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TITLE:

Challenge models to assess new therapies in chronic obstructive pulmonary disease

ABSTRACT:

Chronic obstructive pulmonary disease (COPD) is a major cause of morbidity and mortality. Current therapies confer partial benefits either by incompletely improving airflow limitation or by reducing acute exacerbations, hence new therapies are desirable. In the absence of robust early predictors of clinical efficacy, the potential success of novel therapeutic agents in COPD will not entirely be known until the drugs enter relatively large and costly clinical trials. New predictive models in humans, and new study designs are being sought to allow for confirmation of pharmacodynamic and potentially clinically meaningful effects in early development. This review focuses on human challenge models with lipopolysaccharide endotoxin, ozone, and rhinovirus, in the early clinical development phases of novel therapeutic agents for the treatment and reduction of exacerbations in COPD.

Lipopolysaccharide challenge ::: Introduction:

Lipopolysaccharide (LPS) is a macromolecular cell wall surface antigen of Gram-negative bacteria. It is made up of three components: the O antigen (or O polysaccharide) side chain, the core oligosaccharide, and the lipid A moiety.⁸ LPS is an extremely biologically active substance and has been used for many years in preclinical and clinical research, due to its role in activating many transcription factors. In the serum, LPS binds to a lipid-binding protein, which facilitates the association between LPS and CD14 on the cell membranes. This in turn facilitates the transfer of LPS to the TLR4/MD2 complex (Figure 1).⁹ This triggers a signaling cascade in macrophage lineage and endothelial cells, resulting in the secretion of proinflammatory cytokines and nitric oxide, and the activation of complement and the coagulation systems that contribute to characteristic features of inflammation, and with excessive stimulation, “endotoxic shock.” In monocytes and macrophages, LPS triggers the production of powerful inflammatory mediators including cytokines (eg, interleukin [IL]-1, IL-6, IL-8, tumor necrosis factor [TNF]- α and platelet-activating factor), which stimulate production of prostaglandins and leukotrienes. In addition, LPS activation results in enhanced macrophage phagocytic and cytotoxic activity. Activation of alternative complement pathway factors C3a and C5a induce histamine release, and affect neutrophil chemotaxis and accumulation. Kinin activation releases bradykinins and other vasoactive peptides, which cause hypotension. The release of these mediators and subsequent systemic response make LPS a powerful research tool in evaluating inflammatory pathways. Healthy subjects inhaling endotoxin show a systemic and pulmonary inflammatory response, recruiting neutrophils and macrophages to the lung tissue. Inhalation of nebulized doses (up to 50 μ g) of LPS via a dosimeter in healthy volunteers, leads to an increase in temperature, blood C-reactive protein (CRP), blood and sputum neutrophils, blood monocytes and lymphocytes, and blood and sputum proinflammatory mediators, including: IL-8, TNF α , myeloperoxidase (MPO), matrix metalloproteinase-9, IL-6, IL-1 β , monocyte chemoattractant protein-1, and macrophage inflammatory protein-1 β .^{10,11}

Bronchial segmental instillation induces an early phase response (0–24 hours), resulting in a statistically significant increase in neutrophils, TNF, IL-1 β , IL-1R antagonist, IL-6, and granulocyte colony-stimulating factor. Neutrophils, macrophages, and monocytes increase 24–48 hours post instillation.^{11,12}

Intranasal LPS challenge may be the least invasive and best tolerated model. Clinical symptoms are minimal; however, very little or no data have been published to date using this model. Further validation of the intranasal model needs to be performed to compare it to the LPS inhalation challenge model, to better understand the relevance of the LPS-triggered nasal inflammation to the phenomena that occur in the central and distal airways in COPD.

Many of the effects of exogenous LPS can be blocked by medications. In one study, pretreatment with oral prednisolone or cilomilast had no effect on the local LPS-induced inflammatory response in the lung;¹³ pretreatment with prednisolone alone significantly inhibited the LPS-induced CRP response. Cilomilast attenuated the increase in CRP, but not significantly. Similarly, in another study, subjects who received simvastatin 40–80 mg demonstrated a reduction in neutrophils, MPO, TNF α , matrix metalloproteinase-7, -8, and -9 in the bronchoalveolar lavage fluid (BALF), as

well as a reduction in plasma CRP, versus placebo.¹⁴ Hohlfeld et al¹⁵ used LPS to show that roflumilast reduced the influx of total cells, neutrophils, and eosinophils into the airways of healthy subjects after segmental challenge with endotoxin, with statistical significance. It is important to remember that inhaled LPS challenge is a model of acute neutrophilic inflammation and not a model of COPD.¹⁶ The model can be used to understand the biological effects of compounds that inhibit the LPS pathway (Table 1).

Ozone challenge :: Introduction:

Ozone (O₃) is a major component of urban environmental air pollution. It is formed in the troposphere from primary precursor pollutants. In the presence of light, NO₂ is cleaved by sunlight to NO• + O•, allowing the formation of O₃ (O₂ + O•) (Figure 2). In epidemiological studies, O₃ levels have been associated with exacerbations of asthma, COPD, and pneumonia.^{17–19} Experimental O₃ exposure in healthy human subjects is known to elicit a reversible impairment in lung function, as well as acute proximal airways neutrophilic inflammation, and an increase in the concentration of several cytokines and mediators of inflammation within the airways.²⁰ In the first reported study of the inflammatory effects of low-level O₃ exposure (80 ppb O₃ for 6.6 hours) in healthy volunteers,²¹ there were statistically significant increases in polymorphonuclear neutrophils, prostaglandin E₂, lactate dehydrogenase, IL-6, α₁-antitrypsin, and decreased phagocytosis via the complement receptor. This is similar to a more recent study with low-level exposure to O₃ at 80 ppb for 6.6 hours,²² in which there were increased airway neutrophils, monocytes, and dendritic cells, as well as modifications of the expression of CD14, HLA-DR, CD80, and CD86 on monocytes. In another study examining whether circulating CD11b plays a role in the inflammatory response following inhaled O₃ exposure, 22 volunteers underwent controlled exposure to O₃ (400 ppb for 2 hours) and to clean air on two separate occasions.²³ Induced sputum collected from subjects exposed to O₃ revealed marked neutrophilia, and increased expression of mCD14 on airway macrophages and monocytes. Circulating CD11b levels also predicted the magnitude of the airway neutrophil response following inhaled O₃ exposure.

A number of different classes of therapeutic agents have been studied in the O₃ challenge model in healthy volunteers. Therapeutic classes include corticosteroids (administered orally and by inhalation) and nonsteroidal anti-inflammatory drugs. More recently, studies investigating the effects of CXC chemokine receptor (CXCR) 1, 2 antagonists have been reported.^{24–28} Holz et al²⁴ conducted a double-blind, double-dummy, placebo-controlled, three-period crossover study. Eighteen healthy subjects, who had been shown at screening to produce more than a 10% increase in sputum neutrophils in response to exposure to 250 ppb O₃, were randomly assigned to receive alternating single orally inhaled doses of fluticasone 2 mg, 50 mg of prednisolone orally, and placebo at least 2 weeks apart. Compared with placebo, pretreatment with inhaled or oral corticosteroids resulted in a significant reduction of sputum neutrophils, by 62% and 64%, respectively. This was associated with statistically significant reductions in sputum MPO, by 55% for inhaled corticosteroids and 42% for oral steroids. Compared with placebo, there was a mean reduction in sputum IL-8 levels, by 49% after inhaled corticosteroids and 34% after oral corticosteroids.

Similar results were obtained in a study conducted by Alexis et al.²⁵ In subjects receiving fluticasone 0.5 mg and 2 mg, sputum neutrophilia was significantly reduced by 18% and 35%, respectively. The following inflammatory markers were also significantly reduced in a dose-dependent manner in subjects receiving fluticasone: CD11b, mCD14, CD64, CD16, HLA-DR, and CD86 on sputum monocytes. Serum Clara cell protein 16 levels (a marker of pulmonary damage) were significantly increased post-O₃ challenge.

Schelegle et al²⁶ pretreated healthy volunteers with indomethacin, which was shown to significantly reduce O₃-induced decrements in FEV₁ and forced vital capacity, when compared to no drug or placebo. This was associated with reductions in subjective symptoms of cough, shortness of breath, and throat tickle on indomethacin treatment, suggesting that cyclooxygenase products play a partial role in subjective symptoms associated with O₃ exposure. Hazucha et al²⁹ demonstrated a similar reduction of O₃-induced decrements in FEV₁ and forced vital capacity following single-dose treatment with either 200 mg or 800 mg of ibuprofen compared to placebo, which was associated with reduced post-O₃ BALF levels of prostaglandin E₂, thromboxane B₂, and IL-6.

SCH527123 is a novel, selective, oral CXC chemokine receptor 2 antagonist that inhibits neutrophil activation and modulates neutrophil trafficking in animal models. Eighteen healthy O₃ responders (>20% increase in sputum neutrophils) underwent O₃ challenge tests (250 ppb, 3

hours intermittent exercise) 1 hour after the last treatment dose, and sputum was induced at 3 hours postchallenge²⁷ following SCH527123 treatment. The O₃ challenge resulted in statistically significantly lower sputum neutrophil counts ($0.136 \times 10^6 \text{ mL}^{-1}$) compared with prednisolone ($0.846 \times 10^6 \text{ mL}^{-1}$; $P = 0.001$) or placebo ($2.986 \times 10^6 \text{ mL}^{-1}$; $P = 0.001$). Comparable results were obtained for total cell count, percentage of sputum neutrophils, and for IL-8 and myeloperoxidase in sputum supernatant. Post challenge, SCH527123 inhibited neutrophilia in peripheral blood, but significantly less than in sputum.

Gaga et al³⁰ investigated the use of SCH527123 in subjects with severe neutrophilic asthma. When averaged over the 4-week treatment period, sputum neutrophils were significantly reduced in the active group by 57% compared to placebo ($P = 0.01$). There were fewer mild exacerbations (1.3 vs 2.25; $P = 0.05$), and there was a trend towards fewer severe exacerbations in the SCH527123 group. The Asthma Control Questionnaire score was improved by 0.42 points in the active group compared with the placebo-treated group ($P = 0.053$), although the difference did not reach clinical significance, and no changes were observed in FEV₁. This shows that in asthma, the O₃ challenge model has proved useful in demonstrating inhibition of neutrophil numbers, associated with a clinical meaningful effect.

More recently, in a randomized, double-blind, placebo controlled three-way crossover trial of the CXCR2 antagonist SB-656933, 24 healthy nonsmoking male subjects were randomly assigned to receive a single dose of 50 mg, 150 mg, or placebo, 1 hour prior to O₃ challenge.³¹ Single doses of SB-656933 reduced O₃-induced airway inflammation in a dose-dependent manner. There were corresponding reductions in myeloperoxidase levels in the sputum supernatant, by 32.8% (confidence interval: 9.2, 50.3) and 50.5% (confidence interval: 33.3, 63.3).

Studies in COPD have been conducted using O₃ concentrations in the range of 120–250 ppb with 7.5–15 minutes of exercise every 30 minutes, aiming to maintain a ventilatory rate of between 20–30 L/min.^{32–34} In a study of nine subjects with COPD and ten age-matched controls, Gong et al³⁵ found an increase in specific airway resistance and a statistically significant decrease in FEV₁ in the COPD subjects versus the age-matched controls.

In summary, O₃ challenge has been well tolerated in healthy volunteers and in older subjects, as well as subjects with asthma or COPD. The O₃-challenge model potentially provides critical decision-making data in understanding whether new compounds have the desired biological effect in healthy volunteers and patients with COPD; hence it can de-risk decisions to move forwards into large Phase II safety and efficacy trials.

Rhinovirus challenge ::: Introduction:

Rhinovirus is responsible for the common cold and is spread through infected respiratory secretions from one person to another. Human rhinovirus (HRV) replicates at 33°C–35°C and thus has been linked to upper airway infections, where mucosal surfaces are cooler. Evidence exists that HRV is not limited to the upper airways. Gern et al³⁶ detected HRV using reverse transcription polymerase chain reaction in both nasal secretions and BALF, in healthy subjects after experimental infection with rhinovirus 16.

HRV binds to intracellular adhesion molecule (ICAM)-1, the major HRV receptor.³⁷ The low-density-lipoprotein receptor³⁸ binds to a minor group of HRV (HRV2). The gene for ICAM-1 maps to human chromosome 19, as do the genes for a number of other picornavirus receptors.

Several studies have shown induction of proinflammatory genes implicated in neutrophil activation following rhinovirus induction of bronchial epithelial cells (eg, IL-8 regulated by NF- κ B signaling pathways and Gro α).^{39–41}

Rhinovirus infection of epithelial cells leads to the release of proinflammatory cytokines and chemokines including IL-6 and IL-8. Chemokines attract inflammatory cells (eg, neutrophils, eosinophils). These cells release toxic products, stimulating mucus production and leading to tissue damage, with possible long-term loss of lung function. Some mediators, such as endothelin-1, have a direct effect in causing bronchoconstriction and vasoconstriction, resulting in airflow obstruction and impaired gas exchange.

Healthy subjects, subjects with asthma, and subjects with allergic asthma have been intensively studied in clinical trials inoculating them with rhinovirus 16 or other rhinovirus serotypes.^{42–44} These studies demonstrated that rhinovirus infection of the lower airways is common after experimental inoculation.

Several studies looking at causes of exacerbations in COPD have shown that viruses account for up to 60% of exacerbations, and that HRV is numerically the most important virus type.^{30,45–50}

Figure 3 depicts the total viral and HRV exacerbation rate in seven exacerbation studies. Other viruses associated with acute exacerbations of COPD are coronavirus, influenza A and B, parainfluenza, adenovirus, and respiratory syncytial virus.^{45,51–55}

To develop a model of viral exacerbation in subjects with COPD, Mallia et al⁵⁶ conducted a virus dose-escalating study infecting four COPD subjects with rhinovirus. In this study, the median tissue culture infective dose (TCID₅₀) of rhinovirus was administered by the inhaled route using a nebulizer, to elicit a COPD exacerbation. Although there was a decrease in FEV₁ (16%) and peak expiratory flow (12%) maximal on day 9, there was not a statistically significant increase in total sputum cell count or peripheral neutrophil count. Symptoms of cold and lower respiratory tract symptoms, as well as lung function changes that are characteristic of viral-induced exacerbations of COPD, were observed. There was an increase, although not statistically significant, in the proinflammatory cytokines IL-6 and IL-8.

In another study, there were significant increases in total respiratory scores in both COPD subjects and healthy controls.⁵⁷ Peak expiratory flow fell by 23.5 mL in the controls (*P* = not significant) and by 50.5 mL (*P* < 0.05) in the COPD patients. Peripheral white cell counts and neutrophils increased in both groups. Sputum neutrophil count also increased in the COPD patients but not in the controls. More recently, both the upper and lower symptom scores were found to be significantly higher in the COPD subjects.⁵⁸ In this study, ten of the 11 infected COPD subjects met the criteria defining an exacerbation of COPD. Subjects in the COPD group demonstrated significant decreased peak expiratory flow from baseline, while those in the control group did not. The blood and sputum showed a significant increase in peripheral neutrophils in the COPD subjects but not the controls. However, CRP was significantly increased in both groups on day 5. Subjects in the COPD group had significantly increased sputum neutrophil elastase levels over baseline on days 9 and 15, as well as IL-8 levels on day 9. Sputum neutrophil elastase levels were significantly higher in subjects with COPD, compared with control subjects on days 9–15. To date, only one laboratory has published on this model and as such, the data should be interpreted with caution.

The main advantage of this model is that it will give a clear understanding and insight into the molecular and cellular inflammatory processes that take place during a viral-associated exacerbation of COPD. There are no published data to date on the effect of pharmacological interventions in this model.

The rhinovirus challenge model has the potential for use as a preclinical and clinical tool to identify and investigate novel drug targets and establish whether new therapeutic agents have potential clinical utility. These include (but are not limited to) targets against soluble ICAM-1 and thus inhibit interaction of HRV with ICAM-1,^{59,60} inhibitors of rhinovirus RNA-dependent RNA polymerases 3D,⁶¹ activators of retinoic acid-inducible gene 1,⁶² inhibitors of rhinovirus capsid protein VP-163 and inhibitors of different rhinovirus proteases (eg, 2A, 3C).^{64,65} Currently, this is the only model that reflects the underlying mechanism of viral exacerbations of COPD.

Discussion:

The use of challenge models has the potential to significantly inform early decision making, before embarking on long-term Phase II and III clinical trials designed to test interventions that may treat or avert exacerbations of COPD. Although challenge models are good predictive models of acute exacerbations of COPD, there are ethical considerations associated with inducing exacerbations in subjects with COPD. Therefore, safety boards may be advised to only consider subjects with mild COPD for inclusion in these studies. Healthy subjects could be used as an alternative, when determining the effects of a developmental drug's mechanism of action on lung inflammation. The LPS and O₃ models have been used successfully in healthy subjects.^{13–15,22,24,26–28} As these models represent the local inflammation in the lung during an exacerbation, and test the mechanism of action of potential novel drugs, these data may be used for future decision making. The LPS challenge model is the best validated model in subjects with COPD. Pharmaceutical companies have used LPS models as a means to establish proof of principle early during the clinical development process, because they are relatively simple to perform and have few adverse events. This model is cost effective because it can be conducted in healthy subjects, who are easy to recruit. LPS challenge data, whether positive or negative, can provide valuable information to aid investment decision making. One disadvantage of the LPS model is that it is a model of lung inflammation, but not of the disease state, thus preclinical validation of the developmental drug's effects on LPS pathways is essential. For anti-inflammatory targets that are involved in the toll-like receptor 4, NF- κ B pathway, the LPS challenge model is the model of choice.

Despite the longstanding knowledge and understanding of the adverse effects of O₃ on pulmonary biology, the use of O₃ as a challenge model to assess the potential of new drugs for the prevention of acute exacerbations in COPD, is relatively new. The model has been shown to be safe and to have few side effects in healthy volunteers, and in patients with asthma and COPD.^{24,25,28,66} Additionally, it is reliable and reproducible. It has been used successfully to generate biological effect and systemic effect for fluticasone and the CXCR2 antagonists, SCH527123 and SB-656933.^{27,31} A limitation of the O₃ model is that it has yet to be determined whether inhibition of neutrophilia translates into clinical benefits for patients with COPD. Preliminary data indicate that inhibition of the neutrophil response following O₃ challenge may be associated with beneficial changes in system scores obtained in subjects with COPD. Challenge with rhinovirus 16 to elicit mild exacerbations in subjects with COPD appears to be safe and well tolerated, but only a few COPD subjects have been exposed to this model. The observation that FEV₁ does not always return to baseline after inducing an exacerbation in COPD subjects may call to question the feasibility of using the challenge in a broader population of patients with COPD, in addition to raising ethical considerations. This remains an exciting model with a great deal of potential, as rhinovirus models are good predictive models of viral-induced acute exacerbations of COPD.

Conclusion:

In order for pharmaceutical companies to succeed in the COPD arena, innovative approaches to clinical trial design and conduct are required that will generate critical, high-quality proof of efficacy and biologic target engagement data to support early investment decision making, early drug termination, and facilitation of better-informed decisions regarding those drugs in which proof of effect has been clearly demonstrated. Challenge models in COPD, which expose fewer individuals for short periods of time to eliciting agents, may serve as surrogate of potential efficacy and thus may help early decision making and reduction in clinical development timelines.