NIH Public Access
Author Manuscript
J Biochem Mol Toxicol. Author manuscript; available in PMC 2014 April 29.

Published in final edited form as:
J Biochem Mol Toxicol. 2013 January ; 27(1): 77–86. doi:10.1002/jbt.21467.

Vitamin D Treatment Modulates Organic Dust-Induced Cellular and Airway Inflammatory Consequences

Gregory A. Golden, DO[1], **Todd A. Wyatt, PhD**[3,1,2], **Debra J. Romberger, MD**[3,1], **Daniel Reiff**[1], **Michael McCaskill, PhD**[2], **Christopher Bauer, BS**[1], **Angela M. Gleason, MA**[1], and **Jill A. Poole, MD**[1]

[1]Pulmonary, Critical Care, Sleep and Allergy Division; Department of Medicine, University of Nebraska Medical Center, 985300 The Nebraska Medical Center, Omaha, NE 68198-5300.

[2]Departments of Environmental, Agricultural, and Occupational Health, University of Nebraska Medical Center, 985300 The Nebraska Medical Center, Omaha, NE 68198-5300.

[3]Veterans Administration-Nebraska Western Iowa Healthcare System, Omaha, NE 68105.

Abstract

Exposure to organic dusts elicits airway inflammatory diseases. Vitamin D recently has been associated with various airway inflammatory diseases, but its role in agricultural organic dust exposures is unknown. This study investigated whether vitamin D reduces organic dust-induced inflammatory outcomes in cell culture and animal models. Organic dust extracts obtained from swine confinement facilities induced neutrophil chemokine production (human IL-8, murine CXCL1/CXCL2). Neutrophil chemokine induction was reduced in human blood monocytes, human bronchial epithelial cells and murine lung slices pretreated with 1,25-$(OH)_2D_3$. Intranasal inhalation of organic dust extract induced neutrophil influx and CXCL1/CXCL2 release also was decreased in mice fed a relatively high vitamin D diet as compared to mice fed a low vitamin D diet. These findings were associated with reduced tracheal epithelial cell PKCα and PKCε activity and whole lung TLR2 and TLR4 gene expression. Collectively, vitamin D plays a role in modulating organic dust-induced airway inflammatory outcomes.

INTRODUCTION

Pulmonary disease is an established occupational hazard of agricultural work (1). In the United States and worldwide, agriculture systems have increased in size to maximize production, which has led, in part, to the creation of largely indoor swine animal feeding confinement facilities (2). Agriculture workers in these facilities are at high risk to develop respiratory diseases including chronic bronchitis, obstructive lung disease, and asthma symptoms as a result of their exposure to the organic dust environments (3,4). However, there is variability in disease occurrence and severity among workers, which has not been entirely explained by levels of dust and/or endotoxin concentrations within the operations

Send Correspondence to: Jill A. Poole, MD, Pulmonary, Critical Care, Sleep & Allergy Division; Department of Medicine, University of Nebraska Medical Center, 985300 The Nebraska Medical Center, Omaha, NE 68198-5300, japoole@unmc.edu; Fax: 402-559-8210; Phone: 402-559-4087.

(3), suggesting that other host and/or environmental factors may be important. Vitamin D is a potential immunomodulator that may play a role in agricultural-induced lung disease as recent studies have found that low serum vitamin D levels are associated with increased risk of asthma severity and chronic bronchitis (5,6). Moreover, vitamin D may have a relevant role in indoor farming work because others have found that indoor work correlates with diminished sunlight exposure and lower serum 25-hydroxy (25OHD) vitamin D levels (7–9). However, the role of vitamin D in agricultural organic dust exposure-induced respiratory disease has not been described.

Organic dust from swine confinement environments represents a complex mixture of particulate matter and a wide diversity of microbial components from Gram-positive and Gram-negative bacteria, archeabacteria and fungi (3). Organic dust exposures can elicit airway inflammatory responses marked by neutrophil influx and release of pro-inflammatory mediators in humans and animals including neutrophil chemoattractants, human interleukin (IL)-8 and murine homologs, CXCL1 and CXCL2 (10,11). Several important mechanisms to explain organic dust-induced airway inflammatory response have been demonstrated. Activation of protein kinase C (PKC) isoforms is important in mediating dust-induced epithelial cell responses, and activation of PKCα and PKCε parallels dust-induced airway inflammatory consequences (11–13). Innate immune pattern recognition receptors, specifically Toll-like receptor 2 (TLR2) and TLR4, have also been implicated in mediating large animal (swine) confinement organic dust-induced airway disease (10,14,15). Namely, mice deficient in TLR2 and TLR4 demonstrate reduced airway inflammatory responses following swine confinement organic dust exposures (10,15). However, practical strategies other than physical strategies to prevent and/or alleviate airway disease from exposure to complex organic dusts are lacking.

There is mounting evidence to support a potential role for vitamin D to reduce inflammatory respiratory diseases. Mice deficient in the vitamin D receptor show increased NF-κB activity (16), and moreover, this increased NF-κB activity leads to an increase in lung inflammation, cytokine production, and increased fibroblast cells (17). In addition, exposure to 1,25-$(OH)_2D_3$ (active vitamin D) potentiates the beneficial effects of allergen immunotherapy in the mouse model of allergic asthma (18). Importantly, treatment with 1,25-$(OH)_2D_3$ has been shown to reduce peripheral blood mononuclear cell TLR2 and TLR4 expression (19), and decrease lipopolysaccharide (LPS)-induced inflammatory cytokine production in bone marrow-derived monocytes (20). Finally, in severe asthmatics, lower serum concentrations of 25OHD have been associated with impaired lung function, increased airway hyper-responsiveness and reduced response to glucocorticoids (5).

Based on these observations, we hypothesized that vitamin D would reduce organic dust-induced inflammatory consequences *in vitro* and *in vivo*, and that vitamin D would modulate organic dust-induced PKC isoform activation and TLR2 and TLR4 expression.

METHODS

Swine Facility Organic Dust Extract (ODE)

Organic dust was collected from settled dust (~3 feet above floor level) at local swine confinement feeding operations housing more than 500–700 hogs as previously described (11). Briefly, aqueous dust extracts were prepared by incubating 1g of the dust in 10ml of Hank's Balanced Salt Solution (Life Technologies, Grand Island, NY) at room temperature for one hour. Mixture was centrifuged twice at 500*g* and final supernatant was filter (0.22 μm) sterilized, which is a process that also removes coarse particles. Batches of stock (100%) aqueous extracts (ODE) were frozen at −80°C, and ODE was diluted (vol/vol) in growth media or sterile phosphate buffered saline (PBS) for *in vitro* and *in vivo* experimental studies, respectively. The diluted 1%–5% ODE has previously been determined to elicit optimal pro-inflammatory chemokine release from cultured cells (13,21), and the diluted 12.5% ODE has been shown to elicit maximal airway inflammation in mice and is well tolerated (10). Complete analysis of the dust extract has been previously published (14). Briefly, stock (100%) ODE contains 23.3–31.1 mg/ml of total protein as measured by nanodrop spectrophotometry (NanoDrop Technologies, Wilmington, DE). Endotoxin levels in stock ODE range from 184 to 760 EU/ml as assayed using the limulus amebocyte lysate assay according to manufacturer's instruction (Sigma, St. Louis, MO).

Cell Culture

BEAS-2B cells (American Tissue Culture Collection, Manassas, VA), an SV40-transformed human bronchial epithelia cell line, were plated on type I collagen-coated (Celtrix Laboratories (Palo Alto, USA)) 100mm×155mm dishes and maintained in serum-free LHC-9-RPMI (Sigma-Aldrich, St. Louis, MO) supplemented with Fungizone and Penicillin/Streptomycin (Invitrogen, Grand Island, NY) at 37°C in 5% CO_2. Confluent monolayers (~80% confluency) were pretreated with or without 1,25-$(OH)_2D_3$ (100 nM) (Sigma-Aldrich) for 18 hours. Next, cells were washed and fresh control or vitamin D-supplemented media was reapplied and epithelial cells were simulated with 5% ODE or saline for 24 hours. Cell-free supernatants were collected and frozen at −80°C for later chemokine analysis. Cells were harvested to determine protein concentrations by a nanodrop spectrophotometer. Viability of cell cultures was assured by lactate dehydrogenase assay (Sigma-Aldrich).

Human peripheral blood monocytes were collected from volunteer donors at the institution's Elutriation Core Facility as previously described (21). Briefly, monocytes were isolated by countercurrent centrifugal elutriation of mononuclear leukocyte-rich fractions and purity of monocyte populations confirmed by determination of CD14 cell surface expression by flow cytometry (>99%). Peripheral blood was taken with written informed consent, and studies were approved by the University of Nebraska Medical Center Institutional Review Board. Cells (1×10^6/ml) were cultured in complete RPMI supplemented with Fungizone (Invitrogen) and penicillin/streptomycin (Invitrogen). Consistent with epithelial cell experimental studies for chemokine production assessment, monocytes were pretreated with or without 100nM of 1,25-$(OH)_2D_3$ for 18 hours, whereupon cells were washed, and stimulated with 1% ODE in the presence or absence of freshly supplemented vitamin D media for 24 hours. Cell-free supernatants were collected and frozen at −80°C until later chemokine analysis. Cell viability was assured by trypan blue exclusion method.

Preparation of Murine Lung Slices

Precision-cut murine lung slices from control C57BL/6 mice were prepared in cultures as previously described (22). Lung slices were pre-treated with 1,25-$(OH)_2D_3$ (100nM) for 18 hours, and subsequently re-stimulated with or without 5% ODE for 24 hours. Cell-free culture supernatants were collected and stored at −80°C for later analysis.

Animal Model and Exposure

Male C57BL/6 mice were purchased from The Jackson Laboratory (Bar Harbor, ME) at 3–4 weeks of age. Upon arrival, mice were randomly assigned to a specially ordered rodent chow (Land O' Lakes-Purina; Minneapolis, MN) diet of standard soy-based (soy naturally contains small amounts of vitamin D) rodent chow supplemented with 0 IU/g or 5 IU/g of 1,25 hydroxyvitamin D. Manufacturer-provided samples of the diet were independently tested by N-P Analytical Laboratories (St. Louis, MO), which reported concentrations of 2.3 IU/gm and 5.55 IU/gm of 1,25-$(OH)_2D_3$ in the low and high concentration diets, respectively. Mice were weighed twice weekly to assure proper and equal growth between groups. At age 8 weeks (chosen because the half-life of the active form 1,25-$(OH)_2D_3$ is approximately 7 days) (23) mice were anesthetized by isoflurane and treated with 50 μl of ODE (12.5%) or sterile saline via intranasal route as previously described (11). All experimental procedures were reviewed and approved by the Institutional Animal Care and Use Committee of the University of Nebraska Medical Center.

Whole Lung Lavage

Five hours post-exposure, animals were euthanized by intraperitoneal injection of 50 mg/kg of sodium pentobarbital (Nembutal; Abbott Labs, Chicago, IL). The trachea was exposed and a cannula was intra-luminally placed just below the larynx. Bronchoalveolar lavage fluid (BALF) was collected by whole lung lavage with 3×1 ml of sterile PBS as previously described (11). Cell-free BALF supernatant from first lavage was frozen at −80°C for later chemokine analysis and cells from all three lavages were pooled. Total cells were enumerated and spun onto slides with Cytopro cytocentrifuge (Wescor, Logan, UT) and stained with DiffQuick (Dade Behring, Newar, DE). Counts of the cells determined the differential ratio of cell types in 200 cells per slide per mouse.

Chemokine Assays

Murine neutrophil chemoattractants, KC/CXCL1 (cytokine-induced neutrophil-attracting chemokine) and MIP-2/CXCL2 (macrophage inflammatory protein 2-alpha*)*, were quantitated in cell-free BALF supernatants according to the manufacturer's instructions using commercially available ELISA kits (R&D Systems, Minneapolis, MN) with sensitivities of 15.6 pg/ml and 7.8 pg/ml, respectively. The human neutrophil chemoattractant, interleukin-8 (IL-8)/CXCL8, was quantitated from cell culture supernatant by sandwich ELISA as previously described (12) with sensitivity of 21 pg/ml.

PKC Activity

Protein kinase C (PKC) isoform activity from murine tracheal epithelial cells following *in vivo* stimulation with ODE and saline was conducted. Whole tracheas were snap frozen in cell lysis buffer and stored at −80°C until later PKCε and PKCα activity assays could be performed as previously described (11). Prior to assay, the tracheae are thawed and the epithelial cells are extracted using a sterile cell scraper. The collected epithelial cell fraction in lysis buffer is then sonicated and assayed for kinase activity. PKC activity was expressed in relation to the total amount of cellular protein assayed as picomoles of phosphate incorporated per minutes per milligram. PKC activity is reported as fold-increase from baseline: dust-induced kinase activity divided by saline-alone kinase activity.

Serum Vitamin D

Whole blood was collected from mice at time of sacrifice, and serum 25(OH) vitamin D levels were quantified by the institutions' core clinical standard high performance liquid chromatography-tandem mass spectrometry methods.

Real-time Quantitative RT-PCR (qRT-PCR)

Human peripheral blood monocytes were stimulated with 1% ODE or saline for 24 hours whereupon RNA was extracted from cell pellets using the Magmax 96 kit (Applied Biosystems, Foster City, CA) according to the manufacturer's instructions. For lung tissue, after BALF was removed, the right ventricle was perfused with 10 ml of sterile PBS with heparin to remove blood from the pulmonary vasculature. Whole lung tissues were harvested and stored in RNA later (Applied Biosystems) until RNA extraction could be performed by using TRIzol reagent (Invitrogen). RNA concentration and purity was determined by NanoDrop spectrophotometer and samples had A260/A280 ratio of 1.9–2.0. cDNA was synthesized as previously described (24). Real-time PCR reactions were prepared in triplicate using 1x TaqMan Master Mix (Applied Biosystems) and primers and probed for TLR2 (Applied Biosystems; human: Hs00152932_m1; mouse: Mm00442346_m1) and TLR4 (human: HS00152939_m1; mouse: Mm00442346_m1). Ribosomal (18s) RNA was used as an endogenous control. PCR was performed using an ABI PRISM 7700 Sequence Detection System (Applied Biosystems). Threshold values were normalized to the expression of ribosomal RNA. Real-time-PCR results are either expressed as the percent fold-increase in induction (normalized copy number of stimulated cells divided by normalized copy number of unstimulated cells×100) or as values normalized to expression of ribosomal RNA.

Flow Cytometry

Human peripheral blood monocytes were evaluated for cell-surface molecule expression by means of flow cytometry for TLR2 and TLR4 after incubation with and without vitamin D (100 nM) for 24 and 48 hours. Cells (5 x10^5) were stained in a standard procedure with antibodies against TLR2, TLR4 (BioLegend, San Diego, CA), and irrelevant isotype control antibodies (to account for nonspecific binding) in PBS containing 0.1% bovine serum albumin. Flow cytometry analyses were performed with the FACSCalibur dual-laser cytometers available in the UNMC Flow Cytometry core (Becton-Dicksinson, Lincoln Park, NJ).

Statistical Analysis

Data are presented as the mean ± standard error of mean (SEM). Statistics were performed using a two-tailed, non-paired *t*-test to determine significant differences between treatment groups. One-way analysis of variance (ANOVA) with Tukey multi-comparison post-test was employed to compare differences among three or more treatment groups. In all analyses, GraphPad (version 5.01) software was used, and *p* values less than 0.05 were considered statistically significant.

RESULTS

Vitamin D Treatment Reduces Monocyte TLR2 and TLR4 Expression in a Time-Dependent Manner

Because our group and others have demonstrated an important role for TLR2 and TLR4 receptor signaling pathways in mediating ODE-induced airway disease (14,15), we first sought to confirm recent reports that vitamin D reduces TLR2 and TLR4 monocyte cell surface expression (19). Treatment with vitamin D reduces monocyte TLR2 and TLR4 mRNA expression as assessed by quantitative real-time PCR and cell surface protein expression as assessed by flow cytometry (Figure 1A–B). This was not an immediate response because significant suppression of monocyte mRNA and protein were not observed until 24 hours following treatment with vitamin D (data not shown and Figure 1), suggesting that prolonged pretreatment with vitamin D would be required to determine chemokine responses.

Vitamin D Reduces Organic Dust-Induced Epithelial Cell, Monocyte, and Lung Tissue Neutrophil Chemokine Release

We next sought to determine if vitamin D could down-regulate ODE-induced human neutrophil chemoattractant, IL-8, release. ODE-induced IL-8 production was reduced with vitamin D pretreatment (18 hour) in both human epithelial cells and monocytes (Figure 2A–B). Consistent with single cell culture studies, vitamin D pretreatment resulted in reduced ODE-stimulated CXCL1 and CXCL2 (murine neutrophil chemokine homologs) production from lung slices, a representation of tissue-structured multicellular lung responses.

Dust-induced Airway Cellular Inflammation and Chemokine Release Is Reduced In Mice Fed A Relatively High Vitamin D Supplemented Diet

Consistent with previous studies (11), acute ODE intranasal inhalation resulted in significant ($p<0.05$) increases in neutrophil influx and release of murine neutrophil chemoattractants, CXCL1 and CXCL2, in BALF at 5 hours post-exposure (Figure 3A–B). However, the increase in total leukocytes and CXCL1 and CXCL2 release following *in vivo* ODE challenge was significantly reduced ($p<0.05$) in mice fed a relatively high vitamin D supplemented diet as compared to mice fed a relatively low vitamin D diet (Figure 3A–B). Moreover, serum 25(OH) vitamin D levels were significantly reduced ($p<0.05$) by approximately 25% in mice given the low vitamin D diet (mean ± SEM: 16.6 ng/ml ± 1.231) as compared to high vitamin D diet (20.5 ng/ml ± 1.009).

Vitamin D Supplementation Reduces Organic Dust-Induced PKCα And PKCε Activity

In our previous work, we reported that PKCα and PKCε activity was important in mediating human bronchial epithelial cell ODE-induced IL-8 release (12), and that tracheal epithelial cell PKCα and PKCε were activated *in vivo* following organic dust exposure (11). In this study, there was activation of tracheal epithelial cell PKCα and PKCε in the low vitamin D treatment group following *in vivo* ODE challenge, which was nearly absent in the high vitamin D + ODE treatment group (Figure 4).

Dietary Vitamin D Supplementation Modulated Whole Lung TLR2 And TLR4 Mrna Response To ODE

To determine whether dietary vitamin D supplementation was important in lung TLR2 and TLR4 expression following ODE exposure, whole lung mRNA expression of TLR2 and TLR4 was investigated following ODE exposure in mice fed a low vs. high vitamin D diet for 5 weeks. Mice fed a low vitamin D diet had significantly increased TLR2 and TLR4 expression following ODE exposure as compared to saline exposure (Figure 5). Interestingly, this ODE-induced up-regulation in TLR2 and TLR4 mRNA was not observed in mice fed a relatively high vitamin D diet (Figure 5).

DISCUSSION

These studies provide evidence that vitamin D may be an important immunomodulator in organic dust-induced airway responses. Vitamin D treatment led to reductions in neutrophil chemoattractant release from *ex vivo* ODE-stimulated monocytes, epithelial cells and lung tissues. Furthermore, high dietary intake of vitamin D resulted reduced neutrophil influx and neutrophil chemoattractants release in mice, which was associated with blunted tracheal epithelial cell PKCα and PKCε activity and modulated whole lung TLR2 and TLR4 expression.

Dietary manipulation of vitamin D began immediately following the weaning period (at weeks 3–4), which allowed for normal murine lung development (by week 2) (25). This distinction in approach is important because deficiencies in vitamin D during early development have been associated with decreased lung volume and lung function, but not alterations in lung architecture (25–26). Although conversion between human and mouse vitamin D intake cannot be precisely made, the approximated difference between the low vs. high vitamin D diet represented a difference of 1500 IU per day for a human. Despite this modest difference, airway inflammatory outcomes differed, suggesting that small increases in vitamin D could have an impact in airway diseases.

Monocyte cell surface TLR2 and TLR4 expression was down-regulated with vitamin D treatment, which is consistent with other studies (19), and moreover, our data support that vitamin D plays a role in modulating lung TLR2 and TLR4 expression following *in vivo* ODE exposure. Organic dusts within large animal feeding operations are complex and contain diverse mixtures of microbial components (3,27,28). Endotoxins from Gram-negative bacteria are recognized by TLR4, and TLR2 can recognize Gram-positive peptidoglycans, lipoteichoic acids, lipoarabinomannan, zymosan, and other lipoproteins (29). Mice deficient in TLR2 and TLR4 demonstrate reduced airway inflammatory consequences following acute organic dust challenges (14,15). Therefore, vitamin D supplementation may represent a clinically relevant translational approach to intervene in agriculture workers to reduce airway disease burden through its impact on TLR signaling pathways.

Several immunomodulatory properties have been ascribed to vitamin D on monocytes including decreased cytokine production through activation of NF-κB following bacterial challenges as well as enhancement of macrophage function (19,30,31). We found that vitamin D reduced the release of neutrophil chemoattractants from ODE stimulated monocytes and also epithelial cells. This observation was extended to an animal model with the functional consequence of reduced neutrophil recruitment following ODE exposure. This later finding is consistent with other studies showing a role for 1,25-$(OH)_2D_3$ as a negative regulator for neutrophil activation among differing cell types (16,32). Finally, previous studies have linked PKCα/PKCε activity with ODE-induced neutrophil recruitment (11), and our data suggest that vitamin D decreases neutrophil recruitment through its action on epithelial cells PKCα/PKCε activity. It is possible that the reduction in PKC activity was secondary to diminished TLR pathway activation via down-regulation of TLR expression by vitamin D. Others have reported that MyD88 is an important scaffolding protein coupling TLRs to PKC epsilon (33). Lung cell specific roles need to be further defined.

Complex organic dust mixtures from industrialized livestock farming environments elicit respiratory disease in exposed workers; yet considerable variability in respiratory disease outcomes occurs amongst workers. As agriculture work becomes more specialized and indoors, the likelihood that workers will be exposed to decreasing amounts of natural sunlight exists, and vitamin D may be a potential confounder. It is not known whether workers are deficient in vitamin D levels, but our findings suggest that future investigations are warranted because dietary vitamin D supplementation may be an important therapeutic option.

Acknowledgments

The authors would like to thank Beth Klein and Art Heires for technical assistance, and Lisa Chudomelka for manuscript preparation assistance.

Disclosure footnote: Study supported by grants from the National Institute of Environmental Health Sciences (R01: ES019325 to JAP) and DHHS/CDC/NIOSH (#1U54OH010162-01 to JAP and TAW).

References

1. Linaker C, Smedley J. Respiratory illness in agricultural workers. Occup Med (Lond). 2002; 52:451–459. [PubMed: 12488515]
2. Honeyman MS. Sustainability Issues of U.S. Swine Production. J Anim Sci. 1996; 74:1410–1417. [PubMed: 8791216]
3. Poole JA, Romberger DJ. Immunological and inflammatory responses to organic dust in agriculture. Current Opinion in Allergy and Clinical Immunology. 2012; 12:126–132. [PubMed: 22306554]

4. Larsson KA, Eklund AG, Hansson LO, Isaksson BM, Malmberg PO. Swine dust causes intense airways inflammation in healthy subjects. Am. J. Respir.Crit.Care Med. 1994; 150:973–977. [PubMed: 7921472]
5. Sutherland ER, Goleva E, Jackson LP, Stevens AD, Leung DYM. Vitamin D Levels, Lung Function, and Steroid Response in Adult Asthma. Am. J.Respir. Crit. Care Med. 2010; 181:699–704. [PubMed: 20075384]
6. Zhao G, Ford ES, Tsai J, Li C, Croft JB. Low concentrations of serum 25-hydroxyvitamin D associated with increased risk for chronic bronchitis among US adults. Br. J. Nutr. 2011 epub ahead of print.
7. Itoh H, Mori I, Matsumoto Y, Maki S, Ogawa Y. Vitamin D deficiency and seasonal and inter-day variation in circulating 25-hydroxyvitamin D and parathyroid hormone levels in indoor daytime workers: a longitudinal study. Ind Health. 2011; 49:475–481. [PubMed: 21697621]
8. Rodríguez Sangrador M, Beltrán de Miguel B, Quintanilla Murillas L, Cuadrado Vives C, Moreiras Tuny O. The contribution of diet and sun exposure to the nutritional status of vitamin D in elderly Spanish women: the five countries study (OPTIFORD Project). Nutr Hosp. 2008; 23:567–576. [PubMed: 19132265]
9. Devgun MS, Paterson CR, Johnson BE, Cohen C. Vitamin D Nutrition in Relation to Season and Occupation. Am J Clin Nutr. 1981; 34:1501–1504. [PubMed: 7270473]
10. Bailey KL, Poole JA, Mathisen TL, Wyatt TA, Von Essen SG, Romberger DJ. Toll-Like Receptor 2 Is Upregulated by Hog Confinement Dust in an IL-6-Dependent Manner in the Airway Epithelium. Am J Physiol Lung Cell Mol Physiol. 2008; 294:L1049–L1054. [PubMed: 18359883]
11. Poole JA, Wyatt TA, Oldenburg PJ, Elliott MK, West WW, Sisson JH, Von Essen SG, Romberger DJ. Intranasal organic dust exposure-induced airway adaptation response marked by persistent lung inflammation and pathology in mice. Am.J.Physiol.Lung Cell Mol.Physiol. 2009; 296:L1085–L1095. [PubMed: 19395665]
12. Wyatt TA, Slager RE, Heires AJ, DeVasure JM, Von Essen SG, Poole JA, Romberger DJ. Sequential Activation of Protein Kinase C Isoforms by Organic Dust Is Mediated by Tumor Necrosis Factor. Am J Respir Cell Mol Biol. 2010; 42:706–715. [PubMed: 19635931]
13. Wyatt TA, Sisson JH, Von Essen SG, Poole JA, Romberger DJ. Exposure to hog barn dust alters airway epithelial ciliary beating. Eur. Respir. J. 2008; 31:1249–1255. [PubMed: 18216064]
14. Poole JA. Toll-like receptor 2 regulates organic dust-induced airway inflammation. Am.J. Respir. Cell Mol. Biol. 2011; 45:711–719. [PubMed: 21278324]
15. Charavaryamath C, Juneau V, Suri SS, Janardhan KS, Townsend H, Singh B. Role of toll like receptor 4 in lung inflammation following exposure to swine barn air. Experimental Lung Research. 2008; 34:19–35. [PubMed: 18205075]
16. Sun J, Kong J, Duan Y, Szeto FL, Liao A, Madara JL, Li YC. Increased NF-κB Activity in Fibroblasts Lacking the Vitamin D Receptor. Am J Physiol Endocrinol Metab. 2006; 291:E315–E322. [PubMed: 16507601]
17. Do JE, Kwon SY, Park S, Lee ES. Effects of vitamin D on expression of Toll-like receptors of monocytes from patients with Behcet's disease. Rheumatology (Oxford). 2008; 47:840–848. [PubMed: 18411217]
18. Taher YA, van Esch BCAM, Hofman GA, Henricks PAJ, van Oosterhout AJM. 1alpha,25-dihydroxyvitamin D3 potentiates the beneficial effects of allergen immunotherapy in a mouse model of allergic asthma: role for IL-10 and TGF-beta. J. Immunol. 2008; 180:5211–5221. (2008). [PubMed: 18390702]
19. Sadeghi K, Wessner B, Laggner U, Ploder M, Tamandl D, Friedl J, Zügel U, Steinmeyer A, Pollak A, Roth E, Boltz-Nitulescu G, Spittler A. Vitamin D3 down-regulates monocyte TLR expression and triggers hyporesponsiveness to pathogen-associated molecular patterns. European Journal of Immunology. 2006; 36:361–370. [PubMed: 16402404]
20. Zhang Y, Leung DY, Richers BN, Liu Y, Remigio LK, Riches DW, Goleva E. Vitamin D inhibits monocyte/macrophage proinflammatory cytokine production by targeting MAPK phosphatase-1. J. Immunol. 2012; 188:2127–2135. [PubMed: 22301548]

21. Poole JA, Wyatt TA, Von Essen SG, Hervert J, Parks C, Mathisen T, Romberger DJ. Repeat organic dust exposure-induced monocyte inflammation is associated with protein kinase C activity. J. Allergy Clin. Immunol. 2007; 120:366–373. [PubMed: 17555806]
22. Wyatt TA, Sisson JH, Allen-Gipson DS, McCaskill ML, Boten JA, DeVasure JM, Bailey KL, Poole JA. Co-Exposure to Cigarette Smoke and Alcohol Decreases Airway Epithelial Cell Cilia Beating in a Protein Kinase Cɛ-Dependent Manner. Am J of Pathology. 2012 epub ahead of print.
23. Smith JE, Goodman DS. The turnover and transport of vitamin D and of a polar metabolite with the properties of 25-hydroxycholecalciferol in human plasma. J Clin Invest. 1971; 50:2159–2167. [PubMed: 4330006]
24. Klein E, Weigel J, Buford MC, Holian A, Wells SM. Asymmetric Dimethylarginine Potentiates Lung Inflammation in a Mouse Model of Allergic Asthma. Am J Physiol Lung Cell Mol Physiol. 2010; 299:L816–L825. [PubMed: 20889675]
25. Amy RW, Bowes D, Burri PH, Haines J, Thurlbeck WM. Postnatal growth of the mouse lung. J. Anat. 1977; 124:131–151. (1977). [PubMed: 914698]
26. Soutiere SE, Mitzner W. Comparison of Postnatal Lung Growth and Development Between C3H/HeJ and C57BL/6J Mice. J Appl Physiol. 2006; 100:1577–1583. [PubMed: 16282432]
27. Nehme B, Létourneau V, Forster RJ, Veillette M, Duchaine C. Culture-independent approach of the bacterial bioaerosol diversity in the standard swine confinement buildings, and assessment of the seasonal effect. Environmental Microbiology. 2008; 10:665–675. [PubMed: 18237302]
28. Nehmé B, Gilbert Y, Letourneau V, Forster RJ, Veillette M, Villemur R, Duchaine C. Culture-Independent Characterization of Archaeal Biodiversity in Swine Confinement Building Bioaerosols. Appl. Environ. Microbiol. 2009; 75:5445–5450. [PubMed: 19561186]
29. Kawai T, Akira S. The role of pattern-recognition receptors in innate immunity: update on Toll-like receptors. Nature Immunology. 2010; 11:373–384. [PubMed: 20404851]
30. Du T, Zhou ZG, You S, Lin J, Yang L, Zhou WD, Huang G, Chao C. Regulation by 1, 25-dihydroxy-vitamin D3 on altered TLRs expression and response to ligands of monocyte from autoimmune diabetes. Clinica Chimica Acta. 2009; 402:133–138.
31. Yuk JM, Shin DM, Lee HM, Yang CS, Jin HS, Kim KK, Lee ZW, Lee SH, Kim JM, Jo EK. Vitamin D3 Induces Autophagy in Human Monocytes/Macrophages via Cathelicidin. Cell Host & Microbe. 2009; 6:231–243. [PubMed: 19748465]
32. Nonn L, Peng L, Feldman D, Peehl DM. Inhibition of P38 by Vitamin D Reduces Interleukin-6 Production in Normal Prostate Cells Via Mitogen-Activated Protein Kinase Phosphatase 5: Implications for Prostate Cancer Prevention by Vitamin D. Cancer Res. 2006; 66:4516–4524. [PubMed: 16618780]
33. Faisal A, Saurin A, Gregory B, Foxwell B, Parker PJ. The scaffold MyD88 acts to couple protein kinase C epsilon to Toll-like receptors. J Biol Chem. 2008; 283(27):18591–19600. [PubMed: 18458086]

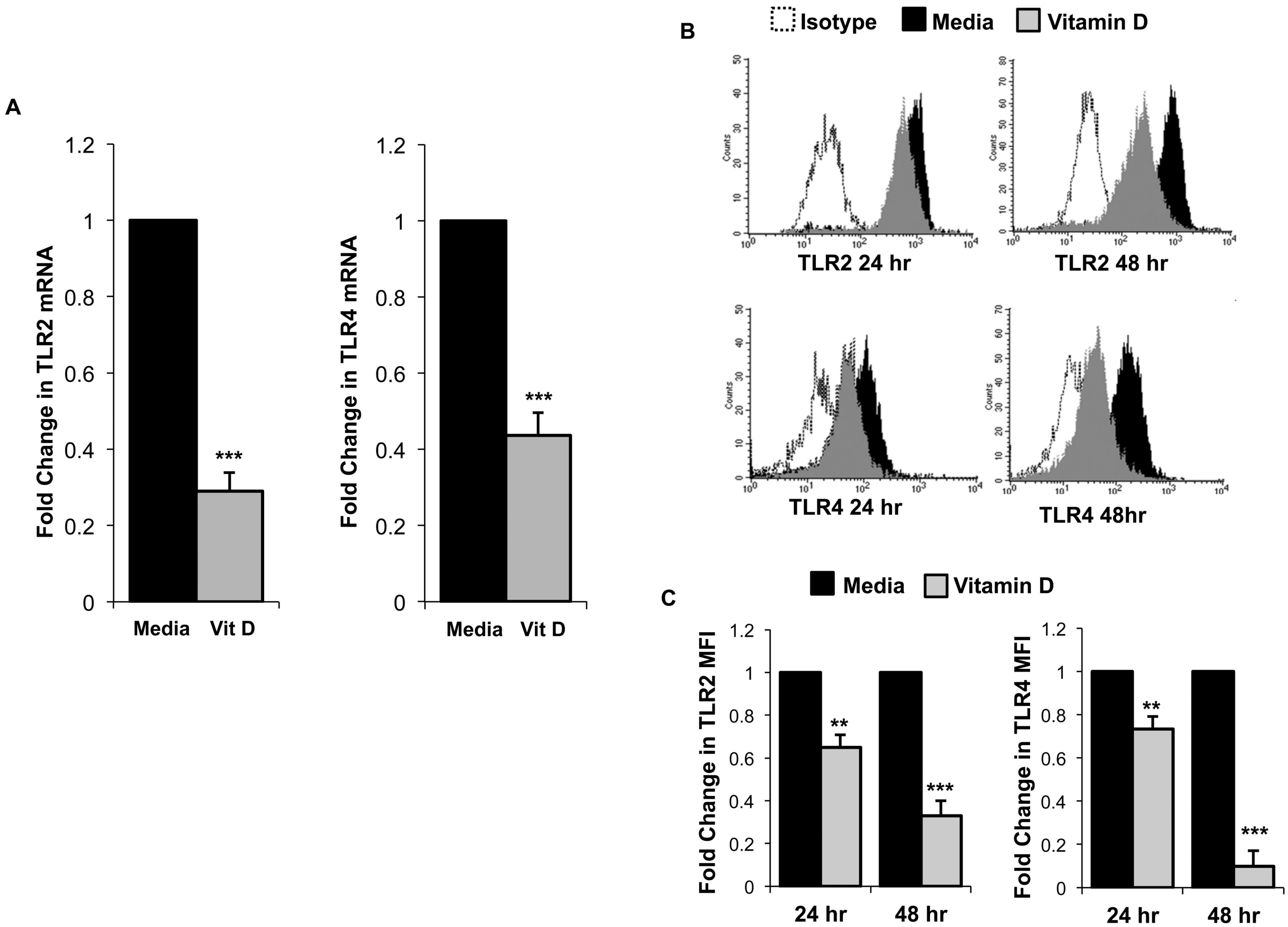

Figure 1. Vitamin D treatment decreased TLR2 and TLR4 expression in human peripheral blood monocytes

Vitamin D (100 nmol) decreased TLR2 and TLR4 mRNA at 24 h in human peripheral blood monocytes (**A**). Results represent mean (± SEM) of TLR2 and TLR4 mRNA normalized to endogenous ribosomal control (N=3 independent experiments). Cell surface protein expression of TLR2 and TLR4 is decreased at 24 and 48 h by flow cytometry in monocytes. **B,** Representative histogram of one of 4 independent experiments, and **C**, Mean ± SEM of the mean fluorescence intensity (MFI) (n=4). Asterisks denote statistical significance as compared to respective media control (*p<0.05, **p<0.01) and ##p<0.05 denotes statistical significance vs. ODE alone.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

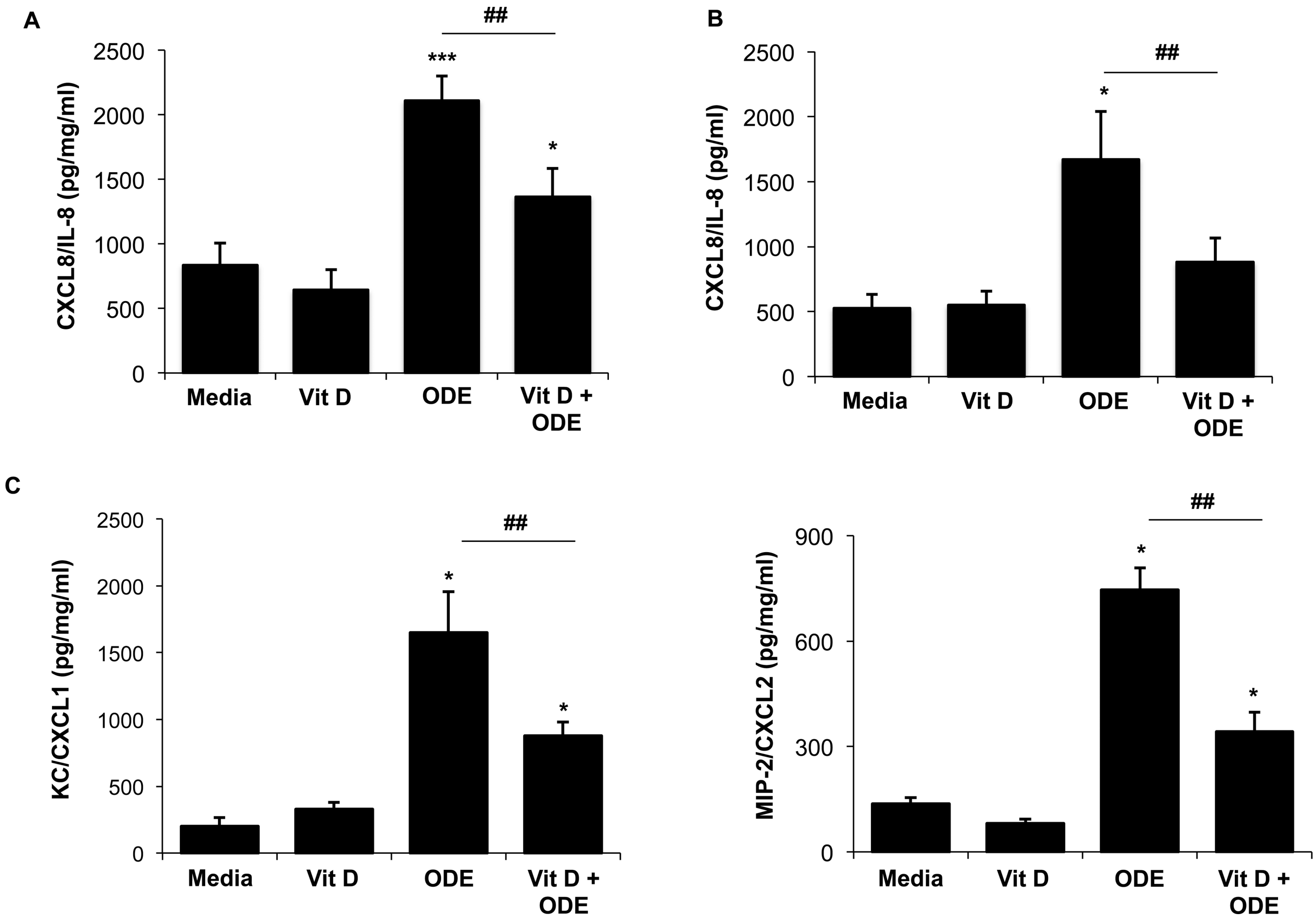

Figure 2. Vitamin D pretreatment reduces ODE-induced neutrophil chemoattractant production in bronchial epithelial cells, monocytes, and lung tissue

A, Human bronchial epithelial cells (BEAS-2B), **B**, human peripheral blood monocytes, and **C**, murine lung slices were pre-treated with vitamin D (100 nmol) or saline for 18 hours and subsequently re-stimulated with or without ODE for 24 hours. Results represent mean ± SEM (N=7) of cell-free supernatant levels of neutrophil chemoattractant(s) (human CXCL8/IL-8 and murine CXCL1 and CXCL2) as determined by ELISA. Asterisks denote statistical significance as compared to respective media control (*p<0.05, **p<0.01, ***p<0.001) and hatchtexts (#p<0.05) denote statistical significance vs. ODE alone.

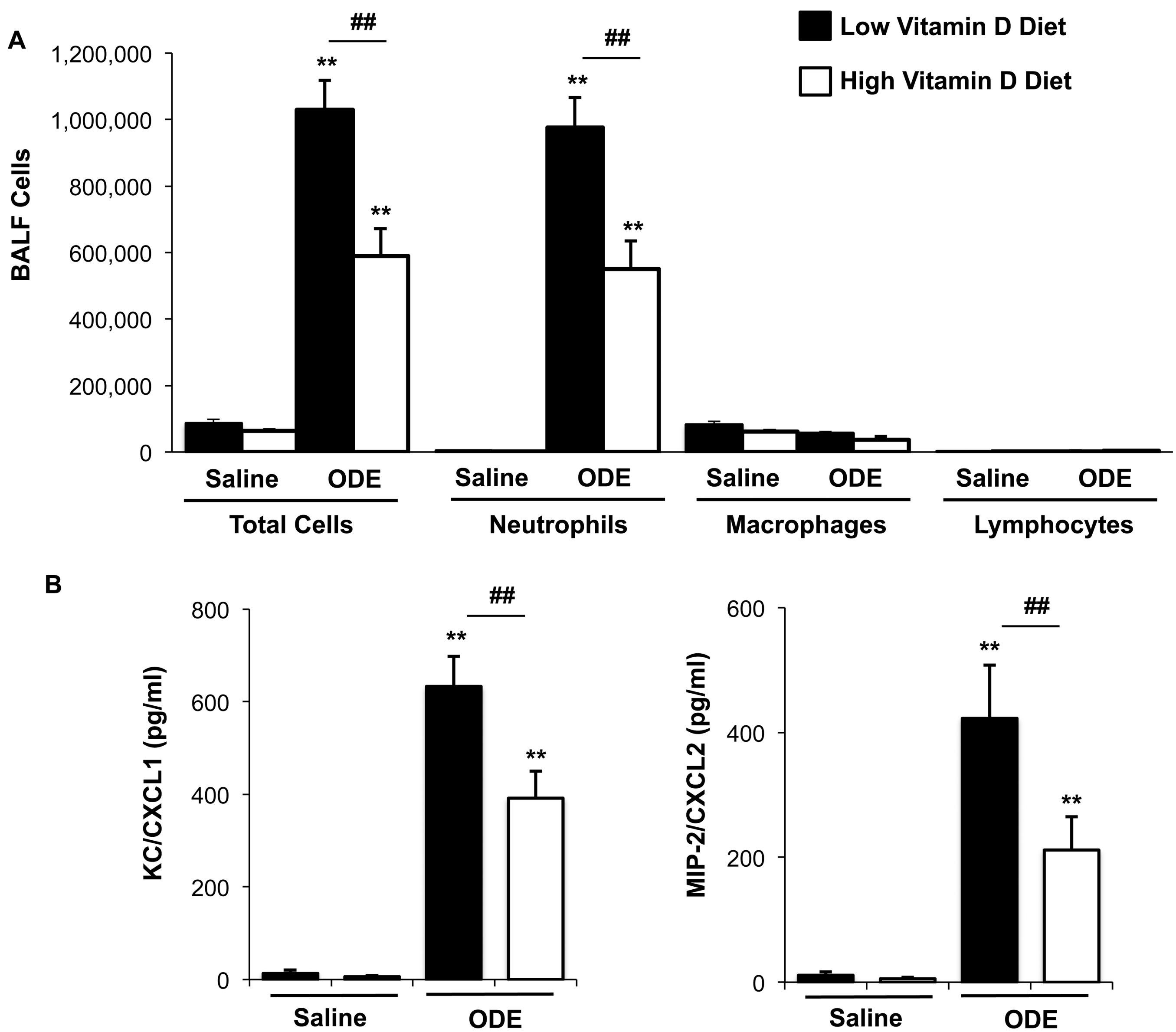

Figure 3. High vitamin D diet resulted in decreased ODE-induced neutrophil influx and neutrophil chemoattractant production in mice

C57BL/6 mice were fed relatively low (2.04 IUD/g) vs. high (5.11 IU D/g) vitamin D supplemented rodent chow diet for 6 weeks initiated immediately after weaning (age 3–4 wk). Mice were treated with ODE or sterile saline via intranasal inhalation. Results represent (mean ± SEM) of whole lung lavage total cell counts and differential (**A**) and levels of neutrophil chemokines, CXCL1 and CXCL2 (**B**) at 5 h post-exposure. Asterisks (**p<0.01) denote statistical significance compared to matched saline control. Hatchtexts (##p<0.01) denote statistical significance comparing high vs. low vitamin D diet. Experimental study with N=4 mice per group, repeated twice with representative sample shown.

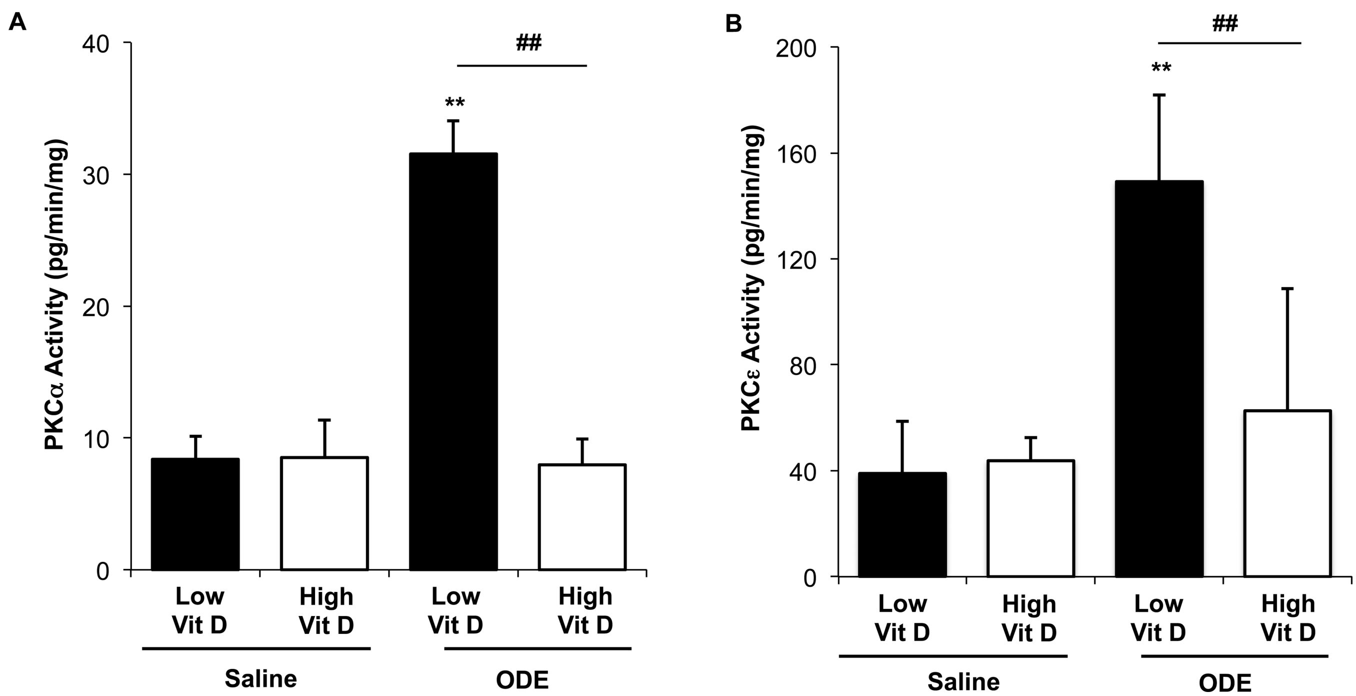

Figure 4. ODE-induced murine trachea epithelial cell PKCα and PKCε activity is significantly reduced in mice fed a relatively high vitamin D diet

C57BL/6 mice were fed relatively low (2.04 IUD/g) vs. high (5.11 IU D/g) vitamin D supplemented rodent chow diet for 5 weeks initiated immediately after weaning (age 3–4 wk). Results represent mean (± SEM) of PKCα and PKCε activity from isolated tracheal epithelial cells at 5h following *in vivo* ODE or sterile saline treatment. Asterisks (**p<0.01) denote statistical significance compared to matched saline control. Hatchtexts (#p<0.05, ##p<0.01) denote statistical significance comparing high vs. low vitamin D diet.

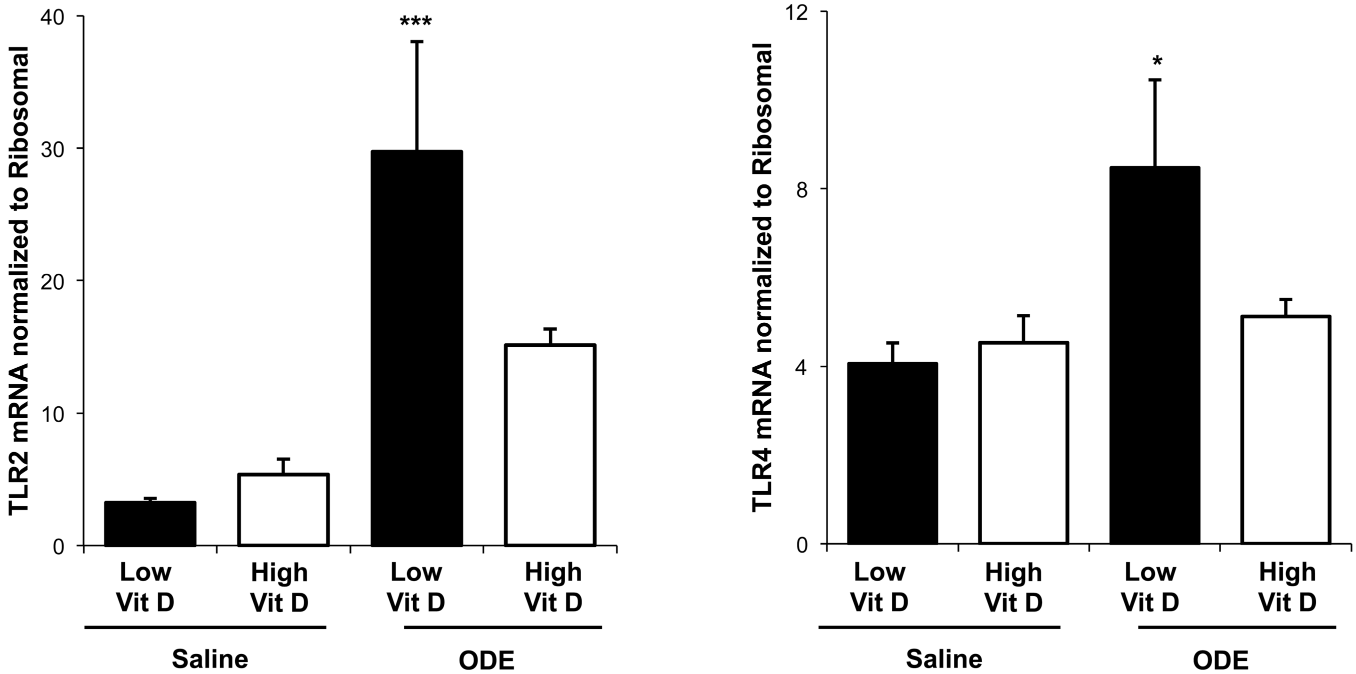

Figure 5. High dietary Vitamin D is associated with reduced TLR2 and TLR4 mRNA expression in mice following ODE exposure

C57BL/6 mice were fed relatively low (2.04 IUD/g) vs. high (5.11 IU D/g) vitamin D supplemented rodent chow diet for 6 weeks initiated immediately after weaning (age 3–4 wk). Whole lung tissue TLR2 and TLR4 mRNA expression was increased in mice that consumed a relatively low vitamin D diet and exposed to ODE as compared to sterile saline treated mice. ODE-induced TLR2 and TLR4 mRNA expression in lung tissue was not observed in mice fed a high vitamin D diet (N=7–8 mice/group). Asterisks denote statistical significance as compared to respective media control (*$p<0.05$, **$p<0.01$) denotes statistical significance vs. ODE alone.