In Vivo and In Vitro Proinflammatory Effects of Particulate Air Pollution (PM\textsubscript{10})

X.Y. Li,1 P.S. Gilmour,2 K. Donaldson,2 and W. MacNee1

1Unit of Respiratory Medicine, 2Royal Infirmary and the Department of Biological Sciences, Napier University, Edinburgh, United Kingdom

Epidemiologic studies have reported associations between fine particulate air pollution, especially particles less than 10 mm in diameter (PM\textsubscript{10}), and the development of exacerbations of asthma and chronic obstructive pulmonary disease. However, the mechanism is unknown. We tested our hypothesis that PM\textsubscript{10} induces oxidant stress, causing inflammation and injury to airway epithelium. We assessed the effects of intratracheal instillation of PM\textsubscript{10} in rat lungs. The influx of inflammatory cells was measured in bronchoalveolar lavage (BAL). Airspace epithelial permeability was assessed as total protein in bronchoalveolar lavage fluid (BALF) in vivo. The oxidant properties of PM\textsubscript{10} were determined by their ability to cause changes in reduced glutathione (GSH) and oxidized glutathione (GSSG). We also compared the effects of PM\textsubscript{10} with those of fine (CB) and ultrafine (ufCB) carbon black particles. Six hours after intratracheal instillation of PM\textsubscript{10}, we noted an influx of neutrophils (up to 15% of total BAL cells) in the alveolar space, increased epithelial permeability, an increase in total protein in BALF from 0.39 ± 0.01 to 0.62 ± 0.01 mg/ml (mean ± SEM) and increased lactate dehydrogenase concentrations in BALF. An even greater inflammatory response was observed after intratracheal instillation of ufCB, but not after CB instillation. PM\textsubscript{10} had oxidant activity in vivo, as shown by decreased GSH in BALF (from 0.36 ± 0.05 to 0.25 ± 0.01 nmol/ml after instillation. BAL leukocytes from rats treated with PM\textsubscript{10} produced greater amounts of nitric oxide, measured as nitrite (control 3.07 ± 0.33, treated 4.45 ± 0.23 mM/1 x 10\textsuperscript{6} cells) and tumor necrosis factor alpha (control 21.0 ± 3.1, treated 179.2 ± 29.4 unit/1 x 10\textsuperscript{6} cells) in culture than BAL leukocytes obtained from control animals. These studies provide evidence that PM\textsubscript{10} has toxic radical activity and causes lung inflammation and epithelial injury. These data support our hypothesis concerning the mechanism for the adverse effects of particulate air pollution on patients with airway diseases. — Environ Health Perspect 105(Suppl 5):1279–1283 (1997)

Key words: air pollution, reactive oxygen species, oxidant, antioxidant, glutathione, epithelial cells

Introduction

Particulate matter with an aerodynamic diameter of ≤10 μm (PM\textsubscript{10}) is a ubiquitous pollutant of urban air (1). Numerous epidemiologic studies have shown that particulate air pollution is associated with increased morbidity and mortality (2). PM\textsubscript{10} levels in ambient air are associated with reductions in lung function (3) and hospital admissions for asthma (4) and for chronic obstructive pulmonary disease (5). In addition there is an association between PM\textsubscript{10} levels and cardiovascular deaths (2). These associations have been demonstrated in diverse geographical locations (1) where the source of PM\textsubscript{10} has varied from primarily industrial to mainly vehicle exhaust, which suggests that the exact composition of the particulate air pollution may not be critical.

Although epidemiologic evidence strongly supports an association between PM\textsubscript{10} and adverse health effects, the mechanism is not understood (6). Moreover, the development of adverse effects with PM\textsubscript{10} at such low airborne mass concentrations remains a puzzle. We hypothesized (Figure 1) that exposure to PM\textsubscript{10} particles produces airway inflammation, increased airspace permeability, and interstitialization of the particles, thus enhancing the inflammatory response (7), which has been proposed for other inhaled particles as a result of their oxidant properties (8). This inflammation results in exacerbations of airway disease and also causes changes in the coagulation and rheology of blood cells through both local and systemic effects. This latter effect may be critical in precipitating cardiovascular events and hence deaths in a susceptible population (7). The purpose of this study was to test this hypothesis by measuring proinflammatory potential and the oxidant activity of PM\textsubscript{10} in the lungs. We have also tested this hypothesis by comparing the effects of PM\textsubscript{10} with those of fine (CB) and ultrafine carbon black particles (ufCB).

Materials and Methods

Particle Suspensions

PM\textsubscript{10} particles were collected on glass fiber filters from a tapered element oscillating microbalance at the Edinburgh monitoring site of the U.K. Enhanced Urban Network. Such PM\textsubscript{10} samplers have been established in several cities by the U.K. government. This sampler has an impactor that enables a collection of particles, of which at least 50% have a diameter of less than 50 μm. The filters were stored for up to 4 months until used as described below.

The PM\textsubscript{10} filter was cut into small pieces and 0.8 ml phosphate-buffered saline (PBS) was added and vortexed for 20 sec. The filter was removed to avoid further contamination with fiber filters, and the suspension was then sonicated for 30 sec (Ultrasonic Cleaner BP-1, Burkard Scientific Sales Vineland, NJ). Since the extraction procedure produced a suspension of PM\textsubscript{10} contaminated with small numbers of filter fibers (0–10 per light microscopic field at x80 magnification), a filter fiber suspension (FFS) was prepared by sonicating an unused filter of the same type used to collect PM\textsubscript{10} in PBS for 30 sec. This suspension contained greater than 300 fibers per light microscopic field (x80 magnification).
We calculated the mean weight of the particles on eight filters as 996 ± 182 μg (mean ± SEM). The method of preparation removed 20 to 50% by weight of the particles. Thus we estimate that between 199 to 498 μg of particles were present in 0.8 ml of PBS. Since 0.2 ml was instilled, this volume contained between 50 to 125 μg of particles. U.K. air quality standards have 50 μg/m³ as an upper level of PM₁₀. The preparation was used within 24 hr.

The effects of instillation of PM₁₀ in rat lungs were compared with instillation of those of CB (Degussa Huber NG90, diameter 200–250 nm) and ufCB (Degussa printex 19, diameter 20 nm; 125 μg in 0.2 ml PBS).

**Intratracheal Instillation of Particle Suspensions**

Syngeneic male Wistar-derived rats of the HAN strain, 12 weeks of age, were anesthetized with pentobarbitone, and 0.2 ml PBS–particle suspension was instilled intratracheally. The controls for these experiments were animals that did not receive any instillation and animals instilled with 0.2 ml PBS alone. Experiments were also carried out after intratracheal instillation of 0.2 ml filter fiber suspension.

**Bronchoalveolar Lavage**

Six hours after intratracheal instillation of particle suspensions, rats were sacrificed, and 4 ml PBS at 37°C was instilled and withdrawn from the lungs. After centrifugation this solution was referred to as bronchoalveolar lavage fluid (BALF). To obtain bronchoalveolar lavage (BAL) leukocytes, 4×10⁶ ml PBS was used to wash the lungs and then collected in a universal tube. The cell suspension was spun and cell pellets were resuspended in Dulbecco’s minimum essential medium (DMEM) medium (GIBCO, Paisley, UK) plus 0.2% low endotoxin–bovine serum albumin (BSA) (Sigma, Poole, UK) in which the cells from the first lavage were combined. The total number and differential count of BAL leukocytes were obtained. BAL leukocytes from control animals consisted of greater than 99% macrophages.

Soluble lung homogenate was prepared for measurement of reduced (GSH) and oxidized glutathione (GSSG). Postlavage lungs were resected and blotted dry. One gram of lung tissue was randomly sampled from all lung lobes. The samples were homogenized in 5% sulfosalicylic acid and the supernatant was then diluted in 0.1 M potassium phosphate buffer.

**Collection of Cell Culture Supernatant**

BAL leukocytes from control rats and rats after intratracheal instillation of PM₁₀ were cultured in DMEM + 0.2% BSA at a concentration of 1×10⁶ per ml for 24 hr in DMEM. Thereafter the supernatant was collected for the measurement of nitrite and tumor necrosis factor (TNF) as described below.

The A549 human type II alveolar epithelial cell line was purchased from ECACC (Salisbury, UK) and maintained in DMEM containing 10% fetal calf serum. To assay particle-induced A549 epithelial cell permeability and changes in glutathione, we co-incubated the cells with particle suspensions in DMEM + 2% BSA for 6 hr.

**Measurement of Epithelial Permeability in Vivo and in Vitro**

Rat lung epithelial permeability was assessed as the total protein concentration in BALF (9). This technique produced results similar to measurements of airspace epithelial permeability assessed as the passage of ¹²⁵Iodine-labeled BSA from airspace to blood (10). Protein concentrations were determined by incubating BALF with Biorad solution (BioRad, Munich, Germany) for 10 min at room temperature. The absorbance was read at 595 nm on a Unicam 8700 series spectrophotometer (Unicam, Cambridge, UK). Protein concentration was determined by comparison with a standard curve for BSA.

As a model of airspace epithelium, the permeability of A549 type II epithelial cell monolayers was determined using a modification of a technique that we developed previously (10). However, instead of ¹²⁵I-BSA, we used unlabeled BSA in the assay. Briefly, A549 cells were cultured on Nunc tissue culture inserts (GIBCO) in a 24-well plate to form cell monolayers. The monolayers were incubated with particle suspensions for 6 hr. The media in both inserts and wells were replaced with PBS followed by the addition of 1 mg of BSA into the insert. Thirty minutes later, PBS in the wells was sampled and albumin concentrations were determined.
Tumor Necrosis Factor, Lactate Dehydrogenase, and Nitrite Assays

Tumor necrosis factor activity in BALF and supernatant from cell monolayers were measured using the L929 cell bioassay as described previously (9). Lactate dehydrogenase (LDH) concentrations were assayed using the method of Bergmeyer and co-workers (11).

Nitric oxide (NO) generation was determined as accumulated nitrite measured by a modified microplate assay using the Griess reagent (12).

Measurement of GSH and GSSG

The total cellular GSH concentration was assayed by the GSSG-reductase–DTNB recycling procedure as described previously (10). To measure GSSG, GSH in the samples was first depleted by incubation with 2-vinylpyridine followed by the GSSG-reductase–DTNB recycling procedure. GSH concentrations were then calculated by subtracting GSSG values from total GSH values. GSH and GSSG values were determined by comparison with GSH and GSSG (Sigma) standard curves.

Statistical Analysis

Results were expressed as mean ± SEM. Differences between mean values were assessed by analysis of variance.

Results

Intratracheal instillation of PM10 caused neutrophil influx in rat lungs 6 hr after instillation, which accounted for 10 to 15% of the total BAL leukocyte numbers (Figure 2). Compared with animals that had instillations of PBS, CB instillations produced a small but significant neutrophil influx. However, the greatest inflammatory cell influx occurred after instillation of uCB (Figure 2). In this case, neutrophils accounted for 40% of the total BAL leukocyte count. BAL leukocytes obtained 6 hr after PM10 instillation produced greater amounts of TNF and NO in culture compared with BAL leukocytes from PBS-instilled control animals (Figure 3). Although inflammatory BAL leukocytes showed a greater potential to produce TNF and NO in culture, TNF and NO in BALF were not significantly different 6 hr after PM10 instillation compared with BALF levels in PBS-instilled control animals (Table 1). PM10 increased airspace epithelial permeability 6 hr after instillation, as shown by elevated total protein levels in BALF compared with PBS-instilled control animals (Figure 4). At this time point, LDH levels were higher than those in control BALF (Table 1). As with the influx of inflammatory leukocytes, the greatest increase in airspace epithelial permeability occurred after instillation of uCB. CB produced a lesser increase in epithelial permeability than PM10 or uCB (Figure 4).

Addition of PM10 to A549 type II alveolar epithelial monolayers in vitro increased their permeability to BSA (penetrated BSA control 0.10 ± 0.02; PM10 0.20 ± 0.02 mg/ml; p < 0.01). This increased epithelial permeability was not due to cell death, as monolayers of A549 cells incubated with PM10 for 6 hr did not release increased amounts of LDH (control LDH 23.5 ± 2.5; PM10 LDH 21.0 ± 7.1 U/2 million cells; p > 0.05).

Intratracheal instillation of PM10 decreased GSH without any significant change in GSSG in BALF 6 hr after instillation, compared with PBS-instilled animals (Figure 5). However, GSH and GSSG levels in lung tissue were the same in PBS- and PM10-treated rats (data not shown).

To clarify the role of fiber contamination in the activity of the PM10 suspension, we compared the effects of PM10, FFS, and PBS instillations in the rat lung. Table 2 shows that FFS did not significantly alter

Table 1. TNF, NO, and LDH levels in rat lung BALF 6 hr after intratracheal instillation of PM10

|        | TNF, U/ml | Nitrate, µM/ml | LDH, U/ml |
|--------|-----------|----------------|-----------|
| PBS control | 0 ± 2.9 | 12.9 ± 3.9 | 13.0 ± 2.0 |
| PM10   | 8.0 ± 5.8 | 10.5 ± 1.0 | 453.0 ± 52.3*** |

Mean ± SEM of three rats. ***p < 0.001 compared with PBS control values.
These with 0.05 to the increase in the oxidant effects of PM$_{10}$ comes from preliminary studies from our laboratory indicating that the free radical activity of PM$_{10}$ is abolished in the presence of the iron chelator desferrioxamine (17).

This effect may reflect the surface chemistry of the ultrafine component (18). We noted that the supernatant from high-speed centrifugation of PM$_{10}$ suspension to clarity, which presumably contained only the ultrafine components, still caused the same degree of plasmid DNA scission (17). This strongly suggests that ultrafine particles provide the bulk of free radical activity of PM$_{10}$.

Our hypothesis that ultrafine particles have free radical activity is derived from our previous studies showing the oxidant potential of another ultrafine particle, TiO$_2$. This material has free radical activity in the ultrafine form (20 nm in diameter) but is inert as larger sized particles (250 nm) (8).

Further evidence in support of the contention that it is the free radical activity of PM$_{10}$ that is responsible for its biological activity in vivo is shown by changes in the important lung antioxidant glutathione. PM$_{10}$ decreased GSH but had no effect on GSSG levels in BALF after instillation. Furthermore, intracellular GSSG/GSH ratios were not affected by PM$_{10}$ either in lung tissue in vivo or in epithelial cells in vitro, at least at the single time point when measurements were made. It is possible that such changes may have occurred at earlier time points, resulting in compensatory mechanisms, such as upregulation of the genes involved in GSH synthesis, after exposure to cigarette smoke, as we have reported (19).

Analysis of the exact composition of the PM$_{10}$ sample that we used is not yet available. However, the composition of PM$_{10}$ obtained from other sources indicates that carbonaceous material makes up 50% of the mass of PM$_{10}$ (20). Therefore, we compared the effects of instillation of both CB and uCB with those of PM$_{10}$ in similar doses, in the rat lungs. These studies show that uCB produces similar qualitative but greater quantitative proinflammatory effects to those of PM$_{10}$ in the rat lungs. The greater inflammatory effect of uCB could have been anticipated from our hypothesis, as uCB is composed entirely of ultrafine particles; this is not the case for PM$_{10}$, which has only 50% of its particles less than 10 μm in aerodynamic diameter. This supports our contention that the ultrafine component of PM$_{10}$ has the greatest inflammatory potential.

A decrease in lung GSH is associated with increased epithelial permeability caused by cigarette smoke, which has enormous oxidant potential (10). The present study showed a decrease in GSH in BALF but not in lung GSH after PM$_{10}$ instillation. Further studies on the time course of changes in lung GSH are required to determine if a similar mechanism applies to the effects of PM$_{10}$. Other candidate inflammatory mediators may be involved in increasing epithelial permeability, such as TNF (9) and NO (21). Data from the present study do not show increased NO or TNF in BALF in association with a neutrophil influx into the airspaces after instillation of PM$_{10}$. However, in vitro BAL leukocytes from PM$_{10}$-treated rats produced significantly more NO and TNF in culture than those from control BAL cells. We believe that the release of these mediators results from the effect of loading the cells with particles (22) but also from PM$_{10}$-induced oxidant stress (23). In addition, there is an interaction between these two inflammatory mediators in that TNF can stimulate NO production (24). The absence of detectable TNF and NO levels in BALF from PM$_{10}$-treated rats compared with control animals is likely a result of the presence of inhibitors in BALF.

These studies are preliminary and are limited because of the lack of the availability of large quantities of PM$_{10}$. As a result, we were only able to study an animal model of instillation rather than the preferred inhalation model, which would be more relevant to environmental exposures. Thus, comparative calculations of the doses relative to environmental exposures are difficult. Therefore, in this preliminary study, where only one dose and one time point could be investigated because of the availability of PM$_{10}$, we opted to study a dose that was higher than environmentally plausible.

However, this study does provide evidence that PM$_{10}$ has oxidant activity and causes an inflammatory response and epithelial injury in the lungs. These data provide support for our hypothesis (7) of the role of PM$_{10}$ in exacerbating airway diseases.

### Table 2. The effect of intratracheal instillation of PBS or FFS on BAL leukocyte components, epithelial permeability, and GSH/GSSG in BALF 6 hr after intratracheal instillation in rat lungs.

| Treatment | Neutrophils in BALF, 10$^6$ | Protein in BALF, mg/ml | GSH in BALF, mmol/ml |
|-----------|-----------------------------|------------------------|----------------------|
| PBS       | 0.68 ± 0.28                 | 0.57 ± 0.03            | 0.44 ± 0.08          |
| FFS       | 0.58 ± 0.15                 | 0.55 ± 0.11            | 0.96 ± 0.08          |

Mean ± SEM of three rats for each group. *p < 0.01 compared with PBS control.
REFERENCES

1. Schwartz J. Air pollution and daily mortality: a review and meta-analysis. Environ Res 64:36–52 (1994).
2. Pope CA, Bates DV, Raizenne ME. Health effects of particulate air pollution: time for reassessment? Environ Health Perspect 103:472-480 (1995).
3. Pope CA, Kanner RE. Acute effects of PM10 pollution on pulmonary function of smokers with mild to moderate chronic obstructive pulmonary disease. Am Rev Respir Dis 147:1336–1340 (1993).
4. Schwartz J, Slater D, Larson TD, Pierson WE, Koenig JQ. Particulate air pollution and hospital emergency room visits for asthma in Seattle. Am Rev Respir Dis 147:826–831 (1993).
5. Schwartz J. Air pollution and hospital admissions for the elderly in Detroit, Michigan. Am J Respir Crit Care Med 150:648–655 (1994).
6. Ostro B. The association of air pollution and mortality: examining the case for inference. Arch Environ Health 48:336–342 (1993).
7. Seaton A, MacNee W, Donaldson K, Godden D. Particulate air pollution and acute health effects. Lancet 345:176–178 (1995).
8. Donaldson K, Gilmore PS, MacNee W, Oberdorster G. Free radical activity associated with ultrafine titanium dioxide particles and PM10 material. Am J Respir Crit Care Med 151:A64 (1995).
9. Li XY, Donaldson K, Brown D, MacNee W. The role of tumour necrosis factor in increased airspace epithelial permeability in acute lung inflammation. Am J Respir Cell Mol Biol 13:185–195 (1995).
10. Li XY, Donaldson K, Rahman I, MacNee W. An investigation of the role of glutathione in increased epithelial permeability induced by cigarette smoke in vivo and in vitro. Am J Respir Crit Care Med 149:1518–1525 (1994).
11. Bergmeyer HU, Bernt E, Hess B. Lactate dehydrogenase. In: Method of Enzymatic Analysis (Bergmeyer HU, ed). New York:Verlag Chemie, 1965:736–741.
12. Ding AH, Nathan CF, Stuehr DJ. Release of reactive nitrogen intermediates and reactive oxygen intermediates from mouse peritoneal macrophages. J Immunol 141:2407–2412 (1988).
13. Vallyathan V, Shi X, Dalal NS, Irr W, Castranova V. Generation of free radicals from freshly fractured silica dust: potential role in acute silica-induced lung injury. Am Rev Respir Dis 138:1213–1219 (1988).
14. Dalal NS, Suryan MM, Vallyathan V, Green FHY, Jafari B, Wheeler R. Detection of reactive free radicals in fresh coal mine dust and their implications for pulmonary injury. Ann Occup Hyg 33:79–84 (1989).
15. Faux SP, Howden PJ, Levy LS. Iron-dependent formation of 8-hydroxydeoxyguanosine in isolated DNA and mutagenicity in Salmonella typhimurium TA102 induced by crocidolite. Carcinogenesis 15:1749–1751 (1994).
16. Kennedy TP, Dodson R, Rao NV, Henry KY, Hopkins C, Baser M, Tolley E, Hoidal JR. Dusts causing pneumoconiosis generate 'OH and produce hemolysis by acting as Fenton catalysts. Arch Biochem Biophys 269:359–364 (1989).
17. Gilmore PS, Brown DM, Lindsay TG, Beswick PH, MacNee W, Donaldson K. Adverse health effects of PM10: involvement of iron in the generation of hydroxyl radical. Occup Environ Med (in press).
18. Oberdorster G, Gelein R, Ferin J, Weiss B. Particulate air pollution and acute mortality: involvement of ultrafine particles. Inhalation Toxicol 7:111–124 (1995).
19. Rahman I, Li XY, Donaldson K, Harrlson DJ, MacNee W. Glutathione homeostasis in alveolar epithelial cells in vitro and lung in vivo under oxidative stress. Am J Physiol 269:L285–L292 (1995).
20. Clarke AG, Willson MJ, Zeki EM. A comparison of urban and rural aerosol composition using dichotomous samples. AJ Mos Environ 18:1707–1775 (1984).
21. Kubes P. Nitric oxide modulates epithelial permeability in the feline small intestine. Am J Physiol 262:G1138–G1142 (1992).
22. Driscoll KE, Lindeschmidt RC, Maurer JK, Higgins JM, Ridder G. Pulmonary response to silica or titanium dioxide: Inflammatory cells, alveolar macrophage-derived cytokines and histopathology. Am J Respir Cell Mol Biol 2:381–390 (1990).
23. Punjabi CJ, Laskin JD, Pendino K., Goller NL, Durham SK, Laskin DL. Production of nitric oxide by rat type II pneumocytes: increased expression of inducible nitric oxide synthase following inhalation of a pulmonary irritant. Am J Respir Cell Mol Biol 11:165–172 (1994).
24. Thiemerman C, Wu C-C, Szabo C, Perretti M, Vane JR. Role of tumour necrosis factor in the induction of nitric oxide synthase in a rat model of endotoxin shock. Br J Pharmacol 110:177–182 (1993).