Inter-alpha-trypsin inhibitor heavy chain 4: a novel biomarker for environmental exposure to particulate air pollution in patients with chronic obstructive pulmonary disease

Kang-Yun Lee1,3
Po-Hao Feng1,2
Shu-Chuan Ho4
Kai-Jen Chuang5,6
Tzu-Tao Chen3
Chien-Ling Su2,4
Wen-Te Liu2,4
Hsiao-Chi Chuang3

1Department of Internal Medicine, School of Medicine, College of Medicine, Taipei Medical University, 2Division of Pulmonary Medicine, Department of Internal Medicine, Shuang Ho Hospital, Taipei Medical University, 3Graduate Institute of Clinical Medicine, College of Medicine, Taipei Medical University, 4School of Respiratory Therapy, College of Medicine, Taipei Medical University, 5Department of Public Health, School of Medicine, College of Medicine, Taipei Medical University, 6School of Public Health, College of Public Health and Nutrition, Taipei Medical University, Taipei, Taiwan

Abstract: Chronic obstructive pulmonary disease (COPD) is a chronic inflammatory disease that is correlated with environmental stress. Particulate matter ≤10 μm (PM_{10}) is considered to be a risk factor for COPD development; however, the effects of PM_{10} on the protein levels in COPD remain unclear. Fifty subjects with COPD and 15 healthy controls were recruited. Gene ontology analysis of differentially expressed proteins identified immune system process and binding as the most important biological process and molecular function, respectively, in the responses of PM_{10}-exposed patients with COPD. Biomarkers for PM_{10} in COPD were identified and compared with the same in healthy controls and included proteoglycan 4 (PRG4), inter-alpha-trypsin inhibitor heavy chain 4 (ITIH4), and apolipoprotein F (APOF). PRG4 and ITIH4 were associated with a past 3-year PM_{10} exposure level. The receiver operating characteristic curve analysis showed that ITIH4 is a sensitive and specific biomarker for PM_{10} exposure (area under the curve [AUC] = 0.690, P = 0.015) compared with PRG4 (AUC = 0.636, P = 0.083), APOF (AUC = 0.523, P = 0.766), 8-isoprostane (AUC = 0.563, P = 0.405), and C-reactive protein (CRP; AUC = 0.634, P = 0.086). ITIH4 levels were correlated with CRP (r = 0.353, P = 0.005), suggesting that ITIH4 may be involved in an inflammatory mechanism. In summary, serum ITIH4 may be a PM_{10}-specific biomarker in COPD and may be related to inflammation.

Keywords: air pollution, apolipoprotein F, C-reactive protein, inflammation, proteoglycan 4, oxidative stress

Introduction

Epidemiological and toxicological research has identified adverse human health effects due to particulate air pollution exposure. Particulate matter ≤10 μm in aerodynamic diameter (PM_{10}) is associated with increased hospital admissions and mortality due to pulmonary and cardiovascular diseases.1 Air pollutants participate in the development of pulmonary disease by interfering with both nonspecific and specific lung defenses.2 Chronic obstructive pulmonary disease (COPD), for instance, is recognized as an environmentally related pulmonary disease that is associated with exposure to air pollution.3 Schikowski et al4 in 2014, provided evidence that the chronic effects of air pollution affect the prevalence and incidence of COPD among adults. Kumar et al5 (2013) noted the association between acute COPD exacerbation and particulate air pollution, finding that the risk of acute COPD exacerbation increased by 2.3% following a unit increase in PM_{2.5} (≤2.5 μm). However, the effects of PM_{10} on protein expression in COPD are not well understood.
A protein biomarker is capable of objectively and quantitatively acting as an indicator to identify normal or pathological processes and the corresponding exposure to environmental stresses. For example, 8-isoprostan and C-reactive protein (CRP), the biomarkers for oxidative stress and inflammation, respectively, have been widely used to evaluate the cardiopulmonary toxicity of PM\(_{10}\). However, they are nonspecific PM\(_{10}\) biomarkers for oxidative inflammatory reactions. Thus, an increasing number of studies have attempted to identify more specific biomarkers for the assessment of specific pollutant exposures. For example, urinary p-nitrophenol has been reported to be a specific biomarker for occupational exposure to methyl parathion, and DNA modifications, such as \(F2RL3\) methylation, have been suggested as biomarkers for tobacco exposure. Ideally, a quality biomarker can be used for treatment and intervention decisions. However, biomarker measurement may also vary according to exposure sources and susceptible populations.

A useful biomarker not only differentiates stable disease from exacerbations but also predicts the severity of pollutant exposure. The objective of this study was to identify biomarkers for PM\(_{10}\) exposure in patients with COPD. This study identified and assessed the use of serum biomarkers in the evaluation of PM\(_{10}\) compared with the existing biomarkers of inflammation, namely 8-isoprostan and CRP. We used a proteomics approach to comprehensively screen protein profiles in healthy subjects and patients with COPD exposed to low and high levels of PM\(_{10}\) over the past 3 years. The identified protein candidates were determined in serum samples obtained from 50 patients with COPD and 15 subjects without COPD. The specific and sensitive values of 8-isoprostan, CRP, and identified biomarkers were compared.

Materials and methods

Study population

We recruited 50 patients with COPD and 15 subjects without COPD (nonsmokers and smokers) in a medical center in Taiwan between January 2013 and August 2014. All subjects were between 40 years and 80 years of age at the time of inclusion. Patients identified with current cancer or active inflammatory disease or who had an exacerbation during the 4 weeks before the study were excluded. All subjects with COPD were informed of diagnosis and exhibited postbronchodilation forced expiratory volume in 1 second (FEV\(_1\)/forced vital capacity (FVC)) ratios of <70%. Subjects without COPD exhibited an FEV\(_1\)/FVC ratio of ≥75% and FEV\(_1\) ≥80% of predicted value. The Ethics Committees of Taipei Medical University-Joint Institutional Review Board approved the study protocol (number 201310027). The Chinese Clinical Trial Register number is ChiCTR-OCC-13004025. All subjects received written and oral information before inclusion and provided informed consent.

Data collection

Before recruitment into the study, a physical examination was performed, as was a clinical interview regarding smoking habits, comorbidities, and medicinal use. All subjects with COPD continued with a stable regimen of medications throughout the study. Lung function parameters were assessed at the time of recruitment using a Vitalograph Spirotac V™. Postbronchodilation measurements for FEV\(_1\) and FVC were taken, and FEV\(_1\)/FVC was calculated. Serum samples were obtained and stored at −80°C for analysis.

PM\(_{10}\) exposure

PM\(_{10}\) data were obtained from 25 monitoring stations (operated by the Taiwan Environmental Protection Administration, Taiwan) throughout northern Taiwan. The daily concentrations of PM\(_{10}\) were collected, corresponding to subject exposure. If a subject resided within 10 km of multiple monitoring stations, the weighted average was used to calculate the PM\(_{10}\) levels. The PM\(_{10}\) data were used to estimate the 1-year, 2-year, and 3-year effects of PM\(_{10}\) on COPD.

Protein digestion

To determine the effects of PM\(_{10}\) on protein expression in COPD, the five subjects with the highest average 3-year PM\(_{10}\) values were classified as the High Ambient Particles (HAP) group (exposure range =63.2–64.5 μg/m\(^3\)), and the five subjects with the lowest average 3-year PM\(_{10}\) served as the Low Ambient Particles (LAP) group (exposure range =35.4–43.9 μg/m\(^3\)). Serum samples from healthy controls, HAP, and LAP were collected and pooled together following protein digestion. After protein depletion to remove albumin and immunoglobulin, the serum samples were diluted and denatured with 8 M urea/10 mM ammonium bicarbonate for 1 hour; they were then alkylated with 50 mM iodoacetamide for 30 minutes, tryptically digested in a solution of 50 mM ammonium bicarbonate at 37°C for 18 hours, and desalted on C18 columns.

Mass spectrometry and protein identification

Tryptic samples were analyzed using a mass spectrometer (LTQ Orbitrap XL; Thermo Fisher Scientific, Bremen,
Inhibitor heavy chain 4 (ITIH4), and apolipoprotein F (APOF; MyBioSource, San Diego, CA, USA) according to the manufacturer’s instructions.

Statistical analysis
All ELISA experiments were performed at least three times. Data are expressed as the mean ± standard deviation. For multiple comparison analysis, one-way analysis of variance with Tukey’s post hoc was used. Spearman’s rank correlation coefficient was used to examine the correlation of quintiles of PM$_{10}$ with PRG4, ITIH4, and APOF, as well as the correlation of 8-isoprostane and CRP with PRG4, ITIH4, and APOF. Receiver operating characteristic (ROC) curve analysis was used to determine the specificity and sensitivity of PRG4, ITIH4, and APOF to PM$_{10}$ ($\geq$50 µg/m$^3$ and $<$50 µg/m$^3$) in COPD. Statistical analyses were performed using GraphPad Version 5 (La Jolla, CA, USA) for Windows. The level of significance was set to $P<0.05$.

Results
Characteristics of study subjects
Fifty subjects with COPD, ten healthy controls, and five healthy smoking volunteers were enrolled. Detailed baseline characteristics of the 65 subjects in the study population are presented in Table 1. The ages of healthy controls, healthy smokers, and subjects with COPD were 67.8±6.2 years, 59.8±14.6 years, and 70.7±8.4 years, respectively. The majority of the study population consisted of men with body mass indexes that ranged between 22.5 kg/m$^2$ and 24.8 kg/m$^2$. The current smoking percentage among the subjects with COPD was 9.1%. The FEV$_1$ percentages of predicted values for the healthy controls, healthy smokers, and subjects with COPD were 88.0%±11.5%, 85.5%±14.9%, and 42.6%±12.4%, respectively. The levels of 8-isoprostane and CRP for subjects with COPD were 13.4±3.0 pg/mL and 5.6±6.4 mg/L, respectively. The average PM$_{10}$ concentrations for the study subjects were estimated, as shown in Table 2, and were 46.0±8.4 µg/m$^3$.

### Table 1 Baseline characteristics of healthy control subjects, smokers, and patients with COPD

<table>
<thead>
<tr>
<th>Categorical variables</th>
<th>Healthy controls (n=10)</th>
<th>Healthy smokers (n=5)</th>
<th>Patients with COPD (n=50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>67.8±6.2</td>
<td>59.8±4.6</td>
<td>70.7±8.4</td>
</tr>
<tr>
<td>Men, %</td>
<td>75.0</td>
<td>75.0</td>
<td>95.5</td>
</tr>
<tr>
<td>BMI, kg/m$^2$</td>
<td>22.5±2.9</td>
<td>24.8±4.0</td>
<td>23.8±3.7</td>
</tr>
<tr>
<td>Current smoking, %</td>
<td>0</td>
<td>100</td>
<td>9.1</td>
</tr>
<tr>
<td>FEV$_1$, % predicted</td>
<td>88.0±11.5</td>
<td>85.5±14.9</td>
<td>42.6±12.4</td>
</tr>
<tr>
<td>8-Isoprostane, pg/mL</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
</tr>
<tr>
<td>CRP, µg/L</td>
<td>ND</td>
<td>ND</td>
<td>13.4±3.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.6±6.4</td>
</tr>
</tbody>
</table>

Note: Data is presented as mean ± SD.

Abbreviations: BMI, body mass index; FEV$_1$, forced expiratory volume in 1 second; CRP, C-reactive protein; ND, no data.
Table 2 Environmental exposure to PM$_{10}$ over the previous 1 year, 2 years, and 3 years in the study subjects with COPD

<table>
<thead>
<tr>
<th>Duration</th>
<th>PM$_{10}$ μg/m$^3$ (Mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-year average</td>
<td>46.0±8.4</td>
</tr>
<tr>
<td>2-year average</td>
<td>48.5±7.2</td>
</tr>
<tr>
<td>3-year average</td>
<td>50.8±7.0</td>
</tr>
</tbody>
</table>

**Abbreviations:** PM$_{10}$, particulate matter ≤10 μm; SD, standard deviation.

...for the 1-year average, 48.5±7.2 μg/m$^3$ for the 2-year average, and 50.8±7.0 μg/m$^3$ for the 3-year average.

**Selection of potential biomarkers in patients with COPD**

Overlaps in protein profiles between healthy controls and the LAP- and HAP-exposed subjects with COPD were compared to investigate protein expression in COPD (Figure 1A). A total of 179 proteins were identified in the healthy controls, and 178 and 187 proteins were identified in the LAP- and HAP-exposed subjects with COPD, respectively (Table S1). A total of 14 and 23 proteins were unique to LAP- and HAP-exposed subjects with COPD, respectively. Six serum proteins were common to both LAP- and HAP-exposed subjects with COPD: PRG4, ITIH4, APOF, Ig kappa chain V-I region DEE, type I cytoskeletal 16 keratin, and type II cytoskeletal 6A keratin.

PANTHER analysis was conducted on the proteins unique to LAP- and HAP-exposed subjects with COPD to understand their biological context (Figure 1B). The common biological processes identified in the LAP and HAP groups included biological regulation (29% for LAP), cellular component organization or biogenesis (13% for HAP), cellular process (14% for LAP and 13% for HAP), developmental process (13% for HAP), immune system process (29% for LAP and 25% for HAP), localization (14% for LAP and 13% for HAP), metabolic process (14%...
for LAP and 13% for HAP), and response to stimulus (13% for HAP), with immune system process terms being the most common. The common molecular functions identified between the LAP and HAP groups included binding (50% for LAP and 50% for HAP), catalytic activity (17% for LAP and 25% for HAP), enzyme regulator activity (17% for LAP), structural molecule activity (25% for HAP), and transporter activity (17% for LAP), with binding terms being the most common.

Validation of Prg4, ITIh4, and APOF in patients with COPD and control subjects

The levels of PRG4, ITIH4, and APOF in healthy controls, smokers, and subjects with COPD are presented in Figure 2. There were no differences in the PRG4, ITIH4, and APOF levels between healthy controls and healthy smokers. The PRG4 levels in the subjects with COPD were significantly higher than those in healthy controls or smokers ($P<0.05$). The ITIH4 levels in subjects with COPD were lower than those in healthy controls ($P<0.05$) but not those of healthy smokers. There was no significant difference in the APOF levels across subjects with COPD, healthy controls, or smokers.

Correlation of PM$_{10}$ with PRG4, ITIh4, and APOF

The changes in PM$_{10}$ for the 1-year, 2-year, and 3-year averages in quintiles were related to PRG4, ITIH4, and APOF (Figure 3). The PRG4 levels were correlated with 2-year ($r=0.278$, $P=0.033$) and 3-year ($r=0.349$, $P=0.007$)
Figure 3  The relationship of serum PRG4, ITIh4, and APOF levels to 1-year, 2-year, and 3-year changes in PM$_{10}$ levels.

Notes: Study subjects were divided equally based on quintiles of PM$_{10}$. The values in parentheses along the X-axis represent the mean PM$_{10}$ values for each quintile group. Spearman’s rank correlation coefficient was used to examine the correlation of quintiles of PM$_{10}$ with PRG4, ITIh4, and APOF. PRG4 levels were correlated with the 2-year ($r=0.278$, $P=0.033$) and 3-year PM$_{10}$ averages ($r=0.349$, $P=0.007$), whereas the ITIh4 levels were correlated with the 1-year ($r=-0.325$, $P=0.012$), 2-year ($r=-0.401$, $P=0.002$), and 3-year ($r=-0.342$, $P=0.008$) PM$_{10}$ averages.

Abbreviations: APOF, apolipoprotein F; ITIh4, inter-alpha-trypsin inhibitor heavy chain 4; PM$_{10}$, particulate matter $\leq 10\ \mu m$; PRG4, proteoglycan 4.
PM$_{10}$ averages, whereas the ITIH4 levels were correlated with the 1-year ($r=-0.325$, $P=0.012$), 2-year ($r=-0.401$, $P=0.002$), and 3-year PM$_{10}$ averages ($r=-0.342$, $P=0.008$). There was no correlation between APOF and PM$_{10}$ levels over the previous 3 years.

Figure 4 shows the ROC curve of the sensitivity and specificity obtained for the PRG4, ITIH4, and APOF levels when discriminating between the $\geq50 \mu g/m^3$ and $<50 \mu g/m^3$ average 3-year PM$_{10}$ levels in patients with COPD. The area under the curve (AUC) value was 0.563 (95% confidence interval).

**Figure 4** Diagnostic performance of serum 8-isoprostane, CRP, PRG4, ITIH4, and APOF in receiver operating characteristic (ROC) curve analyses.

**Notes:** ROC curve of the sensitivity and specificity of PRG4, ITIH4, and APOF levels for discriminating between the $\geq50 \mu g/m^3$ and $<50 \mu g/m^3$ average 3-year PM$_{10}$ value in COPD. The area under the curve value was 0.563 (95% CI: 0.413–0.713, $P=0.405$) for 8-isoprostane, 0.634 (95% CI: 0.486–0.782, $P=0.086$) for CRP, 0.636 (95% CI: 0.492–0.780, $P=0.083$) for PRG4, 0.690 (95% CI: 0.545–0.836, $P=0.015$) for ITIH4, and 0.523 (95% CI: 0.376–0.671, $P=0.766$) for APOF.

**Abbreviations:** APOF, apolipoprotein F; CI, confidence interval; COPD, chronic obstructive pulmonary disease; CRP, C-reactive protein; ITIH4, inter-alpha-trypsin inhibitor heavy chain 4; PM$_{10}$, particulate matter $\leq10 \mu m$; PRG4, proteoglycan 4.
interval [CI] = 0.413–0.713, \( P = 0.405 \) for 8-isoprostan, 0.634 (95% CI = 0.486–0.782, \( P = 0.086 \) for CRP, 0.636 (95% CI = 0.492–0.780, \( P = 0.083 \) for PRG4, 0.690 (95% CI = 0.545–0.836, \( P = 0.015 \) for ITIH4, and 0.523 (95% CI = 0.376–0.671, \( P = 0.766 \) for APOF.

**Correlation of 8-isoprostan and CRP with PRG4, ITIH4, and APOF**

Correlations between 8-isoprostan and CRP with PRG4, ITIH4, and APOF for COPD were determined (Figure 5).

There were no statistical associations of 8-isoprostan and CRP to PRG4 and APOF in patients with COPD. Only ITIH4 was correlated with the CRP levels (\( r = 0.353, P = 0.005 \)).

**Discussion**

COPD, a chronic inflammatory disease, is recognized by irreversible airflow obstruction and by structural modifications in the proximal and peripheral airways.\(^ {15} \) An abnormal inflammatory response of the lung to PM\(_{10} \) appears to play a central role in the pathogenesis of COPD;\(^ {16,17} \) however, few
studies have investigated protein profiles in patients with COPD residing in polluted urban areas. The present study discovered differences in protein expression in patients with COPD who were exposed to low and high levels of PM$_{10}$ (LAP and HAP). Three major findings are reported in the present study: 1) immune system process and binding are the most important biological process and molecular function, respectively, in the response to PM$_{10}$ in patients with COPD, 2) ITIH4 is a biomarker for PM$_{10}$ in COPD, and 3) ITIH4 is associated with inflammatory response.

Oxidative stress and inflammatory reactions are considered common biological responses that result from the inhalation of PM$_{10}$. Toxicology exposure experiments in animals and humans have identified several biological mechanisms that may be affected by the inhalation of PM$_{10}$, including oxidative stress and systemic inflammation.$^{18}$ The present study identified the immune system process as an important biological process in the response to PM$_{10}$ in COPD and the binding terms as important molecular functions. Immune response is considered an important determinant for the exacerbation of COPD.$^{19,20}$ and immune disorder commonly associated with PM$_{10}$ contributes to lung function impairment and mortality. Systemic inflammation is considered a common link between COPD and immune response.$^{21}$ Furthermore, a link between binding and COPD has been reported.$^{22}$ For example, a heavy subunit with a regulatory light subunit can modulate glutamate cysteine ligase activity.$^{23}$ Notably, a key common feature between PM$_{10}$ exposure and COPD is “inflammatory response.” Oxidative inflammatory reactions may be a result of exposure-related variances in protein regulation; therefore, an investigation of the effect of PM$_{10}$ on protein profiling in COPD is important.

Discovering biomarkers for susceptible populations assists with human environmental exposure assessment and risk evaluation. Despite increased efforts to identify COPD biomarkers, however, the gap between clinical and risk evaluation. Despite increased efforts to identify COPD biomarkers, however, the gap between clinical and molecular function is substantial. We identified six biomarker candidates from healthy controls and from LAP- and HAP-exposed patients with COPD using a proteomics approach on serum samples: PRG4, ITIH4, APOF, Ig kappa chain V-I region DEE, type I cytoskeletal 16 keratin, and type II cytoskeletal 6A keratin. Type I cytoskeletal 16 keratin and type II cytoskeletal 6A keratin are associated with epithelial tissues from nail beds, esophagus, tongue, and hair follicles,$^{24,25}$ which are less likely related to the mechanisms of PM$_{10}$ and COPD. Thus, we next examined PRG4, ITIH4, and APOF as candidate biomarkers. We observed that the PRG4 levels in subjects with COPD were significantly higher than those in healthy controls and smokers, whereas the ITIH4 levels were significantly lower than those in healthy controls. These results suggest PRG4 and ITIH4 could be the potential biomarkers for COPD and that APOF is not sensitive as a potential biomarker for COPD and PM$_{10}$ exposure. We then correlated the PM$_{10}$ levels for the previous 1-year, 2-year, and 3-year averages with these three biomarker candidates. The correlations showed that PRG4 and ITIH4 may be biomarkers for alteration in PM$_{10}$ levels, particularly ITIH4. Previously, 8-isoprostane and CRP were characterized as biomarkers of oxidative stress and inflammation, respectively, in response to particulate air pollution.$^{26}$ Therefore, we used them for the comparison with PRG4, ITIH4, and APOF in COPD. The US Environmental Protection Agency’s health-based national air quality standard for PM$_{10}$ (annual average of 50 µg/m$^3$) was used as the cutoff level for the ROC analysis. We discovered that ITIH4 is the only significant biomarker for PM$_{10}$ in COPD; no significance was observed for 8-isoprostane, CRP, PRG4, and APOF. This finding suggests that ITIH4 is a good biomarker for evaluating PM$_{10}$ exposure in subjects with COPD.

To understand the potential mechanisms underlying PM$_{10}$-regulated COPD in the present study, 8-isoprostane and CRP were correlated with PRG4, ITIH4, and APOF. Statistical significance was observed between CRP and ITIH4 in COPD, suggesting that ITIH4 may be involved in inflammatory responses. ITIH4 is a type II acute phase protein and has been associated with inflammatory responses.$^{27,28}$ Our findings are consistent with those of a previous study that observed correlation between the ITIH4 and CRP levels.$^{27,28}$ However, the correlations between PM$_{10}$ and ITIH4 are negatively associated with increasing PM$_{10}$ concentrations. CRP is commonly used in the assessment of several acute clinical conditions, such as COPD.$^{20}$ Notably, CRP levels are also elevated in many other conditions, including infective, inflammatory, and neoplastic pathologies.$^{30-32}$ Because of CRP’s involvement in multiple pathologies, ITIH4 may be a more specific biomarker for PM$_{10}$ in COPD than CRP.

**Conclusion**
In conclusion, circulating ITIH4 is an important biomarker to assess PM$_{10}$ exposure in patients with COPD and could be involved in postexposure inflammatory responses. Furthermore, metabolic process and catalytic activity are the important biological process and molecular function, respectively, in response to PM$_{10}$ exposure in COPD. The limitation of the present study is the sex distribution in the study subjects. The sex difference may associated with the biomarker identification for PM$_{10}$ exposure. Future studies are
required to investigate the potential mechanisms underlying PM_{10} exposure and to determine whether ITIH4 can provide a specific index for evaluating PM_{10} exposure in COPD.

Acknowledgments

The authors thank Yi-Syuan Lin and Ching-Hsuan Law for their technical assistance in this research. This study was funded by the Ministry of Science and Technology of Taiwan (MOST103-2314-B-038-018 and MOST102-2314-B-038-055-MY2), Taipei Medical University (TMU103-AE1-B12), and the Taipei Medical University-Shuang Ho Hospital (103TMU-SHH-01-1).

Author contributions

All authors have contributed substantially to the concept and design of the study, the drafting of the article, and the critical revision of the manuscript for important intellectual content. All authors have read and approved the final version of the manuscript for publication.

Disclosure

The authors report no conflicts of interest in this work.

References


