Ozone (O₃) is a ubiquitous pollutant in outdoor air, frequently reaching 1-hr concentrations that exceed the National Ambient Air Quality Standard of 120 ppb. Because O₃ is formed through photochemical reactions involving nitrogen oxides and hydrocarbons, the highest and most broadly peaked O₃ concentration profiles often occur downwind of, rather than directly in, major source areas such as large cities.

Short-term exposures to ambient-level O₃ concentrations have been shown to result in a spectrum of effects on the human respiratory system, including drops in lung function (i.e., measures of lung volume and expiratory flow rates), increases in lung reactivity to other irritants, and pulmonary inflammation (1-4). The bulk of the data revealing these effects derive from chamber studies, which typically involve the study of relatively small numbers of healthy, white, adult, male volunteers exposed to pure O₃ under controlled laboratory conditions along with some form of exercise. While each individual chamber study has necessarily been limited in scope, the large number of chamber studies carried out in the past 20 years has yielded a rather extensive database for certain outcomes, most notably lung function. McDonnell and colleagues (5) accumulated data on 290 adult, white, male subjects from 5 separate chamber studies, with the goal of determining whether individual lung function response to O₃ is related to age, height, baseline lung function, allergen sensitivity, and other factors. Of these factors, only age had a consistent influence on responsiveness, with response diminishing with increasing age.

From the perspective of assessing the public health impact of O₃ exposures under real-world conditions, however, the chamber study database presents some limitations. First, the precisely controlled exposure conditions are unlike those that occur during many ambient episodes, where broad, multi-hour peaks, often accompanied by fine particulate matter, are observed. Second, relatively few chamber data are available on children and those with moderately severe lung disease, two population subgroups that may be at elevated risk of ozone-induced health impacts.

Epidemiologic studies have examined the acute pulmonary effects of ambient O₃ under natural conditions. These “field studies” can be categorized into three general types: summer camp studies, exercise studies, and daily life studies. All three designs involve collection of repeated measurements on individuals and analyze the association between lung function and day-to-day changes in O₃ concentrations, with each subject serving as his or her own control. In contrast to chamber studies, field studies examine the human health effects of O₃ under real-world conditions, with natural patterns of O₃ exposure and levels of co-pollutants and other environmental factors.

The most extensively and consistently used field study design for investigating acute O₃ effects has been the camp study, which involves collection of sequential (usually daily) lung function data on children attending summer camps, along with concurrent measurements of air pollution concentrations and meteorological conditions. Camp studies, involving sequential, usually daily, measurements of lung function and air pollution concentrations, offer the significant advantage that individual pollution exposures in a potentially large subject population can be easily and accurately estimated using a single, on-site monitoring station. In addition, these studies directly investigate associations of pulmonary function with natural diurnal patterns of O₃ and associated co-pollutants, which often involve prolonged daytime peaks. Finally, the focus is on children, whose lungs are still developing.
Many camp studies have supported the conclusion that ambient \( \text{O}_3 \) exposures in active children are associated with short-term declines in population average lung function (3,6). Other studies have yielded negative or equivocal results (7–10). It is not clear to what extent these differences are merely due to variations in data analysis and reporting methods across studies and to what extent they may represent substantive differences in results. Concerns about potential confounding by other pollutants or weather variables, which may co-occur with \( \text{O}_3 \), have led some to question the attribution of the observed associations to \( \text{O}_3 \) per se. These uncertainties have limited the causal inferences that can be drawn from the camp studies and have limited their use in risk assessment and regulatory decision making.

Due to the common study design, data from camp studies are amenable to reanalysis. By pooling data from several studies, a more robust overall relationship between naturally occurring \( \text{O}_3 \) exposures and decreased lung function can be estimated. A collective analysis also can yield insights into differences across studies in the relationship between lung function and \( \text{O}_3 \), without the influence of differing analytical methods.

This article presents the results of our reanalysis of the original lung function and \( \text{O}_3 \) data from six recent summer camp studies. These studies include two in northwestern New Jersey (3,11), two in southern California (6,9), and two in Ontario (8,12). Using a consistent analytical method, results are reported on the relationship between lung function and \( \text{O}_3 \) for each individual study and for all studies combined.

**Methods**

The 1984 Fairview Lake, New Jersey, study was conducted by researchers from New York University and Harvard University during a 4-week period in July and August at a summer YMCA camp in northwestern New Jersey (3). Once per day, usually in the afternoon, lung function was measured on each of up to 91 children (53 males and 38 females, 8–15 years of age). The Fairview Lake study was repeated in 1988, this time with 46 campers (33 males and 13 females, 8–14 years of age) and with function measurements collected in both the morning and the late afternoon (11). This design allowed consideration of changes in function during the course of each day.

The Lake Couchiching study was conducted collaboratively by Health and Welfare Canada and Harvard University over 10 days in late June and early July of 1983 (7,12). Lung function data were collected twice daily (0730–0930 hr and 1630–1830 hr) for 52 campers (including 23 asthmatics: 12 males and 11 females, and 29 nonasthmatics: 16 males and 13 females), who ranged from 7 to 15 years of age. These researchers also conducted a follow-up study at a Girl Guide camp located beside Lake Erie in southern Ontario during 6 weeks in June, July, and August 1986 (7,8). In that study, referred to as "CARES," spirometry was performed daily on 112 female campers, who averaged 11.6 years of age.

Two summer camp studies were conducted in California with support from General Motors Corporation. The first took place at a church-sponsored summer camp in the San Bernardino Mountains (elevation 1740 m) (6). Over a 3-week period in June and July 1987, 43 children (19 males and 24 females, 7–13 years of age) performed spirometry up to three times per day. During late June through early August 1988, a follow-up study was conducted at Pine Springs Ranch, east of Los Angeles (9,10). Lung function testing was carried out twice daily on each of 295 campers (ages 8–17) who attended one of six separate, sequential, 1-week camps.

Working data sets for each study reviewed above were obtained either directly from members of the original study teams, or through third parties (see Acknowledgments). A common feature of all six data sets was the availability of afternoon spirometric lung function data collected over many days on many subjects, along with the previous 1-hr average \( \text{O}_3 \) concentrations. For consistency, the present analysis focused on afternoon lung function measurements. Except as noted, if more than one afternoon lung function measurement was available for a given subject on one day, only the last measurement was used in the analysis. Because too few asthmatic subjects were available to analyze as a separate group (only the Lake Couchiching study included asthmatics), asthmatics were excluded from these analyses.

In each of the original studies, lung function data were collected by spirometry using methods that conformed closely to guidelines published by the American Thoracic Society (13). The present analysis was limited to data on forced expiratory volume in 1 sec (FEV\(_1\)) and peak expiratory flow rate (PEFR). Ozone measurements were collected using automated real-time monitors (based on either UV photometry or chemiluminescence), with instrument checks and calibrations conducted at regular intervals.

Data were analyzed using analysis of covariance methods via the GLM procedure of the SAS system (SAS Institute, Cary, North Carolina). The analysis was performed using data on four variables from each study: subject ID, FEV\(_1\), PEFR, and the 1-hr average \( \text{O}_3 \) concentration in the hour preceding the lung function measurements.

For each study, linear regression models were fit relating FEV\(_1\) or PEFR (the dependent variables) to \( \text{O}_3 \) (the independent variable). Regression models included a single, pooled \( \text{O}_3 \) slope and separate intercepts for each subject (to account for differences in average lung function across subjects). After obtaining study-specific results, the combined six-study data set was used to estimate the mean slopes across all studies for FEV\(_1\) or PEFR regressed on \( \text{O}_3 \). These analyses were repeated with the addition of linear or higher-order functions of test number in order to fit the time-trend in repeated lung function measurements noted in previous studies (9,14,15). Ambient temperature was not included as a covariate in the analysis because human chamber studies have shown that direct effects of temperature on lung function are minimal within the normal ambient range (16).

**Results**

Table 1 presents data summaries for the six studies. Tables 2 and 3 present slope estimates for FEV\(_1\) and PEFR, respectively, for each of the six studies analyzed separately. Nearly all of the slopes were negative, indi-

| Study                  | Total no. of subjects | Total no. of observations | Mean observations/subject | Mean \( \text{O}_3 \) (ppb)* | Maximum \( \text{O}_3 \) (ppb) | Mean FEV\(_1\) (l) | Mean PEFR (l/sec) |
|------------------------|-----------------------|----------------------------|---------------------------|----------------------------|------------------------|------------------|------------------|
| Fairview Lake, 1984    | 91                    | 1237                       | 13.6                      | 53                        | 113                    | 2.14             | 4.36             |
| Fairview Lake, 1988    | 46                    | 577                        | 12.5                      | 69                        | 137                    | 2.39             | NA               |
| Lake Couchiching, 1983 | 29                    | 244                        | 8.4                       | 59                        | 95                     | 2.41             | 5.48             |
| CARES, 1986            | 112                   | 1228                       | 11.0                      | 71                        | 143                    | 2.34             | 5.51             |
| San Bernardino, 1987   | 43                    | 265                        | 5.9                       | 123                       | 245                    | 2.06             | 5.17             |
| Pine Springs, 1988     | 295                   | 3925                       | 6.2                       | 94                        | 161                    | 2.19             | 4.52             |

Abbreviations: FEV\(_1\), forced expiratory volume in 1 sec; PEFR, peak expiratory flow rate; NA, PEFR data not available for this study.

*1-hr average, at time of afternoon lung function measurement.
cating that higher concentrations of $O_3$ were consistently associated with decreased lung function. FEV$_1$ slopes spanned an approximate fourfold range (-0.2 to -1.3 ml/ppb). Five of the six slopes were statistically significant. Peak flow results (Table 3) were less consistent. Four of the five slopes were negative, two of which were statistically significant. The PEFR slope for the Pine Springs study was unique in being positive and statistically significant. Individual analysis (not shown) of the 6 separate weeks of the Pine Springs camp revealed that only week 6 had a statistically significant positive slope of PEFR on $O_3$. Over the 6 days of data collection during week 6, both PEFR and $O_3$ increased markedly, resulting in a strong positive, but likely spurious, correlation between these two variables. The increase in PEFR probably reflected the positive training effect that has been noted in previous studies. These results illustrate the potential for confounding of $O_3$ effects by time trends in repeated spirometry. Exclusion of week 6 from the analysis of Pine Springs data resulted in a slightly positive, but nonsignificant, overall slope for Pine Springs. There was no evidence that the overall results for the Pine Springs camp were unduly influenced by data from a subset of subjects with very narrow ranges in $O_3$ exposures.

The relationship between lung function and $O_3$ was analyzed for the combined, six-study data set (Table 4). The overall FEV$_1$ slope on $O_3$ was -0.50 ml/ppb (SE = 0.07; $p = 0.0001$). The overall PEFR slope was positive but non-significant. This PEFR result was heavily influenced by data from the Pine Springs camp, which, as noted earlier, had a positive slope and had the largest number of subjects (295) and observations (1826). When data from this one study were set aside, the PEFR slope was -0.99 ml/sec/ppb (SE = 0.33; $p = 0.003$).

Exploratory analysis of the time trend in FEV$_1$ (independent of $O_3$) showed that FEV$_1$ tended to drop over the first four to five measurements, followed by a gradual increase and leveling off (results not shown). This trend was well fit by a third-order polynomial (i.e., linear, squared, and cubed trend variables were all statistically significant in a multiple regression analysis). The temporal pattern for PEFR was adequately fit by a simple linear increase over time. The temporal patterns observed here were qualitatively similar to those reported in a recent study from Holland (15). The regression of lung function on $O_3$ was repeated with these time-trend variables included in the models (Table 5). The overall FEV$_1$ slope on $O_3$ was reduced (in absolute magnitude) by about half in this model: -0.26 ml/ppb (SE = 0.07; $p = 0.0003$). Thus, inclusion of variables accounting for temporal trends in FEV$_1$ reduced but did not eliminate its relationship with $O_3$. The overall PEFR slope was -0.15 ml/sec/ppb (SE = 0.34; $p = 0.65$) with the linear time-trend variable in the regression model. Setting aside the Pine Springs data resulted in an overall PEFR slope of -1.06 ml/sec/ppb (SE = 0.33; $p = 0.001$). Thus, the PEFR slope on $O_3$ became slightly more negative after controlling for time trends.

Discussion

This study analyzed the relationship between daily variations in lung function and ambient $O_3$ concentrations for children attending six summer camps. When analyzed individually using a common method, FEV$_1$ was inversely related to $O_3$ concentrations at each of the camps. Pooling the data across camps, an average FEV$_1$ decline of 0.5 ml/ppb $O_3$ was observed. Pooled analysis of PEFR indicated no statistically significant overall relationship with $O_3$ concentrations. However, there was strong evidence for heterogeneity across camps, with four of five available studies yielding negative slopes (two of which were statistically significant) and one yielding a significant positive slope. The latter result appeared to be confounded by a strong training effect for PEFR.

While negative slopes relating FEV$_1$ and $O_3$ were seen for each camp, there was variation in the slope estimates across camps. This variation was found to be statistically significant using an F-test for heterogeneity (results not shown). Possible reasons for these differences include camp-to-camp variations in subject activity levels (resulting in different $O_3$ doses at a given measured exposure level), differences in temporal patterns of $O_3$ concentrations (with broad peaks likely to have greater effects on lung function per ppb $O_3$), potentiation of the $O_3$ effect by other pollutants, variations across populations in inherent $O_3$ sensitivity and/or prior adaptation to $O_3$ and confounding by meteorologic factors or airborne allergens. Because of limitations in the available data, the relative roles of each of these factors in the observed variations across camps can be discussed only in qualitative terms.

There are few quantitative data on subject activity levels at the six camps. Although activity surely contributes to the random variability within and between camps, it cannot be quantified. While $O_3$ concentration profiles are often sharp and peaked in cities (e.g., Los Angeles), all of the camps analyzed here were located outside of major source areas and exhibited similarly shaped diurnal $O_3$ patterns, implying that this is unlikely to be an important differential factor. Potentiation of $O_3$ effects on lung function in asthmatics by acid aerosols has been demonstrated in a chamber study in which $O_3$ exposure was administrated 1 day after a 3-hr expo.
sure to 100 µg/m³ H₂SO₄ (17). Although the relevance of these data to the nonasthmatic subjects who experienced much lower acid levels at northeastern summer camps is not clear, they do demonstrate that potential can occur between these pollutants under laboratory conditions. Another recent chamber study investigating the interactive effects of O₃ and H₂SO₄ on lung function observed marginal evidence for interaction, but concluded that “O₃ is more important than H₂SO₄ as a cause of short-term respiratory irritant effects” (18: p. 431). Further, the wide range of FEV₁/O₃ slopes observed across the four northeastern camps (two in southern Ontario and two in New Jersey, all experienced similar acid aerosol levels, suggests that differential acid exposures are not likely to be a significant factor in the inter-camp variation in response seen here.

Acute respiratory responses to O₃ vary markedly across people, for reasons that are not entirely understood (5,19). This physiologic variation in responsiveness is surely present in the camp studies, but it is not likely to have a large effect on the average population response estimated for each camp. Differences in average population responsiveness might occur due to differing levels of prior exposure to O₃, with associated tolerance/adaptation. However, the results of our analysis do not suggest a systematically lower response in the California studies, where elevated prior exposures may have occurred.

Data have not been reported on comparative levels of airborne allergens during the camp studies. None of the subjects analyzed here reported a history of asthma, minimizing the likelihood of confounding by airborne allergens. However, given the lack of allergen data and the potential for substantial numbers of “silent hyperresponders” (8), this possibility cannot be completely discounted.

It is possible that several of the factors discussed above, acting together, could underlie the variation in FEV₁ response observed across the six camps. However, given the many potential sources of camp-to-camp variability, it is both surprising and noteworthy that results are fairly consistent across the six studies. Further, a statistically significant drop in FEV₁ was observed in the pooled data set in an analysis that incorporated both the within-camp and between-camp variability. Thus, in spite of variations across camps, it can be concluded that children exposed to O₃ under natural conditions do experience acute decreases in lung function of the kind that have been demonstrated in great detail and precision in chamber studies. This confirms the real-world public health significance of these laboratory observations and raises concern that other acute respiratory effects observed in chamber studies (e.g., pulmonary inflammation) may also occur in people exposed to ambient O₃.

Quantitative comparison of the population average FEV₁ response observed here (-0.5 ml/ppb) with responses reported in chamber studies is complicated by the issues discussed above, as well as by differences in the designs and analytical methods used in the two types of studies. No in-depth analysis taking these differences into account has been reported to date. However, a brief review of chamber results suggests a reasonable degree of concordance. Setting aside nonlinearities in response, the results of the present study imply a 2.7% drop in FEV₁ for a 120 ppb increase in O₃ exposure in this population (mean FEV₁ was 2.23 l in the data set analyzed). This change is nearly identical to the 2.8% change in FEV₁ observed in 23 vigorously exercising male children exposed for 2.5 hr to 120 ppb O₃ (17). The change is smaller than the 7–13% declines seen in studies of adults exposed for longer periods (6.6 hr) to between 80 and 120 ppb O₃, with intermittent exercise (2,20). In the absence of detailed further analysis, these data offer no evidence for systematic differences in the quantitative relationships between FEV₁ and O₃ observed in camp and chamber studies.

The data analysis presented here yields population-average results within and across camps. It does not explicitly address interindividual variations in responsiveness, which, as noted earlier, are likely to be present. As pointed out by Brunekeeff and colleagues (19), this variation is difficult to analyze in detail in acute epidemiologic studies because it is obscured by substantial amounts of random variability. As a result, attempts to determine, for example, which individuals are most responsive to O₃ using data from camp studies are problematic and generally should be avoided.

The pooled slope of FEV₁ on O₃ was reduced somewhat (in absolute magnitude) but remained statistically significant when the regression model included trend variables designed to account for training effects (14,15). A third-order polynomial provided a good fit to the observed time trend in FEV₁, which was characterized by a decline over the first four to five measurements, followed by a gradual increase and leveling. The pooled slope of PEFR on O₃ increased slightly after accounting for a more simple linear increase in PEFR over time. The trend variables were highly statistically significant, confirming the importance of this phenomenon. These effects on the estimated associations between lung function and O₃ suggest that confounding due to time trends may occur in some cases. In summary, our results confirm a small, statistically significant, population-average decline in FEV₁ (but not PEFR) associated with O₃ exposures that is qualitatively similar to that reported in chamber studies. Evidence for heterogeneity in average FEV₁ response across studies was observed. Limitations of currently available data preclude definitive evaluation of the reasons for the variation in results across camps.

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