A Novel Anti-Inflammatory and Pro-Resolving Role for Resolvin D1 in Acute Cigarette Smoke-Induced Lung Inflammation

Hsi-Min Hsiao  
*University of Rochester*

Ramil E. Sapinoro  
*St. John Fisher College, rsapinoro@sjfc.edu*

Thomas H. Thatcher  
*University of Rochester*

Amanda Croasdell  
*University of Rochester*

Elizabeth P. Levy  
*University of Rochester*

How has open access to Fisher Digital Publications benefited you?

Publication Information


Please note that the Publication Information provides general citation information and may not be appropriate for your discipline. To receive help in creating a citation based on your discipline, please visit http://libguides.sjfc.edu/citations.

This document is posted at https://fisherpub.sjfc.edu/pharmacy_facpub/376 and is brought to you for free and open access by Fisher Digital Publications at St. John Fisher College. For more information, please contact fisherpub@sjfc.edu.
A Novel Anti-Inflammatory and Pro-Resolving Role for Resolvin D1 in Acute Cigarette Smoke-Induced Lung Inflammation

Abstract

Introduction: Cigarette smoke is a profound pro-inflammatory stimulus that contributes to acute lung injuries and to chronic lung disease including COPD (emphysema and chronic bronchitis). Until recently, it was assumed that resolution of inflammation was a passive process that occurred once the inflammatory stimulus was removed. It is now recognized that resolution of inflammation is a bioactive process, mediated by specialized lipid mediators, and that normal homeostasis is maintained by a balance between pro-inflammatory and pro-resolving pathways. These novel small lipid mediators, including the resolvins, protectins and maresins, are bioactive products mainly derived from dietary omega-3 and omega-6 polyunsaturated fatty acids (PUFA). We hypothesize that resolvin D1 (RvD1) has potent anti-inflammatory and pro-resolving effects in a model of cigarette smoke-induced lung inflammation.

Methods: Primary human lung fibroblasts, small airway epithelial cells and blood monocytes were treated with IL-1β or cigarette smoke extract in combination with RvD1 in vitro, production of pro-inflammatory mediators was measured. Mice were exposed to dilute mainstream cigarette smoke and treated with RvD1 either concurrently with smoke or after smoking cessation. The effects on lung inflammation and lung macrophage populations were assessed.

Results: RvD1 suppressed production of pro-inflammatory mediators by primary human cells in a dose-dependent manner. Treatment of mice with RvD1 concurrently with cigarette smoke exposure significantly reduced neutrophilic lung inflammation and production of pro-inflammatory cytokines, while upregulating the anti-inflammatory cytokine IL-10. RvD1 promoted differentiation of alternatively activated (M2) macrophages and neutrophil efferocytosis. RvD1 also accelerated the resolution of lung inflammation when given after the final smoke exposure.

Conclusions: RvD1 has potent anti-inflammatory and pro-resolving effects in cells and mice exposed to cigarette smoke. Resolvins have strong potential as a novel therapeutic approach to resolve lung injury caused by smoke and pulmonary toxicants.

Disciplines
Pharmacy and Pharmaceutical Sciences

Comments
This article was originally published as:


Creative Commons License

This work is licensed under a Creative Commons Attribution 4.0 License.

Authors

This article is available at Fisher Digital Publications: https://fisherpub.sjfc.edu/pharmacy_facpub/376
A Novel Anti-Inflammatory and Pro-Resolving Role for Resolvin D1 in Acute Cigarette Smoke-Induced Lung Inflammation

Hsi-Min Hsiao1, Ramil E. Sapinoro2,3*, Thomas H. Thatcher2,3, Amanda Croasdell2,4, Elizabeth P. Levy2,3, Robert A. Fulton2,3, Keith C. Olsen2,5, Stephen J. Pollock2,4, Charles N. Serhan6, Richard P. Phipps2,4,5,7, Patricia J. Sime2,3,4,5*

1 Department of Pathology and Laboratory Medicine, University of Rochester, Rochester, New York, United States of America, 2 Lung Biology and Disease Program, University of Rochester, Rochester, New York, United States of America, 3 Division of Pulmonary and Critical Care Medicine, University of Rochester, Rochester, New York, United States of America, 4 Department of Environmental Medicine, University of Rochester, Rochester, New York, United States of America, 5 Department of Microbiology and Immunology, University of Rochester, Rochester, New York, United States of America, 6 Center for Experimental Therapeutics and Reperfusion Injury, Department of Anesthesiology, Perioperative, and Pain Medicine, Brigham and Women’s Hospital, Harvard Institutes of Medicine and Harvard Medical School, Boston, Massachusetts, United States of America

Abstract

Introduction: Cigarette smoke is a profound pro-inflammatory stimulus that contributes to acute lung injuries and to chronic lung disease including COPD (emphysema and chronic bronchitis). Until recently, it was assumed that resolution of inflammation was a passive process that occurred once the inflammatory stimulus was removed. It is now recognized that resolution of inflammation is a bioactive process, mediated by specialized lipid mediators, and that normal homeostasis is maintained by a balance between pro-inflammatory and pro-resolving pathways. These novel small lipid mediators, including the resolvins, protectins, and maresins, are bioactive products mainly derived from dietary omega-3 and omega-6 polyunsaturated fatty acids (PUFA). We hypothesize that resolin D1 (RvD1) has potent anti-inflammatory and pro-resolving effects in a model of cigarette smoke-induced lung inflammation.

Methods: Primary human lung fibroblasts, small airway epithelial cells and blood monocytes were treated with IL-1β or cigarette smoke extract in combination with RvD1 in vitro, production of pro-inflammatory mediators was measured. Mice were exposed to dilute mainstream cigarette smoke and treated with RvD1 either concurrently with smoke or after smoking cessation. The effects on lung inflammation and lung macrophage populations were assessed.

Results: RvD1 suppressed production of pro-inflammatory mediators by primary human cells in a dose-dependent manner. Treatment of mice with RvD1 concurrently with cigarette smoke exposure significantly reduced neutrophilic lung inflammation and production of pro-inflammatory cytokines, while upregulating the anti-inflammatory cytokine IL-10. RvD1 promoted differentiation of alternatively activated (M2) macrophages and neutrophil efferocytosis. RvD1 also accelerated the resolution of lung inflammation after when given the final smoke exposure.

Conclusions: RvD1 has potent anti-inflammatory and pro-resolving effects in cells and mice exposed to cigarette smoke. Resolvins have strong potential as a novel therapeutic approach to resolve lung injury caused by smoke and pulmonary toxicants.

Introduction

Cigarette smoke is a potent pro-inflammatory stimulus and a major risk factor for many diseases including cardiovascular disease, stroke and lung cancer. Tobacco smoking is the primary risk factor for chronic obstructive pulmonary disease (COPD) emphysema and chronic bronchitis, and is the fifth leading cause of death worldwide [1].


Editor: Ali Onder Yildirim, Institute of Lung Biology and Disease (iLBD), Helmholtz Zentrum München, Germany

Received September 24, 2012; Accepted February 1, 2013; Published March 6, 2013

Copyright: © 2013 Hsiao et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: This work was supported by National Institutes of Health Grants R01 HL08325, HL08325-02S1, HL66988, ES07026, 8UL1TR000042 and ES01247. AC is supported by a pre-doctoral fellowship from The PhRMA Foundation. The funders had no role in study design, data collection; and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: TT is a PLOS One Editorial Board Member. CS is an inventor on patents [resolvins] assigned to BWH and licensed to Resolvxx Pharmaceuticals. CS is a scientific founder of Resolvxx Pharmaceuticals and owns equity in the company. CNS’s interests were reviewed and are managed by the Brigham and Women’s Hospital and Partners HealthCare in accordance with their conflict of interest policies. This does not alter the authors’ adherence to all the PLOS ONE policies on sharing data and materials. No other authors have competing interests to declare.

* E-mail: Patricia_Sime@urmc.rochester.edu

† These authors contributed equally to this work.
Inflammation is a key factor contributing to lung diseases caused by smoking. Until recently, it was assumed that resolution of inflammation was a passive process that occurred once the inflammatory stimulus was removed. It is now recognized that resolution of inflammation is a bioactive process, mediated by specialized lipid mediators, and that normal homeostasis is maintained by a balance between pro-inflammatory and pro-resolving pathways [2].

Several classes of pro-resolving mediators have been identified, including resolvins, protectins, and maresins [3]. These specialized lipid mediators are derived via enzymatic processing from dietary omega-3 polyunsaturated fatty acids (ω-3-PUFAs), including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). Several of these mediators have anti-inflammatory and pro-resolving activity in pre-clinical disease models such as peritonitis [4], colitis [5], dermal inflammation [6] and asthma [7]. Protectin D1 and resolvin E1 reduce airway hyperresponsiveness and inflammation in animal models of pneumonia and asthma [8,9]. Furthermore, diets rich in ω-3-PUFAs appear to have beneficial effects in lung diseases such as COPD and asthma [10,11]. These findings support the idea that pro-resolving lipid mediators in the lung could play a key role in controlling inflammation and return to homeostasis.

Many cell types in the lung respond to cigarette smoke by producing pro-inflammatory mediators. We have previously reported that lung fibroblasts play a significant role in orchestrating inflammatory responses, and respond to cigarette smoke by increasing expression of COX-2 and production of pro-inflammatory prostaglandins and other pro-inflammatory mediators [12]. Macrophages also respond to cigarette smoke by producing pro-inflammatory mediators [13]. These pro-inflammatory mediators recruit immune cells such as neutrophils and additional macrophages and stimulate nearby epithelial and endothelial cells resulting in inflammation and tissue damage.

Interestingly, lung macrophages play a dual role in the response to cigarette smoke. Classically activated, so-called M1 macrophages, express inducible nitric oxide synthase (iNOS) and tumor necrosis factor-α (TNF-α), and are generally thought to be pro-inflammatory. Recent research has demonstrated the importance of alternatively activated, or M2 macrophages, which are activated by Th2 cytokines such as IL-4 and IL-13, or the immunosuppressive cytokines IL-10 and TGF-β [14]. M2 lung macrophages play an essential role in the clearance of inhaled particles, pathogens and apoptotic cells including neutrophils (efferocytosis) [15–17]. Studies have shown that cigarette smoking is associated with defects in lung macrophage function [18] and macrophages isolated from COPD patients had a reduced ability to clear apoptotic neutrophils [19,20], suggesting that macrophage defects are a key pathogenic feature of the disease. Thus, fibroblasts and macrophages are not only useful as in vitro models to evaluate new anti-inflammatory and pro-resolving molecules, but are highly relevant to in vivo therapeutic outcomes.

Resolvins D1 (RvD1, 7S,9R,17S-trihydroxy-4Z,9E,11E,13-Z,15E,19Z-docosahexaenoic acid) is a derivative of DHA [4] with potent anti-inflammatory and pro-resolving properties. The 17R epimer of RvD1 (17R-RvD1) is produced via an alternative biochemical pathway but has similar in vitro and in vivo activity and uses the same receptors as RvD1. Notably, 17R-RvD1 is resistant to inactivation by the endogenous enzyme 15-prostaglandin dehydrogenase/eicosanoid oxidoreductase (15-PDGH) and potentially has a longer duration of effect in vivo [21]. RvD1 and 17R-RvD1 inhibit neutrophilic inflammation and promote efferocytosis in several disease models [22–25]. RvD1 also promotes M2 differentiation in mouse models of peritonitis and obesity-induced adipose tissue inflammation and insulin resistance [26,27].

Here, we investigated the impact of RvD1 on the production of pro-inflammatory mediators by human primary lung fibroblasts, epithelial cells and blood-derived macrophages stimulated with cigarette smoke extract or IL-1β and in a mouse model of acute cigarette smoke (CS)-induced lung inflammation. RvD1 has potent anti-inflammatory effects in vitro and in vivo, and inhibition of inflammation is associated with increased differentiation and function of M2 lung macrophages. These results suggest that RvD1 may be a potential new therapeutic for cigarette smoke-induced lung injury and other inflammatory lung diseases.

Materials and Methods

Ethics Statement

All animal procedures were approved and supervised by the University of Rochester University Committee on Animal Resources (UCAR permit number 2007-127). For euthanasia, mice were anesthetized with an intraperitoneal injection of avertin (2,2,2-tribromoethanol, 250 mg/kg), followed by exsanguination and removal of the lungs for analysis, and all efforts were made to minimize suffering. Primary human lung fibroblasts were derived from culture of tissue explants following biopsy specimens from patients undergoing lung resection surgery for hamartoma, a benign lung tumor. The fibroblasts were grown tissue from anatomically normal areas of the specimen distal to the lesion. Human blood monocytes were isolated from peripheral blood collected from healthy donors. All blood and tissue donors provided informed written consent as described in study protocols approved by the University of Rochester Institutional Review Board and conforming to the Helsinki Declarations. Primary human small airway epithelial cell cultures were obtained from a commercial source.

Cell Culture and Analysis of Pro-inflammatory Mediators

Primary human lung fibroblast cultures were established from lung tissue explants as previously described [28] and used at early passage (P3–P9). Primary human small airway epithelial cells (SAEC) were purchased from a commercial vendor (Lonza, Allendale, NJ) and cultured in small airway epithelial cell growth medium supplemented as recommended by the supplier. Blood monocytes were cultured in RPMI 1640 as described [29].

Serum starvation was performed to reduce the effect of serum components on induction of cyclooxygenase-2 (COX-2) and other inflammatory mediators. Aqueous cigarette smoke extract (CSE) was prepared as previously described [30]. Briefly, smoke from two reference cigarettes (1R3F, University of Kentucky) was bubbled through 20 ml of serum free medium. This is arbitrarily defined as “100% CSE.” To adjust for batch-to-batch variation, the average absorbance at 320 nm for several batches of CSE was measured and determined to be 0.65 absorbance units. Thereafter, CSE preparations are diluted as needed so that 100% CSE has a standard OD320 = 0.65. The pH of the CSE is adjusted to 7.4, and the CSE is then sterile filtered with a 0.45-μm filter (25-mm Acrodisc; Pall, Ann Arbor, MI). CSE was freshly prepared for each experiment and diluted with serum-free MEM immediately before use. Cultures were pre-treated with 10 nM, 100 nM or 1 μM RvD1 or vehicle control solution (0.1% ethanol) for 24 hours prior to the addition of 1% or 5% CSE or 1 ng/ml IL-1β (R&D Systems, Minneapolis, MN) for an additional 24 hours. As the RvD1 was supplied in ethanol, vehicle control cultures were treated with the same final concentration of ethanol (0.1%). Inflammatory mediators were determined in cell culture superna-
Cigarette Smoke Exposures

Adult female C57BL/6j mice were purchased from The Jackson Laboratory (Bar Harbor, ME) and used at 8–12 weeks of age. Mice were exposed to dilute mainstream cigarette smoke (CS) for 1 hour, twice per day, for 3 days, as described [31]. Resolvin D1 (78,8R,17S-trihydroxy-4Z,9E,11E,13Z,15E,19Z-docosahexaenoic acid) and 17R-RvD1 (78,8R,17R-trihydroxy-4Z,9E,11E,13Z,15E,19Z-docosahexaenoic acid) were obtained from Cayman Chemical. In the pre-treatment exposure model, 100 ng RvD1 in 40 μl saline was given by oropharyngeal aspiration on day 0, and 1 hour prior to the first smoke exposure on days 1, 2 and 3. Control animals were treated with saline vehicle. Smoke exposures were quantified by determining total suspended particulate matter (TPS) by gravimetric sampling. The smoke concentration was set at a nominal value of 450 mg/m³ vehicle. Smoke exposures were quantified by determining total aspiration on day 0, and 1 hour prior to the first smoke exposure in days 1–3. On day 3, after the final smoke exposure, and on days 4 and 5, the mice were treated with vehicle or 100 ng RvD1 by oropharyngeal aspiration as described. The mice were euthanized and analyzed on day 4 and 6.

Analysis of Bronchoalveolar Lavage Fluid (BALF) and Lung Tissues

BALF was collected from smoke-exposed mice and analyzed as previously described [31]. The lung right was frozen in liquid nitrogen for later analysis. Total protein in BALF was determined by the bicinechonic acid (BCA) colorimetric assay (Thermo Scientific, Rockford, IL). The right lung was homogenized in RIPA buffer as described [32], and lung proteins were analyzed for expression of COX-2 (Clone CX229, Cayman Chemical, Ann Arbor, MI), Arg-1 (H-52; Santa Cruz Biotechnologies, Santa Cruz, CA) and total actin (CP01; Calbiochem, San Diego) by western blotting. In some experiments, the lungs were inflated with 10% neutral buffered formalin without undergoing fixation. Western blotting was performed and run on a mini gel running system (Biorad, Hercules, CA) and total actin (CP01; Calbiochem, San Diego) was probed by anti-actin antibody (A-5316; Sigma-Aldrich, St. Louis, MO). The bands were imaged using an EZ-Radiograph Imaging System ( Kodak, Rochester, NY). The intensity of the bands was determined using ImageJ software (National Institutes of Health, Bethesda, MD).

Immunohistochemistry

Lung-infiltrating neutrophils were stained with rat anti-mouse Ly-6B.2 (MCA771GA, Serotec, Oxford, UK) and HRP-conjugated goat anti-rabbit antibodies, followed by visualization with AEC chromagen (Vector Lab, Burlingame, CA) and hematoxylin counter staining.

Analysis of Cytokines and Chemokines

Human IL-6, IL-8 and MCP-1 were measured in cell culture media by commercial ELISA according to the manufacturer’s instructions (R&D Systems). Prostaglandin E2 (PGE2) was measured by competitive enzyme immunoassay (EIA) using commercially available reagents as described (Cayman Chemical) [33]. Mouse cytokines and chemokines were measured by ELISA (MP-2, KC; R&D Systems) or by bead-based multiplex analysis of lung homogenates (IL-1β, IL-6, MCP-1, IFN-γ and IL-10; Millipore, Billerica, MA) using a Luminex FlexMAP3D instrument (Luminex, Austin, TX). Results are expressed as picograms of cytokine per milligram of total protein in the homogenate.

Assessment of Macrophage Phagocytosis of Neutrophils

Lungs were harvested from mice exposed to smoke and treated with RvD1 as described above. One lobe was digested with collagenase and a single cell suspension was prepared. Total lung macrophages were isolated by CD11b magnetic bead separation (Miltenyi Biotec, Cambridge, MA) [34]. The cells were then labeled with FITC-conjugated anti-mouse F4/80 antibody (MB6; Invitrogen; Camarillo, CA) for 30 minutes, then fixed with 4% paraformaldehyde and permeabilized with 0.1% Triton X-100. Neutrophils were labeled by staining permeabilized cells with PE-conjugated anti-mouse Gr-1 (RB6-8C5; BD Pharmingen) antibodies for 30 minutes and analyzed by flow cytometry (FACS Canto II; BD Biosciences, San Jose, CA). Forward and side scatter was first used to exclude doublets or macrophages that are attached to but did not fully engulf neutrophils. Cells were then gated based on F4/80 positive staining. The frequency of cells that are F4/80 and GR-1 double positive was then quantified.

Macrophage Phagocytic Activity in vitro

Alveolar macrophages were harvested from naive mice by lavage in PBS buffer containing 0.6 mM EDTA and glucose (0.1%). Macrophages were activated with 1 ng/ml IL-1β for 30 minutes and then incubated with RvD1 (100 nM in 0.1% ethanol) or 0.1% ethanol alone for an additional 30 minutes before the addition of a 10-fold excess of FITC-conjugated latex microspheres for 1 hour. Uptake of FITC-labeled latex microspheres was measured by flow cytometry (FACS Canto II, BD Biosciences).

Characterization of Alveolar Macrophages

Lungs were lavaged extensively (0.5 ml for 5–10 times) with PBS containing 0.1% glucose to collect lung macrophages. Collected cell suspensions were enriched for macrophage by adherence on tissue culture-treated plastic dishes for 1 hour in minimum essential medium (MEM; Gibco, Camarillo, CA) containing 10% fetal bovine serum. Non-adherent cells were discarded by gently washing twice with PBS. RNA was extracted from the enriched adherent macrophages by RNeasy kit according to manufacturer’s instructions (Qiagen; Valencia, CA). RNA (1 μg) was reverse-transcribed using the iScript cDNA synthesis Kit (BioRad; Hercules, CA) and the cDNA was subjected to quantitative real-time PCR using SYBR Green Supermix, 0.5 μl forward and reverse primer, 7.5 μl of the 1:5 diluted cDNA template. The real-time PCR was performed under the following conditions: 1 cycle at 95°C for 3 minutes, then 40 cycles at 95°C for 10 seconds, 55°C for 30 seconds, 95°C for 1 minute followed by 55°C for 1 min. The intron-spanning primers were designed as described by using sequence information from the NCBI database. The Ct values were normalized to the endogenous control (18sRNA). Primer sequences are listed below:

- m18sRNA: 5′-GCTTGGCTCGGCGTTCCTTTACCTCCT-3′
- m18sRNA: 5′-TCACCTGACCGCCGTCGTGGATGA-3′
- mArg1-F: 5′-CAGAGAATGGAAGAGTCAG–3′
- mArg1-R: 5′-CAGATATGCAGGCAGGGAGTCACC -3′
- mMrc1-F: 5′-TCACTGTACCGGCCGTGCGTA-3′
- mMrc1-R: 5′-GTGGAACGGGTCGATGTCAC -3′
- m18sRNA: 5′-GCTTGCTCGCGCTTCCTTACCTCCT-3′
- m18sRNA: 5′-TCACCTGACCGCCGTCGTGGATGA-3′
- mArg1-F: 5′-CAGAGAATGGAAGAGTCAG–3′
- mArg1-R: 5′-CAGATATGCAGGCAGGGAGTCACC -3′
- mMrc1-F: 5′-TCACTGTACCGGCCGTGCGTA-3′
- mMrc1-R: 5′-GTGGAACGGGTCGATGTCAC -3′
- miNOS-F: 5′- GTTCTCAGCCCAACAATACAAGA -3′
- miNOS-R: 5′- GTGGACCGGTCGATGTCAC -3′
with 5% CSE to induce a strong response, but were more sensitive
more resistant to CSE than fibroblasts and required treatment
levels of PGE2 which was not significantly increased further by
In these experiments the monocytes produced high background
induced expression of IL-6 and IL-8 from human monocytes. A
one-hour pre-treatment with RvD1 significantly inhibited produc-
tion of IL-6 or IL-8 from SAEC (data not shown). Both IL-1
mediators in human lung fibroblasts, although at lower levels than
IL-1β strongly induced production of pro-
inflammatory mediators including IL-6, IL-8, MCP-1 and PGE2
(Figure 1). RvD1 significantly inhibited the production of MCP-1 and
PGE2 at 1000 nM. CSE also induced these pro-inflammatory
expression, which is strongly inhibited by RvD1 (Figure 5I and
findings that CS increases PGE2 production and COX-2
exposure induces the expression of neutrophil chemoattractants
reduced with RvD1 treatment (Figure 5A). Acute cigarette smoke
edema, was also increased with CS exposure and significantly
increased with RvD1 (1000 nM) significantly attenuated COX-2 expression (Figure 1I),
suggesting a potent anti-inflammatory function for RvD1 in
human lung fibroblasts.

RvD1 Inhibits Production of Inflammatory Mediators in
Monocytes and Lung Epithelial Cells

Macrophages and epithelial cells are important sources of
inflammatory cytokines in cigarette smoke-exposed lungs. To
evaluate the effect of RvD1 on these cell types, human primary
small airway epithelial cells (SAECs) and blood-derived monocytes
were pre-treated with the indicated concentrations of RvD1 before
the addition of IL-1β or CSE for an additional 24 hours. RvD1
significantly dampened production of IL-6 and IL-8 from SAEC
treated with IL-1β (Figure 5A-B). In our hands, IL-1β did not
stimulate release of PGE2, and CSE did not stimulate production of
IL-6 or IL-8 from SAEC (data not shown). Both IL-1β and CSE
induced expression of IL-6 and IL-8 from human monocytes. A
one-hour pre-treatment with RvD1 significantly inhibited produc-
tion of IL-6 and IL-8 in a dose-dependent manner (Figure 2C-F).
In these experiments the monocytes produced high background
levels of PGE2 which was not significantly increased further by
CSE, therefore an effect of RvD1 on PGE2 production could not
be determined (data not shown). Interestingly, monocytes were
more resistant to CSE than fibroblasts and required treatment
with 5% CSE to induce a strong response, but were more sensitive
to RvD1, with potent inhibition seen at 10 nM (Figure 2G-F).

RvD1 Attenuates Cigarette Smoke-induced Inflammation
in vivo

Based on our in vitro results, we hypothesized that administration
of RvD1 would attenuate cigarette smoke-induced acute lung
inflammation in vivo. Mice received 100 ng RvD1 by inhalation 1
hour prior to cigarette smoke exposure daily for 3 days. On day 4,
the mice were euthanized, bronchoalveolar lavage fluid (BALF)
was collected, and inflammation was evaluated by differential cell
counting. Cigarette smoke (CS) exposure induced significant
increases in total BAL cells, neutrophils and lymphocytes, but
not macrophages or eosinophils (Figure 3), consistent with prior
experience with this model [37,38]. The increase in total cell
number is almost entirely due to recruitment of neutrophils
(Figure 3C). CS-exposed mice pre-treated with RvD1 had
significantly fewer neutrophils in BALF compared to vehicle-
treated controls, expressed either as neutrophil number (Figure 3C)
or percentage (Figure 3F) of total cells. There was no change in
the absolute numbers of macrophages between CS and CS+RvD1-
treated mice (Figure 3B). As noted, RvD1 had no significant
impact on the numbers of BAL lymphocytes (Figure 3D) and
eosinophils (Figure 3E). Interestingly, while total macrophage
numbers were not changed, there was a significant increase in the
percentage of macrophages in the BALF with RvD1 treatment
(Figure 3F).

RvD1 Reduces Cigarette Smoke-induced Neutrophilic
Lung Inflammation

The location of infiltrating neutrophils in lung tissues was
determined by immunohistochemical staining for the neutrophil
specific marker Ly-6B.2. In RvD1-treated, air-expose lung,
neutrophils were sparsely detected (Figure 4A and 4B). Acute
smoke exposure causes accumulation of neutrophils around vessels
(v), airways (a) (Figure 4C, arrows) and in the parenchyma
(Figure 4D), with neutrophils prominent in the interstitial spaces
(Figure 4D, arrows) and the alveoli (Figure 4D, solid triangles).
RvD1 reduces the appearance of CS-induced neutrophils in lung
tissue consistent with the results of differential cell counts in BALF
that RvD1 reduces neutrophil accumulation in the lung.

RvD1 Decreases Production of Pro-inflammatory
Mediators

Levels of pro-inflammatory cytokine and chemokine were
determined in BALF and lung homogenates of smoke-exposed
mice. Total protein in BALF, an indication of vascular leakage and
edema, was also increased with CS exposure and significantly
reduced with RvD1 treatment (Figure 5A). Acute cigarette smoke
exposure induces the expression of neutrophil chemotacticants
KC and MIP-2, which was significantly inhibited by RvD1 (Figure 5,
panels B and C). CS exposure also resulted in increased
production of pro-inflammatory cytokines including IL-1β, IL-6,
and MCP-1. RvD1 markedly decreased IL-1β and IL-6 but not
MCP-1 (Figure 5, panels D-F). IFN-γ content was increased with
CS and decreased with CS+RvD1 treatment, however the
difference was not significant (Figure 5G). Interestingly, the anti-
inflammatory cytokine IL-10 was significantly increased in lungs
from CS-exposed mice pre-treated with RvD1 (Figure 5H). We
also evaluated expression of COX-2 protein and PGE2 levels in
lung homogenates, which showed results consistent with our in vitro
findings that CS increases PGE2 production and COX-2
expression, which is strongly inhibited by RvD1 (Figure 5I and
5J, respectively).
Figure 1. RvD1 inhibits IL-1β-induced and CSE-induced cytokine and chemokine production from primary human lung fibroblasts. Primary human lung fibroblasts were pre-treated with the indicated concentrations of RvD1 for 24 hours then stimulated with IL-1β (1 ng/ml) or cigarette smoke extract (CSE, 1%) for an additional 24 hours. Culture media from IL-1β-treated cells (A–D) or CSE-treated cells (E–H) were subjected to ELISA and EIA to detect various pro-inflammatory mediators as described in the Methods. Data shown are mean ± SD for n = 4 replicate cultures, from one representative experiment of 3 performed. COX-2 and GAPDH expression (I) were determined in cell lysates by Western blotting. Blots shown are representative of three independent experiments, and the lanes were run non-contiguously on the same gel. ***P < 0.001, **P < 0.01, *P < 0.05 compared to IL-1β-treated or CSE-treated cultures without RvD1, ###P < 0.001 versus vehicle-treated control cultures by one-way ANOVA with Bonferroni post-tests.

doi:10.1371/journal.pone.0058258.g001
Resolvins are reported to be pro-resolving as well as anti-inflammatory [39]. To evaluate whether resolvins could accelerate the resolution of CS-induced inflammation, we exposed mice to CS for 3 days, and initiated resolvin treatment after the final smoke exposure. For these experiments, we used the 17R epimer of RvD1 (17R-RvD1) as it is less susceptible to \textit{in vivo} inactivation [4]. RvD1 and 17R-RvD1 bind the same receptor and have similar activities \textit{in vitro} [21]. Mice were euthanized on day 4 (after a single 17R-RvD1 treatment on day 3) or day 6 (after receiving 17R-RvD1 on days 3, 4 and 5). A single dose of 17R-RvD1 accelerated the resolution of acute CS-induced inflammation, with significant reductions in total BAL cells, macrophages and neutrophils on day 4 (Figure 6, panels A, B and C). Although the number of inflammatory cells was significantly reduced by 17R-RvD1, the percentages of neutrophils and macrophages did not significantly change, as the number of macrophages, neutrophils, and total cell numbers were reduced together (Figure 6E, F). Inflammation on day 6 was also reduced with 17R-RvD1, although less dramatically than on day 4. 17R-RvD1 also significantly reduced production of the pro-inflammatory cytokine IL-6 (Figure 6F), neutrophil chemokines KC and MIP-2 (Figure 6G and H, respectively) and PGE\textsubscript{2} (Figure 6I).
Figure 3. RvD1 attenuates CS-induced inflammation in vivo. Mice were treated with 100 ng RvD1 (grey bars) or saline vehicle (Veh, black bars) by inhalation 1 hour prior to cigarette smoke, daily for 3 days. Mice were euthanized at day 4, and differential cell counts were performed on BALF cells. Total cell number (A), number of macrophages (B), neutrophils (C), lymphocytes (D), eosinophils (E) and percentage of macrophages and neutrophils (F) are reported. Data are shown as mean ± SEM for n = 6–7 mice per group from one of 3 independent experiments. ***P < 0.001, versus smoke-exposed mice by two-way ANOVA with Bonferroni post-tests. ###P < 0.001, versus air-exposed control mice by one-way ANOVA with Bonferroni post-tests.

doi:10.1371/journal.pone.0058258.g003
RvD1 Enhances the Clearance of Neutrophils in vivo and in vitro

We hypothesized that one mechanism by which RvD1 promotes resolution of CS-induced inflammation is by increasing the phagocytosis of neutrophils by lung macrophages. To investigate this mechanism, lung macrophages were harvested from CS-exposed mice, fixed and permeabilized, then co-stained for the macrophage marker, F4/80, and the neutrophil marker Gr-1. Treatment with RvD1 increased the percentage of F4/80 and Gr-1 double positive cells, suggesting that clearance of apoptotic neutrophils is enhanced in the presence of RvD1 (Figure 7A). We also investigated whether RvD1 increased macrophage phagocytosis ex vivo. Alveolar macrophages were isolated from naive mice and stimulated with IL-1β (1 ng/ml) for 30 minutes, followed by RvD1 or vehicle for an additional 1 hour. The phagocytic ability of the macrophages was assessed using FITC-labeled latex beads and analyzed by flow cytometry. RvD1 enhanced overall bead uptake by 59% (Figure 7, panel B).

Figure 4. RvD1 reduces CS-induced neutrophilic lung inflammation. Lungs from mice that had not been lavaged were inflated and fixed with neutral buffered formalin, and 5 μm paraffin sections were stained with a neutrophil-specific antibody (brown) and counter-stained with hematoxylin. An occasional neutrophil was observed in air-exposed mice treated with RvD1 (A, B), similar to air-exposed mice treated with vehicle (not shown). CS induces a neutrophilic inflammation around vessels and airways (C) and in the parenchyma (D), with neutrophils prominent in the interstitial spaces (arrows) and the alveoli (solid triangles). RvD1 treatment reduces perivascular and peribronchial (E) as well as parenchymal (F) accumulation of neutrophils. A, airway; v, vessel. Arrows, interstitial neutrophils; solid triangles, neutrophils in airspaces.

doi:10.1371/journal.pone.0058258.g004
In addition to increasing the percentage of macrophages that had phagocytosed at least one bead, RvD1 also increased the number of beads phagocytosed per cell, with a 220% increase in the percentage of cells ingesting 3 and a 660% increase in the percentage of cells ingesting 4 or more beads (Figure 7C).

Figure 5. RvD1 decreases production of pro-inflammatory mediators in BALF and total lung homogenate but increases IL-10. Total protein (A) in BALF was measured by BCA assay. Neutrophil chemoattractants KC (B) and MIP-2 (C), IL-1β (D), IL-6 (E), MCP-1 (F), IFN-γ (G), PGE2 (H) and IL-10 (I) were determined in lung homogenates by multiplex assay or EIA and normalized to total protein concentration. N.D., not detected. Data are shown as mean ± SEM for n = 6–8 mice per group and are representative of 3 independent experiments. *P<0.05, **P<0.01, ***P<0.001 versus smoke-exposed mice by two-way ANOVA with Bonferroni post-tests. ###P<0.001 compared to air-exposed control mice by one-way ANOVA with Bonferroni post-tests. Expression of COX-2 and total actin (J) were determined in whole lung homogenates by Western blotting using COX-2 and total actin specific antibodies. Each lane represents an individual mouse.

doi:10.1371/journal.pone.0058258.g005
Figure 6. 17R-RvD1 promotes the resolution of acute lung inflammation induced by CS exposure. Mice were exposed to CS exposure on days 1, 2 and 3. The mice received 100 ng 17R-RvD1 (grey bars) or saline vehicle (Veh, black bars) by inhalation on day 3 (1 hour after the last cigarette smoke exposure), day 4 and day 5. Mice were euthanized at days 4 and 6 and differential cell counts were performed on BAL cells. Total cell number (A), number of neutrophils (B), and macrophages (C), percentage of neutrophils (D) and macrophages (E) are reported. BALF was collected and analyzed by ELISA or EIA for IL-6 (F), KC (G), MIP-2 (H) and PGE₂ (I). Data are shown as mean ± SEM for n = 4–5 mice per group. N.D., not detected. *P<0.05, **P<0.01 compared to Vehicle/Smoke mice by two-way ANOVA with Bonferroni post-tests.
doi:10.1371/journal.pone.0058258.g006
RvD1 Resolves Cigarette Smoke Inflammation

A

Veh/Smoke

RvD1/Smoke

Gr-1^+ 

F4/80^+

2.95

1.95

RvD1/Smoke

F4/80^+

Gr-1^+

5.04

B

FITC-

FITC+

No bead

RvD1

Veh

% of Max

1 bead

2 beads

3 beads

≥4 beads

FITC

C

<table>
<thead>
<tr>
<th></th>
<th>FITC-</th>
<th>FITC+</th>
<th>1 Bead</th>
<th>2 Beads</th>
<th>3 Beads</th>
<th>≥4 Beads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle (%)</td>
<td>81.8±0.9</td>
<td>18.2±0.9</td>
<td>13.8±0.5</td>
<td>3.1±0.3</td>
<td>0.6±0.12</td>
<td>0.2±0.03</td>
</tr>
<tr>
<td>RvD1 (%)</td>
<td>71.1±1.7</td>
<td>28.9±1.7</td>
<td>18.5±0.6</td>
<td>6.6±0.5</td>
<td>1.9±0.3</td>
<td>1.1±0.3</td>
</tr>
<tr>
<td>Increase (%)</td>
<td>-</td>
<td>59***</td>
<td>33***</td>
<td>114***</td>
<td>220**</td>
<td>660*</td>
</tr>
</tbody>
</table>
RvD1 Drives Polarization of Alternatively Activated Macrophages

Given the increased IL-10 production and increased phagocytic activity seen with RvD1 treatment, we hypothesized that RvD1 drives macrophage polarization to an M2 phenotype. RvD1 increased protein levels of arginase I (Arg1), a marker of M2 macrophages, in total lung homogenates (Figure 8A). We also extracted RNA from lung macrophages from mice exposed to air or CS, with or without RvD1 treatment, and determined mRNA levels by quantitative RT-PCR. In macrophages from air-exposed mice, RvD1 induced the M2 genes Arg1, mannose receptor 1 (Mrc1) and IL-10 demonstrating that the number of M2 macrophages increased after RvD1 treatment in the absence of inflammatory stimuli (Figure 8B-D). In CS-exposed mice, RvD1 significantly increased mRNA expression of Arg1, Mrc1 and IL-10 from alveolar macrophages compared to vehicle-treated CS-exposed mice (Figure 8, panels B-D). RvD1 significantly reduced mRNA expression of iNOS and TNF-α (Figure 8, panels E and F), two mediators highly expressed in classically-activated (M1) macrophages. Taken together, these results clearly demonstrate that RvD1 significantly augments the polarization of alveolar macrophages to the M2 phenotype.

Discussion

Human lungs are exposed daily to thousands of liters of air containing numerous environmental insults and pro-inflammatory stimuli including dust, pollen, mold, ozone and hydrocarbon pollutants. Given this, regulating the balance between pro-inflammatory and pro-resolving signaling pathways is crucial to maintain normal lung homeostasis [39]. Cigarette smoke is a powerful pro-inflammatory stimulus and a leading cause of lung, cardiovascular and other diseases [1,13]. Resolvin D1 is a member of a novel class of lipid mediators with anti-inflammatory and pro-resolving functions [3]. Here, we report that RvD1 is a potent inhibitor of cigarette smoke-induced pro-inflammatory signaling in human lung cells in vitro and has potent anti-inflammatory and pro-resolving properties in a mouse model of acute cigarette smoke-induced lung inflammation.

We first investigated the response of primary cells to RvD1 in vitro. RvD1 significantly reduced inflammatory responses in primary human lung fibroblasts and blood-derived monocytes using both IL-1β and CSE as inflammatory stimuli, and from human small airway epithelial cells stimulated with IL-1β (Figures 1 and 2). We used IL-1β as a model stimulus because we and others have shown that CS exposure upregulates IL-1β levels in both mice and humans exposed to cigarette smoke (Figure 4) [40]. Therefore, lung cells are likely exposed to IL-1β following smoke exposure in vivo. Cigarette smoke extract is widely used as an in vitro analog to inhalation of smoke but an exact equivalence between in vitro and in vivo exposures can not be determined [41]. It is interesting to note that RvD1 abolished IL-1β-induced PGE2 production in lung fibroblasts and inhibited PGE2 production in vivo. The role of PGE2 in regulating inflammation is complex, as PGE2 has both pro-inflammatory and pro-resolving properties. PGE2 is a potent neutrophil chemokine, and is upregulated by cigarette smoke (Figure 5) [12,42,43]. However, PGE2 also has anti-inflammatory properties in neutrophils, and is involved in activating lipid mediator class switching between pro-inflammatory and pro-resolving mediators [44,45]. Here, RvD1 has a net anti-inflammatory effect, perhaps because its pro-inflammatory effects are suppressed by RvD1, while its pro-resolving effects are replaced by exogenous RvD1.

Cigarette smoking causes both acute and chronic lung inflammation with prominent involvement of neutrophils. Neutrophilic airway inflammation is one of the key underlying pathophysiological processes in the development of COPD [46]. Recently, it was shown that cigarette smoke disrupts the normal resolution of neutrophilic lung inflammation by reducing neutrophil apoptosis and efferocytosis [47]. Impairment of neutrophil clearance can lead to irreversible local tissue damage via production of mediators including neutrophil elastase and reactive oxygen species [48]. Here we report that RvD1 damps neutrophil recruitment and enhances neutrophil clearance in acute CS-induced inflammation. These results suggest that RvD1 or 17R-RvD1 might be useful as therapies to reduce chronic inflammation and lung injury in diseases of chronic smoke exposure such as COPD.

Alternatively activated or type II macrophages (M2) are immunoregulatory cells that possess anti-inflammatory properties and eliminate tissue debris and apoptotic bodies via phagocytosis. Previous reports have shown that RvE1 and RvD2 enhanced macrophage phagocytosis of bacterial ligands and apoptotic neutrophils in sepsis and asthma models [49,50]. Here we show that RvD1 promotes differentiation of pro-resolving macrophages that have enhanced phagocytic activity in vitro and in vivo (Figure 7). It was recently reported that RvD1 regulates pro- and anti-inflammatory micro RNAs via signaling through its G-protein receptors ALX and GPR32, resulting in increased production of IL-10 and decreased NF-kB activity [51]. Additionally, it is known that IL-10 promotes the M2 phenotype [14,16]. These results, combined with our findings that IL-10 is elevated in RvD1-treated lungs (Figure 3H) and alveolar macrophages (Figure 8D), demonstrate that RvD1 and IL-10 enhance M2 polarization by a positive feedback mechanism initiated by RvD1-mediated G-protein signaling.

Although neutrophil chemokines (MIP-2, KC) and broad-spectrum pro-inflammatory signals (IL-1β, IL-6) were strongly inhibited by RvD1, the macrophage chemoattractant MCP-1, which was also induced by CS, was not reduced by RvD1 in mouse lung. Interestingly, it has been reported that MCP-1 enhances efferocytosis by alveolar macrophages, and that MCP-1 is important for the resolution of inflammation [52]. This is consistent with our observations that macrophage numbers were not reduced by RvD1 and that RvD1 enhances efferocytosis (Figure 7). RvD1 also up-regulated production of IL-10, a potent immunoregulatory cytokine that is reported to be essential for the resolution of lung inflammation [53] and which is significantly decreased in sputum samples from COPD patients [54,55]. Taken together, this suggests that RvD1 is not an indiscriminate anti-inflammatory agent, but rather selectively activates specific anti-inflammatory and pro-resolving pathways that include inhibition.
of neutrophilic inflammation and the activation of a subset of anti-inflammatory, pro-resolving macrophages.

Smoking-related inflammation of the lungs, cardiovascular system and other organs persists for months or even years after smoking cessation, and COPD not only persists but also may continue to worsen [1,2]. This suggests that development of novel therapeutics should be focused on promoting resolution, rather than preventing inflammation. Here, a single dose of 17R-RvD1 given after the final smoke exposure resulted in accelerated reduction in BAL neutrophils and IL-6 (Figure 6). The pro-resolving activity was maintained for at least 3 days, with continued reductions in neutrophils and key pro-inflammatory mediators. These results are similar to results recently reported from Dr. Serhan’s laboratory that RvD1 and 17R-RvD1 accelerated the resolution of allergic airway inflammation in the mouse ovalbumin model [25]. 17R-RvD1 is an alternate epimer of RvD1 produced endogenously in the presence of aspirin, which acetylates the COX-2 resulting in a shift from the 17S to the 17R epimer [21]. The 17S epimer is subject to rapid inactivation by the endogenous enzyme 15-prostaglandin dehydrogenase/eicosanoid oxidoreductase (15-PGDH) whereas the 17R epimer is not. While RvD1 was effective at inhibiting inflammation when given immediately prior to smoke exposure, we were concerned that it may not have a long enough half-life to be effective at promoting resolution when given after smoke exposure. 17R-RvD1 has similar biological activity and uses the same receptors [21] but is
have demonstrated that RvD1 possesses potent anti-inflammatory activity in vitro and in vivo. Inhalation therapy with RvD1 may offer an alternative approach for treating human inflammatory lung diseases including chronic lung injury and COPD resulting from cigarette smoking and other chronic injuries.

**Acknowledgments**

We thank K. A. Smolnycky, W. C. Narrow, Dr. A. A. Kulkarni and D. M. Krentsky for expert technical assistance.

**Author Contributions**

Conceived and designed the experiments: HH RS TT AC CS RP PS. Performed the experiments: HH RS RF EL RO AC SP. Analyzed the data: HH RS TT AC CS RP PS. Wrote the paper: HH RS TT AC CS RP PS.