ORIGINAL ARTICLE

Innate immunity but not NLRP3 inflammasome activation correlates with severity of stable COPD

Antonino Di Stefano,1 Gaetano Caramori,2 Adam Barczyk,3 Chiara Vicari,1 Paola Brun,4 Andrea Zanini,1 Francesco Cappello,5,6,7 Elvira Garofano,2 Anna Padovani,2 Marco Contoli,2 Paolo Casolari,2 Andrew L Durham,8 Kian Fan Chung,8 Peter J Barnes,8 Alberto Papi,2 Ian Adcock,8 Bruno Balbi1

ABSTRACT

Background  In models of COPD, environmental stressors induce innate immune responses, inflammasome activation and inflammation. However, the interaction between these responses and their role in driving pulmonary inflammation in stable COPD is unknown.

Objectives  To investigate the activation of innate immunity and inflammasome pathways in the bronchial mucosa and bronchoalveolar lavage (BAL) of patients with stable COPD of different severity and control healthy smokers and non-smokers.

Methods  Innate immune mediators (interleukin (IL)-6, IL-7, IL-10, IL-27, thymic stromal lymphopoietin (TSLP), interferon γ and their receptors, STAT1 and pSTAT1) and inflammasome components (NLRP3, NALP7, caspase 1, IL-1β and its receptors, IL-18, IL-33, ST2) were measured in the bronchial mucosa using immunohistochemistry. IL-6, soluble IL-6R, sgp130, IL-7, IL-27, HMGB1, IL-33, IL-37 and soluble ST2 were measured in BAL using ELISA.

Results  In bronchial biopsies IL-27+ and pSTAT1+ cells are increased in patients with severe COPD compared with control healthy smokers. IL-7+ cells are increased in patients with COPD and control smokers compared with control non-smokers. In severe stable COPD IL-7R+, IL-27R+ and TSLPR+ cells are increased in comparison with both control groups. The NALP3 inflammasome is not activated in patients with stable COPD compared with control subjects. The inflammasome inhibitory molecules NALP7 and IL-37 are increased in patients with COPD compared with control smokers. IL-6 levels are increased in BAL from patients with stable COPD compared with control smokers. IL-6 levels are increased in BAL from patients with stable COPD compared with control smokers and non-smokers.

Conclusions  Increased expression of IL-27, IL-37 and NALP7 in the bronchial mucosa may be involved in progression of stable COPD.

INTRODUCTION

Inflammation is important in the pathogenesis of stable COPD.1 Environmental stress such as cigarette smoke activates the innate immune response which may drive COPD inflammation.2 Interleukin 6 (IL-6) is a multifunctional pro-inflammatory cytokine3 that acts via two molecules: the IL-6R (IL-6 receptor) and gp130.4 Soluble gp130 (sgp130) inhibits IL-6 trans-signalling via the soluble IL-6R (sIL-6R) and classic signalling via the membrane bound IL-6R (mIL-6R).4

IL-27, an IL-12/IL-23 family member, stimulates T helper 1 (Th1) lymphocyte differentiation.5 It also stimulates haematopoiesis, increases antigen presentation by antigen-presenting cells and inhibits angiogenesis.6 The IL-27 receptor (IL-27Ra or WSX-1) activates the Janus kinase (JAK) pathway with phosphorylation of signal transducer and activator of transcription (STAT)-1 and STAT3.6 IL-10, in contrast, potently inhibits the expression of inflammatory proteins such as IL-1β, tumour necrosis factor α and matrix metalloproteinase 9.1

IL-7 is primarily produced by stromal and epithelial cells8 and promotes human T-cell development, naïve T-cell homeostasis, T-cell proliferation and survival of memory T cells.7 IL-7 binds to the IL-7R, a heterodimer consisting of the IL-7Rα (CD127) and the common γ chain (γc or CD132), causing STAT1 and STAT3 activation.7 Thymic stromal lymphopoietin (TSLP) is an IL-7 family member involved in the activation, expansion and survival of T lymphocytes and dendritic cells acting through a heterodimeric IL-7Rα and TSLPR complex.9

High mobility group box 1 (HMGB1) is a nuclear protein that can act as a damage-associated...
molecular pattern to activate immune cells, including Th1 lymphocytes.

NLRs are categorised into five subfamilies. A typical inflammasome is composed of an NLR, an adaptor protein such as apoptosis-associated speck-like protein containing a CARD (ASC) and an effector caspase that activates proinflammatory cytokines. Within the NLRP3 complex, auto-catalytic cleavage of pro-caspase 1 enables removal of IL-1β and IL-18 pro sequences resulting in biologically active forms and thereby initiating Th1 and Th17 adaptive immune responses. HMGB1 is also induced by NLRP3 activation. The expression of IL-33, another member of the IL-1 family, may also be enhanced through activation of the inflammasome. IL-33 acts through its receptor ST2 and may activate immune cells. IL-6 is induced by NLRP3 but in an inflammasome-independent manner.

The NLRP3 inflammasome is activated by infectious agents, double-strand DNA and extracellular ATP. NALP7 decreases transcription of pro-IL-1β expression and IL-10 and IL-27 can modulate NLRP3 activity whereas IL-37 can downregulate inflammation and innate immunity independently of the inflammasome.

The aim of this study was to investigate the presence of innate immune mediators (IL-6, IL-7, IL-10, IL-27, IL-37, TSLP, interferon γ (IFNγ), their receptors, and signalling proteins STAT1 and pSTAT1) and inflammasome components (NLRP3, caspase 1, IL-1β, IL-18, IL-33, NALP7, ST2) in the bronchial mucosa and bronchoalveolar lavage (BAL) of patients with stable COPD of differing severity and age-matched control subjects with normal lung function.

METHODS

Subjects

All subjects were recruited from the Respiratory Medicine Unit of the ‘Fondazione Salvatore Maugeri’ (Veruno, Italy), the Section of Respiratory Diseases of the University Hospital of Ferrara, Italy, and the Section of Respiratory Diseases of the University Hospital of Katowice, Poland for immunohistochemistry and ELISA experiments. The severity of the airflow limitation, as determined by spirometry, was graded using Global Initiative for Chronic Obstructive Lung Disease (GOLD) criteria.

All former smokers had stopped smoking for at least 1 year. COPD and chronic bronchitis were defined, according to international guidelines: COPD, presence of a post-bronchodilator forced expiratory volume in 1s (FEV1)/forced vital capacity ratio <70%; chronic bronchitis, presence of cough and sputum production for at least 3 months in each of two consecutive years (http://www.goldcopd.com). All patients with COPD were stable. The study conformed to the Declaration of Helsinki. We obtained and studied bronchial biopsies from 55 subjects: 32 had a diagnosis of COPD in a stable clinical state, were current or ex-smokers with normal lung function, and 11 were non-smokers with normal lung function (table 1). The smoking history was similar in the three smoker groups: mild/moderate and severe/very severe COPD, and healthy smokers with normal lung function. Clinical details of the patients in whom BAL was collected are summarised in table 2. The results provided are the data from 26 patients with COPD and 18 control smokers with normal lung function. Due to the necessity to concentrate the BAL supernatants the results provided for each ELISA are the data from 15 patients with COPD and 14 control smokers with normal lung function which are not the same patients for all mediators measured.

A detailed description of subjects, lung function tests, fibroptic bronchoscopy and processing of bronchial biopsies and BAL, immunohistochemistry, scoring system for immunohistochemistry, double staining and confocal microscopy, ELISA tests performed on the BAL fluid and ‘in vitro’ experiments performed on normal human bronchial epithelial (NHBE) cells and details of statistical analysis are provided in the online supplementary data repository.

Table 1 Clinical characteristics of subjects studied by immunohistochemistry

<table>
<thead>
<tr>
<th></th>
<th>Control non-smokers</th>
<th>Control smokers normal lung function</th>
<th>COPD grade I/II (mild/moderate)</th>
<th>COPD grade III/IV (severe/very severe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>11</td>
<td>12</td>
<td>14</td>
<td>18</td>
</tr>
<tr>
<td>Age (years)</td>
<td>67±1</td>
<td>61±7</td>
<td>67±8</td>
<td>66±9</td>
</tr>
<tr>
<td>M/F</td>
<td>10/1</td>
<td>9/3</td>
<td>12/2</td>
<td>11/7</td>
</tr>
<tr>
<td>Pack years</td>
<td>0</td>
<td>43±26</td>
<td>40±19</td>
<td>54±36</td>
</tr>
<tr>
<td>Ex/current smokers</td>
<td>0</td>
<td>2/10</td>
<td>5/9</td>
<td>13/5</td>
</tr>
<tr>
<td>FEV1, pre-β2 (% predicted)</td>
<td>116±14</td>
<td>104±13</td>
<td>66±14*</td>
<td>35±8**</td>
</tr>
<tr>
<td>FEV1, post-β2 (% predicted)</td>
<td>ND</td>
<td>ND</td>
<td>72±12</td>
<td>38±9</td>
</tr>
<tr>
<td>FEV1/FVC (%)</td>
<td>85±10</td>
<td>81±6</td>
<td>60±8*</td>
<td>44±10**</td>
</tr>
<tr>
<td>Chronic bronchitis</td>
<td>0</td>
<td>5</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

Statistical analysis Differences between groups were analysed using analysis of variance and Kruskal–Wallis tests. Correlation coefficients were calculated using the Spearman rank method.

RESULTS

Measurement of inflammatory cells in the bronchial submucosa

These results are reported in full in the online supplementary data repository and in table E1. Briefly, these data confirm
elevated numbers of CD8 T cells, CD68 macrophages and neutrophils in patients with COPD.\(^{20}\)

**Immunohistochemistry for innate immunity and inflammasome pathways in the bronchial epithelium**

The number of IL-27+ (figure 1 and table 3), IL-27R+, TSLPR+, NALP7 and STAT1+ immunoreactive cells was increased in the epithelium of patients with severe stable COPD compared with control non-smokers (p=0.0048, p=0.017, p=0.008, p=0.054, p=0.011, respectively). IL-27+, TSLPR+, NALP7+ and STAT1+ cells also differed significantly in comparison with control healthy smokers (p=0.043, p=0.0019, p=0.0009 and p=0.023, respectively) (table 3). In contrast, no significant differences in bronchial epithelial expression of IL-1β, IL-1βRI and RII, caspase-1, IL-18, IL-18Rα, IL-18Rβ, IL-18RBP, NLRP3, IL-6, IL-6Rα, IL-7, IL-7Rα, IL-10, IL-10Rα, IL-33, ST-2, IFNγ, IFNγRI, pSTAT1, TSLP and IL-37 were observed between groups (table 3). Due to the fewer number of subjects who were current smokers within the severe stable COPD group we were unable to perform subanalysis of current versus former smokers across groups.

**Immunohistochemistry for innate immunity and inflammasome pathways in the bronchial submucosa**

Mononuclear cells (lymphocytes and macrophages) and endothelial cells were the most represented immunostained cells in the submucosa. The number of IFNγ+ cells was significantly higher in patients with mild/moderate (p=0.010) and severe (p=0.008) stable COPD compared with control non-smokers, confirming previously reported data.\(^{21}\) The number of IFNγRI+ cells was increased in patients with severe COPD compared with patients with mild COPD (p=0.031), control smokers (p=0.0033) and control non-smokers (p=0.006). IL-18Rβ showed a slight increase in patients with severe COPD compared with those with mild/moderate COPD (p=0.045) and control smokers (p=0.059) but did not differ in comparison with control non-smokers. The number of IL-7+ (see online supplementary figure E1) cells was higher in patients with severe COPD (p=0.008), patients with mild/moderate COPD (p=0.010) and in control smokers (p=0.012) compared with control non-smokers. In addition, the number of IL-7Rα+
### Table 3  Immunohistochemical quantification of innate immunity and inflammasome pathways expression in the bronchial mucosa

<table>
<thead>
<tr>
<th></th>
<th>Healthy non-smokers</th>
<th>Healthy smokers</th>
<th>Patients with mild/moderate COPD</th>
<th>Patients with severe COPD</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Epithelium (score 0–3)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-6 0.25 (0–0.5)</td>
<td>0.25 (0–0.5)</td>
<td>0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.346</td>
</tr>
<tr>
<td>IL-6 Rα</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>n.v.</td>
</tr>
<tr>
<td>IL-7 0.5 (0.5–1)</td>
<td>0.75 (0.25–2)</td>
<td>0.5 (0.25–1.5)</td>
<td>0.75 (0.5–2)</td>
<td>0.671</td>
<td></td>
</tr>
<tr>
<td>IL-7 Rα</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0.985</td>
<td></td>
</tr>
<tr>
<td>IL-10</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0.513</td>
<td></td>
</tr>
<tr>
<td>IL-10 Rα</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0.688</td>
<td></td>
</tr>
<tr>
<td>IL-27 0.5 (0.25–1)</td>
<td>0.75 (0.25–1.5)</td>
<td>0.75 (0–1.5)</td>
<td>1 (0.5–2)**</td>
<td>0.0279</td>
<td></td>
</tr>
<tr>
<td>IL-27 R</td>
<td>0 (0–0.5)</td>
<td>0.25 (0–0.75)</td>
<td>0.25 (0–1)**</td>
<td>0.0748</td>
<td></td>
</tr>
<tr>
<td>IL-33</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0.962</td>
<td></td>
</tr>
<tr>
<td>ST2</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0.25)</td>
<td>0.752</td>
<td></td>
</tr>
<tr>
<td>TSLP 0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.5 (0–1)</td>
<td>0.37 (0–1)</td>
<td>0.545</td>
<td></td>
</tr>
<tr>
<td>TSLP-R</td>
<td>0.25 (0.25–0.5)</td>
<td>0.25 (0.25–1.5)</td>
<td>0.25 (0.25–1.5)</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>IL-18 1 (0–2)</td>
<td>1 (0.5–2.5)</td>
<td>1.5 (0.25–2.5)</td>
<td>1 (0.5–2.5)</td>
<td>0.386</td>
<td></td>
</tr>
<tr>
<td>IL-18 Rα</td>
<td>2.5 (0.75–2.75)</td>
<td>2.5 (1–3)</td>
<td>2.5 (1–3)</td>
<td>0.869</td>
<td></td>
</tr>
<tr>
<td>IL-18 Rβ</td>
<td>2.25 (1–2.5)</td>
<td>1.5 (0.25–2.5)</td>
<td>2 (1–2.75)</td>
<td>0.095</td>
<td></td>
</tr>
<tr>
<td>IL-18 BP</td>
<td>0 (0–0)</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0.093</td>
<td></td>
</tr>
<tr>
<td>NLRP-3 1.62 (1.2–2)</td>
<td>1.5 (1–2.75)</td>
<td>1.5 (1–3)</td>
<td>2 (1.5–2.5)**</td>
<td>0.220</td>
<td></td>
</tr>
<tr>
<td>Caspase-1</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>n.v.</td>
<td></td>
</tr>
<tr>
<td>IL-1β 0</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0 (0–0.25)</td>
<td>0.671</td>
<td></td>
</tr>
<tr>
<td>IL-1β Rl</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>n.v.</td>
<td></td>
</tr>
<tr>
<td>IL-1β Rl 0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.25 (0–1)</td>
<td>0.380</td>
<td></td>
</tr>
<tr>
<td>IL-37 1.5 (0.25–2.25)</td>
<td>1.12 (0.75–2.25)</td>
<td>1.5 (0.75–2.25)</td>
<td>1.5 (0.75–2.25)</td>
<td>0.915</td>
<td></td>
</tr>
<tr>
<td>NALP7 1.25 (0.5–2.5)</td>
<td>1.62 (0.25–1.75)</td>
<td>1.62 (0.25–2.5)</td>
<td>1.87 (0.5–3.0)**</td>
<td>0.006</td>
<td></td>
</tr>
<tr>
<td>STAT1 0.37 (0.25–1.5)</td>
<td>0.5 (0.2–0.25)</td>
<td>1.0 (0.25–2.25)</td>
<td>1.37 (0.25–2.75)**</td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>pSTAT1 0</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>0 (0–0)</td>
<td>n.v.</td>
<td></td>
</tr>
<tr>
<td>IFN-γ 1.5 (0–2)</td>
<td>1.25 (0.75–2.5)</td>
<td>1.25 (0.75–3)</td>
<td>2.25 (0.75–2.5)</td>
<td>0.282</td>
<td></td>
</tr>
<tr>
<td><strong>Submucosa (cells/mm²) median (range)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-6 24 (9–54)</td>
<td>27.5 (8–64)</td>
<td>36.5 (4–126)</td>
<td>44 (6–169)</td>
<td>0.294</td>
<td></td>
</tr>
<tr>
<td>IL-6 Rα 0</td>
<td>11 (0–55)</td>
<td>7 (0–18)</td>
<td>10 (0–37)</td>
<td>0.259</td>
<td></td>
</tr>
<tr>
<td>IL-7 72 (32–226)</td>
<td>126 (56–269)**</td>
<td>140 (32–484)**</td>
<td>140 (52–233)**</td>
<td>0.023</td>
<td></td>
</tr>
<tr>
<td>IL-7 Rα 13 (0–71)</td>
<td>32 (6–108)</td>
<td>44.5 (5–163)</td>
<td>91 (16–302)*<strong><strong>,</strong>,</strong>,**</td>
<td>0.0053</td>
<td></td>
</tr>
<tr>
<td>IL-10 0</td>
<td>7 (0–28)**</td>
<td>6.5 (0–113)**</td>
<td>9 (0–55)**</td>
<td>0.0519</td>
<td></td>
</tr>
<tr>
<td>IL-10 Rα 0</td>
<td>0 (0–8)</td>
<td>0 (0–48)</td>
<td>0 (0–23)</td>
<td>0.367</td>
<td></td>
</tr>
<tr>
<td>IL-27 54 (8–113)</td>
<td>51 (14–140)</td>
<td>73 (9–400)</td>
<td>77 (36–542)**</td>
<td>0.113</td>
<td></td>
</tr>
<tr>
<td>IL-27 R 12 (0–24)</td>
<td>9 (0–51)</td>
<td>35 (8–81)*****</td>
<td>48 (6–151)*****</td>
<td>0.0027</td>
<td></td>
</tr>
<tr>
<td>NALP-5 0</td>
<td>6 (0–23)</td>
<td>5 (0–54)</td>
<td>6 (0–86)</td>
<td>0.606</td>
<td></td>
</tr>
<tr>
<td>IFN-γ 1.5 (0.5–2.75)</td>
<td>1.25 (0.75–2.5)</td>
<td>2.25 (0.75–2.5)</td>
<td>0.282</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data expressed as median (range). Statistics: the Kruskal–Wallis test was used for multiple comparisons followed by the Mann–Whitney U test for comparison between groups:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*p&lt;0.05, significantly different from control non-smokers;  **p&lt;0.05, significantly different from control smokers with normal lung function;  ***p&lt;0.05, significantly different from patients with mild COPD. The exact 'p' values for comparison between groups are given in the Results section.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFN, interferon; IL, interleukin; n.v., no value; TSLP, thymic stromal lymphopoietin.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
cells was significantly higher in patients with severe COPD compared with patients with mild/moderate COPD (p=0.040), control smokers (p=0.009) and control non-smokers (p=0.002). IL-10 was poorly expressed but the number of IL-10+ cells was higher in patients with severe stable COPD (p=0.005), patients with mild/moderate COPD (p=0.047) and in control smokers (p=0.054) compared with control non-smokers.

The number of IL-27+ (figure 1) and pSTAT1+ (see online supplementary figure E2) cells was significantly higher in patients with severe COPD (p=0.032 and p=0.018, respectively) compared with control smokers but did not differ in comparison with the other groups. Interestingly, the number of IL-27R+ cells was significantly higher in patients with severe COPD (p=0.010 and p=0.002) and patients with mild/moderate COPD (p=0.054 and p=0.009) compared with control smokers and non-smokers. Similarly, the number of total STX1+ cells was significantly higher in patients with severe COPD (p=0.0043 and p=0.015) and patients with mild/moderate COPD (p=0.022 and p=0.029) compared with control smokers and non-smokers.

The number of TSLPR+ cells was higher in patients with severe COPD compared with control smokers (p=0.005) and non-smokers (p=0.044). TSLPR+ cell numbers were also increased in patients with mild/moderate stable COPD with control smokers (p=0.013).

The number of IL-37+ (figure 2) and NALP7+ (see online supplementary figure E3) cells was higher in patients with severe stable COPD compared with control smokers (p=0.054 and p=0.0015 respectively) and in patients with mild/moderate stable COPD in comparison with control smokers (p=0.008 and p=0.0043 respectively). Furthermore, the number of IL-37+ cells in patients with mild/moderate stable COPD was significantly increased in comparison with control non-smokers (p=0.023) (table 3).

No significant differences were observed for IL-1β, IL-1βRI, IL-1βRII, caspase-1, IL-18, IL-18Ra, IL-18BP, NLRP3, IL-6, IL-6Ra, IL-10Ra, IL-33, ST-2 and TSLP immunostaining between groups.

Double staining and confocal microscopy

The percentage of CD68+IL-27+ double-stained cells was significantly increased in patients with COPD (34±8%) compared with control smokers (8±2%, p=0.0209) (see online supplementary figure E4 and data repository for more details).

ELISA assays in the BAL supernatants

BAL levels of IL-6 were significantly increased in patients with stable COPD compared with the control healthy smokers (p=0.0001; figure 3A), without a significant change in the BAL level of sIL-6R and sgp130 between the two groups (see online supplementary figure E5A and E6A). In contrast, BAL IL-7 (see online supplementary figure E5B) and IL-27 (see online supplementary figure E5C) levels were not significantly different between the two subject groups. BAL HMGB1 was significantly decreased in patients with stable COPD compared with control healthy smokers (p=0.0174; figure 3C). However, this difference was lost after removal of the outliers (p=0.0540). The BAL level of soluble ST2 (p=0.0073; figure 3D) and IL-1RA (p=0.0307; figure 3B) are significantly decreased in patients with stable COPD compared with control smokers with normal lung function without significant changes in the BAL level of IL-1β (see online supplementary figure E6B), IL-18 (see

![Figure 2](http://example.com/image2.png)
Correlations between inflammatory cell counts, IL-27-related molecules in the bronchi and clinical parameters

Correlations restricted to patients with COPD alone show that the number of IFNγRI+ cells correlated with the number of IL-27+ (R=0.42, p=0.036) and IL-27R+ (R=0.51, p=0.014) cells in the bronchial submucosa (figure 4A,B). The number of IFNγRI+ cells also correlated with numbers of IL-7Rα (R=0.68, p=0.0009). IL-7+ cell numbers correlated with the number of IL-27+ (R=0.43, p=0.010) and IL-27R+ (R=0.51, p=0.003) cells in the bronchial submucosa of patients with stable COPD alone (figure 4C,D; see also online data supplement).

Inflammation and oxidative stress enhance IL-27 mRNA and protein expression in NHBE cells in vitro, but not inflammasome-related mRNAs

Stimulation of human bronchial epithelial cells in vitro with a combination of oxidants (H₂O₂) and inflammatory cytokines significantly increased IL-27B mRNA and protein, but not the inflammasome-related IL-1β, IL-18 and caspase 1 encoding mRNAs (see online supplementary data repository and figures E7, E8 and E9).

DISCUSSION

We show significantly increased expression of IL-27 in the bronchial epithelium of patients with severe stable COPD compared with smoking and non-smoking controls. In addition, the number of IL-27+ and pSTAT1+ cells is also increased in the bronchial submucosa of patients with severe stable COPD compared with control smokers. This is associated with an increase in the number of IL-27R+ cells in patients with severe stable COPD compared with controls. Finally, in smokers, and in patients with COPD, the number of IFNγRI+ cells correlated with the number of IL-27+ and IL-27R+ cells. We failed to show evidence for NLRP3 activation in the airways of patients with stable COPD. Indeed, the levels of NLRP7 and IL-37, inhibitors of NLRP3 activity, were upregulated in COPD.

We have previously reported increased pSTAT4 expression linked to IFNγ expression but IL-27 can also induce IFNγ transcription through a STAT1- and STAT3-mediated process. IL-27 also increases proliferation and IFNγ and granzyme B production from human CD3-activated naïve CD8 cells. This results in increased CD8+ T-cell-mediated cytotoxicity. IL-27 also drives inducible regulatory T cells to produce IL-10. We observed a significant increase in the number of IL-10+ cells in bronchial submucosa of patients with COPD and healthy smokers, these numbers were very low in all subjects. Furthermore, there was no difference in IL-10R expression in the bronchial mucosa of patients with COPD. This, in conjunction with the previous lack of changes in FoxP3+ regulatory T cells, and low FoxP3 expressions in BAL T lymphocytes from patients with stable COPD, suggests that a predominantly non-regulatory CD25+ helper T-cell population is present in smokers and patients with stable COPD. However, IL-10 expression is reduced in the sputum of patients with stable COPD and additional studies are required to clarify this discrepancy.

IL-27B mRNA and protein expression was upregulated in normal primary human bronchial epithelial cells by combined oxidative and pro-inflammatory stimuli. Although elevated levels of IL-27 have been reported in COPD sputum there was no increase in BAL IL-27 levels in patients with mild to severe stable COPD in this study. This may reflect the different compartments sampled by BAL and by sputum or that IL-27 is released from dead or dying sputum macrophages since we show here that CD68 cells are the main source of IL-27.

IL-7+ cell numbers were increased in the bronchial mucosa of stable COPD and control smokers compared with control non-smokers despite no changes in BAL IL-7 being found. IL-7
is produced by stromal and epithelial cells whereas its receptor is expressed mainly on T cells and monocytes.7 8 The increased levels of IL-7, IL-7R and TSLPR observed here indicate that IL-7 may have a local pro-inflammatory function increasing the activation and survival of T cells and monocytes in the bronchial submucosa of patients with severe stable COPD.29

IL-7+ cell numbers correlate with IL-27+ and IL-27R+ cells, suggesting a functional relationship. The correlation between numbers of IL-7Rα+ and INFγRI on one side, and the inverse relationship between IL-7Rα and FEV1 % predicted on the other, suggests a link between increased expression of this receptor and increased severity in stable COPD. Overexpression of IL-7Rα is linked to increased severity of inflammatory bowel disease.8

High levels of IL-6 are released by sputum and BAL macrophages in vitro7 and IL-6 is increased in sputum of patients with COPD during exacerbations.30 In our study, BAL levels of IL-6, but not its soluble decoy receptor, were increased in COPD despite no change in the numbers of IL-6+ and IL-6R+ cells. Thus, our BAL data may simply reflect the presence of activated macrophages in the peripheral airways of patients with stable COPD. Soluble gp130 inhibits IL-6 trans-signalling via the sIL-6R and classic signalling via the mIL-6R.31 In animal models, sIL-6R-mediated signalling is an important intermediary in the resolution of neutrophilic inflammation,32 but we were unable to observe any significant difference in the expression of gp130 in BAL from patients with stable COPD compared with control smokers with normal lung function.

We report similar expression levels of NLRP3 in COPD and control subjects, an absence of caspase-1 expression in patients with COPD and controls, and no differences in the expression of IL-1β, its receptors and IL-18 in COPD bronchial biopsies and in the BAL level of IL-1β, IL-1RA, IL-18 and IL-18BPα, and their IL-1β/IL-1RA and IL-18/IL-18BPα ratios in patients with stable mild/moderate COPD versus control smokers with normal lung function. This suggests that the NLRP3 inflammasome only plays, at most, a minor role in the inflammatory response in the central airways of stable COPD. The increased levels of IL-18Rβ in bronchial biopsies of patients with severe COPD, compared with patients with mild COPD and control smokers, reported here, in the absence of a parallel increase in its own ligand, IL-18, may have a limited biological function (table 3, figure 5).

We did not find any difference in either IL-1β or IL-18 expression in the bronchial mucosa of patients with stable COPD and control subjects in this study. This is in contrast to increased levels of serum, sputum and BAL IL-1β,32–35 and plasma and sputum IL-1836 37 reported in patients with COPD compared with control smokers and non-smokers. Furthermore, there is discordance between the levels of IL-18 and IL-1β in patients with COPD, suggesting that coordinated induction through the NLRP3 inflammasome is not critical for their expression.36 38 Animal models of COPD also provide discordant data on the role of the NLRP3 inflammasome.35 38 39 Original data38 suggested a role for IL-1β in smoke-induced emphysema and airway remodelling but more recent data in mice favour a role for inflammasome-independent induction of IL-1β in driving smoke-induced inflammation.35 39 The expression of other inflammasome components in patients with stable COPD has not been reported but the failure to detect increased IL-1β and IL-18 expression in the bronchial mucosa and BAL in this study suggests they may also play a limited role in patients with stable COPD. However, NLRP3 inflammasome activation may be important during viral and bacterial infections.11 13 Previous studies have shown elevated levels of IL-1β in exhaled breath condensate and sputum during COPD exacerbations, particularly when associated with bacterial infections.40 We observed a modest, albeit significant, reduction of IL-1RA in the BAL of patients with stable COPD compared with control

---

**Figure 4** Regression analysis between numbers of (A) interferon (IFN)-γRI+ and interleukin (IL)-27+, (B) IFNγRI+ and IL-27R+, (C) IL-7+ and (D) IL-27+, IL-7+ and IL-27R+ cells in the bronchial submucosa of all patients with COPD. Correlation coefficients were calculated using the Spearman rank method.
patients with stable COPD indicate its potential role in the
immunity such as interleukin (IL)-27 and IL-7 (A). Molecules inducing activation of the in
lation of in
ation pathway may be clinically irrelevant. This is in line with data from unpublished clinical trials showing that monoclonal antibodies neutralising IL-1β signalling are ineffective in the treatment of patients with stable COPD (http://clinicaltrials.gov/ct2/show/results/NCT00581945).

Plasma and sputum HMGB1 levels have been previously reported to be increased in patients with stable COPD compared with control subjects but these studies were limited by not having controls matched for age and smoking history. BAL levels of HMGB1 have been reported as either increased in patients with stable COPD or no different from controls. In steroid-naïve patients with stable COPD, we found significantly decreased BAL HMGB1 levels, in comparison with age-matched control smokers with normal lung function, although this difference was lost when outliers were removed, again suggesting a minor role of inflammasome activation in the peripheral airways or a role limited to a subset of COPD patients only.

Overexpression of human IL-37 in mice results in downregulation of inflammation. The increased expression of IL-37 seen in the bronchial submucosa, but not in BAL, of patients with stable COPD compared with control smokers suggests a counter-regulatory role of this molecule. NALP7 attenuates caspase-1-dependent IL-1β secretion by inhibiting the processing of pro-IL-1β and pro-caspase 1.12 The increased expression of NALP7 in the submucosa, but not BAL, of patients with stable COPD may act to prevent the activation of the inflammasome pathway (figure 5).

One limitation of this study is the failure to apply a Bonferroni correction to the large number of biomarkers analysed. With Bonferroni correction the expression of IFNγRI, NALP7, STAT1, IL27R and IL7Rα in the submucosa and of NALP7 and TSLPR in the epithelium remain significantly different in patients with COPD, which supports the general message reported here.

In summary, our results showing an increased expression of the innate immune cytokine IL-27 in the bronchial mucosa of patients with stable COPD indicate its potential role in the progression of severity of chronic bronchial inflammation. The absence of NLRP3 inflammasome increase in patients with COPD is associated with an increased expression of the inflammatory and inflammasome inhibitory molecules IL-37 and NALP7. These data suggest a relevant role for innate immunity and a silent state of inflammasome activation in patients with stable COPD.

Author affiliations
1Divisione di Pneumologia e Laboratorio di Citoinmunopatologia dell’Apparato Cardio Respiratorio, Fondazione Salvatore Maugeri, IRCCS, Veruno (NO) e Tradate, Pavia, Italy
2Centro Interdipartimentale per lo Studio delle Malattie Inflammatorie delle Vie Aeree e Patologie Fumo-correlate (CEMICIF; formerly Centro di Ricerca su Asma e BPCO), Sezione di Medicina Interna e Cardiorespiratoria (formerly Sezione di Malattie dell’Apparato Respiratorio), Università di Ferrara, Ferrara, Italy
3Katedra i Klinika Pneumonologii Śląskiego Uniwersytetu Medycznego w Katowicach, Śląskie, Poland
4Department of Molecular Medicine, Histology Unit, University of Padova, Padova, Italy
5 Dipartimento di Biomedicina Sperimentale e Neuroscienze Cliniche, Sezione di Anatomia Umana, Università di Palermo, Palermo, Italy
6Istituto Euro-Mediterraneo di Scienza e Tecnologia, Palermo, Italy
7Istituto Paolo Sottigli, Libera Università degli Studi di Scienze Umane e Tecnologiche, Lugano, Switzerland
8Airway Disease Section, National Heart and Lung Institute, Imperial College London, London, UK

Acknowledgements We thank Ada Patriarca and Isabella Gennemi for technical assistance.

Contributors Conception, design, analysis and interpretation, drafting the manuscript: ADS, GC, AB, FC, PB, AD, KFC, PJB, AP, IA, BB. Conduction of experiments and patient recruitment: ADS, CV, MC, AZ, EG, PC, AnnaP. ADS and ADS and AB and FC coordinated experiments and patient recruitment: ADS, GC, AB, FC, PB, AD, KFC, PJB, AP, IA, BB. Conduction of experiments and patient recruitment: ADS, CV, MC, AZ, EG, PC, AnnaP. ADS and GC contributed equally.

Funding This work was supported by Fondazione Salvatore Maugeri, IRCCS, Ricerca Corrente and Regione Piemonte, Ricerca Sanitaria Finalizzata, 2009 and FAR of the University of Ferrara 2010, 2011 (to GC). Research by IMA, AD, KFC and PJB is supported by the Wellcome Trust (G93080/210/2) and by the MRC (G1001367/1).

Competing interests None.

Patient consent Obtained.

Ethics approval The study conformed to the Declaration of Helsinki and was approved by the ethics committees of the Fondazione Salvatore Maugeri (Veruno (Novara), Italy), the University Hospital of Ferrara, Italy and the University Hospital of Katowice, Poland. Written informed consent was obtained from each subject and bronchial biopsies and BAL were performed according to the local ethics committee guidelines.

Provenance and peer review Not commissioned; externally peer reviewed.
Chronic obstructive pulmonary disease

Open Access This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 3.0) license, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. See: http://creativecommons.org/licenses/by/3.0/

REFERENCES

15 Smith DE. The biological paths of IL-1 family members IL-18 and IL-33. J Leukoc Biol 2011;89:383–92.
28 Gabbers C, Thaiss W, Jones GW, et al. Inhibition of classic signaling is a novel function of soluble glycoprotein 130 (sgp130), which is controlled by the ratio of interleukin 6 and soluble interleukin 6 receptor. J Biol Chem 2011;286:42959–70.
Innate immunity but not NLRP3 inflammasome activation correlates with severity of stable COPD

Antonino Di Stefano, Gaetano Caramori, Adam Barczyk, Chiara Vicari, Paola Brun, Andrea Zanini, Francesco Cappello, Elvira Garofano, Anna Padovani, Marco Contoli, Paolo Casolari, Andrew L Durham, Kian Fan Chung, Peter J Barnes, Alberto Papi, Ian Adcock and Bruno Balbi

Thorax 2014 69: 516-524 originally published online January 15, 2014
doi: 10.1136/thoraxjnl-2012-203062

Updated information and services can be found at:
http://thorax.bmj.com/content/69/6/516

Supplementary material can be found at:
http://thorax.bmj.com/content/suppl/2014/01/15/thoraxjnl-2012-203062.DC1.html

These include:

References

This article cites 43 articles, 13 of which you can access for free at:
http://thorax.bmj.com/content/69/6/516#BIBL

Open Access

This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY 3.0) license, which permits others to distribute, remix, adapt and build upon this work, for commercial use, provided the original work is properly cited. See:
http://creativecommons.org/licenses/by/3.0/

Email alerting service

Receive free email alerts when new articles cite this article. Sign up in the box at the top right corner of the online article.

Topic Collections

Articles on similar topics can be found in the following collections

Open access (122)
Health education (1065)
Smoking (908)
Tobacco use (909)
Inflammation (918)
Pneumonia (infectious disease) (499)
Pneumonia (respiratory medicine) (484)
TB and other respiratory infections (1112)

To request permissions go to:
http://group.bmj.com/group/rights-licensing/permissions

To order reprints go to:
http://journals.bmj.com/cgi/reprintform

To subscribe to BMJ go to:
http://group.bmj.com/subscribe/