Final Technical Report

Date of Final Report: August 31, 2006
EPA Grant Number: R827352C009
Center Name: Southern California Particle Center and Supersite (SCPCS)
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Title: The Role of Quinones, Aldehydes, Polycyclic Aromatic Hydrocarbons, and other Atmospheric Transformation Products on Chronic Health Effects in Children
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Project Period: June 1, 1999–May 31, 2005 (no-cost extension to May 31, 2006)
Period Covered by the Report: June 1, 1999–May 31, 2006
RFA: Airborne Particulate Matter (PM) Centers (1999)
Research Category: Particulate Matter

Topic C: Studies of the Effects of Varying Spatial and Temporal Patterns of Ambient Particulate Matter (PM) and Co-pollutants and Resulting Health Effects with Emphasis on the Role of Atmospheric Chemistry

Objective(s) of the Research Project: The overall purpose of this project was to provide exposure data on ambient organic pollutants in 12 communities participating in a long-term study of children's respiratory health. Two specific objectives were identified for this project: (1) characterize the annual levels and seasonal variability of selected polycyclic aromatic hydrocarbons (PAHs), aldehydes, and quinones in ambient air in the study communities; and (2) apply the resulting data to ongoing analyses of health and ambient pollution exposure, to help disentangle a previously identified and highly inter-correlated package of pollutants associated with decrements in human health. See Table 1 for a list of target analytes.

Table 1. Target Analytes of the Organics Sampling Study

PAHs	***Quinones***	***Carbonyls***
Naphthalene (NAP)	1,2-Naphthoquinone (1,2NQ)	Formaldehyde (FOR)
Acenaphthene (ACE)	1,4-Naphthoquinone (1,4NQ)	Acetaldehyde (ACD)
Fluorene (FLU)	9,10-Phenanthroquinone (PQ)	Acetone (ACE)
Phenanthrene (PHE)	9,10-Anthroquinone (AQ)	Acrolein (ACR)
Anthracene (ANT)		Propionaldehyde (PRO)
Fluoranthene (FLT)		Crotonaldehyde (CRO)
Pyrene (PYR)		Butanone (BUT)
Benz[a]anthracene (BAA)		Butyraldehyde (MET)
Chrysene (CRY)		Benzandehyde (BEN)

PAHs	***Quinones***	***Carbonyls***
Benzo[*b*]fluoranthene (BBF)		Isovalerandehyde
Benzo[*k*]fluoranthene (BKF)		Valeraldehyde (VAL)
Benzo[a]pyrene (BAP)		o-tolualdehyde (OTO)
Indeno[*1,2,3-c,d*]pyrene (IND)		m-tolualdehyde (MTO)
Dibenz[*a,h]*anthracene (DBA)		p-tolualdehyde (PTO)
Benzo[*g,h,i*]perylene (BGP)		Hexaldehyde (HEX)

Background

In 1993, a multi-year study of public school children, Children's Health Study (CHS), was established in Southern California to assess the potential chronic health effects of ambient air pollution (Peters, et al., 1999). Twelve CHS communities were identified for study participation, based on their historic and predicted air pollution profiles, community demographics, and school district support. Over 6,000 4th, 7th, and 10th grade students were recruited, enrolled, and annually evaluated across these communities, to assess annual lung function growth, respiratory symptoms, and school-based absences caused by respiratory infection. To characterize local air quality, existing community air monitoring stations in each of the 12 communities were augmented with additional air sampling instrumentation, or a central air monitoring station was established, to provide continuous long-term information about ambient ozone, oxides of nitrogen, and particle concentration (as PM_{10} or $PM_{2.5}$ mass), as well as particle speciation ($PM_{2.5}$ acids, sulfates, nitrates, ammonium, elemental and organic carbon).

Several health-based manuscripts have reported on the observed associations between specific pollutants, or inter-correlated groups of pollutants, and various health outcomes measured in the CHS (Gauderman, et al., 2000; Gauderman, et al., 2004; McConnell, et al., 1999; Gilliland, et al., 2001; Avol, et al., 2001; McConnell, et al., 2002).

The co-linear behavior of several monitored pollutants made efforts to assess the relative importance of single pollutant measures with observed health outcomes difficult. In developing this component of the Southern California Particle Center and Supersite's (SCPCS) research program, the hypothesis was that measurement of specific organic compounds could provide alternative exposure metrics, less complicated by collinearity. In addition, the study was designed to provide data regarding the inter-community variability of organic pollutants of potential health importance, such as PAHs, primary and secondary aldehydes, and quinones, all of which are associated with the current urban living environment and motor vehicle emissions

Summary of Findings: Using an innovative sampler deployment approach to collect seasonal samples in 12 sampling locations with only three sets of instrumentation, field sampling was successfully performed in consecutive two-month deployments across all 12 CHS communities between 2001 and 2003. In the course of field operations, an improved sampling matrix was

developed to successfully capture and stabilize particle and vapor-phase PAHs, aldehydes, and quinones in a multiple-media sampling matrix for 24-hour sampling intervals.

The collected samples were analyzed, edited, and developed into a cumulative database. Analyses were performed by both environmental researchers interested in the chemical interaction of pollutants in ambient air and by health researchers seeking to potentially disentangle previous associations among assorted respiratory health outcomes and a highly inter-correlated bundle of pollutants arising from energy combustion and vehicle emissions.

Achievements of Project Objectives

The collected data have been invaluable with regard to achievement of the exposure characterization objective. This work has produced a rich database on exposure to a set of organic compounds found in the ambient air of twelve Los Angeles area communities. As a result of this study, the interplay among ambient temperature, re-distribution of chemical species between gas and particle phases, and air toxics emissions associated with vehicle exhaust, energy combustion, and photochemistry has advanced substantially. Three manuscripts were published on these subjects (Eiguren-Fernandez, et al., 2004; Eiguren-Fernandez, et al., 2007; Cho, et al., 2004).

The project's second objective, to apply this data to health analyses to potentially de-couple previously observed relationships between a number of co-linear pollutants and respiratory health outcomes has also been achieved. Some associations between target analytes and two key respiratory health effect measures (lung function level and growth) have been observed. However, the analytical results developed thus far have not identified specific pollutants that provide explanatory power significantly beyond that of routinely monitored substances. In two-pollutant models assessing lung function, for example, the apparent effects of routinely collected pollutant data (such as ambient NO_2, $PM_{2.5}$ mass, elemental carbon, and acids) overshadowed the effects of the carbonyls, quinones, and PAHs that were monitored for this study. Additional analyses assessing respiratory symptoms (such as bronchitis and wheeze) and asthma incidence are currently underway.

The research objectives of this project have, in large part, been fully realized. Ambient levels and shifts between vapor and particle phases due to temperature changes of ambient PAHs, carbonyls, and quinones have been characterized. The information collected in the course of the investigation has also suggested several additional lines of inquiry and future analyses.

Project's Significant Technical Details

Methods. Three sets of sampling instrumentation were purchased or assembled for field study applications, in conformance with the project proposal. Samplers were initially evaluated in a multi-day side-by-side comparison in Los Angeles to assure comparability. Samplers were deployed, for alternating two-month periods beginning in mid-2001 and continuing into Fall 2003. Sampling was performed in three CHS communities at a time, with collection beginning at midnight for a 24-hour continuous period once every eight days. Upon completion of seven sampling days (about two months' elapsed time), samplers were relocated to a second set of

three study communities. There, sampling was performed in analogous fashion (e.g., the one-in-eight-day schedule), after which the samplers are re-calibrated and returned to the former three sampling sites for a repetition of the one-in-eight-day, two-month sampling protocol. In this manner, the three sets of samplers were used to collect speciated chemical data across six sampling sites each year, and data were collected at all 12 sampling locations over a two-year sampling period.

In each sampling location, two types of samplers were deployed. A Tisch Environmental Model 1202 Semi-Volatile Organic Compound (SVOC) and $PM_{2.5}$ sampling system and an in-house carbonyls sampler were used to collect PAHs, aldehydes, and quinones (see Table 1). PAH sampling was performed using a quartz filter/polyurethane foam (PUF)/XAD resin sampling matrix, while carbonyl sampling was accomplished utilizing a more conventional DNPH-based sampling cartridge. Additional sampling details have been reported (Eiguren-Fernandez, et al., 2004; Cho, et al., 2004).

Existing community monitoring stations provided supporting air monitoring information for several other pollutants of analytical interest (ozone [O_3], nitrogen dioxide [NO_2], PM mass [PM_{10} and $PM_{2.5}$], elemental carbon [EC], organic carbon [OC], and nitric/formic/acetic acids [acid]). Data from the routine sites were used in one of two ways, either to derive a 1994 through 2003 average level for pollutants of interest, or to develop a 2001 through 2003 concentration metric. The ’94 to‘03 readings were used to compare the relative health outcomes from analyses with those observed in a recent publication of CHS data (Gauderman, et al., 2004). The ’01 to‘03 calculations were used to provide a sampling interval more specifically appropriate to the time-frame of the PAH, carbonyl, and quinone measurements collected in the current study.

Health outcome data used in the analyses included indices of changes in two lung function tests: forced expiratory volume in the first second of exhalation (FEV_1) and maximal mid-expiratory flow rate (MMEF). Changes in FEV_1 or MMEF have been previously shown to be significantly affected by air pollution in this schoolchildren population, and are thought to represent changes in large and small airways, respectively (Gauderman, et al., 2004; Gauderman, et al., 2000; Avol, et al., 2001). To qualitatively compare present analyses with those previously published results of long-term growth interest, only those subjects who entered the CHS as 4th graders (i.e., those whose lung function growth was tracked annually for the duration of the multiple-year CHS study) were included in the health analyses.

Data Analyses. Following editing and validation of the sampling data set, several analytical approaches were applied. For exposure assessment analyses, individual pollutant means, medians, and minimum/maximum values were tabulated by community and in total to assess summary distributions and consider possible correlations across the various pollutant metrics. Correlation tables were developed for all validated pollutants to identify possible unique contributors to any observed health outcomes. Data correlations were compared for observed values of PAHs, carbonyls, and quinones to both the 1994–2003 and 2001–2003 pollution metrics available from the CHS. One and two-pollutant models were then used to explore the possible additional explanatory value contributed by PAHs, carbonyls, or quinones over that provided by the previously available study pollutants in analyses of lung function endpoints.

A multi-stage modeling strategy was used to assess the relationship of PAHs, aldehydes and quinones to lung function measurements from children residing in the study communities and participating in a long-term health study (Gauderman, et al., 2004).

The first-stage model was a linear regression of each pulmonary function measure (log-transformed) on log height, body mass index (BMI), BMI^2, race, Hispanic ethnicity, doctor-diagnosed asthma, any tobacco smoking by the child in the last year, exercise or respiratory illness on the day of the test, and indicator variables for field technician and spirometer.

The second stage consisted of a regression of 48 (2 cohorts × 2 sexes × 12 communities) estimates of lung function growth over an eight-year period on the corresponding mean/median level of PAHs, aldehydes, and quinones in each community. The inverses of the first-stage variances were used as weights, and a community-specific random effect was included to account for residual variation between communities. Modification of the PAH effect by cohort was tested by including a cohort-by-PAH/aldehyde/quinone interaction term. This effect was found to be non-significant; hence all subsequent analyses were based on combined cohort effects. A similar procedure was followed to test for modification effect of PAH by sex. All subsequent models were adjusted for both cohort and sex unless otherwise specified.

Two-pollutant models were also tested by simultaneously regressing growth in lung function over the eight-year period on pairs of pollutants, of which one pollutant was a routinely monitored pollutant such as ambient NO_2, $PM_{2.5}$ mass, elemental carbon, and acids, and the other pollutant was one of the PAHs, aldehydes, or quinones measured in the current study.

Pollutant effect estimates were reported as the difference in the growth between the highest to the lowest pollution community, with negative sign denoting the detrimental effect with increasing exposure. Statistical procedures were performed using a commercially available statistical package (SAS, Version 9). Statistical significance was defined by a two-sided alpha level of 5%.

Selected Results

Pollutant Levels. In the collected samples, virtually all of the total PAH mass was contained in the vapor phase. Vapor phase mass was dominated by naphthalene (NAP), which varied from about 60 ng/m^3 in lightly-trafficked rural communities to over 550 ng/m^3 in communities traversed by ~200,000 vehicles per day. During summer pollution episodes in urban sites, NAP concentrations reached 7 to 30 times the observed annual averages for those same locations.

Except for summer episodes, concentrations of low molecular weight (MW) PAHs showed small seasonal variations, with observed values about twice as high in winter. Similar concentrations of particle-phase PAHs were observed at all sites except for one rural coastal site, which was markedly lower. Benzo[*ghi*]perylene (BGP), a marker of gasoline exhaust emissions, showed the highest concentration among particle-phase PAHs, varying from 23 pg/m^3 in rural areas to over 230 pg/m^3 in communities containing high volumes of freeway traffic (hundreds of thousands of vehicles per day). Benzo[*a*]pyrene and indeno[*1,2,3-cd*]pyrene were found

exclusively in the particle-phase, and they were much higher in urban sites (~ 40 to 100 pg/m^3) than in rural sites (~12 pg/m^3). Winter particle-phase PAHs were 2 to 54 times higher than summer levels. The data suggest that vehicle emissions are a major contributor to particle-phase PAHs in Southern California

Particle-phase PAHs were negatively correlated with mean air temperature in urban sites (r = -0.50 to -0.75). Cold/hot season ratios for PAHs in $PM_{2.5}$ averaged 5.7, with a maximum ratio of 54 calculated for data collected in Long Beach, a coastal community impacted by significant levels of primary emissions from vehicle traffic, commercial shipping, oil refineries, and population activities. These data underscore the importance of seasonal variation in atmospheric metrics such as ambient temperature, photochemical reactivity, and inversion layer height, as well as in gas-to-particle phase shifts of semi-volatile PAHs in ambient air.

Pollutant Correlations. With one exception, vapor-phase PAHs were essentially un-correlated with ambient ozone (as 24 hr, 10am to 6pm, or maximum value metrics), 24 hr NO_2, 24 hr PM_{10}, acids, EC, or OC. Naphthalene was found to be moderately correlated with acids (r=0.643, p=0.02) and with NO_2 (r=0.610, p=0.035). In contrast, there were a number of strong correlations between the routinely monitored pollutants and particulate phase PAHs. Pyrene was correlated with acids (r=0.896, p<0.0001), pyrenes with 24 hr NO_2 (r=0.797, p=0.002), and pyrenes with 24 hr PM_{10} (r=0.707, p=0.01). Particulate acenapthene (r=.769, p=0.003), fluorene (r=0.821, p=0.001), and naphthalene (r=0.708, p=0.01) were all highly correlated with 24 hour O_3, and fluoranthene was found to be highly collinear with 24 hour NO_2 (r=0.869, p=0.0002).

A number of aldehydes (formaldehyde, acetaldehyde, acetone, protonaldehyde, and butanone) were very highly correlated with ambient acids, 24 hour NO_2, 24 hour PM_{10}, OC, and EC (coefficients of 0.7 to 0.9, and p-values typically less than 0.001). The significant correlations suggest that the carbonyl data will not be able to unravel observed health associations among the highly-correlated routinely monitored pollutants.

Among the quinones monitored, particle-phase 1,4-naphthoquinones were strongly correlated with acids (r=0.782, p=0.003), 24 hour NO_2 (r=0.627, p=0.029) and marginally correlated with EC (r=0.561, p=0.058) and 24 hour PM_{10} (r=0.567, p=0.055). Particle-phase phenanthroquinones were found to be correlated with acids (r=0.630, p=0.028). No other particle or gas-phase quinones were correlated with the routinely monitored pollutants.

The correlations and relationships between and among pollutants measured were similar when either the 1994 through 2003 community pollution exposure averages or the 2001 through 2003 community pollution exposure averages were used. The latter were more specific to the current organic sampling study timeframe, but both provided similar and consistent results. This observation provides validation for comparing PAH, aldehyde, and quinone exposures to the longitudinal health outcomes derived from the 10-year cumulative health investigations.

Health Analyses. Two-pollutant models comparing pollution level and lung function growth rate changes were run, to assess the relative importance of each individual organic pollutant monitored in the current study compared to the pollutant data set (i.e., O_3, NO_2, PM_{10}, $PM_{2.5}$, EC, OC, and acids) previously available from the health study communities.

In two-pollutant models with O_3 and the compounds monitored for this study, there were sporadic tests achieving statistical significance. Of those, a few showed significant changes for the organic pollutants monitored. It should be noted that ozone has typically not been associated with statistically significant decrements in lung function growth rates in prior CHS health analyses. When there were significant results (for acetaldehyde, acetone, naphthalene, and phenanthrene, for example), these test pollutants were significant over ozone and showed changes in the predicted (i.e., negative) direction.

However, two-pollutant models with pollutants that have previously been linked to decrements in lung function growth rates showed a distinctly different pattern. In comparisons of NO_2 with the PAHs, quinones, and aldehydes, NO_2 was found to be significant in nearly every comparative case. In models with $PM_{2.5}$ and each test PAH, quinone, or aldehyde measured, $PM_{2.5}$ was found to be the more significant modeled pollutant in most every comparative case.

These results suggest that some of the PAHs, quinones, and aldehydes measured in the study appear to be associated with decrements in lung function growth. However their added explanatory power toward the endpoints of the CHS study is minimal compared to the decrements already identified by associations with the inter-correlated package of pollutants previously monitored (including NO_2, $PM_{2.5}$, EC, and acids). This suggests that, with respect to lung function growth rate indices, the PAHs, quinones, and aldehydes measured have thus far not helped to disentangle the "package" of pollutants previously found to be associated with the lung function growth indices examined. Some routinely monitored pollutants such as NO_2 and $PM_{2.5}$ appear to be either more important or measured with less error than the PAHs, quinones, or aldehydes tested in this study in accounting for the observed effects.

Project's Significant Technical Details

Impurities in the PUF portion of the original sampling matrix led to persistent difficulties in laboratory quinone derivatization procedures. To avoid these problems, a revised sampling matrix that included additional XAD resin was utilized in the second year of sampling, i.e., in the second set of six CHS communities of Long Beach, Lancaster, Santa Maria, Lake Elsinore, Alpine, and Lake Arrowhead. This change dramatically improved the ability to quantify vapor-phase quinones. A few of the targeted collection species' data (anthroquinone and acrolein) had to be invalidated, due to concerns about collection validity and artifact formation on the collection media.

Conclusions

Ambient air samples were collected in 12 Southern California communities to assess seasonal variability and annual estimates of 15 PAHs, four quinones, and 15 aldehydes of environmental and health concern. Analyses revealed that:

1. Virtually all of the total PAH mass was found in the vapor-phase and vapor phase PAHs were dominated by naphthalene.

2. Vapor-phase PAH concentrations were essentially uncorrelated with those of the more commonly measured pollutants (O_3, NO_2, PM_{10}, EC, OC, ambient acids).

3. Several particle-phase PAHs and aldehydes were strongly correlated with more commonly measured pollutants (O_3, NO_2, PM_{10}, EC, OC, ambient acids).

4. Particle-phase PAH levels were similar across most of the study sites.

5. Particle-phase PAH levels were 2 to 54 times higher in winter than summer.

6. Particle-phase PAH concentrations were negatively correlated with mean air temperature.

7. In two-pollutant models assessing decrements in lung function growth rate indices (FEV_1 and MMEF), the PAH, aldehyde, and quinone constituents did not generally provide additional clarification in the health analyses over NO_2 or $PM_{2.5}$.

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Supplemental Keywords: NA

Relevant Web Sites: http://www.scpcs.ucla.edu