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Increased Exhalation of Hydrogen Peroxide in Patients with Stable and Unstable Chronic Obstructive Pulmonary Disease

P. N. RICHARD DEKHUIJZEN, KATJA K. H. ABEN, INGRID DEKKER, LEON P. H. J. AARTS, PASCAL L. M. L. WIELDERS, CEES L. A. VAN HERWAARDEN, and AALT BAST

Department of Pulmonary Diseases, Academic Hospital Nijmegen; and Department of Pharmacochemistry, Free University of Amsterdam, the Netherlands

An imbalance between oxidative stress and antioxidative capacity is thought to play an important role in the development and progression of chronic obstructive pulmonary disease (COPD). To assess the lung oxidative status in patients with COPD, we studied whether exhaled hydrogen peroxide (H$_2$O$_2$) is increased in breath condensate of patients with stable COPD (n = 12, mean FEV$_1$ 51% pred) and in patients with exacerbated COPD (n = 19, actual FEV$_1$ 36% pred) compared with a healthy control group (n = 10, FEV$_1$ 108% pred). Expired breath condensate during 15 min of tidal breathing was collected by cooling. The concentration of H$_2$O$_2$ was measured spectrophotometrically by means of horse radish peroxidase–catalyzed oxidation of tetramethylbenzidine. Concentrations of H$_2$O$_2$ (mean ± SEM) were significantly elevated at 0.205 ± 0.054 nM in patients with stable COPD compared with 0.029 ± 0.012 nM in the control group (p < 0.05) and were further increased to 0.600 ± 0.075 nM in patients with acutely exacerbated COPD (p < 0.001 compared with patients with stable COPD). Patients with pulmonary infiltrates on chest radiograph showed similar values compared with patients without obvious infiltrates. These findings demonstrate that patients with stable COPD exhibit increased oxidant production in the airways and that oxidant production increases further during exacerbations.

Characteristics of Patients with Stable COPD

<table>
<thead>
<tr>
<th>Patient</th>
<th>Age, sex</th>
<th>Smoking*</th>
<th>( P_{A_{O_2}} ) (kPa)</th>
<th>( P_{A_{CO_2}} ) (kPa)</th>
<th>FEV₁ (% pred)†</th>
<th>( H_2O_2 ) (μM)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>63, M</td>
<td>C</td>
<td>9.2</td>
<td>5.8</td>
<td>63</td>
<td>0.000</td>
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<tr>
<td>2</td>
<td>72, M</td>
<td>E</td>
<td>8.9</td>
<td>5.6</td>
<td>36</td>
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<tr>
<td>3</td>
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<td>C</td>
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<td>4.8</td>
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<tr>
<td>4</td>
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<td>E</td>
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<td>5.8</td>
<td>38</td>
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<td>5.2</td>
<td>55</td>
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<td>E</td>
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<td>6.3</td>
<td>18</td>
<td>0.052</td>
</tr>
<tr>
<td>7</td>
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<td>4.8</td>
<td>61</td>
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</tr>
<tr>
<td>8</td>
<td>64, F</td>
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<tr>
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<tr>
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<tr>
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<td>0.4</td>
<td>0.2</td>
<td>4</td>
<td>0.054</td>
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</table>

* Smoking: C = current, E = ex.
† FEV₁: actual value at the morning of collection of breath condensate.

3 mo (FEV₁, 108 ± 6% pred [12]). Patients with COPD were included if postbronchodilator FEV₁ was below 60% pred and/or FEV₁/vital capacity ratio was below 60%. All patients were classified as smokers or ex-smokers (i.e., discontinuation of smoking for at least 3 mo) based on medical history. Exclusion criteria were pulmonary disorders at present or in the past possibly contributing to chronic airflow obstruction (e.g., tuberculosis, sarcoidosis, bronchiectasis, and asthma), clinical signs of bronchial hyperreactivity and/or acute response to an inhaled bronchodilator of more than 15% of predicted value, chronic airflow obstruction without smoking in the past, regular intake of vitamin C and E, and treatment with oral or inhaled N-acetylcysteine. Patients with stable COPD (n = 12; mean [± SEM] age, 70 ± 3 yr; mean FEV₁, 51 ± 4% pred) were defined as having no increase in symptoms and no exacerbations in the previous 3 mo. They were on maintenance therapy with inhaled bronchodilators; one used inhaled corticosteroids, and none received oral steroids. An exacerbation was defined by an acute deterioration of breathlessness, mostly with increased coughing and production of purulent sputum, for which additional medication was indicated (inhaled bronchodilators, oral or intravenous corticosteroids, or antibiotics). In this group, 19 patients were studied (mean [± SEM] age, 69 ± 2 yr; FEV₁, measured within 6 mo before the exacerbation, 49 ± 4% pred). Patients with signs of upper respiratory tract infection were excluded. Measurements in the acute patients were performed on the first or second day after consultation at the outpatient clinic or at hospitalization. Only patients who sought medical attention within 1 wk after the start of exacerbation symptoms were included in the study. All received supplemental oxygen, which was discontinued for at least 30 min before the collection of exhaled breath condensate. The study was approved by the hospital ethics committee; informed consent was obtained from all subjects.

Collection of expired breath and measurement of \( H_2O_2 \). The samples were collected in the morning, approximately 1 h after inhalation of the patient's own bronchodilator. Current smokers were requested to refrain from smoking after midnight. First, FEV₁ was measured. Subsequently, the participants were breathing through a face mask with a two-way valve. The expired air was conducted through a tube with a coll.
lacting system which was placed in ice. The collecting system was connected to a 2 ml sterile plastic tube. In this way, approximately 1 ml of breath condensate was collected within 15 min of tidal breathing. The samples were immediately placed in liquid nitrogen. Measurements of H2O2 were performed within 6 h after sample collection, since preliminary data showed that H2O2 concentrations did not change during this period. The method described by Gallati and Pracht was applied (13). Briefly, 100 μl of 420 μM 3',3',5,5'-tetramethylbenzidine (dissolved in 0.42 M citrate buffer, pH 3.8) and 10 μl of 52.5 U/ml of horseradish peroxidase (HRP; Sigma Chemicals) were added to 100 μl of the condensate. The reaction proceeded for 20 min at room temperature. Subsequently, the mixture was acidified to a pH of 1 with 10 μl of 18 N sulfuric acid. The reaction product was measured spectrophotometrically at 450 nm using an automated microplate reader (model EL312; Bio-Tek Instruments Inc.). The absorbance is directly proportional to the concentration of H2O2. The detection limit was approximately 0.1 μM H2O2. All samples were measured in duplicate; mean values were used for subsequent analysis.

**Statistical analysis.** Data between the three groups were compared using one-way analysis of variance followed by Duncan's multiple range test. A Wilcoxon test was performed to test differences between patients with or without pulmonary infiltrates. Spearman correlation tests were performed to detect a correlation between the concentration of exhaled H2O2 and clinical markers of severity of the disease such as FEV1 and PaO2. All values are presented as mean ± SEM; statistical significance was assumed at p < 0.05.

**RESULTS**

Normal subjects had the lowest concentration of H2O2 in breath condensate (0.029 ± 0.012 μM) (Figure 1). No H2O2 was detected in 6 of 10 healthy subjects. In contrast, patients with stable COPD exhibited an increased concentration of exhaled H2O2 (0.205 ± 0.054 μM, p < 0.05 compared with normal subjects). Hydrogen peroxide was not detected in 2 of these 12 subjects. Finally, H2O2 was detected in all samples of the patients with exacerbated COPD and was elevated in comparison with patients with stable COPD (0.600 ± 0.075 μM, p < 0.001).

Patients with an exacerbation with pulmonary infiltrates on chest radiograph (n = 5) showed similar values compared with patients without obvious infiltrates (n = 14) (0.601 ± 0.166 μM and 0.599 ± 0.087 μM, respectively). In the group of patients with stable COPD, those who still smoked (n = 4, FEV1, 61 ± 1% pred) exhaled 0.077 ± 0.044 μM, whereas the exsmokers (n = 8, FEV1, 47 ± 6% pred) exhaled 0.269 ± 0.068 μM (current versus exsmokers, p = 0.094). No significant correlations were found between the levels of H2O2 and FEV1 (r = 0.13) or PaO2 (r = 0.16) in patients with stable and unstable COPD.

**DISCUSSION**

This study shows increased H2O2 concentrations in exhaled breath condensate in patients with stable COPD, providing direct evidence of increased production of ROS in the airways of these patients. A further increase was observed in patients with an exacerbation.

Concentrations of H2O2 measured in exhaled breath condensate may be considered as the net result of production versus scavenging of H2O2. An increased production of H2O2 may be caused by an increased number of lung inflammatory cells and/or increased production of H2O2 by these cells (7). An increased number of these cells have been found in the lungs of patients with stable COPD. Both bronchial lavage and bronchoalveolar lavage fluid obtained from smokers with COPD contained more neutrophils than found in fluid obtained from healthy nonsmokers (14, 15). Increased numbers of macrophages and T lymphocytes were present in the bronchial mucosa of patients with chronic bronchitis and airflow obstruction compared with healthy nonsmokers (16). Exacerbations of chronic bronchitis in patients with mild COPD (mean FEV1, approximately 66% pred) were associated with increased numbers of eosinophils, neutrophils, and T lymphocytes in the bronchial wall (6).

Indications of increased activation and production of ROS by these cells have been observed in smokers (3, 4, 7, 17). Bronchoalveolar lavage fluid from smokers contained increased numbers of AM with higher densities, which produced more superoxide anion radicals (17). In addition, AM from smokers with a recent lower respiratory tract infection released increased quantities of H2O2 (7).

The production of ROS may be reduced, at least in *vivo*, by medications such as β2 sympathomimetic drugs and theophylline (18). Whether this effect also occurs *in vitro* is unknown. Natural protection against an increased concentration of H2O2 is provided by catalase and—of particular importance in the lungs—glutathione. Only a few studies have addressed the antioxidative capacity of the lungs of smokers (4, 15, 19). Reduced activities of superoxide dismutase, glutathione S-transferase, and glutathione peroxidase were found in the AM of elderly smokers (4). In contrast, enhanced activities of superoxide dismutase and catalase, but not of glutathione peroxidase, were shown in the AM of younger smokers (19). Linden and colleagues (15) demonstrated an increased concentration of total glutathione (free and disulfide bond) in bronchoalveolar lavage fluid obtained from patients with COPD who were current smokers. It is unknown whether this increase in total glutathione is caused by continued smoking or by COPD itself (i.e., also occurring in exsmokers).

In contrast to our findings, Szajdaj and colleagues (10) found significantly higher concentrations of exhaled H2O2 in patients with acute respiratory failure and pulmonary infiltrates compared with those without. These authors also noted that central nervous system involvement in these patients increased exhaled H2O2 levels compared with those patients without involvement; moreover, patients with infiltrates and sepsis exhaled higher levels of H2O2 than those without sepsis. Thus, the differences observed in the study by Szajdaj and colleagues may not be attributed solely to the presence or absence of infiltrates.

The current smokers in the group with stable COPD tended to exhale lower concentrations of H2O2 compared with the exsmokers. The number of patients studied, however, was too small to make any conclusions about the effects of smoking in this respect. In addition, bias may have occurred in our separation.
of smokers and exsmokers, which was based solely on medical history.

Hydrogen peroxide is produced not only in the lower but also in the upper airways. Therefore, patients with clinically suspected upper airway infection were excluded from the study in order to avoid a major contribution of these airways to total H$_2$O$_2$ exhalation. Differences in minute ventilation and breathing pattern may have occurred among the different groups. This, however, was not likely to account for the differences observed in exhaled H$_2$O$_2$ levels, as changes in minute ventilation and breathing pattern did not alter H$_2$O$_2$ exhalation in animal experiments (10).

In conclusion, our data show that increased H$_2$O$_2$ occurs in subjects with stable COPD and even more so in patients with exacerbated COPD. These data are consistent with the concept that ongoing airway inflammation with elevated production of ROS increases lung oxidative stress in patients with stable COPD.

References