses (Chiaromonte et al., 2003; Lupardus et al., 2010; Wood et al., 2003). However, more recent studies have demonstrated that IL-13 also signals and regulates a variety of cellular and tissue responses via IL-13R α 2 (Daines et al., 2006; Fichtner-Feigl et al., 2006, 2007, 2008a, 2008b; Strober et al., 2009; Yang et al., 2010, 2011). The explanation for these different points of view has not been defined. The present studies, however, provide insights into mechanisms that may contribute to these disparate findings because they demonstrate that IL-13 is not the only ligand for IL-13R α 2. Specifically, they characterize the first receptor for any GH 18 moiety by demonstrating that the chitinase-like protein (CLP) Chi311 binds to, signals, and regulates oxidant injury, apoptosis, pyroptosis, inflammasome activation, pathogen responses, melanoma metastasis, and TGF- β ₁ via IL-13R α 2.

Endogenous lectins such as C-type lectins, siglecs, and galectins bind N- and O-linked glycans, resulting in regulatory signals that control immune cell homeostasis and integrate circuits that amplify or silence immune responses (Rabinovich and Croci, 2012). These lectins recognize complex glycan determinants with relatively high affinity, often in the micromolar range (Rabinovich and Croci, 2012; Sulak et al., 2009). CLPs are also lectins and are frequently referred to as chilectins. In keeping with other lectin-glycan interactions, our studies demonstrate that Chi311 binds to the glycopeptide IL-13R α 2 (Kioi et al., 2006) with high affinity. They also demonstrate that this interaction is dependent on the CD and chitin binding motif of Chi311 and the extracellular domain of IL-13R α 2 but did not require IL-13R α 2 N-glycosylation. When combined with our demonstration that Chi311 signals and regulates cellular and tissue responses, these findings allow for the exciting hypothesis that IL-13R α 2 is a receptor for Chi311, putting the Chi311-IL-13R α 2 complex at the interface of glycobiology and protein biology (Coffman, 2008). It is important to point out, however, that our studies do not demonstrate that IL-13R α 2 is the only receptor for Chi311/YKL-40//BRP-39. In fact, our studies suggest that other receptors may exist because, in some of our experimental systems, the elimination of IL-13R α 2 only partially abrogated the specific Chi311/YKL-40/BRP-39 effector response.

Studies were also undertaken to define the interactions of IL-13, IL-13R α 2, and Chi311/YKL-40/BRP-39. These studies demonstrate that these moieties exist in tissues and fluids in a multimeric complex. Our studies do not address the details of the Chi311-IL-13R α 2-IL-13 complex. However, modeling of other lectin-glycan interactions has revealed two- and three-dimensional arrangements of multivalent lectins and glycans in “lattices” that serve as scaffolds that organize plasma membrane domains and modulate the signaling thresholds of

relevant surface glycoproteins and receptors (Rabinovich and Croci, 2012). Thus, it is possible that Chi311, IL-13R α 2, and IL-13 are part of a large multimeric complex or “chitosome” that could include other glycoproteins and lectins. Additional investigation will be required to evaluate the nature of the IL-13R α 2-Chi311 complex and its relationship to IL-13 and other Chi311 receptors.

Using concentrations of Chi311 that can be seen in the circulation of healthy individuals and in patients with disease, these studies demonstrated that Chi311 can activate MAPK and AKT cellular signaling pathways (Areshkov et al., 2012; Chen et al., 2011a; Eurich et al., 2009; Kim et al., 2012; Shao et al., 2009). Our studies added to these observations by demonstrating that Chi311 activates the Wnt/ β -catenin signaling and by demonstrating that IL-13R α 2 is required for the optimal activation of each of these signaling pathways. These findings are in keeping with the reported ability of IL-13 to activate MAPKs, Wnt/ β -catenin, and AKT (Moriya et al., 2011; Ooi et al., 2012; Wang et al., 2008) and the ability of IL-13 to stimulate epithelial HB-EGF via IL-13R α 2 (Allahverdian et al., 2008). Lastly, our studies demonstrate that the antiapoptotic effects of Chi311/YKL-40/BRP-39 are mediated, at least in part, by its ability to activate AKT. When viewed in combination, it is tempting to speculate that these signaling events, in addition to their contribution to the anti-apoptotic effects of Chi311, also contribute to its inflammatory, angiogenic, neoplastic, and other effector responses (Chen et al., 2011b; Coffman, 2008; Eurich et al., 2009; Faibish et al., 2011; Kawada et al., 2012; Lee et al., 2009; Shao et al., 2009).

To define the role(s) of the intracellular domain of IL-13R α 2 in the signaling events that were noted, we compared the effects of Chi311 in cells from IL-13R α 2^{-/-} mice that were transfected with constructs that encoded full-length IL-13R α 2, constructs that lacked the intracellular domain of IL-13R α 2, and controls. These studies demonstrated that the MAPK and AKT activation events did not require the intracellular domain of the receptor. In contrast, the intracellular domain played a critical role in the activation of the Wnt/ β -catenin/AP-1 pathway. The latter findings are in full accord with reports by Fichtner and Feigl (Fichtner-Feigl et al., 2006). When viewed in combination, these findings highlight the different roles of the intracellular domain of IL-13R α 2 in Chi311-induced cell signaling. They also raise the interesting question, how does Chi311 activate ERK and AKT without an intra-cellular domain? Preliminary studies in our laboratory support the possibility that a coreceptor may be involved. However, additional investigation will be required to fully address this possibility.

Chi311/YKL-40/BRP-39 may play a particularly important role in cancer (Coffman, 2008; Goel et al., 2007; Lee et al., 2011). Recent studies by the Strober group also highlighted the importance of IL-13R α 2 in the progression of malignant melanoma, where its activation by IL-13 caused TGF- β 1 elaboration, which inhibited tumor immune surveillance and favored tumor growth (Fichtner-Feigl et al., 2008b; Strober et al., 2009). Previous studies from our laboratory demonstrated that IL-13 stimulates TGF- β 1 via a Chi311/BRP-39-dependent mechanism (Lee et al., 2009). The present studies add to these observations by demonstrating that Tg Chi311/YKL-40 stimulates TGF- β 1 in lungs with metastatic melanoma via an IL-13R α 2-dependent mechanism. Interestingly, they also demonstrated that IL-13R α 2 plays a particularly important role in the production of bioactive TGF- β 1 in

this setting. Thus, in accord with the findings by Strober et al. and prior studies that demonstrate that the levels of circulating Chi311/YKL-40 are increased in patients with advanced melanoma (Schmidt et al., 2006), an IL-13-Chi311/YKL-40-IL-13R α 2-TGF- β 1 axis appears to play a critical role in the progression of malignant melanoma. These studies also suggest that IL-13R α 2-dependent mechanisms may play an important role in TGF- β 1 activation.

In keeping with the retention of CLP over species and evolutionary time, recent studies have demonstrated that Chi3L1 plays essential roles in pathogen clearance and the generation of host tolerance (Dela Cruz et al., 2012). In the setting of pneumococcal lung infection, Chi311 augments bacterial killing and clearance by controlling pyroptosis (Dela Cruz et al., 2012). This prevents the bacteria from killing the macrophage before the macrophage can kill the bacteria (Dela Cruz et al., 2012). Simultaneously, Chi311 diminishes innocent-bystander tissue injury by controlling innate immune inflammasome and purinergic pathway activation (Dela Cruz et al., 2012) and decreases tissue oxidant injury (Sohn et al., 2010). To define the roles of IL-13R α 2 in these events, we characterized these responses in WT mice and Chi311/BRP-39 null mice and evaluated the ability of Tg Chi311/YKL-40 to rescue these responses in mice with WT and null IL-13R α 2 loci. These studies demonstrate that, in the absence of Chi311/BRP-39, pneumococcus causes exaggerated macrophage cell death, inflammation, and tissue injury and decreased bacterial clearance and that each of these responses was significantly ameliorated by Tg Chi311/YKL-40. They also demonstrate that, in the absence of Chi311/BRP-39, oxidants caused exaggerated cellular apoptosis, which was rescued by Chi311/YKL-40. Importantly, qualitatively similar responses were seen in IL-13R α 2 null animals and cells exposed to pneumococcus or H₂O₂. However, the ability of Chi311/YKL-40/BRP-39 to rescue the phenotypes in IL-13R α 2 null mice and or cells was decreased compared to the effects of Chi311/YKL-40 in mice and cells that lacked Chi311/BRP-39. This demonstrates that Chi311 controls pyroptosis, apoptosis, inflammasome activation, and antipneumococcal responses by binding to and activating IL-13R α 2. This further reinforces the concept that IL-13R α 2 is a receptor for Chi311 and more than just a “decoy” receptor for IL-13.

EXPERIMENTAL PROCEDURES

Mice

C57BL/6 mice (the Jackson Laboratory) were bred at Yale. Chi311/BRP-39 null mutant mice (Chi311^{-/-}) and YKL-40 and IL-13 Tg mice were generated and characterized in our laboratory as previously described (Lee et al., 2009; Zhu et al., 1999). IL-13R α 2 null mice (IL-13R α 2^{-/-}) were purchased from The Jackson Laboratory and backcrossed to C57BL/6 backgrounds. All murine procedures were approved by the Institutional Animal Care and Use Committee at Yale University.

Yeast Two-Hybrid Screening

The full-length murine Chi311 gene was amplified by PCR from mouse lung complementary DNA (cDNA) using the following primers: forward, 5'-CCCCGGGCTGCAGGGATCCGG CAGAGAGAAGCCATC-3'; reverse, 5'-CATATGGGAAAGGTCGACCTAAGCCAG

GGCATCCTT-3'). The Chi311 DNA was cloned into the yeast two-hybrid BD vector at the BamHI and *Sall* sites. The Matchmaker System 3 two-hybrid assay using *S. cerevisiae* (Clontech) was used to detect interactions between Chi311 and other cellular proteins. *S. cerevisiae* strain AH109 (Clontech) containing the four reporter genes *ADE2*, *HIS3*, *MEL1*, and *lacZ* was cotransfected with the pGBKT7-Chi311 bait plasmid and the mouse lung cDNA library (Clontech) constructed into the vector pAC2 by the lithium acetate method. Additional experimental details are included in the Extended Experimental Procedures.

Coimmunoprecipitation

Proteins from the lysate, culture supernatant, or BAL fluid were clarified by centrifugation for 10 min at 4°C. Chi311/YKL-40 and human IL-13R α 2 were immunoprecipitated with anti-YKL-40 rabbit polyclonal antibody (MedImmune) or anti-hIL-13R α 2 monoclonal antibody (RayBiotech), respectively, using Catch and Release V2.0 (Reversible Immunoprecipitation System, EMD Millipore). The precipitates were subjected to immunoblotting with antibodies against IL-13R α 2 or YKL-40, respectively.

Double-Label Immunohistochemistry

To localize the expression of BRP-39 and IL-13R α 2, double-label IHC was undertaken with a modification of procedures described previously by our laboratory (Lee et al., 2009). Additional experimental details are included in the Extended Experimental Procedures.

Expression and Purification of IL-13, IL-13R α 2, and YKL40

Genes encoding residues 21–132 of human IL-13, ectodomain residues 29–331 of human IL-13R α 2 (IL-13R α 2-ECD), or human YKL40 were subcloned into the pAcGP67 vector (BD Biosciences) in frame with the baculovirus gp67 signal sequence and followed by the sequence PHHHHHH. Sf9 insect cells (Invitrogen) were cotransfected with one of the above expression constructs and DiamondBac baculovirus genomic DNA (Sigma-Aldrich) to produce recombinant baculoviruses expressing IL-13 or IL-13R α 2-ECD, or YKL40. Virus stocks were amplified with three sequential infections of Sf9 cells. The three proteins were expressed and purified following the same protocol. *Tni* insect cells (Expression Systems) grown at 27°C were infected at a density of 2×10^6 cells/ml with 1.0% (v/v) of third-passage (P3) recombinant baculovirus stock. After culture in suspension for 96–105 hr at 20°C, the culture media was collected and its pH was adjusted with 10 mM HEPES pH 7.5. The overexpressed protein was purified by nickel-affinity chromatography with a HisTrap HP column (GE Healthcare), followed by size-exclusion chromatography on a Superdex 200 10/300 GL column (GE Healthcare). The size-exclusion buffer was 10 mM HEPES pH 7.5, 50 mM NaCl, and 0.5 mM CaCl₂. Protein concentrations were measured by UV spectroscopy at 280 nm using a Nanodrop2000 spectrometer (Thermo Scientific).

Kinetic Binding Analysis by Surface Plasmon Resonance

Surface plasmon resonance experiments were performed with a CM5 sensor chip, at 25°C on a Biacore T100 instrument (GE Healthcare). YKL40 was captured at a low density (2,000–4,000 response units) by direct amine-based coupling. The ethanolamine-blocked surface acted as a reference for the CM5 sensor chip. Dose-response experiments were

performed as 3-fold serial dilutions of IL-13R α 2-ECD in running buffer (10 mM HEPES pH 7.4, 150 mM NaCl). The sensor chip was regenerated with 10 mM NaOAc pH 4.0 and 250 mM NaCl. IL-13R α 2/YKL40 binding kinetics were measured during 180 s association and 780 s dissociation phases, with a flow rate of 45 μ l/min. Data were analyzed with the Biacore T100 evaluation software version 2.0 with a 1:1 Langmuir binding model. All experiments were performed in triplicate.

Deletion Mapping

Deletion mutants of Chi311/YKL-40 and IL-13R α 2 were generated using PCR amplification using primers listed in Tables S1 and S2. The yeast two-hybrid assay was used to evaluate the interactions of each deletion mutants of Chi311 and IL-13R α 2 with full-length IL-13R α 2 and Chi311, respectively.

Nuclear Protein Extraction

The nuclear and cytoplasmic protein fraction from cultured peritoneal macrophage was extracted using NE-PER Nuclear and Cytoplasmic Extraction kit (Thermo Scientific) as per the manufacturer's instructions.

Immunoblotting

Protein lysates were prepared from cultured cells or whole lungs using RIPA lysis buffers and subjected to immunoblotting using a modification of procedures described previously by our laboratory (Lee et al., 2009). Additional experimental details are included in the Extended Experimental Procedures.

RNA Interference Analysis

Human IL-13R α 2 siRNAs (Santa Cruz Biotechnology) were used to knock down IL-13R α 2 according to the protocols provided by the manufacturer. Cells were plated on six-well plates and transfected the next day with IL-13R α 2 or control siRNAs. The cells were harvested at the indicated time points and were subjected to real-time RT-PCR or western blot evaluations.

Cell Death Evaluations

Cell death and DNA injury were evaluated with TUNEL and FACS analyses of Annexin V and propidium iodide (PI) staining as previously described by our laboratory (Lee et al., 2009). The in vivo cell death response was evaluated after the mice (WT, Chi311^{-/-}, and IL-13R α 2^{-/-} mice) were exposed to 100% oxygen or room air for up to 3 days as described previously (Sohn et al., 2010). The in vitro evaluations were done under control conditions, after incubation with H₂O₂ (J. T. Baker Chemical; 500–800 μ g/ml) or after incubation with rFasL (Peprotech). IHAEo-transformed lung airway epithelial cells were obtained from Dr. D. Greunert (University of California, San Francisco). Peritoneal macrophages and proximal renal tubular epithelial cells were isolated from WT, Chi311^{-/-}, and/or IL-13R α 2^{-/-} mice in these in vitro cell death evaluations. AKT inhibitor (*Akt-In*) was purchased from EMD Millipore.

Lactate Dehydrogenase Test

Supernatant LDH was measured using the Cytotoxicity Detection Kit (LDH; Roche Applied Science) as per the manufacturer's instructions.

Bacterial Infection

In vivo and in vitro bacterial infection was done as previously described in our laboratory (Dela Cruz et al., 2012).

Quantification of Caspase-1 Bioactivity

Caspase-1 bioactivity was assessed using the Caspase 1 Colorimetric Assay Kit (Millipore) as per the manufacturer's instructions.

Assessment of Melanoma Lung Metastasis

Mouse melanocytes (B16-F10), established from C57BL/6/J mouse skin melanoma, were purchased from the American Type Culture Collection (CRL-6475). After culture to confluence in ordinary Dulbecco's modified Eagle's medium (DMEM), the cells were delivered to the mice by tail-vein injection (2×10^5 cells/mouse in 200 μ l of DMEM). Lung melanoma metastases were quantified by counting the number of colonies (which appear as black dots) on the pleural surface.

Quantification of TGF- β_1 and IL-1 β

The levels of BAL fluid Th2 cytokines and active and total TGF- β_1 (before and after acid activation, respectively) were measured by ELISA using commercial kits (R&D Systems) as directed by the manufacturer.

Statistical Analysis

Normally distributed data are expressed as mean \pm SEM and were assessed for significance by Student's t test or ANOVA as appropriate. Statistical significance was defined at a p value less than 0.05. All statistical analyses were performed with SPSS version 13.0 (SPSS). Statistical significance was defined at a level of $p < 0.05$.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

Aerts JM, van Breemen MJ, Bussink AP, Ghauharali K, Sprenger R, Boot RG, Groener JE, Hollak CE, Maas M, Smit S, et al. Biomarkers for lysosomal storage disorders: identification and application as exemplified by chitotriosidase in Gaucher disease. *Acta Paediatr Suppl.* 2008; 97:7–14. [PubMed: 18339181]

- Allahverdian S, Harada N, Singhera GK, Knight DA, Dorscheid DR. Secretion of IL-13 by airway epithelial cells enhances epithelial repair via HB-EGF. *Am J Respir Cell Mol Biol.* 2008; 38:153–160. [PubMed: 17717322]
- Areshkov PO, Avdieiev SS, Balynska OV, Leroith D, Kavsan VM. Two closely related human members of chitinase-like family, CHI3L1 and CHI3L2, activate ERK1/2 in 293 and U373 cells but have the different influence on cell proliferation. *Int J Biol Sci.* 2012; 8:39–48. [PubMed: 22211103]
- Chen W, Tabata Y, Gibson AM, Daines MO, Warriar MR, Wills-Karp M, Hershey GK. Matrix metalloproteinase 8 contributes to solubilization of IL-13 receptor alpha2 in vivo. *J Allergy Clin Immunol.* 2008; 122:625–632. [PubMed: 18694590]
- Chen W, Sivaprasad U, Tabata Y, Gibson AM, Stier MT, Finkelman FD, Hershey GK. IL-13R alpha 2 membrane and soluble isoforms differ in humans and mice. *J Immunol.* 2009; 183:7870–7876. [PubMed: 20007572]
- Chen CC, Llado V, Eurich K, Tran HT, Mizoguchi E. Carbohydrate-binding motif in chitinase 3-like 1 (CHI3L1/YKL-40) specifically activates Akt signaling pathway in colonic epithelial cells. *Clin Immunol.* 2011a; 140:268–275. [PubMed: 21546314]
- Chen CC, Pekow J, Llado V, Kanneganti M, Lau CW, Mizoguchi A, Mino-Kenudson M, Bissonnette M, Mizoguchi E. Chitinase 3-like-1 expression in colonic epithelial cells as a potentially novel marker for colitis-associated neoplasia. *Am J Pathol.* 2011b; 179:1494–1503. [PubMed: 21763261]
- Chiaromonte MG, Mentink-Kane M, Jacobson BA, Cheever AW, Whitters MJ, Goad ME, Wong A, Collins M, Donaldson DD, Grusby MJ, Wynn TA. Regulation and function of the interleukin 13 receptor alpha 2 during a T helper cell type 2-dominant immune response. *J Exp Med.* 2003; 197:687–701. [PubMed: 12642601]
- Cho SJ, Kang MJ, Homer RJ, Kang HR, Zhang X, Lee PJ, Elias JA, Lee CG. Role of early growth response-1 (Egr-1) in interleukin-13-induced inflammation and remodeling. *J Biol Chem.* 2006; 281:8161–8168. [PubMed: 16439363]
- Coffman FD. Chitinase 3-Like-1 (CHI3L1): a putative disease marker at the interface of proteomics and glycomics. *Crit Rev Clin Lab Sci.* 2008; 45:531–562. [PubMed: 19003601]
- Daines MO, Tabata Y, Walker BA, Chen W, Warriar MR, Basu S, Hershey GK. Level of expression of IL-13R alpha 2 impacts receptor distribution and IL-13 signaling. *J Immunol.* 2006; 176:7495–7501. [PubMed: 16751396]
- Dela Cruz CS, Liu W, He CH, Jacoby A, Gornitzky A, Ma B, Flavell R, Lee CG, Elias JA. Chitinase 3-like-1 promotes *Streptococcus pneumoniae* killing and augments host tolerance to lung antibacterial responses. *Cell Host Microbe.* 2012; 12:34–46. [PubMed: 22817986]
- Eurich K, Segawa M, Toei-Shimizu S, Mizoguchi E. Potential role of chitinase 3-like-1 in inflammation-associated carcinogenic changes of epithelial cells. *World J Gastroenterol.* 2009; 15:5249–5259. [PubMed: 19908331]
- Faibish M, Francescone R, Bentley B, Yan W, Shao R. A YKL-40-neutralizing antibody blocks tumor angiogenesis and progression: a potential therapeutic agent in cancers. *Mol Cancer Ther.* 2011; 10:742–751. [PubMed: 21357475]
- Fichtner-Feigl S, Strober W, Kawakami K, Puri RK, Kitani A. IL-13 signaling through the IL-13alpha2 receptor is involved in induction of TGF-beta1 production and fibrosis. *Nat Med.* 2006; 12:99–106. [PubMed: 16327802]
- Fichtner-Feigl S, Fuss IJ, Young CA, Watanabe T, Geissler EK, Schlitt HJ, Kitani A, Strober W. Induction of IL-13 triggers TGF-beta1-dependent tissue fibrosis in chronic 2,4,6-trinitrobenzene sulfonic acid colitis. *J Immunol.* 2007; 178:5859–5870. [PubMed: 17442970]
- Fichtner-Feigl S, Strober W, Geissler EK, Schlitt HJ. Cytokines mediating the induction of chronic colitis and colitis-associated fibrosis. *Mucosal Immunol.* 2008a; 1(Suppl 1):S24–S27. [PubMed: 19079223]
- Fichtner-Feigl S, Terabe M, Kitani A, Young CA, Fuss I, Geissler EK, Schlitt HJ, Berzofsky JA, Strober W. Restoration of tumor immunosurveillance via targeting of interleukin-13 receptor-alpha 2. *Cancer Res.* 2008b; 68:3467–3475. [PubMed: 18451175]
- Funkhouser JD, Aronson NN Jr. Chitinase family GH18: evolutionary insights from the genomic history of a diverse protein family. *BMC Evol Biol.* 2007; 7:96. [PubMed: 17594485]

- Goel S, Hidalgo M, Perez-Soler R. EGFR inhibitor-mediated apoptosis in solid tumors. *J Exp Ther Oncol*. 2007; 6:305–320. [PubMed: 18038764]
- Kawada M, Seno H, Kanda K, Nakanishi Y, Akitake R, Komekado H, Kawada K, Sakai Y, Mizoguchi E, Chiba T. Chitinase 3-like 1 promotes macrophage recruitment and angiogenesis in colorectal cancer. *Oncogene*. 2012; 31:3111–3123. [PubMed: 22056877]
- Kim MN, Lee KE, Hong JY, Heo WI, Kim KW, Kim KE, Sohn MH. Involvement of the MAPK and PI3K pathways in chitinase 3-like 1-regulated hyperoxia-induced airway epithelial cell death. *Biochem Biophys Res Commun*. 2012; 421:790–796. [PubMed: 22554524]
- Kioi M, Seetharam S, Puri RK. N-linked glycosylation of IL-13R alpha2 is essential for optimal IL-13 inhibitory activity. *FASEB J*. 2006; 20:2378–2380. [PubMed: 17023392]
- Konstantinidis AK, Puddicombe SM, Mochizuki A, Sheth PD, Yang IA, Yoshisue H, Wilson SJ, Davies DE, Holgate ST, Holloway JW. Cellular localization of interleukin 13 receptor alpha2 in human primary bronchial epithelial cells and fibroblasts. *J Investig Allergol Clin Immunol*. 2008; 18:174–180.
- Lee PJ, Zhang X, Shan P, Ma B, Lee CG, Homer RJ, Zhu Z, Rincon M, Mossman BT, Elias JA. ERK1/2 mitogen-activated protein kinase selectively mediates IL-13-induced lung inflammation and remodeling in vivo. *J Clin Invest*. 2006; 116:163–173. [PubMed: 16374521]
- Lee CG, Hartl D, Lee GR, Koller B, Matsuura H, Da Silva CA, Sohn MH, Cohn L, Homer RJ, Kozhich AA, et al. Role of breast regression protein 39 (BRP-39)/chitinase 3-like-1 in Th2 and IL-13-induced tissue responses and apoptosis. *J Exp Med*. 2009; 206:1149–1166. [PubMed: 19414556]
- Lee CG, Elias JA. Role of breast regression protein-39/YKL-40 in asthma and allergic responses. *Allergy Asthma Immunol Res*. 2010; 2:20–27. [PubMed: 20224674]
- Lee CG, Da Silva CA, Dela Cruz CS, Ahangari F, Ma B, Kang MJ, He CH, Takyar S, Elias JA. Role of chitin and chitinase/chitinase-like proteins in inflammation, tissue remodeling, and injury. *Annu Rev Physiol*. 2011; 73:479–501. [PubMed: 21054166]
- Lupardus PJ, Birnbaum ME, Garcia KC. Molecular basis for shared cytokine recognition revealed in the structure of an unusually high affinity complex between IL-13 and IL-13Ralpha2. *Structure*. 2010; 18:332–342. [PubMed: 20223216]
- Moriya C, Jinnin M, Yamane K, Maruo K, Muchemwa FC, Igata T, Makino T, Fukushima S, Ihn H. Expression of matrix metalloproteinase-13 is controlled by IL-13 via PI3K/Akt3 and PKC-δ in normal human dermal fibroblasts. *J Invest Dermatol*. 2011; 131:655–661. [PubMed: 21191416]
- Ooi AT, Ram S, Kuo A, Gilbert JL, Yan W, Pellegrini M, Nickerson DW, Chatila TA, Gomperts BN. Identification of an interleukin 13-induced epigenetic signature in allergic airway inflammation. *Am J Transl Res*. 2012; 4:219–228. [PubMed: 22611474]
- Rabinovich GA, Croci DO. Regulatory circuits mediated by lectin-glycan interactions in autoimmunity and cancer. *Immunity*. 2012; 36:322–335. [PubMed: 22444630]
- Schmidt H, Johansen JS, Gehl J, Geertsen PF, Fode K, von der Maase H. Elevated serum level of YKL-40 is an independent prognostic factor for poor survival in patients with metastatic melanoma. *Cancer*. 2006; 106:1130–1139. [PubMed: 16456816]
- Shao R, Hamel K, Petersen L, Cao QJ, Arenas RB, Bigelow C, Bentley B, Yan W. YKL-40, a secreted glycoprotein, promotes tumor angiogenesis. *Oncogene*. 2009; 28:4456–4468. [PubMed: 19767768]
- Sohn MH, Kang MJ, Matsuura H, Bhandari V, Chen NY, Lee CG, Elias JA. The chitinase-like proteins breast regression protein-39 and YKL-40 regulate hyperoxia-induced acute lung injury. *Am J Respir Crit Care Med*. 2010; 182:918–928. [PubMed: 20558631]
- Strober W, Kitani A, Fichtner-Feigl S, Fuss IJ. The signaling function of the IL-13Ralpha2 receptor in the development of gastrointestinal fibrosis and cancer surveillance. *Curr Mol Med*. 2009; 9:740–750. [PubMed: 19689301]
- Sulak O, Lameignere E, Wimmerova M, Imberty A. Specificity and affinity studies in lectin/carbohydrate interactions. *Carbohydr Chem*. 2009; 35:356–371.
- Wang ML, Keilbaugh SA, Cash-Mason T, He XC, Li L, Wu GD. Immune-mediated signaling in intestinal goblet cells via PI3-kinase-and AKT-dependent pathways. *Am J Physiol Gastrointest Liver Physiol*. 2008; 295:G1122–G1130. [PubMed: 18832447]

- Wood N, Whitters MJ, Jacobson BA, Witek J, Sypek JP, Kasaian MT, Eppihimer MJ, Unger M, Tanaka T, Goldman SJ, et al. Enhanced interleukin (IL)-13 responses in mice lacking IL-13 receptor alpha 2. *J Exp Med*. 2003; 197:703–709. [PubMed: 12642602]
- Yang JS, Allahverdian S, Singhera GK, MacRedmond RE, Dorscheid DR. IL-13R α 2/AP-1 complex signalling mediates airway epithelial repair without effects on remodeling pathways. *Allergy Asthma Clin Immunol*. 2010; 6(Suppl 3):27. [PubMed: 20846390]
- Yang JSY, Wadsworth SJ, Singhera GK, Dorscheid D. The regulation of IL-13R α 1 and IL-13R α 2 expression and distribution in airway epithelial repair. *Am J Respir Crit Care Med*. 2011; 183:A2812.
- Zhu Z, Homer RJ, Wang Z, Chen Q, Geba GP, Wang J, Zhang Y, Elias JA. Pulmonary expression of interleukin-13 causes inflammation, mucus hypersecretion, subepithelial fibrosis, physiologic abnormalities, and eotaxin production. *J Clin Invest*. 1999; 103:779–788. [PubMed: 10079098]

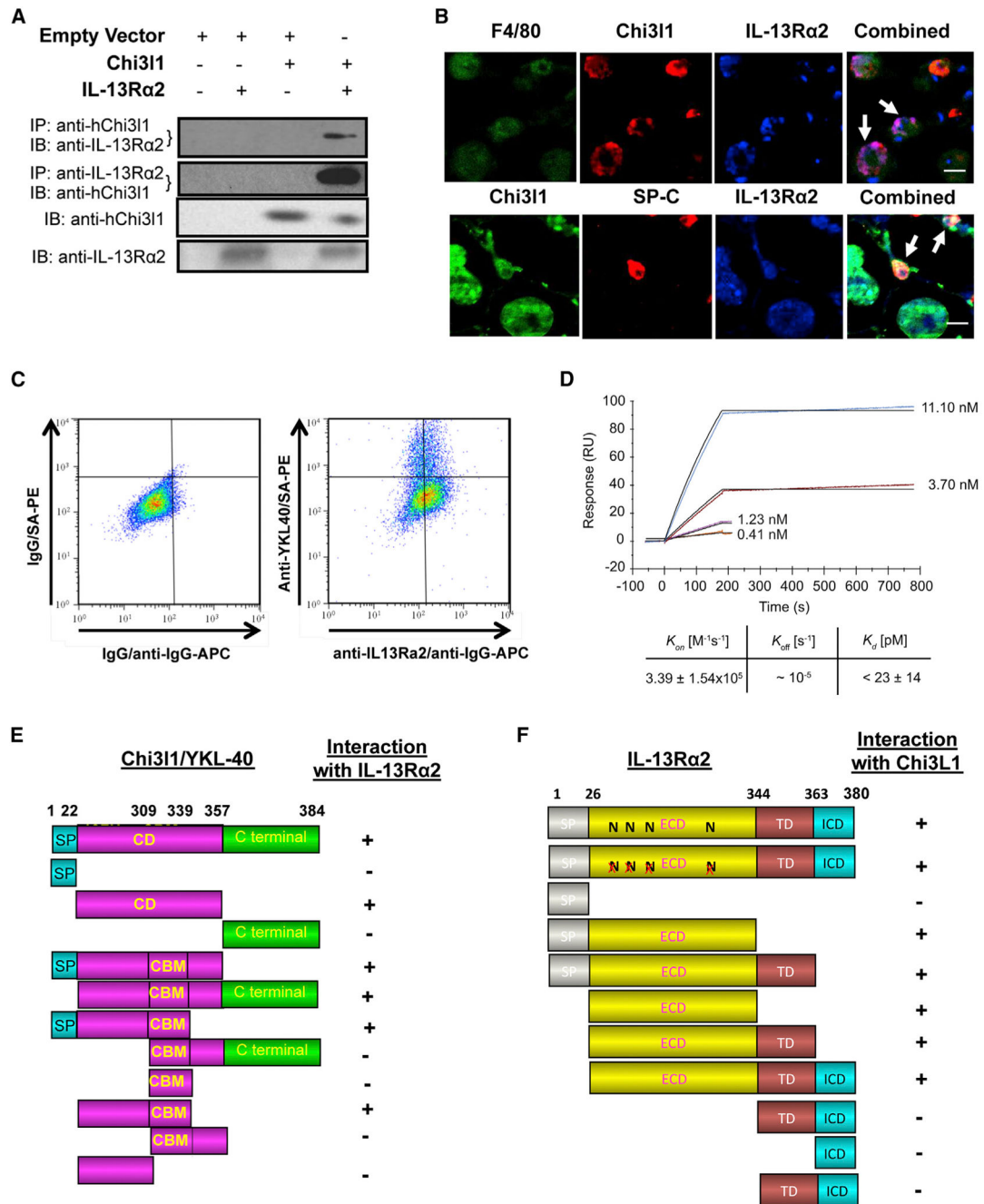


Figure 1. Binding and Localization of Chi311/YKL-40 and IL-13R α 2

(A) A549 cells were transfected with Chi311/YKL-40 (Chi311) and/or human IL-13R α 2 (IL-13R α 2), lysates were prepared and immunoprecipitated (IP) with either anti-Chi311 or anti-IL-13R α 2, and the precipitates were evaluated using immunoblot (IB) analysis as noted. (B) Triple-label IHC to detect the colocalization of IL-13R α 2 and BRP-39 in the macrophages (upper panels) and type 2 alveolar epithelial cells (lower panels) in lungs from IL-13 Tg mice using antibodies to BRP-39, IL-13R α 2, and cell-specific markers of

macrophages (anti-F4/80) and type 2 epithelial cells (anti-SP-C). Arrows highlight some of the colocalized cells.

(C) Cell surface colocalization of Chi311/YKL-40 (Chi311) and IL-13R α 2 (IL-13R α 2). THP-1 cells were incubated in the presence or absence of anti-YKL-40-biotin antibody and anti-iL-13R α 2 immunoglobulin G (IgG) antibody without permeabilization. They were then washed and stained with streptavidin (SA)-PE and anti-igG-APC and subjected to flow cytometric analysis.

(D) Measurement of the affinity and kinetics of IL-13R α 2 binding to Chi311/YKL-40 by surface plasmon resonance (SPR). Chi311/YKL-40 was immobilized and IL-13R α 2 was in the mobile phase.

(E) Yeast two-hybrid characterization of the structures in hChi31 that bind to IL-13R α 2. The 18 GH catalytic domain (CD), chitin binding motif (CBM), signal peptide (SP), and C-terminal fragment are illustrated.

(F) Yeast two-hybrid characterization of the structures in IL-13R α 2 that bind to hChi31. The extracellular domain (ECD), transmembrane domain (TD), intracellular domain (ICD), signal peptide (SP), and sites of N-glycosylation (N) are illustrated.

Each panel is representative of a minimum of three evaluations. Scale bars in (B) represent 10 μ m. See also Figure S1.

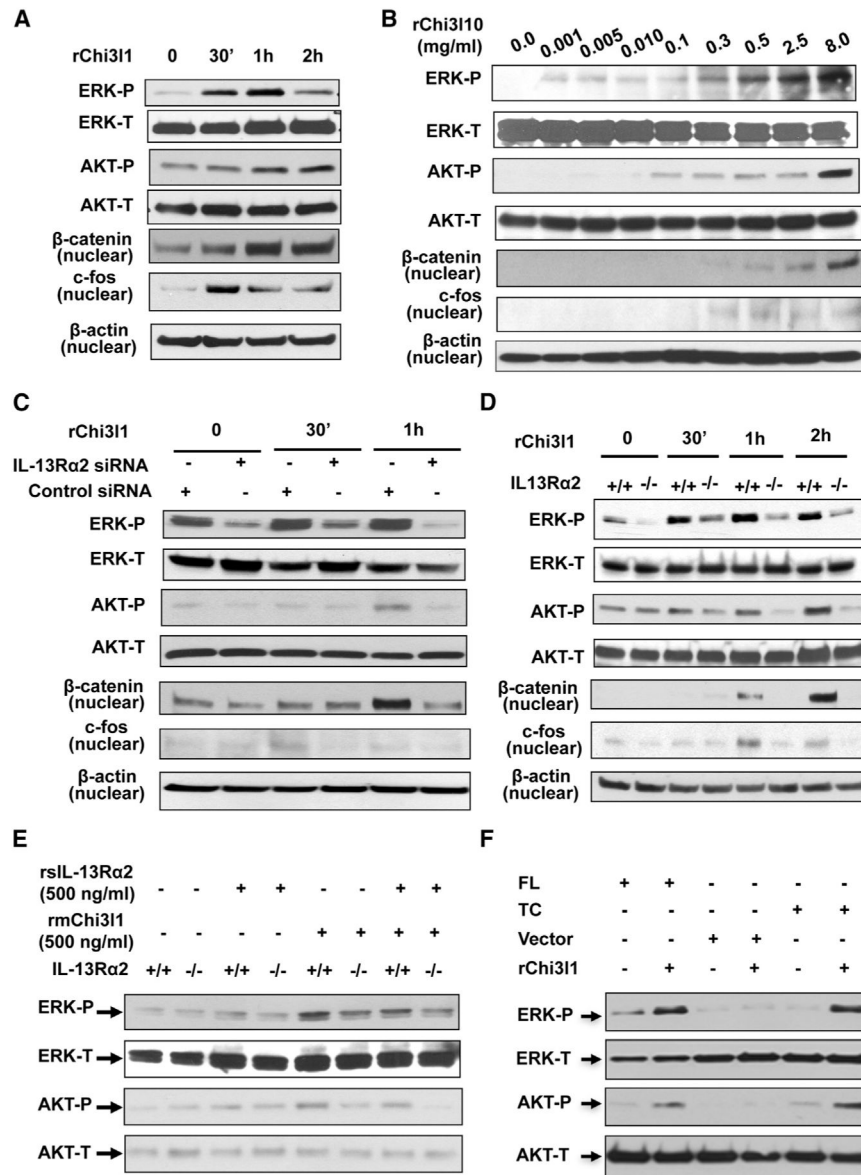


Figure 2. Chi311 and IL-13Rα2 Regulation of Macrophage Signaling

(A and B) THP-1 cells were incubated with recombinant Chi311/YKL-40 (rChi311) for the noted periods of time at the noted doses. Western blot evaluations were used to evaluate ERK1/2 phosphorylation (ERK-P), total ERK 1/2 (ERK-T), AKT phosphorylation (AKT-P), total AKT (AKT-T), β-catenin nuclear translocation, and nuclear *c-fos* accumulation.

(C and D) The role(s) of IL-13Rα2 in these responses was assessed by comparing these signaling events in THP-1 cells treated with IL-13Rα2 siRNA (siRNA⁺) or scrambled controls (siRNA⁻) (C) and peritoneal macrophages from wild-type (+/+) and IL-13Rα2 null (-/-) mice (D). Each panel is representative of a minimum of three evaluations.

(E) The effects of recombinant soluble IL-13Rα2 (rsIL-13Rα2) on Chi311-stimulated signaling were also assessed. In these experiments, peritoneal macrophages from WT and

IL-13R α 2 null mice were treated with PBS or rsIL-13R α 2 and rChi311 as indicated and ERK and AKT activation was evaluated by western blot analysis.

(F) Peritoneal macrophages from IL-13R α 2 null ($-/-$) mice was transfected with full-length (FL) IL-13R α 2, a truncated construct (TC) of IL-13R α 2 that lacked its intracellular domain, or an empty vector. After incubation of the cells with rChi311 (500 ng/ml) as indicated, cell lysates were prepared and ERK and AKT activation was evaluated by western blot analysis. See also Figure S2.

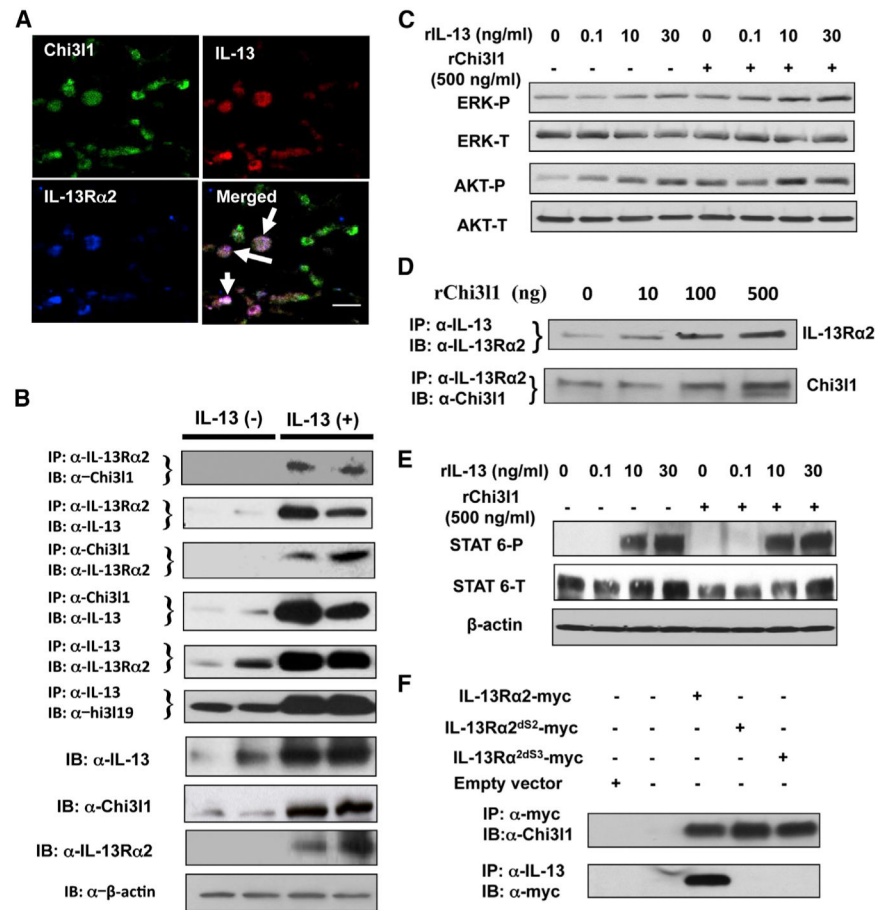


Figure 3. Interactions of IL-13, IL-13R α 2, and Chi311/YKL-40/BRP-39

(A) Triple-label IHC was used to detect the colocalization of IL-13, IL-13R α 2, and Chi311/BRP-39 in lungs from IL-13 Tg mice using antibodies to Chi311/BRP-39, IL-13R α 2, and IL-13. Arrows highlight some of the colocalized cells.

(B) Lung lysates were prepared from WT and IL-13 transgenic mice and immunoprecipitated (IP) with anti-Chi311, anti-iL-13R α 2, or anti-iL-13, and the precipitates were evaluated using immunoblot (IB) analysis as noted.

(C) THP-1 cells were incubated with recombinant (r) IL-13 or Chi311/YKL-40 (rChi311) alone and in combination as noted. Western blot evaluations were used to evaluate ERK1/2 phosphorylation, total ERK1/2, AKT phosphorylation, and total AKT.

(D) Peritoneal macrophages from Chi311^{-/-} mice were incubated overnight with rIL-13 (10 ng/ml), cell lysates were prepared, rChi311 was added at the noted doses, and immunoprecipitation and immunoblot analysis was undertaken with anti-iL-13 or anti-iL-13R α 2 antibodies as noted.

(E) THP-1 cells were incubated with rIL-13 and rChi311 as indicated and western blot evaluations were used to evaluate STAT6 phosphorylation (STAT6-P) and total STAT 6 (STAT6-T).

(F) Peritoneal macrophages were isolated from IL-13R α 2^{-/-} mice and transfected with empty vector, full-length IL-13R α 2 (IL-13R α 2-myc), or deletion mutants lacking IL-13

binding site 2 (IL-13R α 2^{ds2}-myc) or site 3 (IL-13R α 2^{ds3}-myc). Cell lysates were prepared, incubated with rChi311 (500 ng) and rIL-13 (10 ng) overnight, and evaluated using IP and IB with anti-myc, anti-iL-13, or anti-Chi311 as noted.

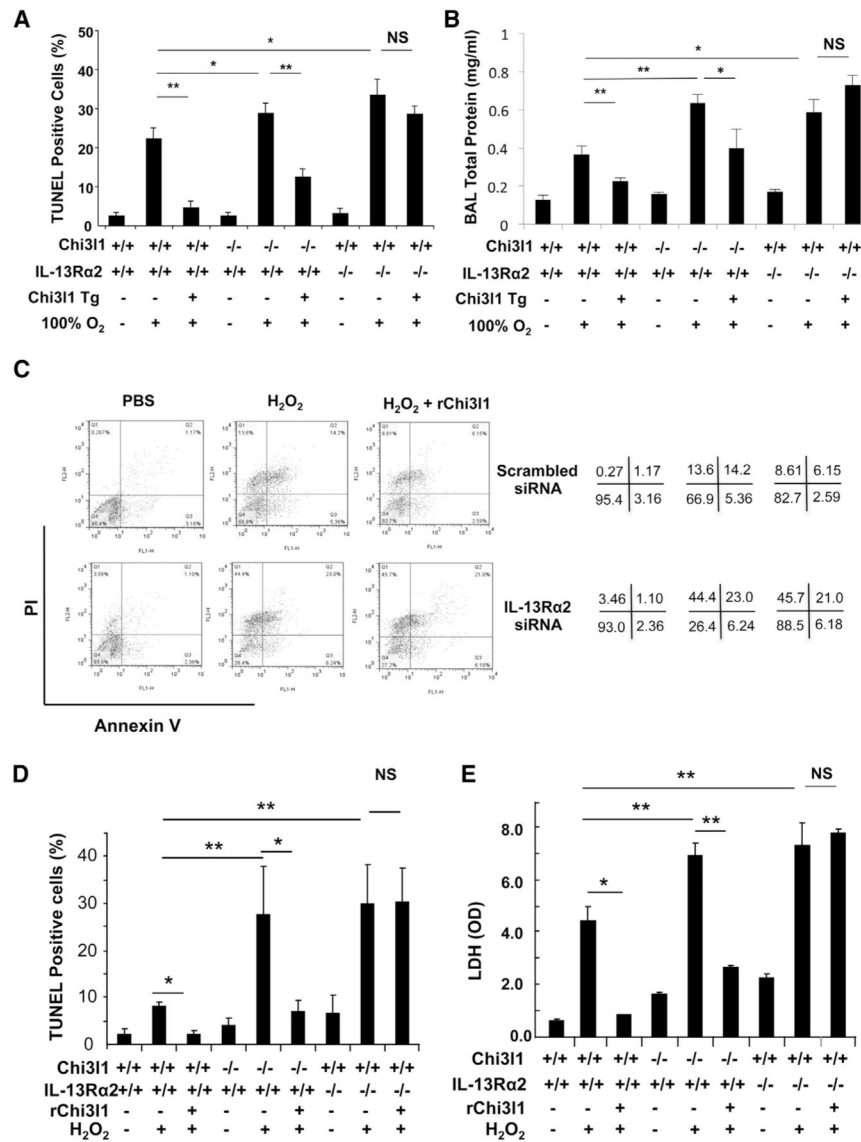


Figure 4. Chi311 and IL-13Ra2 Regulation of Cell Death and Acute Oxidant Injury
 WT (+/+), Chi311/BRP-39 null (-/-), IL-13Ra2 null (-/-), Chi311/YKL-40 Tg (+), Chi311/YKL-40 Tg(+)/BRP-39(-/-), and Chi311/YKL-40 Tg(+)/IL-13Ra2(-/-) mice were exposed to 100% O₂ or room air (100% O₂ -) for 48 hr.
 (A) TUNEL staining of lung sections from those mice.
 (B) BAL fluid total protein.
 (C) Airway epithelial cells (1HAEo) were exposed for 6 hr to H₂O₂ (800 μM). Cells were used that had been treated with IL-13Ra2-specific siRNA or scrambled controls and incubated in the presence and absence of recombinant(r) Chi311. Annexin V and propidium iodide staining was evaluated by FACS analysis.
 (D and E) Peritoneal macrophages from WT (+/+), Chi311 null (-/-), and IL-13Ra2 null (-/-) mice were incubated with H₂O₂ (H₂O₂ +) or its vehicle control (H₂O₂ -) in the presence

and absence of rChi311/BRP-39, and TUNEL staining (D) and LDH release (E) were evaluated.

Values in (A), (B), (D), and (E) represent the means \pm SEM of evaluations of a minimum of four mice. (C) is representative of at least three similar evaluations. * $p < 0.05$, ** $p < 0.01$. NS, not significant. See also Figure S4.

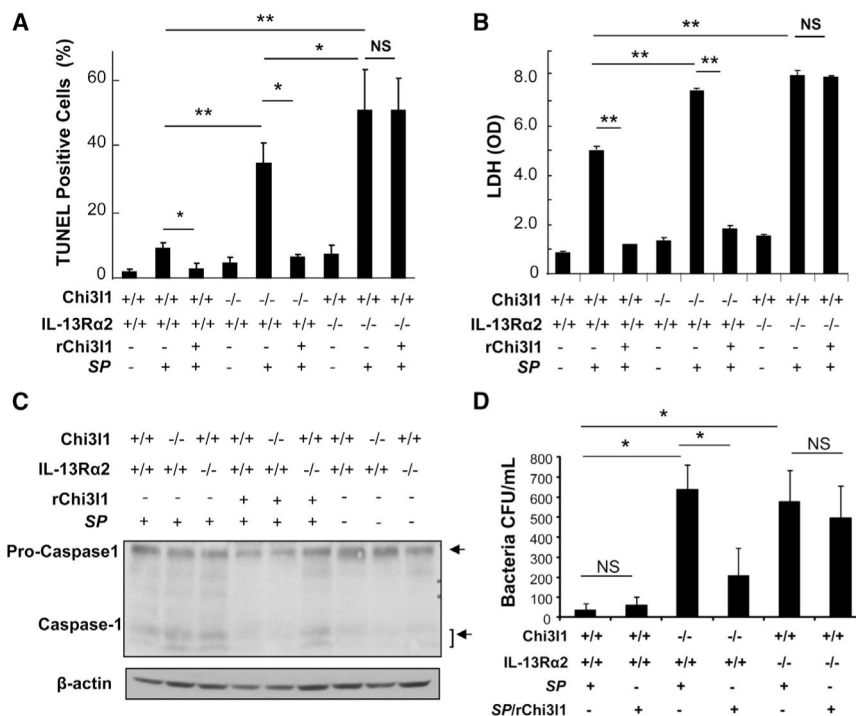


Figure 5. Chi311 and IL-13Rα2 Regulation of SP-Induced Responses

(A and B) Peritoneal macrophages from WT (+/+), Chi311 null (-/-), and IL-13Rα2 null (-/-) mice were incubated with SP (SP+) or its vehicle control (SP-) in the presence and absence of rChi311/BRP-39, and TUNEL staining (A) and LDH release (B) were assessed.

(C) Western blotting was also used to evaluate cell lysate caspase-1 activation.

(D) Peritoneal macrophages from WT (+/+), Chi311 null (-/-), and IL-13Rα2 null (-/-) mice were also incubated with SP (SP+) or SP preincubated for 60 min without antibiotics with rChi311/BRP-39 at a 10:1 SP-to-cell ratio (SP/rChi311). They were then incubated with gentamicin to kill extracellular bacteria and the viable bacteria in the cell lysates were assessed 6 hr later.

Values in (A), (B), and (D) are the means ± SEM of triplicate measurements and are representative of a minimum of three similar evaluations; (C) is representative of three similar evaluations. *p < 0.05, **p < 0.01. NS, not significant.

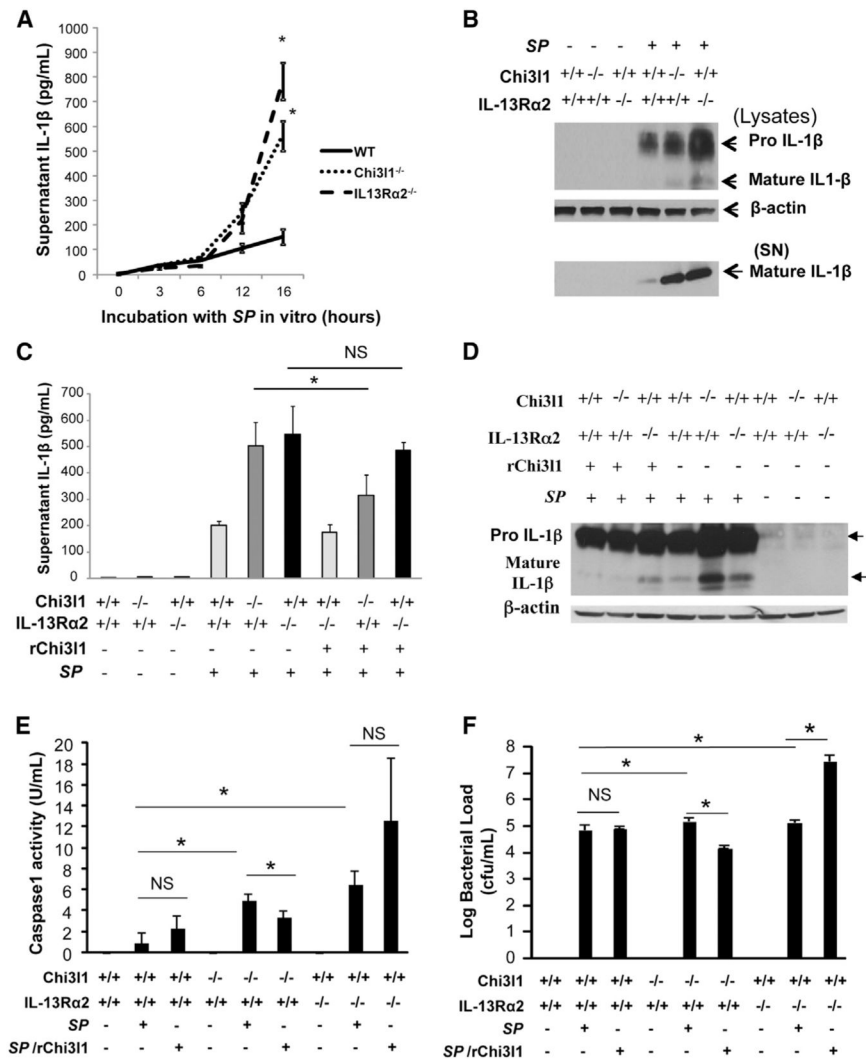


Figure 6. Chi311 and IL-13Rα2 Regulation of SP-Induced Inflammasome Activation

Peritoneal macrophages were obtained from WT mice, Chi311/BRP-39 null (-/-) mice, and IL-13Rα2 null (-/-) mice and incubated with SP.

(A) The kinetics of IL-1β production were evaluated by ELISA.

(B) IL-1β maturation and release into the cell supernatant (SN) was evaluated by western blotting.

(C–F) The ability of rmChi311/BRP-39 to modulate IL-1β production (C) and maturation (D) caspase-1 activity measured by ELISA (E) and bacterial load were also evaluated.

Values in (A), (C), (E), and (F) are the means ± SEM of triplicate measurements and are representative of a minimum of three similar evaluations. (B) and (D) are representative of three evaluations. *p < 0.05. NS, not significant.

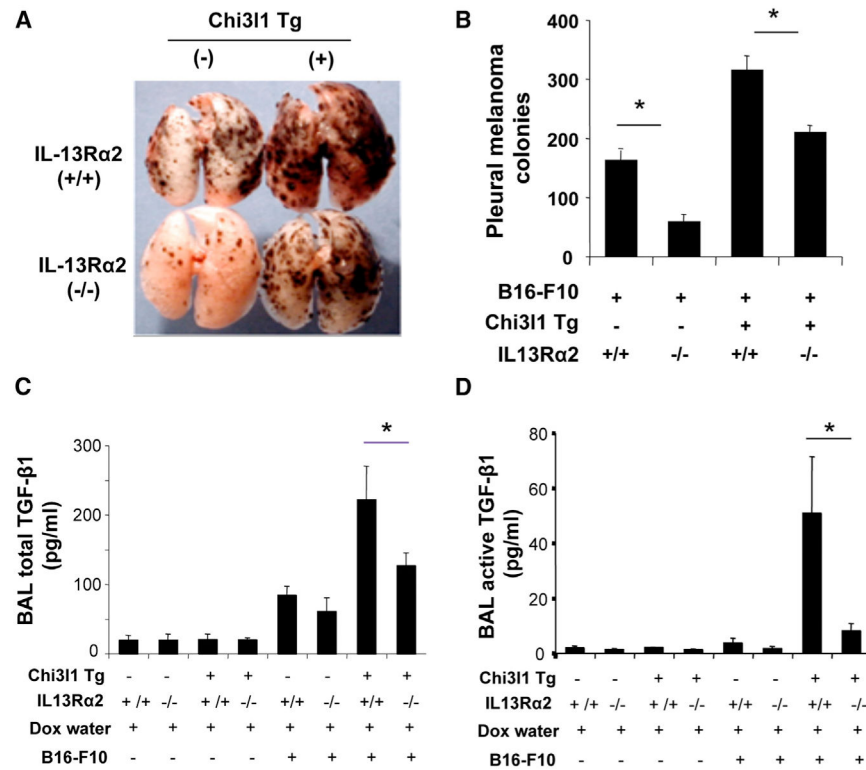


Figure 7. Chi311 and IL-13Rα2 in Melanoma Metastasis and TGF-β1 Production In Vivo WT mice, IL-13Rα2 null (-/-) mice, Chi311/YKL-40 Tg mice (Tg+), and Chi311/YKL-40 Tg/IL-13Rα2 null mice received B16-F10 melanoma cells by tail-vein injection.

(A) Fourteen days later, melanoma metastasis was visually assessed.

(B) Quantification of pleural melanoma colonies.

(C) ELISA evaluation of total BAL TGF-β1.

(D) ELISA evaluation of activated TGF-β1. (A) is representative of three similar evaluations.

Values in (B)–(D) are the means ± SEM of triplicate measurements and are representative of a minimum of three similar evaluations. * $p < 0.05$.