Airway inflammation in aluminium potroom asthma

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Aims: To examine whether asthma induced by exposure to aluminium potroom emissions (potroom asthma) is associated with inflammatory changes in the airways.

Methods: Bronchial biopsy specimens from 20 asthmatic workers (8 non-smokers and 12 smokers), 15 healthy workers (8 non-smokers and 7 smokers), and 10 non-exposed controls (all non-smokers) were analysed. Immunohistochemical staining was performed to identify mucosal total leucocytes (CD45+ leucocytes), neutrophils, and mast cells.

Results: Median RBM thickness was significantly increased in both asthmatic workers (8.2 μm) and healthy workers (7.4 μm) compared to non-exposed controls (6.7 μm). Non-smoking asthmatic workers had significantly increased median density of lamina propria CD45+ leucocytes (1519 cells/mm²) and eosinophils (10 667 cells/mm²) and eosinophils (27 cells/mm²) and significantly increased concentrations of exhaled NO (18.1 ppb v 6.5 and 5.1 ppb) compared to non-smoking healthy workers and non-exposed controls. Leucocyte counts and exhaled NO concentrations varied with smoking habits and fewer leucocytes were observed in asthmatic smokers than in non-smokers. Asthmatic smokers had significantly increased numbers of eosinophils in lamina propria compared to non-exposed controls (10 v 3 cells/mm²). Both eosinophilic and non-eosinophilic phenotypes of asthma were recognised in the potroom workers and signs of airway inflammation were also observed in healthy workers.

Conclusions: Airway inflammation is a central feature of potroom asthma and exposure to potroom emissions induces pathological alterations similar to those described in other types of asthma. Cigarette smoking seems to affect the underlying mechanisms involved in asthma, as the cellular composition of airway mucosa appears different in asthmatic smokers and non-smokers.

METHODS

Subjects

Potroom workers with occupational asthma (eight non-smokers and 12 smokers), healthy potroom workers (eight non-smokers and seven smokers), and 10 healthy non-exposed controls (all non-smokers) were included. All asthmatic workers who had not left the plant were identified by the company physicians and were examined by the main investigator (TS) who confirmed the diagnosis of potroom asthma. From a total asthmatic population of 39 workers, 18 subjects were excluded for different reasons (lack of...)

Abbreviations: DIC, differential interference contrast; FEV₁, forced expiratory volume in one second; FVC, forced vital capacity; NO, nitric oxide; RBM, reticular basement membrane; PEF, peak expiratory flow...
Main messages

- Workers with potroom asthma develop chronic bronchial inflammation.
- Non-smoking potroom asthmatics have similar inflammatory changes in airway mucosa as conventional asthma, shown by thickened RBM, increased leucocyte and eosinophil influx, and increased exhaled NO.
- Smoking potroom asthmatics have thickened RBM but lower leucocyte density than asthmatic non-smokers, suggesting an immunomodulating effect of tobacco smoking.

Policy implications

- Early diagnosis of potroom asthma and relocation is essential to prevent irreversible histopathological changes.

and recording of medical and occupational history was performed by a physician (TS); the subjects underwent spirometry, chest radiography, electrocardiography, blood tests, and measurement of exhaled NO the day before bronchoscopy with bronchial biopsy.

Exposure

In the Norwegian aluminium industry measurements of total airborne fluorides and dust are regularly performed from personal samplers. The mean levels of exposure are mostly far below the Norwegian threshold limit value (total fluorides 0.6 mg/m³ and total particulates 5 mg/m³), but peak exposures frequently occur. About 40% of the measurements for fluorides and 10% of the measurements for particulates are reported to exceed the hygienic limit values. In the present study, levels of exposure are not estimated for the individual worker, and only duration of exposure is recorded.

Measurement of lung function and exhaled NO

Spirometry was performed with a pneumotachograph (Vitalograph, Birmingham, UK) in accordance with the guidelines recommended by European Respiratory Society.18 The reference values of European Coal and Steel Community were used.19 Exhaled NO was measured by a chemiluminescence analyser (LR 2000, Logan Research, UK) at a sampling rate of 250 ml/min as previously described.19

Bronchoscopy and processing of bronchial biopsy specimens

Fibreoptic bronchoscopy and biopsy sampling was performed following the guidelines from the European Society of Pneumology.19 All subjects were premedicated with atropine 0.6 mg subcutaneously, 5 mg diazepam orally, and alfentanil intravenously as needed (0-2 mg) for mild sedation and analgesic. Under local anaesthesia with lidocaine, a bronchoscope with working channel 2.8 mm (Pentax FB-19H or Olympus 20D IT) was used to obtain a maximum of six bronchial biopsy specimens from the second and third generation carinae of the right lung by a single use forceps (Microvasive L267, Radial Jaw, Boston Scientific). The biopsy specimens were immediately embedded in Tissue-Tek Optimal Cutting Temperature Compound (Miles Laboratories, IN), snap frozen in isopentane precooled in liquid nitrogen, and stored at −70°C. Cryo sections were cut serially at 4 μm, dried overnight, and stored at −20°C until use.

Immunohistochemistry

From a lower lobe biopsy, two sections of 100 μm interval were prepared for immunohistochemistry using antibodies (all Dako A/S, Denmark) against total common leucocytes CD45 (catalogue number M701), mast cell tryptase (M7052), and neutrophil elastase (M752). The primary antibodies were applied at optimal dilutions and incubated one hour at room temperature. The sections were prefixed for 10 minutes at 4°C in 2% paraformaldehdye for CD45 staining and in 4% paraformaldehyde for mast cell and neutrophil staining. Goat serum 5% was then applied for 15 minutes to block unspecific binding sites. The secondary layer was biotinylated goat anti-mouse

Study design

The workers were recruited from five Norwegian aluminium smelters during the period 1998–2002. Clinical examination

reversible airway obstruction, atopy, childhood asthma, exercise induced asthma, frequent airway infections, FEV₁ <70% of predicted value, cardiac disease).

Of the 21 asthmatic workers fitting the inclusion criteria, only one was not included because he did not want to undergo a bronchoscopic examination.

The diagnosis of potroom asthma was made by confirming the diagnosis of bronchial asthma according to international guidelines17 and by establishing a causal relation between asthma and the working environment, meeting the criteria for potroom asthma as previously defined.11 Serial monitoring of PEF was performed at work and away from work. The clinical criteria were: initially asymptomatic exposure period (latency), symptoms of airway obstruction (dyspnoea, wheezing, and cough), usually occurring several hours after exposure or during sleep, and improvement of the symptoms after absence from work for several days or longer. Reversible airway obstruction defined as >15% increase in FEV₁ after inhalation of β₂ agonist and diurnal PEF variability >15% was documented in all asthmatic subjects. If work aggravation of underlying asthma was suspected, the subject was excluded. About half of the asthmatic workers were still working in the potrooms, and those relocated were working in non-polluted environments at the smelter. The relocated workers had persistent asthmatic symptoms, although all subjects reported gradual improvement of symptoms after withdrawal from exposure. The healthy workers and non-exposed controls had no symptoms from upper or lower airways and their lung function was normal. The 15 healthy workers and 17 non-polluted controls had no symptoms from upper or lower airways and their lung function was normal. The 15 healthy never-smoking population, responding to a request for volunteers at the University of Oslo. None of the participates had a history of allergy, familiar asthma, or cardiac disease.

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Main messages

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immunoglobulin (Dako A/S) incubated for 1.5 hours followed by 0.5 hour incubation with Streptavidin Alexa 594 conjugate (Molecular Probes, Nederlands) mixed with DNA staining to visualise the nucleus (4,6-diamino-2-phenylinodole (DAPI) Molecular Probes). Figure 1 shows an example of immunohistofluorescent staining of CD45⁺ leucocytes. Methodological controls included sections stained without primary antibody and sections incubated with non-immune mouse immunoglobulin. The adjacent slides were stained with haematoxylin and eosin for examination of eosinophils.

Quantitation of leucocytes
All slides were analysed blind by one observer (TS) using a Zeiss Axioplan2 microscope at 630× magnification. Eosinophils were identified on haematoxylin and eosin stained slides examined by light microscopy in combination with differential interference contrast (DIC) microscopy. This method for identification of eosinophils has been shown to be more reliable in cryo sections than immunohistochemical labelling of eosinophil granule proteins. In cases of doubt, we additionally used the eosin fluorescence to localise the cell. Positively stained cells were counted in intact epithelium (defined as the presence of both basal and columnar cells) and in a tissue zone 114 μm beneath the RBM, referred to as lamina propria. All available area was analysed. The final result, expressed as number of intraepithelial cells per millimetre of intact epithelium or number of cells per square millimetre of lamina propria, was calculated as the average of all the measurements performed of each section. The median length of intact epithelium examined in a subject was 5 mm (range 2–16 mm) and the median area of lamina propria examined was 0.87 mm² (range 0.36–2.24 mm²), corresponding to a basement membrane length of 6.2 mm (2.4–16.0 mm), as recommended.

Measurements of RBM
By use of DIC microscopy combined with light microscopy, a digital captured high power image was used to measure the distance from the base of the bronchial epithelium to the outer limit of the RBM by AnalySIS Soft Imaging System, as illustrated in fig 2. Only perpendicular cut sections were examined and a median of 68 measurements (range 37–161) were performed on each section at approximately 20 μm intervals, as recommended.

Epithelial integrity
The degree of epithelial damage was expressed as epithelial integrity, defined as the length of basal membrane covered with intact epithelium divided by the total length of the membrane. By light microscopy examination (haematoxylin and eosin stained slides and 630× magnification), a test grid (eyepiece reticule) was superimposed on the section, and the length of basal membrane with and without intact epithelium was recorded. A median of 31 grids were analysed for each subject, corresponding to a median length of basement membrane of 6.2 mm.

Statistics
Results are presented as median (range) values. Differences between two groups were compared by the Mann-Whitney U test and correlation coefficients were calculated using Spearman’s rank method. To control for potential confounders

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<th>Table 1 Characteristics of the study population</th>
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<td>Age (years)*</td>
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<td>FEV₁ % pred*</td>
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<td>FEV₁/FVC %*</td>
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<td>Inhaled corticosteroids (n)</td>
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<td>Inhaled β₂ agonist (n)</td>
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<td>Duration of exposure (years)*</td>
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<tr>
<td>Duration of symptoms (years)*</td>
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<td>Latency period (years)*</td>
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<td>Relocated subjects (n)</td>
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*Data are presented as median (range).
FEV₁, forced expiratory volume in 1 second; % pred, percentage of predicted value; FVC, forced vital capacity.

Figure 1 Immunofluorescent staining of CD45⁺ leucocytes (red) combined with 2,6-diamino-2-phenylinodole dihydrochloride (DAPI) to visualise the nucleus (blue) in a bronchial biopsy specimen from a non-smoking subject with potroom asthma. Positively stained cells are seen in both the epithelium and lamina propria. Original magnification × 630. Internal scale bar = 50 μm. (Pseudocolour multilayer image superimposed on differential interference contrast image)
Leucocyte density in lamina propria

Asthmatic non-smokers had significantly higher density of CD45⁺ leucocytes (fig 3A) and eosinophils (fig 3B) compared to both non-smoking healthy workers and non-exposed controls (table 2). In contrast, a rather low density of leucocytes was observed in asthmatic smokers, in whom the densities of CD45⁺ leucocytes, eosinophils, and neutrophils were significantly reduced compared to asthmatic non-smokers (p < 0.001, p = 0.05, and p = 0.04 respectively). The difference in mast cells did not reach the level of significance. Healthy workers (both non-smoking and smoking subgroup) had a significantly increased density of eosinophils compared to non-exposed controls (p = 0.04 and p = 0.01).

Classifying subjects with eosinophil density above the upper range seen in non-exposed controls (0–15 cells/mm²) as eosinophil(+), 50% of the asthmatics and 40% of the healthy workers were eosinophil(+) subjects. This cut-off value coincides with two standard deviations of the mean value in non-exposed controls.

Intraepithelial cell counts

The number of intraepithelial CD45⁺ leucocytes was significantly increased in both asthmatic (22 cells/mm epithelium) and healthy smokers (35 cells/mm epithelium) compared to the non-smoking groups. Within the non-smoking groups there were no difference (varying from 8 to 11 cells/mm epithelium). Intraepithelial mast cells were significantly increased in asthmatic non-smokers compared to non-exposed controls (0.9 v 0.2 cells/mm epithelium, p = 0.05).

Epithelial integrity

In non-smokers, we found no significant difference in epithelial integrity between asthmatics and controls (table 2). Epithelial integrity was significantly increased in asthmatic smokers compared to asthmatic non-smokers (p = 0.03), but no difference was found between asthmatic

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### Table 2  Leucocyte density in lamina propria, reticular basement membrane thickness, epithelial integrity, and exhaled nitric oxide

<table>
<thead>
<tr>
<th></th>
<th>Asthmatic workers (n = 20)</th>
<th>Healthy workers (n = 15)</th>
<th>Non-exposed controls (n = 10)</th>
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<tr>
<td></td>
<td>Non-smokers (n = 8)</td>
<td>Smokers (n = 12)</td>
<td>Non-smokers (n = 8)</td>
</tr>
<tr>
<td>CD45⁺ leucocytes</td>
<td>1519 (720–1917)</td>
<td>675 (452–914)</td>
<td>660 (415–1289)</td>
</tr>
<tr>
<td>Mast cells</td>
<td>27 (6–164)</td>
<td>10 (0–41)</td>
<td>10 (3–241)</td>
</tr>
<tr>
<td>Neutrophils</td>
<td>116 (66–161)</td>
<td>78 (29–141)</td>
<td>93 (43–169)</td>
</tr>
<tr>
<td>Eosinophils</td>
<td>83 (46–162)</td>
<td>42 (13–93)</td>
<td>45 (18–110)</td>
</tr>
<tr>
<td>RBM (μm)</td>
<td>8.2 (7.3–10.2)</td>
<td>8.0 (5.9–12.5)</td>
<td>7.2 (5.6–8.7)</td>
</tr>
<tr>
<td>Epithelial integrity (%)</td>
<td>52 (9–90)</td>
<td>70 (51–96)</td>
<td>41 (18–93)</td>
</tr>
<tr>
<td>Exhaled NO (ppb)</td>
<td>18.1 (6.3–91.1)</td>
<td>4.4 (1.2–80.0)</td>
<td>6.5 (3.1–22.8)</td>
</tr>
</tbody>
</table>

RBM, reticular basement membrane; ppb, parts per billion.

*Data are expressed as median (range).

†p < 0.05 v non-smoking healthy workers and non-exposed controls.

‡p < 0.05 v non-exposed controls.

§p < 0.05 v smoking asthmatic workers.
smokers and the smoking healthy workers. In the damaged area, the ciliated epithelial cells were often absent while the layer of cuboidal basal cells was intact.

Exhaled NO
In non-smoking subjects, the concentrations of exhaled NO were significantly higher in asthmatic workers than in both healthy workers and non-exposed controls (fig 3D). Exhaled NO was, as expected, low in smokers, and NO values in asthmatic smokers did not differ from those in control smokers. In non-smoking asthmatic workers, exhaled NO correlated to the density of lamina propria CD45+ leucocytes \((r = 0.81, p = 0.02)\) and eosinophils \((r = 0.79, p = 0.02)\).

Exposure and outcome variables
We found no association between number of years employed in the potrooms and any of the outcome parameters. There was no difference between asthmatic workers who were still exposed in the potrooms and those who were relocated to non-polluted working environments.
The finding of increased exhaled NO concentrations in non-smoking workers with potroom asthma is in accordance with a preceding study by Lund and colleagues. In addition we found a positive correlation between exhaled NO concentrations and the density of lamina propria CD45+ leucocytes and eosinophils in subjects with potroom asthma. Similar correlations were not observed in the healthy workers.

The observed significant increase in some inflammatory markers in healthy potroom workers is an interesting finding. Compared to non-exposed controls, the healthy potroom workers had a higher density of lamina propria eosinophils and thicker RBM, and their exhaled NO tended to be higher. These findings suggest that exposure to pollutants in aluminium smelters may affect the bronchial mucosa and induce a subclinical airway inflammation, even in healthy asymptomatic workers.

An unexpected finding was the impact of smoking in asthmatics. Asthmatic smokers had lower leucocyte density than asthmatic non-smokers. A higher proportion of asthmatic smokers were treated with inhaled steroids (3/12 of asthmatic smokers v 1/8 of asthmatic non-smokers). However, the difference in leucocyte density and exhaled NO values between the two asthma groups cannot be explained by anti-inflammatory treatment, as excluding the four subjects on inhaled corticosteroids from our analyses did not change the overall results.

A misclassification of asthma also seems unlikely. The smokers who were diagnosed as asthmatics had symptoms, PEF measurements, and reversibility consistent with potroom asthma and not chronic obstructive lung disease, and their median FEV₁ was comparable to that in non-smoking asthmatics (90% v 91% of predicted value). Two of the asthmatic workers and three of the healthy workers were ex-smokers. (The asthmatics had smoked respectively 8 and 20 pack-years and had stopped smoking 3 and 13 years ago. The healthy workers had smoked 2, 5, and 11 pack-years and had stopped respectively 14, 15, and 6 years ago.) No studies are available to clarify a potential effect of cigarette smoking on inflammatory parameters in the airways of previous smokers. Excluding the five ex-smokers from the analyses did not change the main results, but the sample size might be too small to show a hangover effect of smoking.

Studies of asthmatic inflammation in humans have been limited to non-smokers, and to our knowledge there is no published biopsy study including asthmatic smokers.

Hence, an immunomodulating effect of smoking on airway mucosa in asthmatics has not previously been shown, but recent publications from peripheral blood and induced sputum of smoking asthmatics support our data. In agreement with other studies showing smoking to induce an inflammatory airway reaction in non-asthmatics, the smoking healthy workers tended to have higher leucocyte density compared to non-smoking healthy workers.

Smoking in itself may be immunomodulating rather than proinflammatory. This is supported by several human and animal studies. Nicotine was recently shown to have a direct inhibitory effect on the production of proinflammatory mediators by stimulating the nicotinic acetylcholine receptor. Moreover, in a recent study a smoke induced reduction in the number of dendritic cells in the murine lung was reported. The finding that smoke exposure influences the antigen presenting cells may have profound effects on immune responsiveness.

According to this, it is likely that the relatively low number of leucocytes in the airway wall found in our asthmatic smokers was induced by smoking and not by occupational exposure or interaction effects. However, at present we have no explanation for why smoking seems to have a
pro-inflammatory effect in non-asthmatics but an anti-inflammatory effect in asthmatics.

In conclusion, in non-smoking workers with potroom asthma characteristic immunopathological features of asthma such as inflammatory cell infiltrate, thickening of RBM, and increased levels of exhaled NO were shown. In asthmatic smokers, only thickening of RBM was observed, suggesting a different pathophysiological process for potroom asthma in smokers than in non-smokers. In healthy workers, exposure to pot fume emissions may induce a subclinical airway inflammation.

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