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Respiratory virus–induced EGFR activation suppresses IRF1-dependent interferon λ and antiviral defense in airway epithelium

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Viruses suppress host responses to increase infection, and understanding these mechanisms has provided insights into cellular signaling and led to novel therapies. Many viruses (e.g., Influenza virus, Rhinovirus [RV], Cytomegalovirus, Epstein–Barr virus, and Hepatitis C virus) activate epithelial epidermal growth factor receptor (EGFR), a tyrosine kinase receptor, but the role of EGFR in viral pathogenesis is not clear. Interferon (IFN) signaling is a critical innate antiviral host response and recent experiments have implicated IFN-λ, a type III IFN, as the most significant IFN for mucosal antiviral immune responses. Despite the importance of IFN-λ in epithelial antiviral responses, the role and mechanisms of epithelial IFN-λ signaling have not been fully elucidated. We report that respiratory virus–induced EGFR activation suppresses endogenous airway epithelial antiviral signaling. We found that Influenza virus– and RV–induced EGFR activation suppressed IFN regulatory factor (IRF) 1–induced IFN-λ production and increased viral infection. In addition, inhibition of EGFR during viral infection augmented IRF1 and IFN-λ, which resulted in decreased viral titers in vitro and in vivo. These findings describe a novel mechanism that viruses use to suppress endogenous antiviral defenses, and provide potential targets for future therapies.

Respiratory viral infections, which cause pneumonia and exacerbations of chronic lung diseases, are responsible for significant morbidity and mortality. Despite substantial disease burden, there are limited therapies for treating virus–induced pulmonary disease. Viruses induce inflammation, which impairs host responses. Upon infection of airway epithelial cells (AECs), the primary cell type for respiratory viral infection, viruses induce epithelial production of IL–8 (Choi and Jacoby, 1992; Subauste et al., 1995). Our research, and that of other investigators, has shown that virus–induced AEC IL–8 production requires epidermal growth factor receptor (EGFR) activation (Monick et al., 2005; Koff et al., 2008; Liu et al., 2008). Therefore, we investigated the effect of virus–induced EGFR activation on airway epithelial antiviral responses.

EGFR (ErbB1/HER1), a tyrosine kinase receptor present in epithelial cells, is activated in a ligand–dependent manner (Shao et al., 2003). In AECs, EGFR activation involves an integrated signaling pathway that includes NADPH oxidase (Nox) activation of a metalloproteinase (MP), which cleaves an EGFR pro–ligand that is released to bind to, and to activate EGFR (Shao and Nadel, 2005; Burgel and Nadel, 2008). Recently, viruses have been shown to activate EGFR via this signaling pathway in AECs (Koff et al., 2008; Zhu et al., 2009; Barbier et al., 2012).

IFN signaling is a critical innate antiviral host response. Recent experiments have suggested that IFN-λ, a recently discovered type III IFN, is the most significant IFN in AECs (Khaitov et al., 2009; Mordstein et al., 2010). Studies suggest that IFN-λ is the primary IFN that regulates mucosal responses to viral infection, whereas type 1 IFNs (e.g., IFN-α and –β) are essential for clearance of systemic infection (Jewell et al., 2009).

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Despite the importance of IFN-λ in epithelial antiviral responses, the kinetics of airway epithelial IFN-λ production has not been fully elucidated. For example, IFN regulatory factors (IRFs), critical for type I and II IFN signaling (Tamura et al., 2008), have not been analyzed in epithelial IFN-λ production. In addition, the potential for EGFR signaling to suppress IFN-λ has not been explored.

Influenza A virus (IAV) and Rhinovirus (RV) are ssRNA viruses that are significant pathogens that cause viral pneumonia and induce exacerbations of asthma and chronic obstructive pulmonary disease (Johnston, 2005). Recently, both viruses were shown to activate EGFR via Nox and MP-induced release of EGFR ligand (Liu et al., 2008; Zhu et al., 2009; Barbier et al., 2012). Both IAV and RV stimulate epithelial IFN-λ production, and IFN-λ was implicated in effective clearance of these viruses (Contoli et al., 2006; Jewell et al., 2010). Although the role of IRF in epithelial IFN-λ production has not been explored, RV was found to activate IRF1, IRF3, and IRF7 in AECs (Wang et al., 2009b; Zaheer and Proud, 2010).

Here, we examined the interaction between virus-induced EGFR signaling and IFN-λ production in AECs. IAV and RV activated EGFR, and EGFR activation suppressed IRF1-induced IFN-λ production and increased viral infection. In addition, inhibition of EGFR during viral infection augmented IRF1 and IFN-λ production, which resulted in decreased viral titers in vitro and in vivo.

RESULTS AND DISCUSSION
Role for EGFR in respiratory viral infection
To confirm a role for respiratory virus-induced EGFR activation in AECs, we measured total EGFR phosphorylation (EGFR-p) by ELISA after viral infection in an airway epithelial (BEAS-2b) cell line. IAV and RV stimulated EGFR-p, and the addition of a reactive oxygen species (ROS) scavenger (nPG) and an MP inhibitor (TAPI-1) decreased IAV- and RV-induced EGFR-p (Fig. 1A). These results confirmed that virus-induced EGFR activation involves ROS and MP cleavage of an EGFR ligand (Zhu et al., 2009; Barbier et al., 2012). Nox produce ROS and are upstream of EGFR activation (Shao and Nadel, 2005). We found that IAV, RV1b, and RV16 induced Nox in BEAS-2b cells (IAV 91.6 ± 11.5, RV1b 93.6 ± 9.2, and RV16 99.1 ± 10.9 vs. control 58.7 ± 9.4 nM NADP⁺; P < 0.001, n = 5), a result which implicates Nox as a shared epithelial signal in response to multiple respiratory viruses.

Epithelial inflammation augments viral infection, and we hypothesized that EGFR plays a role in respiratory viral infection. To assess the effect of EGFR inhibition on viral infection, IAV and RV1b, and RV16 induced Nox in BEAS-2b cells (IAV 91.6 ± 11.5, RV1b 93.6 ± 9.2, and RV16 99.1 ± 10.9 vs. control 58.7 ± 9.4 nM NADP⁺; P < 0.001, n = 5), a result which implicates Nox as a shared epithelial signal in response to multiple respiratory viruses.

Epithelial inflammation augments viral infection, and we hypothesized that EGFR plays a role in respiratory viral infection. To assess the effect of EGFR inhibition on viral infection, viral titers were quantified by plaque assay at 48 h. In a prophylaxis model (top), Gefitinib was given 16 h before viral infection and then continued daily, and in a therapeutic model (bottom), Gefitinib was given 1 h after viral infection and then continued daily (n = 7–9 mice/group repeated twice, mean ± SEM; **, P < 0.01 and ***, P < 0.001 vs. virus alone).
EGFR inhibition increases epithelial antiviral defense

To address the mechanism by which EGFR inhibition decreases respiratory viral infection, we initially investigated the role of EGFR in viral internalization. Although experiments using certain cancer cells have suggested a role for EGFR in IAV internalization (Eierhoff et al., 2010), we were not able to confirm this result in NHBE cells by qPCR measured at 30 min after infection (Ct values: 21.04 ± 0.11 [IAV] vs. 21.09 ± 0.14 [IAV plus Gefitinib]; n = 4 independent experiments) by flow cytometry (Fig. 2A), and in BEAS-2b cells by Western blot for IAV M1 protein (Fig. 2B) and plaque assay (Fig. 2C).

Therefore, we evaluated the effect of EGFR signaling on endogenous airway epithelial antiviral responses. IFNs play a critical role in innate and adaptive antiviral immunity. Recent studies have implicated IFN-α as the most significant IFN in mucosal responses to viral infection (Khaitov et al., 2009; Mordstein et al., 2010). We confirmed that virus-infected NHBE cells produce significantly more IFN-α than IFN-β or IFN-γ (unpublished data). To investigate the role of EGFR signaling on epithelial IFN-α, NHBE cells infected with IAV and RV16 were treated with a selective EGFR tyrosine kinase inhibitor, AG 1478. Both viruses induced IFN-α production, and the addition of AG 1478 augmented IFN-α production above the amount produced by virus alone (Fig. 2D). These results were confirmed with RV1b (unpublished data).
In addition, we found that Gefitinib-treated mice infected with IAV had increased IFN-α in bronchoalveolar lavage (BAL) fluid compared with IAV infection alone (Fig. 2 E), which was associated with less IAV infection (Fig. 1 D). EGFR activation is a ligand-dependent process, and we confirmed that blocking ligand-induced EGFR activation increased IAV-, RV1b-, and RV16-induced IFN-α production in vitro (unpublished data). These results implicated EGFR-p in virus-induced IFN-α production in vitro and in vivo.

Because EGFR inhibition elevated AEC IFN-α production, we examined the role of IFN-α in the antiviral effects of EGFR inhibition. Neutralizing Abs targeting IFN-α receptor (IFN-αR) and virus-induced IFN-α were used to inhibit IFN-α function, either by preventing IFN-α binding to its receptor or by inactivating secreted IFN-α. BEAS-2b cells were stimulated with IAV, with the addition of Gefitinib and IFN-α Abs, and viral infection was measured by plaque assay. The addition of Abs that suppressed IFN-α function abrogated the ability of Gefitinib to inhibit IAV and RV1b infection, implicating IFN-α in this process (Fig. 3 A). These results were confirmed with RV16 (unpublished data). Thus, airway epithelial IFN-α is required for EGFR inhibition to suppress respiratory viral infection.

Next, we examined the kinetics of AEC IFN-α production using synthetic dsRNA (poly I:C), an intermediate of ssRNA viral replication that is a common model of ssRNA viral infection. In BEAS-2b cells, dsRNA induced peak IFN-α mRNA expression at 4 h (Fig. 3 B), which was associated with an increase in protein production at 8 h, which continued to increase at 24 h (Fig. 3 C).

IFRs play a critical role in IFN production. RV stimulates IRF1 in AECs (Zaheer and Proud, 2010) and recently, IRF1 was shown to interact with the IFN-α promoter (Siegel et al., 2011), implicating IRF1 as a candidate for IFN-α induction. Consistently, we found increased IRF1 mRNA at 2 h (Fig. 3 D). Furthermore, transfection of BEAS-2b cells with IRF1 siRNA significantly inhibited IFN-α production in response to IAV, RV1b, and RV16 infection (Fig. 4 A), which implicates IRF1 in IFN-α production.

To examine the role of IRF1 in the antiviral effect of Gefitinib, BEAS-2b cells infected with IAV were treated with Gefitinib and IRF1 siRNA and compared, by plaque assay, with cells treated with Gefitinib and control siRNA. The addition of IRF1 siRNA abrogated EGFR inhibitor-induced IAV viral suppression (Fig. 4 B). These results were confirmed with RV1b and RV16 (unpublished data). In the IAV in vivo model, we found that Gefitinib-treated mice infected with IAV had increased IRF1 in the lung compared with vehicle-treated mice (Fig. 4 C). IRF3 and IRF7 are recognized to be critical for IFN α and β production (Tamura et al., 2008). dsRNA stimulation of BEAS-2b cells increased IRF3 and IRF7 mRNA expression at 12 h (IRF3) and 24 h (IRF7; Wang et al., 2009b), which is later than IFN-α mRNA

**Figure 3.** IFN-α is required for EGFR inhibitor-induced suppression of viral infection. (A) BEAS-2b cells were treated with IAV and RV1b alone, with 10 µM Gefitinib, and Gefitinib plus two neutralizing Abs to IFN-α receptor (columns 3 and 4), two neutralizing Abs to IFN-α (columns 6 and 7), and isotype-matched Abs (columns 5 and 8) for 24 h and viral titers of cell culture homogenates were assessed by plaque assay (n = 3 independent experiments, mean ± SEM; *, P < 0.05 vs. virus alone; #, P < 0.05 and ##, P < 0.01 vs. virus plus Gefitinib). (B) BEAS-2b cells were treated with serum-free medium alone (empty columns), or dsRNA (gray columns), and IFN-α mRNA was analyzed by quantitative RT-PCR (n = 3 independent experiments, mean ± SEM; **, P < 0.005 vs. serum-free medium). (C) BEAS-2b cells were treated with serum-free medium alone (empty columns), or dsRNA (gray columns), and secreted IFN-α was measured by ELISA at 24 h (n = 3 independent experiments; *, P < 0.01 and **, P < 0.005 vs. serum-free medium). (D) BEAS-2b cells were treated with serum-free medium alone (empty columns), or dsRNA (gray columns), and IRF1 mRNA was analyzed by quantitative RT-PCR (n = 3 independent experiments; *, P < 0.05 vs. serum-free medium).
and protein production. In addition, silencing IRF3 in BEAS-2b cells using siRNA showed no inhibition of dsRNA-induced IFN-λ production at 24 h (Fig. 4 B). Together, these results reveal a novel role for IRF1-dependent induction of IFN-λ in AECs, which are required for the antiviral effect of EGFR inhibition on IAV and RV infection.

**EGFR activation decreases epithelial antiviral defenses**

Because we found that EGFR inhibition was associated with increased virus–induced IRF1 and IFN-λ, we investigated the effect of EGFR activation on suppression of epithelial antiviral defenses. First, we found that the addition of EGFR ligand, decreased IAV-induced IRF1 transcriptional activity in BEAS-2b cells as measured by IRF1 luciferase (Fig. 5 A, left). Next, we showed that EGFR activation suppressed IAV-induced IRF1 protein production in BEAS-2b cells (Fig. 5 A, right). The addition of EGFR also suppressed IAV- and RV16-induced AEC production of IFN-λ (Fig. 5 B), and these results were confirmed with RV1b (not depicted). Finally, BEAS-2b cells were stimulated with EGF before viral infection, and virus was quantified by plaque assay after 24 h. We found that EGF increased IAV and RV16 titers significantly (Fig. 5 C), and these results were confirmed with RV1b (not depicted). These results showed that EGFR activation decreases airway epithelial IRF1 and IFN-λ, and increases respiratory viral infection.

In summary, here we have examined the interaction between EGFR signaling and IRF1-induced IFN-λ pathways in the regulation of viral infection. IAV and RV activated EGFR, and EGFR activation suppressed IRF1-induced IFN-λ production, which increased viral infection; inhibition of EGFR augmented IRF1 and IFN-λ, which resulted in decreased viral titers in vitro and in vivo. These findings show that EGFR and IRF1-induced IFN-λ pathways play different roles in respiratory viral infection. Although the signaling intermediates between IRF1 and EGFR remain to be elucidated, future experiments that investigate individual EGFR phosphorylation sites and downstream MAP kinase signaling will be informative. In conclusion, we have uncovered a novel mechanism that viruses use to suppress endogenous epithelial antiviral defenses.

**MATERIALS AND METHODS**

**Reagents.** EGFR tyrosine kinase inhibitor AG 1478, EGF, TAPI-1, a matrix MP inhibitor with selectivity for TNF converting enzyme (TACE), neutralizing anti-EGFR (Ab-5) mAb, and an isotype-matched Ab were obtained from EMD Millipore. IFN-λ polyclonal Abs, IFN-λ receptor (IL-28R/IL-10Rβ)
EGFR inhibition enhances IFN-α in viral infection

**Cell culture.** J. Falty (San Francisco, CA) provided bronchial epithelial (BEAS-2B) cells. P. Haydens (MatTek Corporation, Ashland, MA) and W. Frickhauser (San Francisco, CA) provided primary NHBE cells from healthy donors. Cells were seeded at 2–4 × 10^4 cells/ml and grown in bronchial epithelial growth medium (BEGM; Lonza) supplemented with growth factors, 100 U/ml penicillin, and 100 μg/ml streptomycin. 16 h before viral infection, EGF and hydrocortisone were removed from cell culture medium. After preliminary experiments were completed with different IAV and RV concentrations at 24 h to determine IFN-α production, subsequent experiments used IAV at a multiplicity of infection (MOI) of 0.5, RV1B at MOI of 1, and RV16 at MOI of 2 in BEAS-2B cells. To maximize viral infection, NHBE cell cultures were infected at 80–90% confluence at MOI = 10, as previously described (Contoli et al., 2006). Chemical inhibitors were added to cell cultures at the time of viral infection, unless stated otherwise. AG 1478 and Gefitinib were used at 10 μM because experiments have shown this concentration to inhibit virus-induced inflammation (Liu et al., 2008; Hewson et al., 2010; Langhammer et al., 2011). We confirmed that AG 1478 and 10 μM Gefitinib inhibited IAV- and RV-induced IL-8 production in AECs, and neither inhibitor induced cell toxicity as measured by LDH production. In addition, higher concentrations of these inhibitors may be active against related HER family members (e.g., erbB2 or erbB4), or other tyrosine kinases (e.g., C-fit). Therefore, we used EGFR siRNA to confirm selectivity for EGFR (Fig. 1 B).

For experiments using the EGFR ligand EGF, we used 10 ng/ml because prior investigators have shown that this concentration increased the effect of RV on AECs (Subauste and Proud, 2001).

Cell cultures were incubated at 37°C and cell culture homogenates and supernatants were harvested at the indicated time points. Total EGFR, phosphorylated at Tyr1068, was measured at 10 min by ELISA (R&D Systems) and Nox activity (Cell Technology, Inc.) in cell lysates was measured at 2 h. Virus in cell culture homogenates was measured at 24 h by plaque assay using MDCK cells (for IAV) and HeLa cells (for RV1B and RV16), and by flow cytometry and Western blotting (in BEAS-2B and NHBE cells) at 2 and 30 min using anti-Influenza A hemagglutinin (HA), anti-nucleoprotein (NP; Santa Cruz Biotechnology, Inc.), and anti-M1 (Abd Sentex) mAbs. IFN-α (R&D Systems), and -α (eBioscience Inc.) were measured in cell culture supernatants at 24 h by ELISA. BEAS-2B cells cultured in serum-free medium, treated with chemical inhibitors, or siRNA were assessed for cytotoxicity using an LDH assay (Roche) and no significant differences were found.

IFN-α and IRF1 mRNA expression was assessed by quantitative RT-PCR, as previously described (Wang et al., 2009a; Gencheva et al., 2010). IAV was analysed by quantitative RT-PCR in BEAS-2B and NHBE cells as previously described (Crowe et al., 2009). Total RNA was extracted using RNeasy kit (QIAGEN). RT-PCR was evaluated with Applied Biosystems Model 7900 sequence detector. The following primers were used: IFN-α (IL-29; forward), 5'-GGGAACCTGTGTCTGAGAACGT-3'; IFN-α (IL-29; reverse), 5'-GAGTAGGGCTCAGCGCATAAATA-3'; IFN-λ (IL-29 reverse), 5'-AGGATTGGCTCTAGCCGATAATA-3'; IRF1 (forward), 5'-CTCTGAACTCACAACAGTAGGG-3'; IRF1 (reverse), 5'-CTGCTGTCAGCCCAATATCCC-3; β-actin (Forward), 5'-GAGTAGGGCTCAGCGCATAAATA-3'; β-actin (Reverse), 5'-CTCTGAACTCACAACAGTAGGG-3'; and IAV (reverse), 5'-CAAGCCGCCTACGGAAGTCG-3', and IAV (forward), 5'-CAAGCCGCCTACGGAAGTCG-3'.

**Viruses.** Purified Influenza A/PR/8/34 (H1N1; Advanced Biotechnologies, Inc.) N-propyl gallete (nPG) was purchased from Sigma-Aldrich. Gefitinib was purchased from Tocris Bioscience. The synthetic dsRNA poly I:C was purchased from InvivoGen. Abs, and isotype-matched Abs were purchased from Santa Cruz Biotechnology, Inc. N-propyl gallete (nPG) was purchased from Sigma-Aldrich. Gefitinib was purchased from Tocris Bioscience. The synthetic dsRNA poly I:C was purchased from InvivoGen.

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Results are presented as both individual data points (control) and IRF1 siRNA (duplex UCCCAAGACGUGGAAGGCCAA-Burgel, P.R., and J.A. Nadel. 2008. Epidermal growth factor receptor-mediated growth factor receptor by respiratory syncytial virus results in increased virus spreading by the anti-tumor drug Gefitinib (Iressa).

Influenza A virus endocytic routes reveal macropinocytosis as an alternative entry pathway. PLoS Pathog. 7:e1001329. http://dx.doi.org/10.1371/journal.ppat.1001329


