

## **Intratracheal Administration of Acat-1 Inhibitor K-604 Reduces Pulmonary Inflammation Following Bleomycin-induced Lung Injury**

**Emily R. Stevenson<sup>1</sup>**, Melissa L. Wilkinson<sup>1</sup>, Elena Abramova<sup>1</sup>, Changjiang Guo<sup>1</sup>,  
Andrew J. Gow<sup>1\*</sup>

<sup>1</sup>Ernest Mario School of Pharmacy, Department of Pharmacology & Toxicology,  
Rutgers, The State University of New Jersey, Piscataway, NJ

**Running Title:** Cholesterol Esterification and acute lung injury

**\*Corresponding Author:** Andrew Gow

Ernest Mario School of Pharmacy

Department of Pharmacology & Toxicology,

Rutgers, The State University of New Jersey

160 Frelinghuysen Road

Piscataway, NJ 08854

(848)-445-4612

[gow@pharmacy.rutgers.edu](mailto:gow@pharmacy.rutgers.edu)

**ORCID:** Emily R. Stevenson (0000-0003-1329-8734), Melissa L. Wilkinson (0000-0002-3482-3975), Changjiang Guo (0000-0002-7447-3762), Andrew J. Gow (0000-0003-0876-5158)

**Text Pages:** 18

**Tables:** 1

**Figures:** 7

**References:** 78

**Abstract:** 239 words

**Introduction:** 514 words

**Discussion:** 1347 words

**Abbreviations:** Acat-1, Acyl Coenzyme A acyltransferase-1; ALI, acute lung injury; A.U., arbitrary unit; BAL, bronchoalveolar lavage; BCA, bicinchoninic acid; Bis-Tris, (Bis(2-hydroxyethyl)-imino-tris(hydroxymethyl)-methane); DMSO, dimethyl sulfoxide; EDTA, ethylenediamine tetraacetic acid; FBS, fetal bovine serum; ITB, intratracheal bleomycin; LXR, liver X receptor; PBS, phosphate buffered saline; PVDF, polyvinylidene fluoride; SP-B, Soat1, Sterol O-acyltransferase-1; surfactant protein B; SP-D, surfactant protein D; TTBS, Tris-Tween buffered saline

**Recommended section assignment:** Inflammation, Immunopharmacology, and Asthma

**Abstract:**

Acute lung injury (ALI) is characterized by epithelial damage, barrier dysfunction, and pulmonary edema. Macrophage activation and failure to resolve play a role in ALI, thus macrophage phenotype modulation is a rational target for therapeutic intervention. Large, lipid-laden macrophages have been observed in various injury models, including intratracheal bleomycin (ITB), suggesting that lipid storage may play a role in ALI severity. The endoplasmic reticulum-associated enzyme Acat-1 (*Soat1*) is highly expressed in macrophages where it catalyzes the esterification of cholesterol, leading to intracellular lipid accumulation. We hypothesize that inhibition of Acat-1 will reduce macrophage activation and improve outcomes of lung injury in ITB. K-604, a selective inhibitor of Acat-1, was used to reduce cholesterol esterification and hence lipid accumulation in response to ITB. Male and female C57BL6/J mice (n=16-21/group) were administered control, control + K-604, ITB, or ITB + K-604 on d0, control or K-604 on d3, and were sacrificed on d7. ITB caused significant body weight loss and an increase in

cholesterol accumulation in BAL cells. These changes were mitigated by Acat-1 inhibition. K-604 also significantly reduced ITB-induced alveolar thickening. Surfactant composition was normalized as indicated by a significant decrease in phospholipid:SP-B ratio in ITB+K-604 compared to ITB. K-604 administration preserved mature alveolar macrophages, decreased activation in response to ITB, and decreased the percentage mature and pro-fibrotic interstitial macrophages. These results show that inhibition of Acat-1 in the lung is associated with reduced inflammatory response to ITB-mediated lung injury.

**Key Words:** Inflammation, macrophage, pulmonary, bleomycin, lipid, Acat-1

**Significance:** Acat-1 is critical to lipid droplet formation, and thus Inhibition of Acat-1 thus presents as a pharmacological target. Intratracheal administration of K-604, an Acat-1 inhibitor, reduces intracellular cholesterol ester accumulation in lung macrophages, attenuates inflammation and macrophage activation, and normalizes mediators of surface-active function after intratracheal bleomycin administration in a rodent model. The data presented within suggest that inhibition of Acat-1 in the lung improves acute lung injury outcomes.

## 1. Introduction

Acute lung injury (ALI) affects approximately 200,000 people in the United States annually and has a high mortality rate due to respiratory failure (Johnson and Matthay, 2010; Dushianthan et al., 2011). ALI is characterized by inflammation, resulting in changes to innate immune cell, endothelial, and epithelial cell function (Matthay and Zimmerman, 2005; Johnson and Matthay, 2010). These alterations present as diffuse alveolar damage, epithelial and endothelial barrier dysfunction (Tam et al., 2011; Müller-Redetzky et al., 2014), pulmonary edema (Y et al., 2016), and surfactant dysfunction (Cross and Matthay, 2011; Mokra and Kosutova, 2015; Y et al., 2016). The primary management strategy for patients is mechanical ventilation (Johnson and Matthay, 2010; Dushianthan et al., 2011; Patel et al., 2018), which can lead to worse patient outcomes due to ventilation-perfusion mismatch, further tissue damage due to barotrauma, and altered inflammatory responses (Ioannidis et al., 2015). Therefore, identifying an effective pharmacological treatment is advantageous for this patient population.

Macrophage-mediated inflammation is a critical component in the pathogenesis of ALI (Huang et al., 2018; Chen et al., 2020). As the first line of defense for innate immune responses (Hussell and Bell, 2014; Hartl et al., 2018), macrophages play a crucial role in detecting foreign toxicants, particulates, and pathogens, initiating a cascade of host defenses (Martin and Frevert, 2005; Hartl et al., 2018). Macrophages are highly plastic (Hussell and Bell, 2014) and can be stimulated to express a spectrum of phenotypes that contribute to both inflammation and injury resolution in the lung (Porcheray et al., 2005; Benoit et al., 2008; Laskin, 2009; Johnston et al., 2012; Laskin et al., 2019). Early in the pathogenesis of ALI, alveolar macrophages release pro-inflammatory cytokines (Patel et

al., 2018; Chen et al., 2020), attracting neutrophils to the site of injury (Cortés et al., 2012; Patel et al., 2017). Macrophages responsible for the generation of reactive oxygen and nitrogen species may contribute to the majority of the cellular injury observed in ALI (Pittet et al., 1997; Ware, 2006). These chemical species damage the alveolar epithelium and endothelium, promoting increased permeability in the lung, leading to edema and proteinaceous debris accumulation in the alveoli (Cortés et al., 2012; Y et al., 2016). When this signaling is aberrant or overly persistent, the macrophage response may promote further injury rather than transition to resolution (Laskin et al., 2019). Therefore, regulating macrophage activation presents as a logical target when considering intervention in ALI.

In addition to ALI, macrophages have been implicated in driving the atherosclerotic process (Yu et al., 2013). Excess accumulation of lipids in macrophages drives their activation and progression towards atherosclerotic plaque formation, contributing to vascular injury (Yu et al., 2013; Chistiakov et al., 2016). Research into the mechanisms of foam cell formation led to the discovery of Acyl Coenzyme A:cholesterol acyltransferase-1 (Acat-1/*Soat1*) (Chang et al., 1993; Chang et al., 2001; Chang et al., 2009). Acat-1 catalyzes the conversion of cholesterol to cholesterol esters, a process essential for lipid droplet formation (Chang et al., 2001; Chang et al., 2009). As such, the persistence of lipid-laden cells is critically dependent upon cholesterol esterification (Sekiya et al., 2011; Yu et al., 2013; Chistiakov et al., 2017). These lipid-laden cells exhibit a 'foamy' appearance and have been implicated as a driving force in atherosclerosis (Ross, 1999; Stöger et al., 2012; Yang et al., 2020). Therefore, altering macrophage phenotype in the context of atherosclerotic plaques has been a topic of

investigation for some time (Chinetti-Gbaguidi et al.; Bouhlel et al., 2007; Yang et al., 2020); prior research in this area may also have utility in the management of pulmonary pathologies.

As lipid-laden macrophages have been observed in animal models of ALI (Venosa et al., 2019), we propose that inhibition of Acat-1 in the lung will lead to a reduction in injury. Studies varying the route of administration of Acat-1 inhibitors led to the hypothesis that the intratracheal administration of K-604 could effectively target pulmonary cells, mitigate lipid accumulation, modulate cell phenotype, and reduce disease severity in a model of ALI. To test this hypothesis, we have utilized the intratracheal bleomycin (ITB)-induced model of ALI (Chen et al., 2001; Genovese et al., 2005; Wilkinson et al., 2020) and the novel intratracheal administration of K-604. We found that K-604 administration reduced ALI severity, altered pulmonary cell cholesterol ester formation, and altered alveolar and interstitial macrophage phenotype. These data suggest that Acat-1 inhibition in the lung reduces the inflammatory response to ITB-mediated injury.

## **2. Materials and Methods**

### **2.1 Animal Use**

6-8 week old male and female wild-type C57BL6/J mice obtained from Jackson Laboratories (Bar Harbor, ME, USA) were used for all experiments. Mice were housed under standard conditions in groups of 4 per cage with food and water provided *ad libitum*. All experiments were conducted in accordance with Rutgers University IACUC-approved protocols adhering to the U.S. National Institutes of Health Guide for the Care and Use of Laboratory Animals.

### **2.1.1 ITB and K-604 administration**

Mice were anesthetized with isoflurane and received a single intratracheal instillation of either 50  $\mu$ L PBS (6% DMSO, control), 50  $\mu$ L 10 mg/kg K-604 in PBS (6% DMSO) (Sigma Aldrich, St. Louis, MO, Cat No. SML1837) (K-604), 50  $\mu$ L 3 U/kg bleomycin in 6% DMSO (Santa Cruz Biotechnology, Inc, Dallas, TX, Cat No. sc-200134B) (ITB), or 10 mg/kg K-604 + 3 U/kg bleomycin (ITB + K-604), at a total volume of 50  $\mu$ L with 6% DMSO (Gaylord Chemical Company, L.L.C., Tuscaloosa, AL) as previously described (Guo et al., 2016; Wilkinson et al., 2020; Golden et al., 2022). Mice were observed to ensure the full dose was administered and mice recovered from anesthesia. 72h later, mice were re-anesthetized and intratracheally administered 50  $\mu$ L PBS or 10 mg/kg K-604 (150  $\mu$ L, 6% DMSO) (Guo et al., 2016; Wilkinson et al., 2020; Golden et al., 2022). Mice were sacrificed 7d post intratracheal administration of K-604 or bleomycin. Mice were euthanized via a single intraperitoneal injection of ketamine (135 mg/kg) and xylazine (30 mg/kg) (Fort Dodge Animal Health, Fort Dodge, IA). Absence of pedal reflex was noted before exposing the chest cavity, and a thoracotomy was performed. Lungs were perfused with PBS via cardiac perfusion.

### **2.2 Bronchoalveolar Lavage (BAL) and Phospholipid Analysis**

BAL fluid was collected by instilling 5 x 1 mL ice cold PBS through a 20-gauge canula inserted into the trachea. BAL fluid was centrifuged at 300 x g for 8 mins, and the supernatant was assessed for protein concentration using a Pierce™ BCA Protein Assay (Thermo Scientific, Rockford, IL). Large and small aggregate fractions of BAL were separated from the large aggregate fraction according to the methods of Bligh & Dyer

(Bligh and Dyer, 1959). Phospholipid analysis was adapted from the method of Bartlett (Bartlett, 1959). Samples of equal phospholipid were loaded onto Bis-Tris gels (4-12%, Thermo Fisher Scientific, Rockford, IL), transferred to PVDF membranes, and blocked in non-fat dried milk (10% with 5% TTBS) to prevent non-specific binding. Membranes were incubated overnight with either SP-D (Duke University, Durham, NC) and SP-B (University of Pennsylvania, Philadelphia, PA) primary antibody and were incubated with Goat-anti-Rabbit HRP (Bio-Rad Cat No. 170-6515) before visualization with ECL Prime Western Blotting Detection Reagent (Amersham Biosciences, Amersham, UK, Cat No. RPN2232). BAL cell pellets were resuspended in 1 mL of staining buffer (5% FBS in 1x PBS, 0.2% sodium azide) and assessed for viability using Trypan Blue Solution (0.4%, Thermofisher Scientific, Rockford, IL).

### **2.3 BAL Cell Cholesterol Measurement**

10,000 to 20,000 cells were reserved from the BAL fluid to determine concentration of total cholesterol, free cholesterol, and cholesterol esters in BAL cell samples. A bioluminescent Cholesterol/Cholesterol Ester-Glo™ Assay (Promega, Madison, WI) was utilized and luminescence was recorded on a SpectraMax®M2 multi-mode microplate reader (Molecular Devices, San Jose, CA) utilizing SoftMax Pro software v5.3.

### **2.4 Histology Preparation and Analysis**

After BAL fluid collection, the large left lung lobe was excised and inflation fixed in paraformaldehyde (3%) and embedded in paraffin. 4 µM sections were stained with hematoxylin and eosin to observe histological changes. Slides were scanned at 40x using a VS120 Virtual Slide Microscope (Olympus, Waltham, MA) and viewed with

OlyVIA viewing software for virtual slide images (Olympus, Waltham, MA) at 400x. Randomly selected areas (n=10) from each histological slide were captured and analyzed by a blinded observer to determine average alveolar wall thickness, cell infiltration (# of nuclei), and tissue consolidation (% open tissue space) using ImageJ (NIH).

## **2.5 Lung Tissue Digestion and CD45+ Cell Separation**

After BAL collection, lung tissue was cut into small pieces and digested in 5 mL of 2 mg/mL collagenase type IV (Sigma Aldrich, St. Louis, MO) in RPMI 1640 1x (ThermoFisher Scientific, Rockford, IL) and 5% FBS (ThermoFisher Scientific, Rockford, IL). Tissue was filtered through a 70  $\mu$ m strainer and washed with RPMI/5% FBS until the strainer was absent of tissue. The filtrate was centrifuged for 6 min at 400 x g and supernatant was aspirated. The remaining cell pellet was resuspended in 1 mL of Red Blood Cell Lysis Buffer (Sigma Aldrich, St. Louis, MO) for 5 min at room temperature. 5 mL of RPMI/5% FBS was added and cells were centrifuged again for 6 min at 400 x g. Supernatant was aspirated and the cell pellet was counted and resuspended at a concentration of  $1 \times 10^8$  in PEF buffer (2% FBS in 1x PBS + 1 mM EDTA). Immunomagnetic selection of CD45+ leukocytes was performed using the EasySep™ Mouse CD45 Positive Selection Kit (Stemcell Technologies, Cambridge, MA). CD45+ selected cells and flowthrough (assumed CD45- cells) were recovered. Cells were then stained and processed for flow cytometry.

## **2.6 Flow Cytometry**

Cells from the BAL or lung tissue digest were brought up to a volume of 100  $\mu$ L of staining buffer. To prevent non-specific binding in the staining and analysis, cells were incubated with TruStain FcX anti-mouse CD16/32 (Fc Block, 1:100) (BioLegend, San Diego, CA, Cat No. 101320) for 10 min at 4°C. Samples from the BAL and CD45+ cells from the lung digest were incubated for 30 min at 4°C in a cocktail of the following antibodies (1:100): CD11b (BioLegend, San Diego, CA, Cat No. 101206), CD206 (BioLegend, San Diego, CA, Cat No. 141706), F4/80 (BioLegend, San Diego, CA, Cat No. 123114), CD11c (BioLegend, San Diego, CA, Cat No. 117312), CD45 (BioLegend, San Diego, CA, Cat No. 103128), Ly6c (B&D Biosciences, San Diego, CA, Cat No. 562728), Siglec F (BD Biosciences, Franklin Lakes, NJ, Cat No. 565528), and MHC II (Invitrogen, Waltham, MA, Cat No. 48-5321-82). Cells were centrifuged for 6 min at 400 x g and washed with staining buffer. Cells were stained with eFluor 780-conjugated fixable viability dye (Invitrogen, Waltham, MA, Cat No. 65-0865-14) for 30 min at 4°C, washed with staining buffer, and fixed in 3% paraformaldehyde. Cells were analyzed using a Gallios 10-color flow cytometer (Beckman Coulter, Brea, CA). Using Kaluza software (Beckman Coulter, Brea, CA) cells were initially sorted based upon forward and side scatter, doublet discrimination, and viability (Supplemental Fig 1, Supplemental Fig 2) and further analyzed to determine discrete cell phenotypes.

## 2.7 RT-qPCR

BAL macrophages recovered from each group were preserved in 1 mL TRIzol™ Reagent (ThermoFisher Scientific, Rockford, IL). In brief, RNA was extracted using phenol-chloroform. After a 15 min centrifugation at 14,000 x g, the aqueous phase was removed and RNA was extracted with isopropanol and spun at 14,000 x g. The pellet

was isolated and washed with 70% ethanol, dried, and resuspended in 15  $\mu$ L of RNase-free ultrapure water. After heating at 70°C for 10 min, RNA was quantitated using a NanoDrop 1000 spectrophotometer (ThermoFisher Scientific, Rockford, IL) and stored. cDNA was prepared according to a High-Capacity cDNA Reverse Transcription Kit (ThermoFisher Scientific, Rockford, IL) with a final target concentration of 200 ng/ $\mu$ L. Taqman assays were used to analyze relative gene expression using Taqman fast master mix (Thermofisher Scientific, Rockford, IL) and the following Taqman primers: *Gapdh* (Mm99999915\_g1), *Nos2* (Mm00440502\_m1), *Arg1* (Mm00475988\_m1), *Abca1* (Mm00442646\_m1), and *Abcg1* (Mm00437390\_m1). A threshold of 40 cycles was used as the limit of detection for gene expression. Thermal cycle numbers greater than 40 were set to 40 cycles for the purpose of the analysis.  $\Delta\Delta$ ct values were calculated using *Gapdh* as the control gene and PBS as the control condition. Fold change was calculated as  $2^{(-\Delta\Delta\text{ct})}$ .

## 2.8 Statistical Analysis

Statistical analysis was performed using GraphPad Prism Software version 9.0.2 for Windows (GraphPad Software, San Diego, CA). Quantitative data were analyzed by 2-way ANOVA. Multiple comparisons were followed by Holm-Sidak test with a significance level of  $p < 0.05$  compared to control (\*) and ITB (#). Data are shown as mean  $\pm$  standard error of the mean.

## 3. Results

### 3.1 K-604 mitigates ALI and improves ITB-induced histological changes

ITB administration resulted in a decreased body weight compared to controls in alignment with previously conducted studies(Barbayianni et al.). On average, ITB mice lost  $14\pm 2.1\%$  body weight over 7d which was significantly blunted to a loss of  $4\pm 1.0\%$  when administered K-604 on d0 and d3. Control mice were not significantly different than those administered K-604 alone ( $3\pm 0.8\%$  vs.  $0.5\pm 0.6\%$ ).

For each whole-lung scan obtained animals in each group (Fig 2A-D), 40x images (n=10) were captured at random and analyzed using ImageJ software to assess cell infiltration (Fig 2E), lung tissue consolidation (Fig 2F), and epithelial thickening (Fig 2G). ITB resulted in an increased number of nuclei per high powered field (Fig 2E) compared to control ( $230\pm 3.3^*$  vs.  $183\pm 5.0$ ), consistent with a macrophage-dominant response to ITB-induced lung injury (Venosa et al., 2021). In the presence of K-604, ITB did not result in a significant increase in the number of nuclei ( $195\pm 7.9^*$ ). ITB resulted in consolidation of the lung tissue (Fig 2F) as indicated by a significant decrease in white space (%) compared to control ( $57\pm 0.5\%^*$  vs.  $70\pm 0.6\%$ ). K-604 did not significantly reduce loss of white space when compared to control ( $62\pm 1.5\%$ ). ITB significantly increased the measured alveolar wall thickness (Fig 2G) compared to control ( $4\pm 0.0^*$   $\mu\text{m}$  vs.  $2\pm 0.1$   $\mu\text{m}$ ), which was significantly reduced by K-604 ( $3\pm 0.1$   $\mu\text{m}\#$ ).

### **3.2 K-604 does not reduce ITB-induced epithelial injury but normalizes lung lining**

ITB mediates ALI by inducing redox cycling and damage within epithelial cells (Allawzi et al., 2019), as such loss of barrier function and the accumulation of edema and protein within the BAL are hallmarks of injury. ITB increased BAL protein concentration compared to control (Fig 3A) ( $2.9\pm 0.23^*$  mg/mL vs.  $0.1\pm 0.19$  mg/mL) which was not mitigated by K-604 administration ( $3.1\pm 0.21$  mg/mL) indicating that K-604 did not alter

the initiating injury event (ITB administration). Phospholipids within the BAL were also quantitated (Fig 3B). ITB resulted in an increase in BAL phospholipids compared to control ( $117 \pm 14.7 \mu\text{g}/30 \mu\text{L}^*$  vs.  $23 \pm 5.7 \mu\text{g}/30 \mu\text{L}$ ) which is only partially reduced by K-604 administration ( $87 \pm 9.6 \mu\text{g}/30 \mu\text{L}$ ). SP-D and SP-B concentrations were determined through western blot of the small and large phospholipid aggregate fraction, respectively (Fig 3C). The SP-D to SP-B ratio was increased with ITB compared to control ( $5 \pm 0.6 \text{ A.U.}^*$  vs  $0.6 \pm 0.2 \text{ A.U.}$ ) consistent with inflammatory activation, while an apparent decrease was observed with K-604 administration ( $3.0 \pm 0.5^*$ ). Phospholipid levels were compared to SP-B protein levels as this ratio is critical to surfactant function (Fig 3D). The phospholipid to SP-B ratio was increased with ITB compared to control ( $13 \pm 2.2 \text{ A.U.}^*$  vs  $1 \pm 0.4 \text{ A.U.}$ ). This ratio was significantly decreased in ITB + K-604 compared to ITB alone ( $8 \pm 1.2 \text{ A.U.}\#$ ), indicating a normalization of surface-active function.

### **3.3 Intratracheal K-604 administration mitigates ITB-induced cholesterol accumulation in BAL cells**

ITB resulted in significant increases in cholesterol accumulation in BAL cells 7d (Fig 4). Per  $1 \times 10^4$  cells, total cholesterol ( $84 \pm 13.3 \mu\text{M}^*$  vs.  $28 \pm 13.2 \mu\text{M}$ ) and free cholesterol ( $73 \pm 11.7 \mu\text{M}^*$  vs.  $16 \pm 9.1 \mu\text{M}$ ) were increased in BAL cells compared to control. K-604 administration in ITB significantly reduced total cholesterol ( $17 \pm 5.7 \mu\text{M}\#$ ), free cholesterol ( $14 \pm 5.4 \mu\text{M}\#$ ), and cholesterol esters ( $7 \pm 1.2 \mu\text{M}\#$ ) compared to ITB alone. These results indicate that intratracheal administration of K-604 reduces ITB-mediated increases in intracellular cholesterol and storage, as an effective dose of K-604 was delivered to inhibit Acat-1 in the lung. In alignment with increased cholesterol ester measurements

with ITB, cells from ITB animal had increased cell diameter compared to control ( $30 \pm 11.6 \mu\text{m}^*$  vs.  $11 \pm 4.3 \mu\text{m}$ ) which was reduced by K-604 ( $14 \pm 3.7 \mu\text{m}\#$ ).

To test whether transporters were involved in the observed changes in cholesterol levels, expression of cholesterol efflux transporters *Abca1* and *Abcg1* was measured in BAL cells. *Abca1* expression was not changed with ITB ( $1.5 \pm 0.1$  vs.  $1.1 \pm 0.1$ ) but expression was reduced in ITB + K-604 ( $0.44 \pm 0.05\#$ ). *Abcg1* expression was decreased with ITB regardless of K-604 treatment compared to control ( $0.65 \pm 0.04^*$ ,  $0.61 \pm 0.05^*$  vs.  $1.08 \pm 0.1$ ). These minimal changes in efflux transporter expression support that the changes in intracellular cholesterol accumulation and cell size are due to effective Acat-1 inhibition in the lung.

### **3.4 K-604 treatment reduces alveolar and interstitial macrophage activation in response to ITB**

To analyze alveolar macrophage activation, we examined BAL cells by flow cytometry using cell surface markers (Table 1). Alveolar macrophages were identified by expression of CD45, F4/80, and Siglec F (Supplemental Fig 1). Alveolar macrophages were further categorized as mature (CD11c+/CD11b-), migratory (CD11c+/CD11b+) or recruited (CD11c-/CD11b+) (Fig 5), where the mature population may be considered tissue-resident, and the migratory and recruited populations may be derived from the circulation or from resident cells taking on a more migratory-like phenotype. A significant loss of the mature alveolar macrophages was observed as a result of ITB administration ( $18 \pm 4.1\%^*$  vs.  $95 \pm 0.67\%$ ) This ITB-mediated decrease was reduced by K-604 ( $48 \pm 6.0\%\#$ ). ITB-induced increases in the migratory ( $24 \pm 4.9\%^*$  vs.  $3 \pm 0.9\%$ ) and recruited ( $10 \pm 2.7\%^*$  vs.  $0.2 \pm 0.1\%$ ) alveolar macrophage populations were also observed

compared to control. K-604 rescued ITB-mediated increases in migratory macrophages ( $12\pm 2\%^*$ ) but did not significantly alter the percentage of recruited macrophages ( $8\pm 2.0\%$ ). Alveolar macrophages were also analyzed for expression of the activation markers Ly6c and CD206. CD206 was only observed within mature alveolar macrophages and was not seen in cells that expressed Ly6c. Ly6c expression was observed in both migratory and recruited macrophages irrespective of treatment. A significant increase in pro-inflammatory (Ly6c+/CD206-) alveolar macrophages was observed following ITB-treatment compared to control ( $21\pm 5.7\%^*$  vs.  $0.5\pm 0.2\%$ ). This increase was mitigated by K-604 administration ( $13\pm 4.0\%\#$ ) indicating reduced acute macrophage activation post-ITB.

Within the lung digest interstitial macrophages were identified by expression of CD45, F4/80, CD11b and the absence of Siglec F (Supplemental Fig 2). The yield of interstitial macrophages was consistent across all groups. However, the percentage of cells expressing marker of maturation (CD11c and CD206) was significantly increased by ITB compared to control (Fig 6) ( $20\pm 1.9\%^*$  vs.  $10\pm 1.5\%$ ). Administration of K-604 with ITB significantly reduced the percentage of CD11c+/CD206+ interstitial macrophages compared to ITB alone ( $6\pm 2.2\%$ ).

Both acute and chronic activation of macrophages have been shown to increase the expression of inducible nitric oxide synthase (*Nos2*) and arginase (*Arg1*) (MacMicking et al., 1997; Shearer et al., 1997; Kobayashi, 2010). ITB significantly increased *Nos2* (Fig 7A) (fold change  $13.5\pm 1.8^*$  vs.  $1.5\pm 0.5$ ) and *Arg1* (Fig 7B) (fold change  $239.5\pm 70^*$  vs.  $2.3\pm 1.2$ ) mRNA in BAL cells. In ITB, both *Nos2* ( $5.9\pm 2.0\#$ ) and *Arg1* ( $57.2\pm 11.0\#$ ) expression was decreased with K-604 compared to ITB alone.

#### 4. Discussion

Herein, we show an increase in cholesterol within macrophages in response to bleomycin which is the first demonstration of such an accumulation in this model of acute lung injury. Further, we have shown that use of an Acat-1 inhibitor reduces ITB-mediated lung injury and macrophage activation. Using intratracheal delivery of K-604, we observed preservation of body weight, improved lung structure, and normalization of lung surfactant (Figs 1-3). In addition, while ITB increased total, free, and cholesterol ester content in alveolar macrophages, K-604 reduced this accumulation (Fig 4). K-604 also reduced the loss of mature alveolar macrophage (Fig 5) and macrophage activation in both the lung lining and the interstitium (Figs 5-7). That K-604 reduces total cholesterol and lessens injury is evidence that lipid accumulation is a significant factor within ALI.

K-604 is a known inhibitor of the enzyme Acat-1, and is highly selective for this particular acyltransferase (Shibuya et al., 2018). Acat-1 is responsible for the esterification of cholesterol to cholesterol ester, and is thus critical to lipid droplet formation (Chang et al., 2001; Chang et al., 2009). Therefore, we have used cholesterol ester as our primary endpoint to determine a sufficient level of pharmacological inhibition of Acat-1 (Fig 4). Changes to free cholesterol, not simply cholesterol ester accumulation alone, may be playing a role in lipid-mediated signaling in these cells. The effects of K-604 may not be limited to cholesterol ester accumulation, as lipid-signaling pathways are complex and highly integrated. Additional work is needed to parse out downstream signaling consequences of inhibiting cholesterol esterification in these cells.

As shown previously (Chen et al., 2001; Genovese et al., 2005; Wilkinson et al., 2020), ITB resulted in a significant loss of body weight (Fig 1). ITB-induced ALI results in increases in infiltrating macrophages, epithelial thickening, and proteinaceous debris deposition in the lung (Lindenschmidt et al., 1986; Izbicki et al., 2002; Ji et al., 2014). We observed significant increases in these criteria (Figs 2, 3) in response to ITB. Acat-1 inhibition with K-604 reduced body weight loss, epithelial thickening, and cellular invasion, however, it did not significantly alter BAL protein. This is consistent with K-604 reducing the inflammatory response to ITB, but not the direct epithelial injury.

The lung lining is a lipid rich environment and the production and recycling of lipid is critical to surfactant function and homeostasis. Both alveolar type II cells and macrophages are critical in maintaining surfactant (Crouch and Wright, 2001; Weaver and Conkright, 2001; Guo et al., 2019). While type II cells produce and recycle surfactant, macrophages are responsible for its degradation (Poelma et al., 2002). SP-B and SP-C, produced by type II cells, are critical to the active regulation of surface tension (Clark et al., 1995; Stahlman et al., 2000; Weaver and Conkright, 2001; Agassandian and Mallampalli, 2013). The ratio of phospholipid:SP-B is thus an indicator of normal surfactant function. ITB increased BAL phospholipid while reducing relative SP-B expression, indicating a loss of surface-active function. K-604 restores SP-B expression, which may normalize function.

SP-D is important in innate immune regulation (Crouch and Wright, 2001; Agassandian and Mallampalli, 2013), producing both pro and anti-inflammatory effects (Agassandian and Mallampalli, 2013). SP-D is exported via a separate vesicular to SP-B by type II cells and its production favors immune regulation over surface-activity. ITB resulted in a

favoring of SP-D production relative to SP-B (Fig 3C). This SP-D:SP-B ratio was reduced by the addition of K-604 to ITB, which is consistent with a reduced inflammatory response. Also, the reduction in oxidative cross linking of SP-D in the ITB + K-604 BAL (Fig 3E), may be indicative of a reduction in oxidative stress. Furthermore, K-604 increases SP-B levels in the BAL irrespective of ITB (Fig 3E), indicating a bias towards surfactant production. A limitation of this study is that intratracheal administration of K-604 targets not only macrophages, but can affect all pulmonary cell types expressing Acat-1. Although macrophages highly express Acat-1, type II cells also express it (Sakashita et al., 2000). Therefore, these changes in lung lining composition may involve type II cells.

Here, we see that 7d after ITB administration there is both cholesterol and cholesterol ester accumulation in BAL cells (Fig 4), which is consistent with foam cell formation and persistent activation (Venosa et al., 2019). Foam cells have been well characterized in models of atherosclerosis and models of lung injury (Venosa et al., 2019), but we cannot confirm their presence in this model simply by measures of cholesterol ester accumulation. The pulmonary microenvironment, even during injury, differs greatly from that of the atherosclerotic plaque, which is known to be mediated by foam cells (Javadifar et al., 2021). In this model, while cholesterol ester accumulation is increased with ITB and reduced by K-604, one cannot conclude that these changes are associated with foam cell formation.

K-604 administration reduces cholesterol ester accumulation, indicating successful inhibition of Acat-1 in the lung. Cholesterol esterification in macrophages has previously been identified as a pharmacological target (Chinetti-Gbaguidi et al.; Bouhlel et al., 2007;

Yang et al., 2020) and the inhibition of Acat-1 reduces lipid-laden cell formation (Ikenoya et al.). Systemic Acat-1 inhibition for the treatment of atherosclerosis, however, resulted in adverse cardiac events, halting the advancement of Acat-1 inhibitors in the clinic (Meuwese et al., 2009). To bypass potential adverse effects linked to systemic administration, we have used intratracheal instillation of K-604, which resulted in inhibition of cholesterol esterification in BAL cells without a significant increase in cell death.

Previously, we have shown that nitrogen mustard exposure down-regulates the ligand-activated liver X receptor LXR (Venosa et al., 2019) and its targets, the efflux transporters *Abca1* and *Abcg1* (Tontonoz and Mangelsdorf, 2003; Beyea et al., 2007), as well as reduced Acat-1 expression. In ITB alone and ITB + K-604, *Abcg1* expression was significantly decreased compared to control (Fig 4C), highlighting that there may be a potential disruption in LXR signaling with ITB that is not rescued by K-604 administration. Although these changes are small, this may be a result of lipid-laden macrophages only being a fraction of the total BAL cell population. Regardless, additional investigation into LXR signaling and its role in lipid-laden cell formation in the context of ALI is needed. However, the changes in efflux transporter expression are insufficient to explain the lipid accumulation seen in BAL cells with ITB.

Altering lipid accumulation within macrophages can significantly alter inflammatory phenotype and indeed both alveolar and interstitial macrophage populations were shifted in response to ITB (Figs 5, 6). There was a significant loss of mature alveolar macrophages in response to ITB (Fig 5B); cells that are important in the maintenance of lung homeostasis (Hussell and Bell, 2014). This population was preserved by K-604,

which is consistent with reducing the post-injury inflammation. Alveolar macrophages play an essential role in surfactant recycling (Weaver and Conkright, 2001; Laskin et al., 2019), and preservation of this population may mediate the K-604-dependent improvement in surfactant homeostasis.

Macrophages are recruited to the lung lining in response to injury (Golden et al., 2022). Here, this response was blunted with K-604, as evidenced by reduced migratory macrophages in the BAL (Fig 5C) and lowered activation (Fig 5E). Phenotypic changes were also observed in interstitial macrophages, where mature activated macrophages were increased in response to ITB (Fig 6B) possibly as a mechanism to replace the diminished mature alveolar macrophage population in the lung (Fig 5). CD206+ interstitial macrophages are immunoregulatory in nature (Bedoret et al., 2009), producing cytokines that promote cell growth and differentiation as well as favoring repair and wound healing (Schyns et al., 2019), and therefore may be pro-fibrotic. Chronic immune cell activation alters tissue composition by collagen deposition and can lead to fibrosis (Klingberg et al., 2013) and negatively impact lung function (Klingberg et al., 2013; Martinez et al., 2017). In this regard, it is significant that this CD11c+/CD206+ population of cells is reduced by K-604, suggesting Acat-1 inhibition can improve resolution and reduce fibrosis. It will be important to study these changes following ITB and K-604 treatment at time points longer than 7d.

Arginine metabolism is critical to macrophage activation, with *Nos2* and *Arg1* expression characterizing acute and chronic activation (Rath et al., 2014; Orecchioni et al., 2019). Both *Nos2* and *Arg1* expression were significantly increased in BAL macrophages from ITB animals (Fig 7A, B), a response that was inhibited by K-604. K-604 therefore

reduces activation without bias towards either *Nos2* or *Arg1*, implying that Acat-1 inhibition reduces both acute and chronic macrophage activation.

In conclusion, in the ITB-mediated ALI model, macrophages experience a lipid-rich extracellular environment due to direct epithelial damage, creating a biological scenario in which there may be increased cholesterol and lipid accumulation. Macrophages in our model become large and display characteristics of the acutely-activated phenotype, which was mitigated by the intratracheal administration of an Acat-1 inhibitor. As well as reducing cholesterol esterification, K-604 reduces the inflammatory effects of ITB-mediated lung inflammation, resulting in preservation of mature alveolar macrophages, reduced recruited and interstitial cell activation, normalization of surfactant alterations, and reduced injury. Acat-1 thus presents a potential pharmacological target in ALI, however further investigations into the mechanisms underlying the effects of Acat-1 inhibition are necessary.

### **Authorship Contributions:**

*Participated in research design:* Stevenson, Guo, Gow

*Conducted experiments:* Stevenson, Wilkinson, Abramova, Guo.

*Performed data analysis:* Stevenson, Wilkinson, Abramova, Guo.

*Wrote or contributed to the writing of the manuscript:* Stevenson, Gow

## References:

- Agassandian M and Mallampalli RK (2013) Surfactant phospholipid metabolism. *Biochimica et biophysica acta* **1831**:612-625.
- Allawzi A, Elajaili H, Redente EF and Nozik-Grayck E (2019) Oxidative Toxicology of Bleomycin: Role of the Extracellular Redox Environment. *Curr Opin Toxicol* **13**:68-73.
- Barbayianni I, Ninou I, Tzouvelekis A and Aidinis V Bleomycin Revisited: A Direct Comparison of the Intratracheal Micro-Spraying and the Oropharyngeal Aspiration Routes of Bleomycin Administration in Mice.
- Bartlett GR (1959) Phosphorous assay in column chromatography. *Journal of Biological Chemistry* **234** 466-468.
- Bedoret D, Wallemacq H, Marichal T, Desmet CJ, Calvo F, Henry E, Closset R and B F Lung interstitial macrophages alter dendritic cell functions to prevent airway allergy in mice.
- Benoit M, Desnues B and Mege JL (2008) Macrophage polarization in bacterial infections. *J Immunol* **181**:3733-3739.
- Beyea MM, Heslop CL, Sawyez CG, Edwards JY, Markle JG, Hegele RA and Huff MW (2007) Selective Up-regulation of LXR-regulated Genes ABCA1, ABCG1, and APOE in Macrophages through Increased Endogenous Synthesis of 24(S),25-Epoxycholesterol\*. *Journal of Biological Chemistry* **282**:5207-5216.
- Bligh EG and Dyer WJ (1959) A rapid method of total lipid extraction and purification. *Can J Biochem Physiol* **37**:911-917.
- Bouhlef MA, Derudas B, Rigamonti E, Dièvert R, Brozek J, Haulon S, Zawadzki C, Jude B, Torpier G, Marx N, Staels B and Chinetti-Gbaguidi G (2007) PPAR $\gamma$  Activation

- Primes Human Monocytes into Alternative M2 Macrophages with Anti-inflammatory Properties. *Cell Metabolism* **6**:137-143.
- Chang CC, Huh HY, Cadigan KM and Chang TY (1993) Molecular cloning and functional expression of human acyl-coenzyme A:cholesterol acyltransferase cDNA in mutant Chinese hamster ovary cells. *J Biol Chem* **268**:20747-20755.
- Chang T-Y, Li B-L, Chang CCY and Urano Y (2009) Acyl-coenzyme A:cholesterol acyltransferases. *Am J Physiol Endocrinol Metab* **297**:E1-E9.
- Chang TY, Chang CC, Lin S, Yu C, Li BL and Miyazaki A (2001) Roles of acyl-coenzyme A:cholesterol acyltransferase-1 and -2. *Curr Opin Lipidol* **12**:289-296.
- Chen ES, Greenlee BM, Wills-Karp M and Moller DR (2001) Attenuation of lung inflammation and fibrosis in interferon-gamma-deficient mice after intratracheal bleomycin. *Am J Respir Cell Mol Biol* **24**:545-555.
- Chen X, Tang J, Shuai W, Meng J, Feng J and Han Z (2020) Macrophage polarization and its role in the pathogenesis of acute lung injury/acute respiratory distress syndrome. *Inflamm Res*. **69**:883-895.
- Chinetti-Gbaguidi G, Colin S and Staels B Macrophage subsets in atherosclerosis (2015). *Nat Rev Cardiol*. **1**:10-7.
- Chistiakov DA, Bobryshev YV and Orekhov AN (2016) Macrophage-mediated cholesterol handling in atherosclerosis. *J Cell Mol Med* **20**:17-28.
- Chistiakov DA, Melnichenko AA, Myasoedova VA, Grechko AV and Orekhov AN (2017) Mechanisms of foam cell formation in atherosclerosis. *J Mol Med (Berl)* **95**:1153-1165.

- Clark JC, Wert SE, Bachurski CJ, Stahlman MT, Stripp BR, Weaver TE and Whitsett JA (1995) Targeted disruption of the surfactant protein B gene disrupts surfactant homeostasis, causing respiratory failure in newborn mice. *Proceedings of the National Academy of Sciences* **92**:7794-7798.
- Cortés I, Peñuelas O and Esteban A (2012) Acute respiratory distress syndrome: evaluation and management. *Minerva Anesthesiol* **78**:343-357.
- Cross LJM and Matthay MA (2011) Biomarkers in Acute Lung Injury: Insights into the Pathogenesis of Acute Lung Injury. *Critical Care Clinics* **27**:355-377.
- Crouch E and Wright JR (2001) Surfactant proteins A and D and pulmonary host defense. *Ann Rev Physiol* **63**:521-554.
- Dushianthan A, Grocott MP, Postle AD and Cusack R (2011) Acute respiratory distress syndrome and acute lung injury. *Postgrad Med J* **87**:612-622.
- Genovese T, Cuzzocrea S, Di Paola R, Mazzon E, Mastruzzo C, Catalano P, Sortino M, Crimi N, Caputi AP, Thiernemann C and Vancheri C (2005) Effect of rosiglitazone and 15-deoxy-Delta12,14-prostaglandin J2 on bleomycin-induced lung injury. *Eur Respir J* **25**:225-234.
- Golden TN, Venosa A and Gow AJ (2022) Cell Origin and iNOS Function Are Critical to Macrophage Activation Following Acute Lung Injury. *Front Pharmacol* **12**.
- Gordon S, Hamann J, Lin HH, Stacey M (2011). F4/80 and the related adhesion-GPCRs. *Eur J Immunol.* **9**:2472-6.
- Guo B, Bai Y, Ma Y, Liu C, Wang S, Zhao R, Dong J and Ji HL (2019) Preclinical and clinical studies of smoke-inhalation-induced acute lung injury: update on both

pathogenesis and innovative therapy. *Ther Adv Respir Dis*

**13**:1753466619847901.

Guo C, Atochina-Vasserman E, Abramova H, George B, Manoj V, Scott P and Gow A

(2016) Role of NOS2 in pulmonary injury and repair in response to bleomycin.

*Free Radic Biol Med* **91**:293-301.

Hartl D, Tirouvanziam R, Laval J, Greene CM, Habel D, Sharma L, Yildirim A, Dela Cruz

CS and Hogaboam CM (2018) Innate Immunity of the Lung: From Basic

Mechanisms to Translational Medicine. *J Innate Immun* **10**:487-501.

Huang X, Xiu H, Zhang S and Zhang G (2018) The Role of Macrophages in the

Pathogenesis of ALI/ARDS. *Mediators Inflamm* **2018**:1264913.

Hussell T and Bell TJ (2014) Alveolar macrophages: plasticity in a tissue-specific

context. *Nat Rev Immunol* **14**:81-93.

Ikenoya M, Yoshinaka Y, Kobayashi H, Kawamine K, Shibuya K, Sato F, Sawanobori K,

Watanabe T, Miyazaki A (2007) A selective ACAT-1 inhibitor, K-604, suppresses  
fatty streak lesions in fat-fed hamsters without affecting plasma cholesterol levels.

*Atherosclerosis* **191**:290-7.

Ioannidis G, Lazaridis G, Baka S, Mpoukovinas I, Karavasilis V, Lampaki S, Kioumis I,

Pitsiou G, Papaiwannou A, Karavergou A, Katsikogiannis N, Sarika E, Tsakiridis

K, Korantzis I, Zarogoulidis K and Zarogoulidis P (2015) Barotrauma and

pneumothorax. *J Thorac Dis* **7**:S38-43.

Izbicki G, Segel M, Christensen T, Conner M and Breuer R (2002) Time course of

bleomycin-induced lung fibrosis. *Int J Exper Pathol* **83**:111-119.

- Javadifar A, Rastgoo S, Banach M, Jamialahmadi T, Johnston TP and Sahebkar A (2021) Foam Cells as Therapeutic Targets in Atherosclerosis with a Focus on the Regulatory Roles of Non-Coding RNAs. *Int J Mol Sci* **22**:2529.
- Ji W-J, Ma Y-Q, Zhou X, Zhang Y-D, Lu R-Y, Sun H-Y, Guo Z-Z, Zhang Z, Li Y-M and Wei L-Q (2014) Temporal and spatial characterization of mononuclear phagocytes in circulating, lung alveolar and interstitial compartments in a mouse model of bleomycin-induced pulmonary injury. *J Immunol Methods* **403**:7-16.
- Johnson ER and Matthay MA (2010) Acute lung injury: epidemiology, pathogenesis, and treatment. *J Aerosol Med Pulm Drug Deliv* **23**:243-252.
- Johnston LK, Rims CR, Gill SE, McGuire JK and Manicone AM (2012) Pulmonary macrophage subpopulations in the induction and resolution of acute lung injury. *Am J Respir Cell Mol Biol* **47**:417-426.
- Klingberg F, Hinz B and White ES (2013) The myofibroblast matrix: implications for tissue repair and fibrosis. *J Pathol* **229**:298-309.
- Kobayashi Y (2010) The regulatory role of nitric oxide in proinflammatory cytokine expression during the induction and resolution of inflammation. *J Leukoc Biol* **88**:1157-1162.
- Laskin DL (2009) Macrophages and inflammatory mediators in chemical toxicity: a battle of forces. *Chem Res Toxicol* **22**:1376-1385.
- Laskin DL, Malaviya R and Laskin JD (2019) Role of Macrophages in Acute Lung Injury and Chronic Fibrosis Induced by Pulmonary Toxicants. *Toxicol Sci* **168**:287-301.

- Lindenschmidt RC, Tryka AF, Godfrey GA, Frome EL and Witschi H (1986) Intratracheal versus intravenous administration of bleomycin in mice: acute effects. *Toxicol Appl Pharmacol* **85**:69-77.
- MacMicking J, Xie QW and Nathan C (1997) Nitric oxide and macrophage function. *Annu Rev Immunol* **15**:323-350.
- Martin TR and Frevert CW (2005) Innate immunity in the lungs. *Proc Am Thorac Soc* **2**:403-411.
- Martinez FJ, Collard HR, Pardo A, Raghu G, Richeldi L, Selman M, Swigris JJ, Taniguchi H and Wells AU (2017) Idiopathic pulmonary fibrosis. *Nat Rev Dis Primers* **3**:17074.
- Matthay MA and Zimmerman GA (2005) Acute lung injury and the acute respiratory distress syndrome: four decades of inquiry into pathogenesis and rational management. *Am J Respir Cell Mol Biol* **33**:319-327.
- Meuwese MC, de Groot E, Duivenvoorden R, Trip MD, Ose L, Maritz FJ, Basart DCG, Kastelein JJP, Habib R, Davidson MH, Zwinderman AH, Schwocho LR, Stein EA (2009) ACAT Inhibition and Progression of Carotid Atherosclerosis in Patients With Familial Hypercholesterolemia: The CAPTIVATE Randomized Trial. *Jama* **301**:1131-1139.
- Misharin AV, Morales-Nebreda L, Mutlu GM, Budinger GRS and Perlman H (2013) Flow cytometric analysis of macrophages and dendritic cell subsets in the mouse lung. *Am J Respir Cell Mol Biol* **49**:503-510.
- Mokra D and Kosutova P (2015) Biomarkers in acute lung injury. *Resp Physiol Neurobiol* **209**:52-58.

- Müller-Redetzky HC, Suttorp N and Witzenrath M (2014) Dynamics of pulmonary endothelial barrier function in acute inflammation: mechanisms and therapeutic perspectives. *Cell Tissue Res* **355**:657-673.
- Orecchioni M, Ghosheh Y, Pramod AB and Ley K (2019) Macrophage Polarization: Different Gene Signatures in M1(LPS+) vs. Classically and M2(LPS-) vs. Alternatively Activated Macrophages. *Front Immunol* **10**:1084-1084.
- Patel U, Rajasingh S, Samanta S, Cao T, Dawn B and Rajasingh J (2017) Macrophage polarization in response to epigenetic modifiers during infection and inflammation. *Drug Discovery Today* **22**:186-193.
- Patel VJ, Biswas Roy S, Mehta HJ, Joo M and Sadikot RT (2018) Alternative and Natural Therapies for Acute Lung Injury and Acute Respiratory Distress Syndrome. *Biomed Res Int* **2018**:2476824.
- Pittet JF, MacKersie RC and Martin TR (1997) Biological markers of acute lung injury: prognostic and pathogenetic significance. *Am J Respir Crit Care Med* **155**:1187-1205.
- Poelma DLH, Zimmermann LJI, Scholten HH, Lachmann B and Iwaarden JFv (2002) In vivo and in vitro uptake of surfactant lipids by alveolar type II cells and macrophages. *Am J Physiol Lung Cell* **283**:L648-L654.
- Porcheray F, Viaud S, Rimaniol AC, Léone C, Samah B, Dereuddre-Bosquet N, Dormont D and Gras G (2005) Macrophage activation switching: an asset for the resolution of inflammation. *Clin Exp Immunol* **142**:481-489.

- Rath M, Müller I, Kropf P, Closs EI and Munder M (2014) Metabolism via Arginase or Nitric Oxide Synthase: Two Competing Arginine Pathways in Macrophages. *Front Immunol* **5**:532-532.
- Roach T, Slater S, Koval M, White L, McFarland EC, Okumura M, Thomas M and Brown E (1997) CD45 regulates Src family member kinase activity associated with macrophage integrin-mediated adhesion. *Curr Biol* **7**:408-417.
- Ross R (1999) Atherosclerosis—an inflammatory disease. *NEJM* **340**:115-126.
- Sakashita N, Miyazaki A, Takeya M, Horiuchi S, Chang CC, Chang TY and Takahashi K (2000) Localization of human acyl-coenzyme A: cholesterol acyltransferase-1 (ACAT-1) in macrophages and in various tissues. *Am J Pathol* **156**:227-236.
- Schyns J, Bai Q, Ruscitti C, Radermecker C, De Schepper S, Chakarov S, Farnir F, Pirottin D, Ginhoux F, Boeckxstaens G, Bureau F and Marichal T (2019) Non-classical tissue monocytes and two functionally distinct populations of interstitial macrophages populate the mouse lung. *Nat Commun* **10**:3964.
- Sekiya M, Osuga J, Igarashi M, Okazaki H and Ishibashi S (2011) The role of neutral cholesterol ester hydrolysis in macrophage foam cells. *J Atheroscler Thromb* **18**:359-364.
- Shearer JD, Richards JR, Mills CD and Caldwell MD (1997) Differential regulation of macrophage arginine metabolism: a proposed role in wound healing. *Am J Physiol* **272**:E181-190.
- Shibuya K, Kawamine K, Ozaki C, Ohgiya T, Edano T, Yoshinaka Y and Tsunenari Y (2018) Discovery of Clinical Candidate 2-(4-(2-((1H-Benzo[d]imidazol-2-yl)thio)ethyl)piperazin-1-yl)-N-(6-methyl-2,4-bis(methylthio)pyridin-3-yl)acetamide

Hydrochloride [K-604], an Aqueous-Soluble Acyl-CoA:Cholesterol O-Acyltransferase-1 Inhibitor. *J Med Chem* **61**:10635-10650.

Stahlman MT, Gray MP, Falconieri MW, Whitsett JA and Weaver TE (2000) Lamellar body formation in normal and surfactant protein B-deficient fetal mice. *Lab Invest* **80**:395-403.

Stöger JL, Gijbels MJJ, van der Velden S, Manca M, van der Loos CM, Biessen EAL, Daemen MJAP, Lutgens E and de Winther MPJ (2012) Distribution of macrophage polarization markers in human atherosclerosis. *Atherosclerosis* **225**:461-468.

Tam A, Wadsworth S, Dorscheid D, Man SFP and Sin DD (2011) The airway epithelium: more than just a structural barrier. *Thorax* **5**:255-273.

Tontonoz P and Mangelsdorf DJ (2003) Liver X receptor signaling pathways in cardiovascular disease. *J Mol Endocrinol* **17**:985-993.

Trowbridge IS and Thomas ML (1994) CD45: an emerging role as a protein tyrosine phosphatase required for lymphocyte activation and development. *Ann Review Immunol* **12**:85-116.

Venosa A, Gow JG, Taylor S, Golden TN, Murray A, Abramova E, Malaviya R, Laskin DL and Gow AJ (2021) Myeloid cell dynamics in bleomycin-induced pulmonary injury in mice; effects of anti-TNF $\alpha$  antibody. *Toxicol Appl Pharmacol* **417**:115470.

Venosa A, Smith LC, Murray A, Banota T, Gow AJ, Laskin JD and Laskin DL (2019) Regulation of Macrophage Foam Cell Formation During Nitrogen Mustard (NM)-Induced Pulmonary Fibrosis by Lung Lipids. *Toxicol Sci* **172**:344-358.

- Ware LB (2006) Pathophysiology of acute lung injury and the acute respiratory distress syndrome, in *Semin Respir Crit Care Med* pp 337-349.
- Weaver TE and Conkright JJ (2001) Function of surfactant proteins B and C. *Ann Rev Physiol* **63**:555-578.
- Wilkinson ML, Abramova E, Guo C, Gow JG, Murray A, Koudelka A, Cechova V, Freeman BA and Gow AJ (2020) Fatty acid nitroalkenes inhibit the inflammatory response to bleomycin-mediated lung injury. *Toxicol Appl Pharmacol* **407**:115236.
- Y B, A K and TC A (2016) Acute Lung Injury: A Clinical and Molecular Review. *Arch Pathol Lab Med* **140**:345-350.
- Yang S, Yuan HQ, Hao YM, Ren Z, Qu SL, Liu LS, Wei DH, Tang ZH, Zhang JF and Jiang ZS (2020) Macrophage polarization in atherosclerosis. *Clin Chim Acta* **501**:142-146.
- Yu X-H, Fu Y-C, Zhang D-W, Yin K and Tang C-K (2013) Foam cells in atherosclerosis. *Clin Chim Acta* **424**:245-252.
- Zaynagetdinov R, Sherrill TP, Kendall PL, Segal BH, Weller KP, Tighe RM and Blackwell TS (2013) Identification of myeloid cell subsets in murine lungs using flow cytometry. *Am J Respir Cell Mol Biol* **49**:180-189.

**Footnotes:**

This work was supported by the National Institutes of Health National Heart, Lung, and Blood Institute [Grant 086621]; and the National Institutes of Health National Institute of Environmental Health Sciences [Grant T32ES01984; P30ES005022].

No author has an actual or perceived conflict of interest with the contents of this article.

## Figure Legends

**Fig 1.** Intratracheal administration of K-604 reduces ITB-mediated loss of bodyweight. Difference between d0 and d7 bodyweight is shown as a percentage of d0 weight (n = 16-21 per group). Values are expressed as mean  $\pm$  standard error of the mean. (\*) represents significantly different from control (p < 0.05); (#) represents significantly different from ITB (p < 0.05).

**Fig 2.** Effect of K-604 on histological markers of ITB-mediated injury. (A) Representative H&E-stained lung tissue sections derived from control (top left), K-604 (bottom left), ITB (top right) and ITB + K-604 (bottom right) treated animals (n=16-21 per group). Images were obtained using a VS120 microscope (inset: 40x; magnified image: 400x). Randomly distributed images (n=10) from each tissue preparation were analyzed for the number of nuclei present (B), percentage of white space (C), and average alveolar wall thickness (D). Values are expressed as mean  $\pm$  standard error of the mean. (\*) represents significantly different from control (p < 0.05); (#) represents significantly different from ITB (p < 0.05).

**Fig 3.** Effects of ITB on total protein, phospholipid and surfactant protein expression within the BAL. Protein concentration (A), phospholipid concentration (B), SP-D:SP-B ratio (C) and phospholipid:SP-B ratio were reported (D) accompanied by representative western blots (E) from analysis of BAL fluid. Values are expressed as mean  $\pm$  standard error of the mean (n=8-12 per group). (\*) represents significantly different from control (p < 0.05); (#) represents significantly different from ITB (p < 0.05).

**Fig 4.** K-604 reduces ITB-mediated increases cholesterol content of BAL cells. Cells from the BAL were analyzed for total cholesterol, free cholesterol, and cholesterol esters

(A) reported as cholesterol ( $\mu\text{M}$ ) per  $1 \times 10^4$  cells. BAL cell expression of *Abca1* (B) and *Abcg1* (C) was determined by RT-qPCR and is shown as fold change over control. Values are expressed as mean  $\pm$  standard error of the mean ( $n=5-16$  per group). (\*) represents significantly different from control ( $p < 0.05$ ); (#) represents significantly different from ITB ( $p < 0.05$ ).

**Fig 5.** Flow cytometric analysis of macrophages in the BAL fluid. Cells were immunostained and analyzed by flow cytometry (Supplemental Fig 1). Cells that were positively stained for both Siglec F and F4/80 were determined to be alveolar macrophages (AMs). Mature macrophages (CD11c+/CD11b-), migratory macrophages (CD11c+/CD11b+), and recruited macrophages (CD11c-/CD11b+) were identified from alveolar macrophages in the BAL (A). The percentage of mature (B), migratory (C), and recruited macrophages (D) was calculated from the total number of alveolar macrophages and were assessed for their Ly6c and CD206 expression. The percentage of CD11b+ alveolar macrophages that were identified as expressing the acutely activated phenotype (Ly6c+/CD206-) was determined (E). Values are expressed as mean  $\pm$  standard error of the mean ( $n= 8-13$  per group). (\*) represents significantly different from control ( $p < 0.05$ ); (#) represents significantly different from ITB ( $p < 0.05$ ).

**Fig 6.** Flow cytometric analysis of macrophages isolated from lung tissue. Cells from digested lung tissue were immunomagnetically-separated based upon CD45 expression. CD45+ cells were isolated, immunostained, and analyzed (Supplemental Fig 2). Cells that expressed F4/80 and CD11b in the absence of Siglec F were categorized as interstitial macrophages and were analyzed for CD11c/CD206 expression (A). The percentage of mature, chronically activated cells (CD11c+/CD206+, green box) was

calculated from the total number of interstitial macrophages (B). Values are expressed as mean  $\pm$  standard error of the mean (n= 8-13 per group). (\*) represents significantly different from control (p < 0.05); (#) represents significantly different from ITB (p < 0.05).

**Fig 7.** K-604 inhibits ITB-mediated induction of the inflammatory enzymes *Nos2* and *Arg1*. BAL cells were analyzed for *Nos2* and *Arg1* expression by RT-qPCR.  $2^{-\Delta\Delta ct}$  values were calculated using *Gapdh* as the control gene and PBS as the control condition to calculate fold change in expression. Values are expressed as mean  $\pm$  standard error of the mean (n= 8 per group). (\*) represents significantly different from control (p < 0.05); (#) represents significantly different from ITB (p < 0.05).

## Tables

**Table 1.** Expression Profile of Surface Markers Used for Flow Cytometric Analysis of Alveolar and Interstitial Macrophages

<b>Cell Surface Marker</b>	<b>Expression Profile</b>
CD45	Myeloid-derived cells, including alveolar and interstitial macrophages (Trowbridge and Thomas, 1994; Roach et al., 1997; Misharin et al., 2013)
Siglec F	Highly expressed on alveolar macrophages (Misharin et al., 2013; Hussell and Bell, 2014)
F4/80	Pulmonary macrophages, including alveolar and interstitial macrophages (Gordon et al.; Misharin et al., 2013; Hussell and Bell, 2014)
CD11b	Indicative of a migratory phenotype; expressed on interstitial macrophages, with low expression in resident alveolar macrophages (Zaynagetdinov et al., 2013; Hussell and Bell, 2014)
CD11c	Resident alveolar macrophages and mature interstitial macrophages (Hussell and Bell, 2014)
CD206	Pro-fibrotic marker on activated interstitial macrophages. Expression on alveolar macrophages indicates an anti-inflammatory bias (Zaynagetdinov et al., 2013; Hussell and Bell, 2014; Ji et al., 2014)

Fig 1.

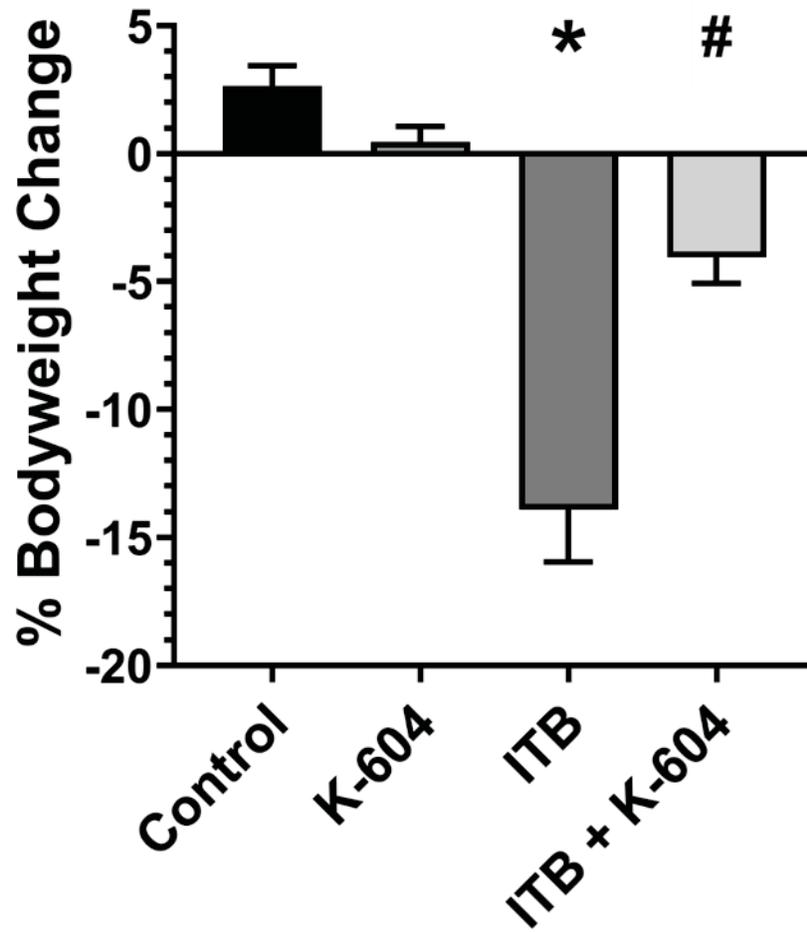
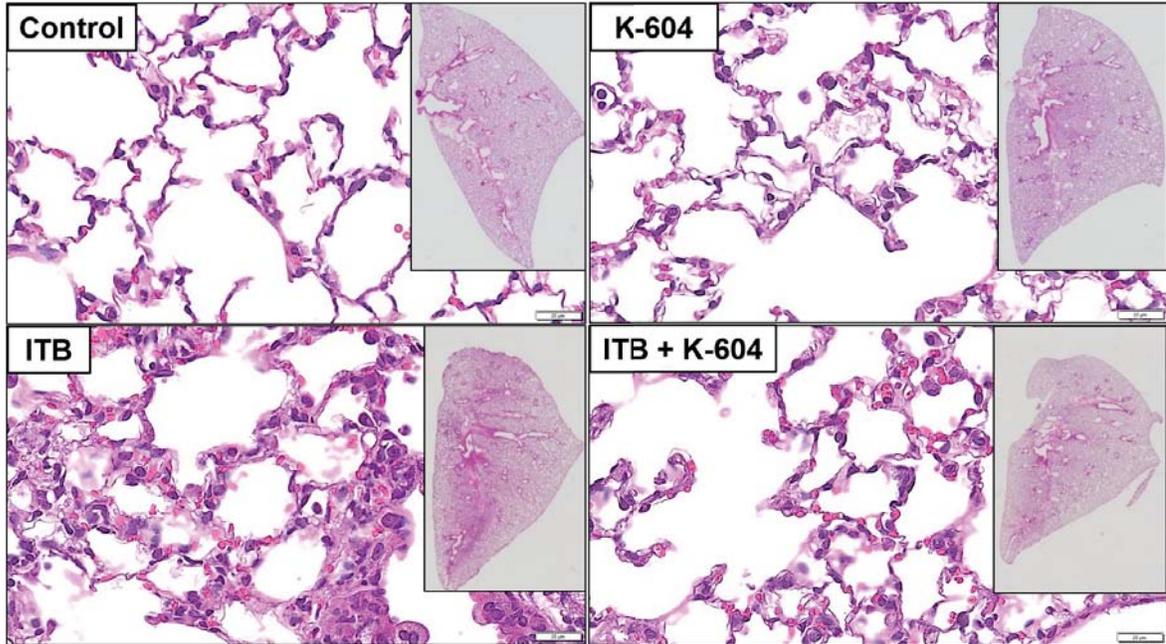
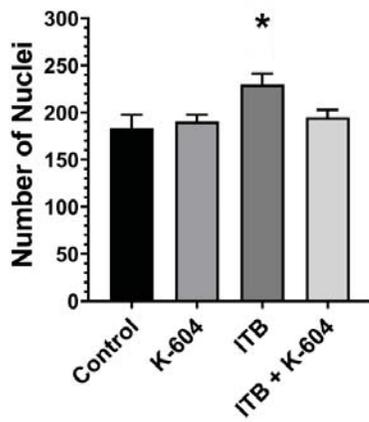


Fig 2.

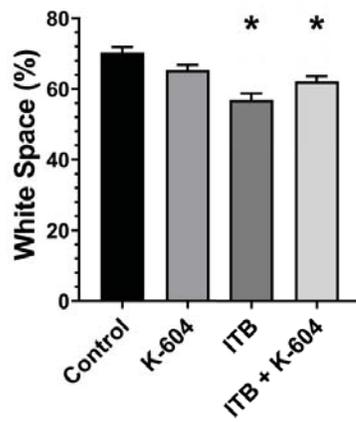
**A**



**B**



**C**



**D**

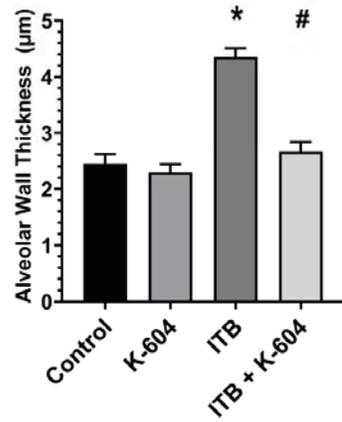


Fig 3.

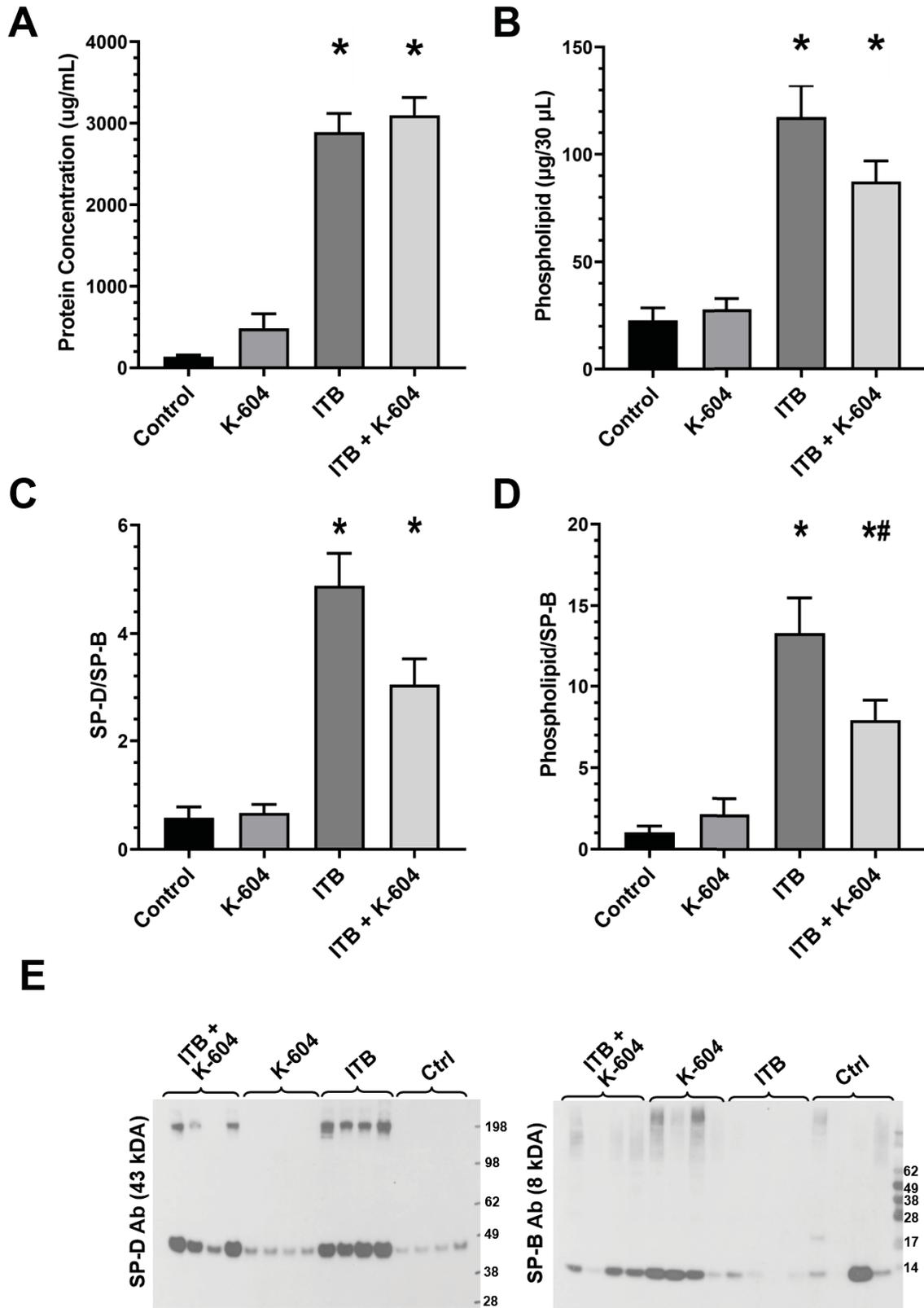


Fig 4.

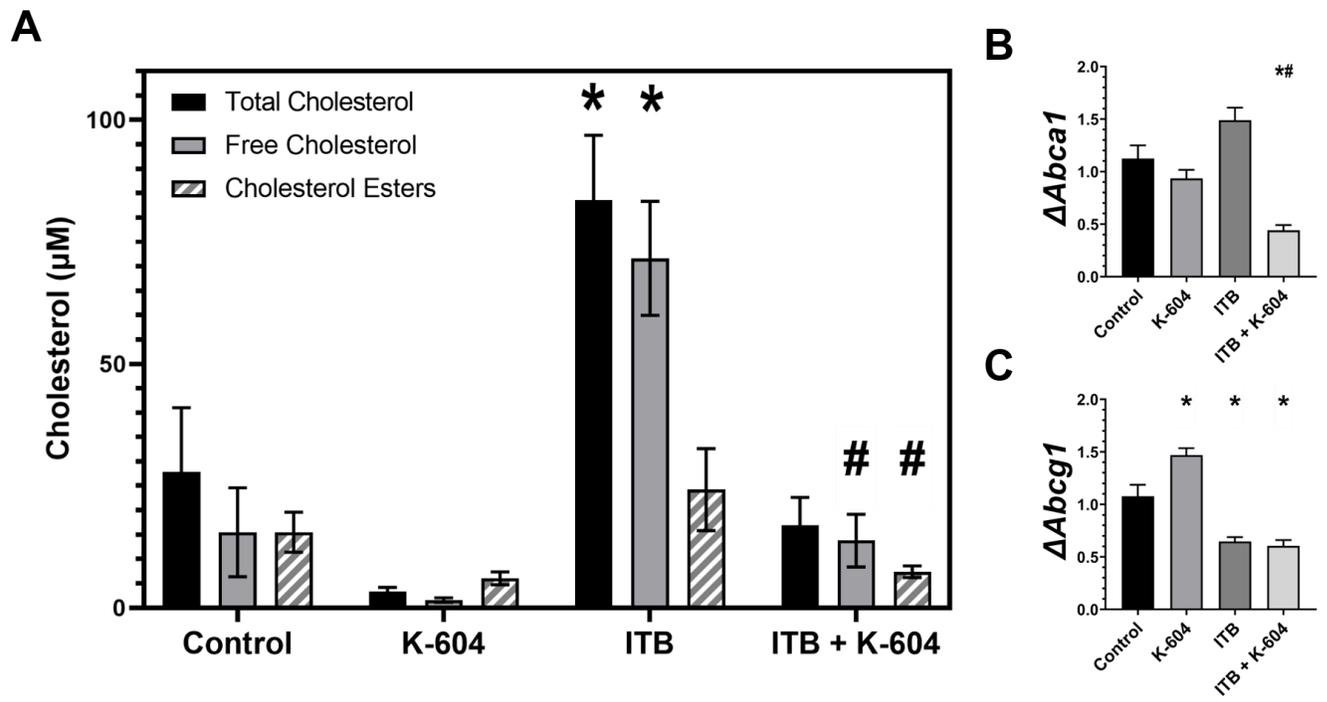


Fig 5.

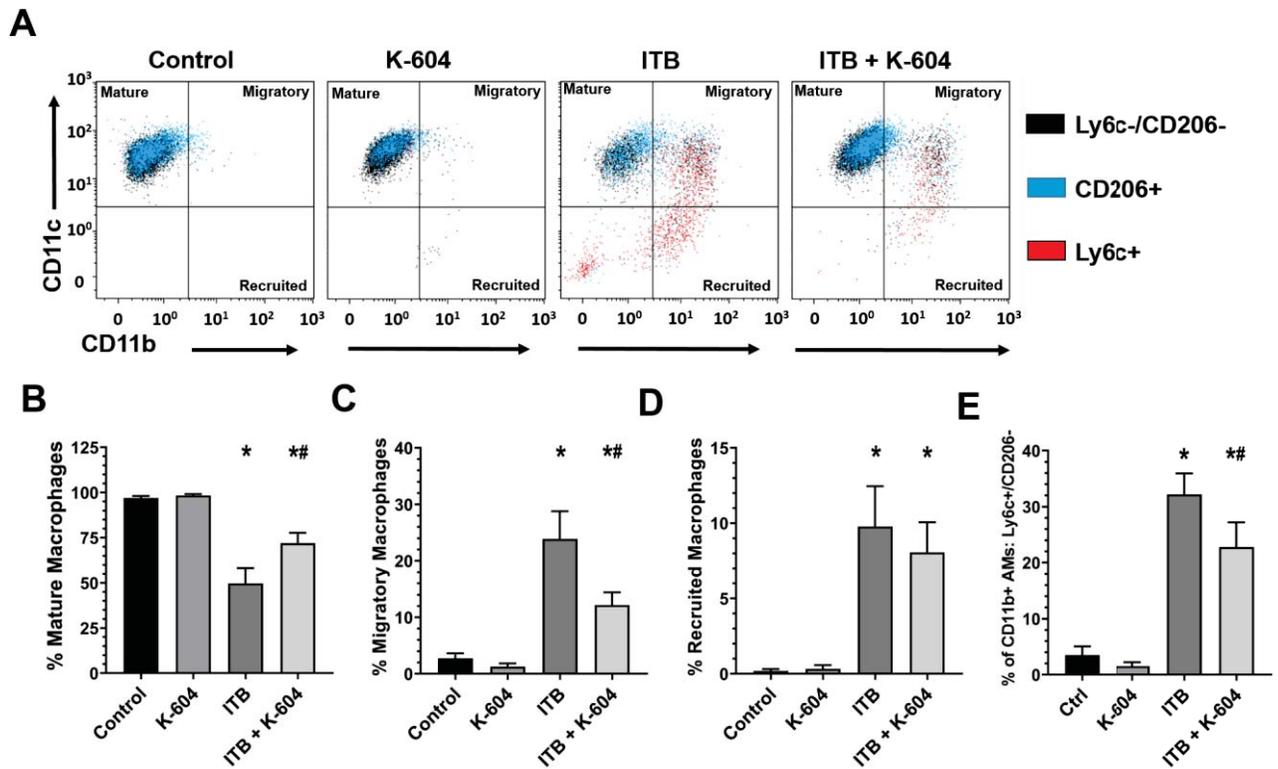


Fig 6.

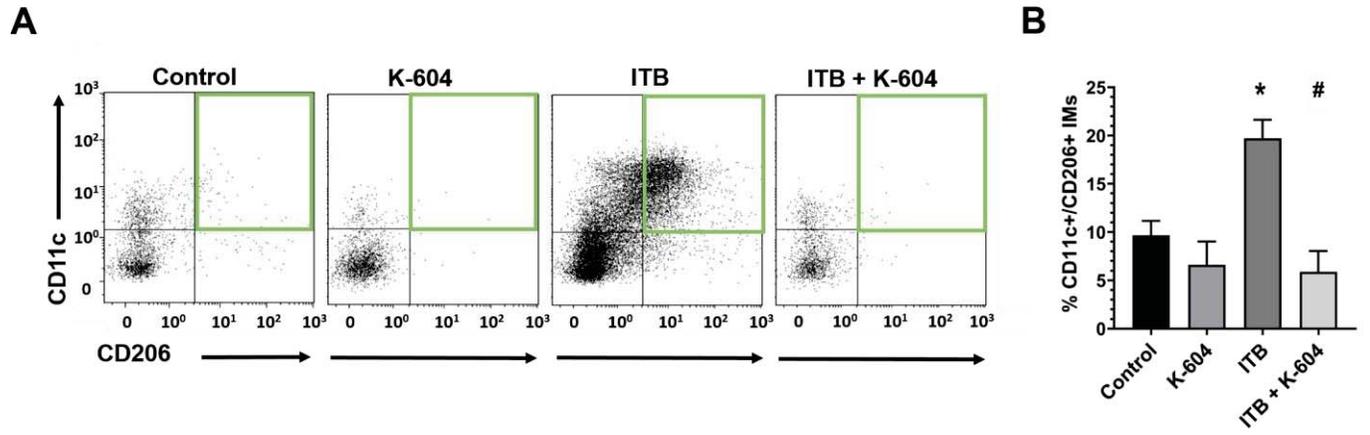
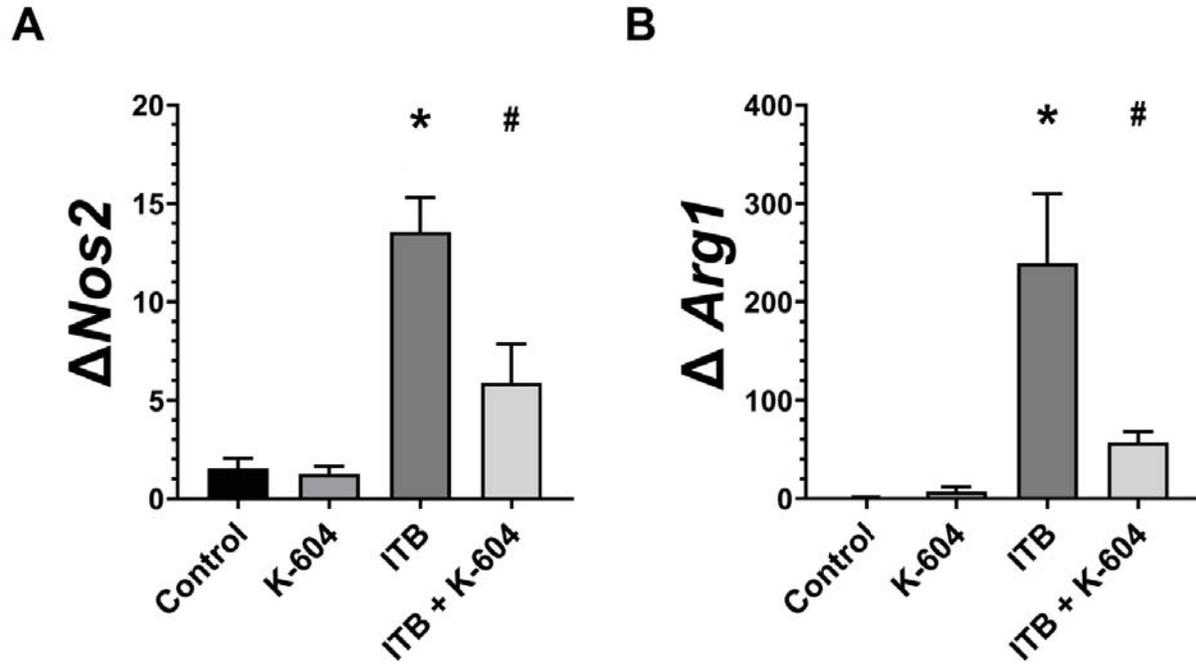


Fig 7.



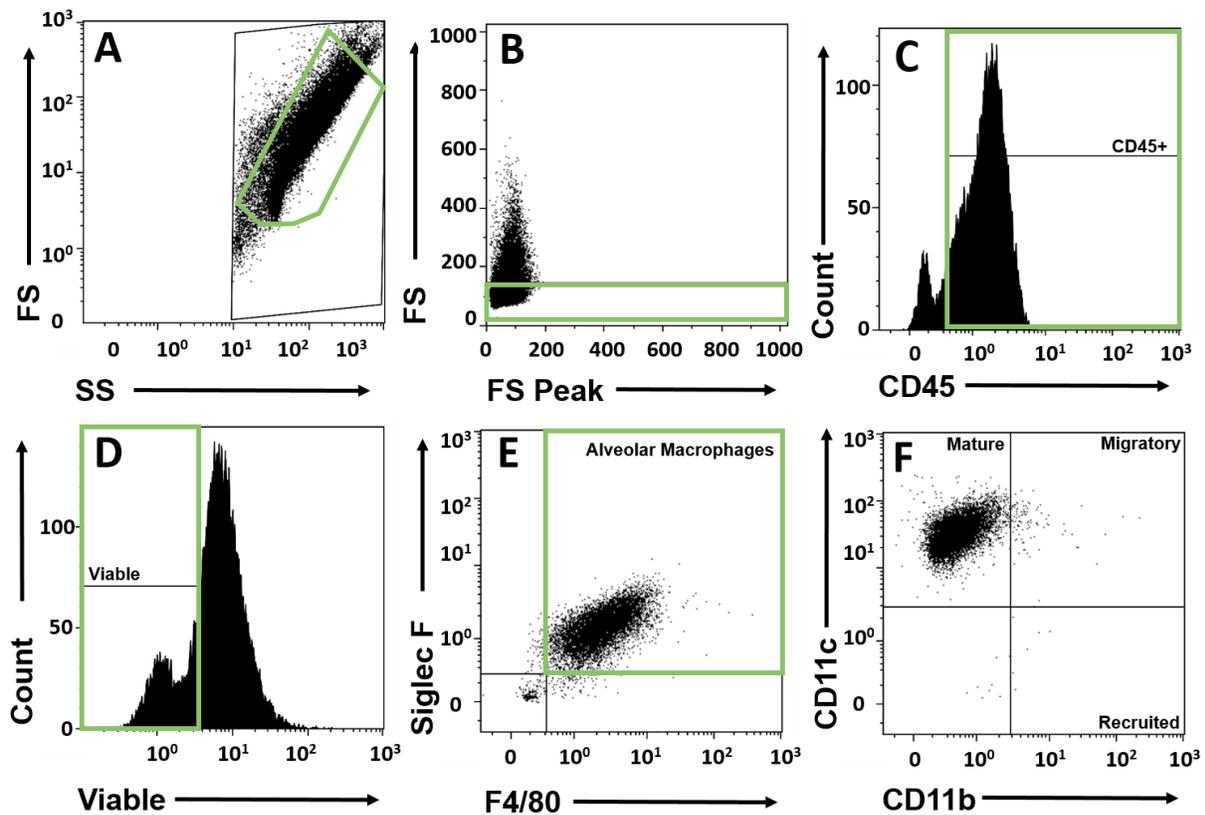
# Intratracheal Administration of Acat-1 Inhibitor K-604 Reduces Pulmonary Inflammation Following Bleomycin-induced Lung Injury

Emily R. Stevenson<sup>1</sup>, Melissa L. Wilkinson<sup>1</sup>, Elena Abramova<sup>1</sup>, Changjiang Guo<sup>1</sup>, Andrew J. Gow<sup>1\*</sup>

The Journal of Pharmacology and Experimental Therapeutics

Manuscript Number: JPET-AR-2022-001284

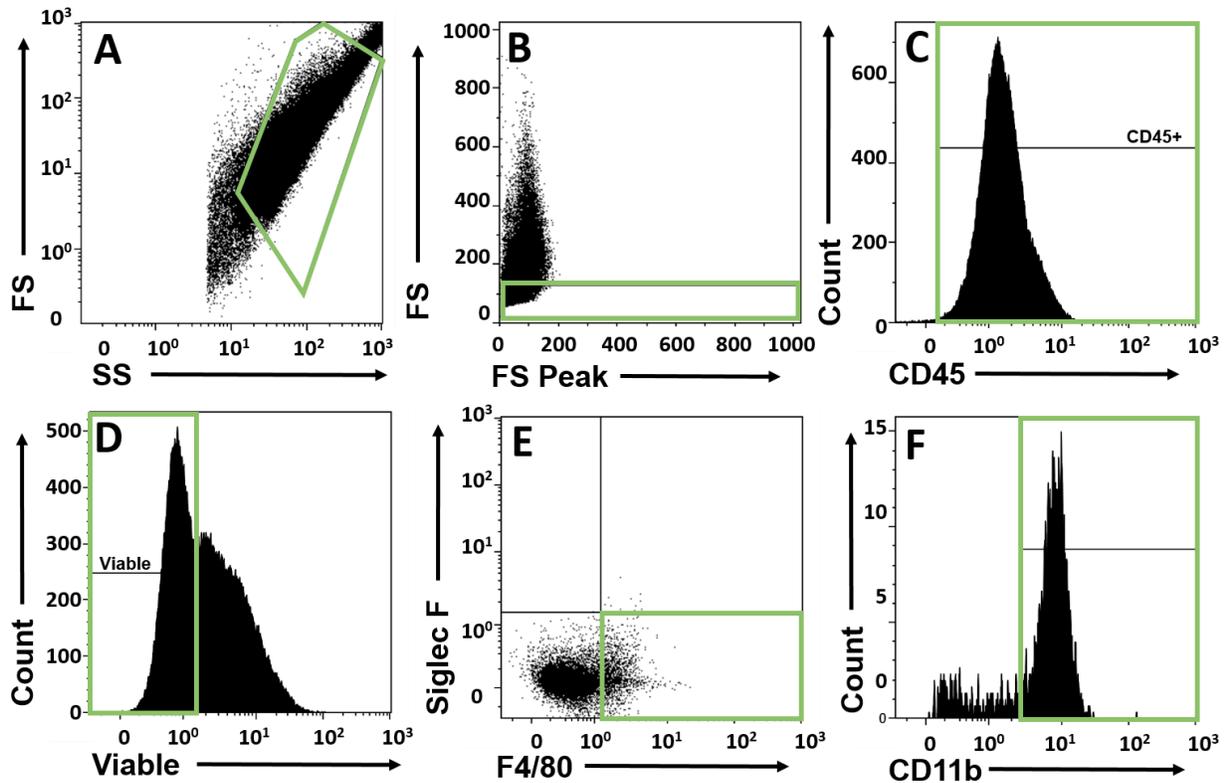
## Supplemental Data



**Supplemental Fig 1.** Flow cytometric analysis of alveolar macrophages in the BAL fluid.

Cells were isolated from the BAL 7d post-ITB or PBS administration, ± intratracheal K-604

administration. Cells were collected and stained with the fluorescent antibodies listed in Table 1. Cells were analyzed using a Gallios 10-color flow cytometer (Beckman Coulter, Brea, CA). Using Kaluza software (Beckman Coulter, Brea, CA) cells were gated upon size and complexity (A, B), CD45 positivity (C) and viability (D). Cells that were positively stained for both Siglec F and F4/80 (E) were determined to be alveolar macrophages (AMs), highlighted in the green square. AMs were then analyzed for CD11c and CD11b expression (F) and further characterized (Fig 5).



**Supplemental Fig 2.** Flow cytometric analysis of interstitial macrophages from lung tissue digest. Right lung lobes from treated animals were digested and immunomagnetically separated based upon the presence of CD45 (Section 2.5). CD45+ cells were isolated and stained with the fluorescent antibodies listed in Table 1. Cells were analyzed using a Gallios 10-color flow cytometer (Beckman Coulter, Brea, CA). Using Kaluza software (Beckman Coulter, Brea, CA) cells were gated upon size and complexity (A, B), CD45 positivity (C) and viability (D). Cells that stained positively for F4/80 and exhibited absence of Siglec F (E) were then analyzed for CD11b expression (F). These cells were categorized as interstitial macrophages for further analyses (Fig 6).