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Acid Fog: Effects on Respiratory Function and Symptoms in Healthy and Asthmatic Volunteers

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Acidic air pollutants generally are dissolved in water droplets. Mean droplet diameter may range from more than 10 μm in dense fog to less than 1 μm at low relative humidity. Droplet size influences the deposition of inhaled acid within the respiratory tract and thus may influence toxicity. To help assess health risks from acid pollution, we performed controlled exposures of normal and asthmatic volunteers to sulfuric acid aerosols at nominal concentrations of 0 (control), 500, 1000, and 2000 μg/m³. Exposures lasted 1 hr with intermittent heavy exercise. Response was assessed by lung function tests and symptom questionnaires. Under foggy conditions (mean droplet size 10 μm, temperature 50°F), no marked effects on lung function were found. However, both normal and asthmatic subjects showed statistically significant dose-related increases in respiratory symptoms. In a separate study, normal subjects exposed at 70°F with mean droplet size 0.9 μm showed no marked effect on function or symptoms. Asthmatics showed dose-related decrements in forced expiratory performance and increases in symptoms, most obvious at 1000 and 2000 μg/m³. The different results of the two studies probably reflect an influence of droplet size, but further investigation is needed to confirm this. The aggregate results suggest that only mild, if any, short-term respiratory irritant effects are likely at acid concentrations attained in ambient pollution.

Introduction

This paper reviews the authors' recent controlled laboratory studies of human volunteers, intended to assess short-term health risks from exposure to ambient acid aerosols. These studies have employed sulfuric acid (H_2SO_4) as a model of ambient acidic pollution. Experimental exposure concentrations were in the occupational range, one to two orders of magnitude higher than observed ambient concentrations, because earlier work failed to show meaningful responses at ambientlike concentrations. In terms of cumulative acid dose, the experimental exposures may have been closer to possible ambient conditions, because experimental exposures lasted 1 hr, whereas ambient pollution episodes may last considerably longer.

Acidic pollutants may occur in a wide range of particle (droplet) sizes, depending on the nature of the pollutants and the prevailing atmospheric conditions. Aerosols with droplets of a mean aerodynamic diameter of 1 μm or less have received most attention in health studies because they are typical of acidic ambient pollution and are respirable into the deep lung. In polluted fog, the majority of mass may be in droplets 10 μm or larger in diameter. Such large droplets usually do not penetrate to the deep lung when inhaled. On the other hand, they may cause comparatively large local doses of acid at preferential impact points in the trachea and larger bronchi. Thus, it is difficult to predict how droplet size will influence health risk from inhaled acid.

The overall rationale for health-risk assessment studies of acid aerosols, including fog, and the results obtained to date, are discussed more extensively in the accompanying papers and in previous publications (*1–3*). In general, unfavorable effects have not been demonstrated at exposure concentrations in the usual ambient range (usually below 50 μg/m³). Koenig et al. (*4*) reported modest but statistically significant lung function decrements in adolescent asthmatics exposed to 100 μg/m³ H_2SO_4 in the submicrometer size range for 40 min, including 10 min exercise. Utell et al. (*5*) reported statistically significant function changes in adult asthmatics after resting exposures to 450 μg/m³ of submicrometer H_2SO_4 aerosol, but no significant changes at an exposure concentration of 100 μg/m³.

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We previously failed to find meaningful lung function or symptom changes in a group of asthmatics exposed to submicrometer H_2SO_4 aerosol at concentrations up to 410 μg/m^3 for 1-hr periods with intermittent heavy exercise (*6*). In a pilot study of acid fog (droplet size near 10 μm, H_2SO_4 concentration up to 680 μg/m^3), we found a modest statistically significant increase in symptoms of respiratory irritation, similar in normal subjects and asthmatics, but lung function tests showed only small equivocal changes (*7*).

The work reported in the following sections was intended to clarify these diverse findings by expanding the data base and extending the dose-response information to higher exposure levels (still within the permissible occupational exposure range).

Experimental Approaches

Exposures were conducted in the Rancho Los Amigos environmental control chamber (*8*). The two separate studies employed the same basic design and protocol. First, a group of 20 or more normal volunteers was exposed to nominal acid concentrations of 0 (clean-air control), 500, 1000, and 2000 μg/m^3. (The nominal concentrations were not achieved exactly because of variability in the aerosol generation equipment's performance.) Different concentrations were presented in random order at 1-week intervals. Following completion of the study of normal subjects, a group of 20 or more asthmatics was exposed similarly. Normal or asthmatic status was established by medical history, lung function tests, and tests of bronchial reactivity to exercise, cold air, and/or methacholine. Most asthmatic subjects had comparatively mild disease. Each exposure lasted 60 min, with alternate 10-min periods of heavy exercise (target ventilation rate 50 L/min) and rest. Lung function tests, including specific airway resistance (SR_{aw}), forced vital capacity (FVC), and forced expired volume in one second (FEV_1), were performed prior to exposure, after the initial exercise, and at the end of exposure. Symptoms were assessed using standardized interview questionnaires before, during, and after exposure; the answers were converted to numerical scores based on the number and severity of symptoms (*9*). Analyses of variance were performed to determine whether responses varied significantly with increasing acid exposure level.

The first study was conducted under conditions simulating California winter fog (*10*). The exposure atmosphere was generated by injecting dilute H_2SO_4 solution through commercial spray nozzles into the chamber's air supply, which was conditioned to 50°F and near 100% relative humidity. The resulting fog had a mean droplet diameter near 10 μm and a liquid water content near 0.1 g/m^3, comparable to natural fog. The second study was conducted at 70°F and approximately 50% relative humidity (*11*). The acid aerosol, generated by Babington nebulizers, had a mass median aerodynamic diameter near 0.9 μm. Acid concentrations were determined by low-volume filter sampling and ion chromatography. Exposure atmospheres were also monitored continuously with a laser aerosol spectrometer, electrical mobility analyzer, and/or optical particle counters. Because the two studies were conducted at different times with different subject groups, caution must be exercised in comparing their results, even though their designs were similar.

Results

Symptom findings from both studies are summarized in Figure 1. The graph shows group mean changes in total symptom scores during exposure as a function of group mean H_2SO_4 exposure concentrations. The scores are derived from 11 different symptoms associated with airborne irritants. Normal subjects exposed to 0.9-μm aerosol showed slight increases in symptoms during all exposures, but no significant increase in their total scores with increasing acid concentration. When symptoms were examined separately, cough showed a very small but statistically significant increase with acid concentration. Asthmatic subjects exposed to 0.9-μm aerosol showed consistently larger symptom increases than normal subjects and statistically significant increases with in-

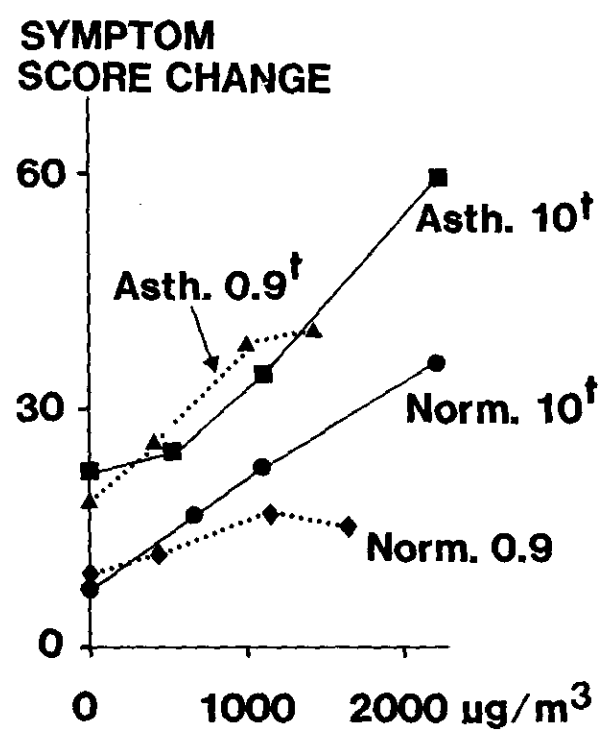

FIGURE 1. Mean changes in total symptom score during exposure as a function of H_2SO_4 concentration in normal and asthmatic subject groups exposed to 10-μm and 0.9-μm aerosols. Dagger (†) indicates significant ($p < 0.01$) increase in symptoms with increasing acid concentration.

creasing acid concentration. Lower respiratory symptoms accounted for most of the change. Nonrespiratory symptoms (headache, fatigue, and/or eye irritation) also increased significantly with concentration, but upper respiratory symptoms did not. Normal subjects exposed to 10-μm fog showed statistically significant increases with increasing acid concentration, to which lower and upper respiratory symptoms contributed. Asthmatics exposed to 10-μm fog again showed consistently larger increases than normal subjects and significant increases with increasing acid concentration, related to both lower and upper respiratory symptoms.

Physiologic findings from both studies are summarized in Figure 2, which shows group mean differences in FEV_1 between pre-exposure and end-exposure measurements, expressed in percentage of the pre-exposure measurement, and plotted as a function of group mean exposure concentrations. The other lung function measures changed in a manner generally consistent with FEV_1 changes. Neither normal subject group showed significant variation attributable to acid exposure. The asthmatic group exposed to 10-μm fog also showed no significant variation, although a slight function decrement was suggested in the nominal 2000-μg/m^3 exposures. Asthmatics exposed to 0.9-μm aerosol showed a significant effect. In clean fog and fog with nominally 500 μg/m^3 of H_2SO_4, asthmatics showed about 5% mean losses in FEV_1, attributable to exercise-induced bronchospasm. But at the two higher acid concentrations, mean losses were about twice as large. These excess function losses were comparatively slow in onset: They were not apparent at measurements early in exposure (after initial exercise).

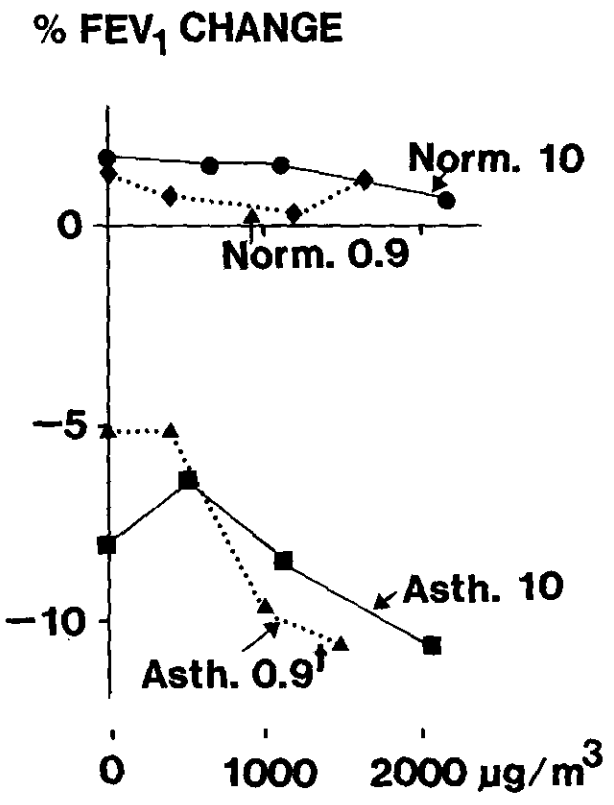

FIGURE 2. Mean changes in FEV_1 during exposure as a function of H_2SO_4 concentration in normal and asthmatic subject groups exposed to 10-μm and 0.9-μm aerosols. Dagger (†) indicates significantly ($p < 0.01$) more negative FEV_1 change with increasing acid concentration.

Discussion

Taken together, these two recent studies suggest that the size of inhaled acid droplets, i.e., the degree to which they penetrate the respiratory tract, does have a meaningful influence on the biological response. Symptoms seemed less pronounced with the 0.9-μm aerosol, although a shortfall in maximum acid concentrations in the 0.9-μm studies complicates the interpretation. On the other hand, the physiologic responses of asthmatics seemed greater with 0.9-μm aerosol than with the large-diameter fog droplets. This pattern seems explainable if we assume that (a) symptoms are caused primarily by large acid droplets deposited in the upper airway or proximal bronchi; and (b) disturbances of pulmonary mechanics in asthmatics are caused primarily by smaller acid droplets deposited in more distal airways. A more rigorous test of these assumptions will require carefully controlled exposures of volunteers to the same acid concentration at different droplet sizes. Such an experiment is now underway in our laboratory. Thus far, only preliminary physiologic results for normal subjects are available. Normal subjects show little response to 2000 μg/m^3 of H_2SO_4 at mean droplet sizes from less than 1 μm to 20 μm, in agreement with the results presented here.

Our results suggest that unfavorable physiologic responses to ambient concentrations of acid (of the order of tens of μg/m^3) are unlikely, even in asthmatic adults. The contrasting findings by Koenig et al. (*4*) suggest that younger asthmatics may be an especially susceptible population, deserving of further study. Another issue deserving further study is the interaction of concentration and time on irritant responses. Conceivably, prolonged exposures at ambient concentrations would produce more unfavorable effects than the 1-hr, high-level exposures studied here, even if cumulative acid doses were similar. Our findings of symptoms in asthmatics at both droplet sizes and in normal subjects exposed to large fog droplets do not show any obvious threshold of response. Thus, in principle, a finite effect might be expected in the ambient concentration range. However, any such effect should be very slight, judging from the dose-response results obtained here.

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