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Outdoor/Indoor/Personal Ozone Exposures of Children in Nashville, Tennessee

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ABSTRACT

An ozone (O_3) exposure study was conducted in Nashville, TN, using passive O_3 samplers to measure six weekly outdoor, indoor, and personal O_3 exposure estimates for a group of 10- to 12-yr-old elementary school children. Thirty-six children from two Nashville area communities (Inglewood and Hendersonville) participated in the O_3 sampling program, and 99 children provided additional time-activity information by telephone interview. By design, this study coincided with the 1994 Nashville/Middle Tennessee Ozone Study conducted by the Southern Oxidants Study, which provided enhanced continuous ambient O_3 monitoring across the Nashville area. Passive sampling estimated weekly average outdoor O_3 concentrations from 0.011 to 0.030 ppm in the urban Inglewood community and from 0.015 to 0.042 ppm in suburban Hendersonville. The maximum 1- and 8-hr ambient concentrations encountered at the Hendersonville continuous monitor exceeded the levels of the 1- and 8-hr metrics for the O_3 National Ambient Air Quality Standard. Weekly average personal O_3 exposures ranged from 0.0013 to 0.0064 ppm (7–31% of outdoor levels). Personal O_3 exposures reflected the proportional amount of time spent in indoor and outdoor environments. Air-conditioned homes displayed very low indoor O_3 concentrations, and homes using open windows and fans for ventilation displayed much higher concentrations.

IMPLICATIONS

This study demonstrates the usefulness of passive O_3 sampling technology in measuring long-term outdoor/indoor/personal exposures. The test subjects did well in following simple directions concerning accurate exposure assessment and in keeping time-activity diaries. Personal O_3 exposure, in between the extremes of higher outdoor and lower indoor exposures, is a function of time spent outdoors. Clearly, those children spending more time outdoors are subject to higher O_3 exposures than are their more housebound peers. Continuous State and Local Air Monitoring System O_3 monitoring results substantially overestimate weeklong indoor and personal O_3 exposure. Centrally air-conditioned indoor environments confer a substantial degree of protection from ambient O_3 levels.

INTRODUCTION

Ozone (O_3) is a secondary air pollutant, produced photochemically from complex mixtures of nitrogen oxides (NO_x) and reactive volatile organic compounds (VOCs). The short-term reversible effects of O_3 on respiratory symptoms and pulmonary function have been well established by toxicological and field studies of both adults and children.[1–4] In a prospective between-community cohort study, Detels and coworkers[5,6] found decreased levels of lung function and steeper declines in lung function among residents of communities more heavily exposed to oxidant pollution. Significantly lower lung function was observed for people living in areas where annual average outdoor O_3 concentrations exceeded 0.04 ppm.[7] Other studies suggest that asthma can be exacerbated by O_3 exposure. Some have suggested that repeated exposure to photochemical smog events can cause asthma, though it is not clear which pollutant or combination of pollutants is responsible.[8] Most studies of chronic health effects are determined by regression analysis of various health endpoints based on ambient monitoring data collected from fixed monitoring sites. Imprecise exposure characterization adds to considerable uncertainty in study results.

One significant limitation of previous O_3 exposure investigations has been the lack of personal and indoor O_3 monitoring. Existing continuous O_3 monitors are bulky, expensive, and impractical for wide-scale personal and indoor exposure monitoring studies. With the development of passive O_3 samplers,[9–12] however, researchers have demonstrated that personal and indoor O_3 monitoring is feasible. Simultaneous measurements using the Harvard O_3 passive sampler and conventional continuous analyzers show good agreement in outdoor, indoor, and personal exposure measurements.[13,14] These O_3 passive samplers were used to monitor personal O_3 exposures of 23 elementary school children, as well as the indoor and outdoor concentrations in their homes.[15] The samplers were used to measure chronic O_3 exposures of 200 children by measuring ambient, outdoor, and personal exposures once a month.[16]

This study measures weekly outdoor, indoor, and personal O_3 exposure estimates during six weeklong periods in the summer of 1994 for two communities in the Nashville, TN, metropolitan area. This study coincided with the 1994 Nashville/Middle Tennessee Ozone Study conducted by the Southern Oxidants Study, which provided enhanced continuous ambient O_3 monitoring across the Nashville area. The study also established the ability of 10- to 12-yr-old children to maintain a demanding time/activity protocol for O_3 exposure assessment. The O_3 exposure estimates were used further to determine if systematic differences among children exist as a result of differing housing characteristics, residential locations, or activity patterns.

EXPERIMENTAL METHODS

Study participants were recruited from elementary schools in the Inglewood and Hendersonville areas of Nashville. Inglewood is an urban community within the city limits of Nashville, 8 km northeast of the city's center, and Hendersonville is a suburban town, 22 km northeast of Nashville. In the summer, both Inglewood and Hendersonville are predominantly on the downwind side of the Nashville metropolitan area. The schools and their neighborhoods were selected, in part, because of their proximity to nearby continuous ambient O_3 monitors. From the two schools, 326 children were asked to complete a preliminary questionnaire. Fifty children responded affirmatively to the questions regarding their presence during the six weekly monitoring periods and had parental permission to participate the study. After initial contact by our staff, 36 of these children agreed to participate. During the study, three children dropped out (two children completed 3 weeks and one child completed 4 weeks) and 33 children completed the six weeklong measurements. The measurements were completed during the school's summer vacation in June and July of 1994.

Continuous O_3 measurements at the ambient monitoring stations were made with Federal Reference Method (FRM) O_3 monitors operated by the Nashville/Davidson County Metropolitan Health Department (Inglewood) and the Tennessee Department of Environment and Conservation (Hendersonville). Both samplers operate according to State and Local Air Monitoring Station (SLAMS) siting and quality assurance guidelines, and their hourly data is submitted to the Aerometric Information and Retrieval System (AIRS). The continuous data used for this analysis were retrieved from AIRS.

Passive outdoor/indoor/personal O_3 measurements were made using Harvard passive O_3 samplers (Ogawa and Co. USA, Inc.).[12] The sampler consists of a Teflon barrel containing two glass-fiber filters coated with nitrite. The sampler estimates O_3 using the oxidation reaction of nitrite by O_3 to form nitrate (NO_3^-). The amount of accumulated NO_3^- is determined by ion chromatography. Time-weighted average O_3 concentrations are estimated by the amount of NO_3^- and effective collection rate. Collection rates were 21.6 cm^3/min for outdoor sampling, 21.4 cm^3/min for indoor sampling (with forced air movement), and 14.8 cm^3/min for personal sampling.[13,17,18] Field blanks were deployed with field samplers every week, and they were matched at 10%. The field blank values were subtracted from the O_3 measurement.

Each participating child and family had a set of personal/indoor/outdoor passive O_3 samplers. The tripod-mounted, weather-capped, outdoor sampler was placed ~2 m off the ground and located in a secure, open area away from vents, driveways, and overhanging trees near the participant's homes. The indoor sampler was placed on a small sampling rack with an integral small fan to provide a constant face velocity of 0.25 m/sec. The fan rack was placed on bookshelves or tabletops in the homes of participants. The child was instructed to wear the passive sampler pinned to the left top front side of their clothes during the active (nonsleep) portion of the day and to place the sampler next to their bed or on a dresser at night. They also were instructed not to get the sampler wet. The children also recorded daily activities, from 8:00 a.m. to 9:00 p.m., in diaries. Information about house characteristics, activity patterns, and families of the 36 children was collected via a questionnaire before the monitoring.

Ninety-nine children were recruited from the same elementary schools to provide additional time/activity information during the summer via telephone survey. This activity information was collected for a sample of 15 nonconsecutive days. The children were informed of the interview ahead of time so that they could record their activities. The activity information was not collected retrospectively if the child was not reachable on that day. A total of 62 children completed the telephone interview at least eight times. These activity patterns were compared with those of the monitored children.

Outdoor, indoor, and personal O_3 concentrations along with children's activity patterns and household characteristics were described using Student's *t* test and one-way analysis of variance. Because there were repetitive measurements of the same child, a mixed model with time as a covariate was used to include random effects and adjust variability accordingly. The analysis determined time trends (temporal) and the individuals in which they were measured (spatial). The data were used to develop a model to predict personal O_3 exposures using a least-squares regression model.

RESULTS AND DISCUSSION

Of the 36 children participating in personal O_3 exposure monitoring, 18 were female, 28 were Caucasian, and eight were African-American. Fourteen were 10 years old, 18 were 11 years old, and four were 12 years old. Twenty-eight lived in detached single-family dwellings. Twenty-one homes had central air conditioning, 11 homes had window air-conditioning units, and one home had no air conditioning. Window fans were "often" used in eight homes, "occasionally" used in six homes, and "not" used in 21 homes. Windows were "frequently" opened in five homes, "occasionally" opened in 21 homes, and "not" opened in nine homes.

Three children dropped out and 33 children completed all six weekly measurements. Among the participating children, 96.5% of children-week personal exposures were measured. A total of 932 passive samplers were used for indoor, outdoor, and personal sampling. Only eight samples were voided because of being "lost, wet, or broken." Seven of these eight were personal samplers. One outdoor sample was lost when the supporting tripod fell during a thunderstorm. No child had more than one occurrence of voided personal sampling. Based on this experience, it is believed the passive sampler can be used effectively to measure chronic O_3 exposure for children.

Duplicate indoor measurements were used to determine the precision of the O_3 passive sampler. When both measurements were below the limit of detection, the pair was not included in the analysis. One hundred and nine duplicate samples were collected; 42 pairs had at least one measurement above the limit of detection. A relative precision of 18.5% was estimated as the standard deviation of the absolute difference between each pair (0.0011 ppm) divided by the mean indoor concentration (0.0061 ppm). The precision was slightly higher than 12% for indoor exposure measurements reported elsewhere.[16] The difference was mainly caused by low indoor levels in this study.

Activity diaries were collected during the O_3 sampling period. The children were asked to record their activities from 8:00 a.m. to 9:00 p.m. When the diary was missing data for less than 3 hr, the time missed at each location was adjusted proportionally to the data available for that day. For the documented times, the children averaged 2.8 hr outdoors, 9.3 hr indoors, and 0.9 hr "in transit."

Weekly outdoor average O_3 concentrations from the continuous monitor and the highest and lowest outdoor passive monitors in Inglewood and Hendersonville are shown in Figure 1. On average, weekly O_3 concentrations were 65% higher for Hendersonville compared with Inglewood (0.033 vs. 0.02 ppm). The 0.12 ppm level of the 1-hr National Ambient Air Quality Standards (NAAQS) for O_3 was exceeded (0.127 ppm) during week 1 in Hendersonville, and the 0.08 ppm level of the 8-hr O_3 NAAQS was exceeded four times (0.101, 0.105, 0.086, and 0.085 ppm) during weeks 1, 2, 4, and 6, respectively, in Hendersonville. Neither standard level was exceeded at the Inglewood monitor. The average ambient O_3 levels encountered during this study are typical of levels measured during the Middle Tennessee Ozone Study.[19]

The ambient O_3 levels in this study were comparable with historical data showing average O_3 levels of ~0.04 ppm during the O_3 season from April to September. Average O_3 NAAQS was exceeded in Hendersonville. Adults exercising outdoors (O_3 levels 0.021–0.074 ppm) and farm workers (O_3 levels 0.013–0.084 ppm) can experience decreased lung function at the O_3 levels observed in this study.[20,21] These ambient O_3 levels have been associated with increased emergency room visits and hospital admissions, including aggravation of

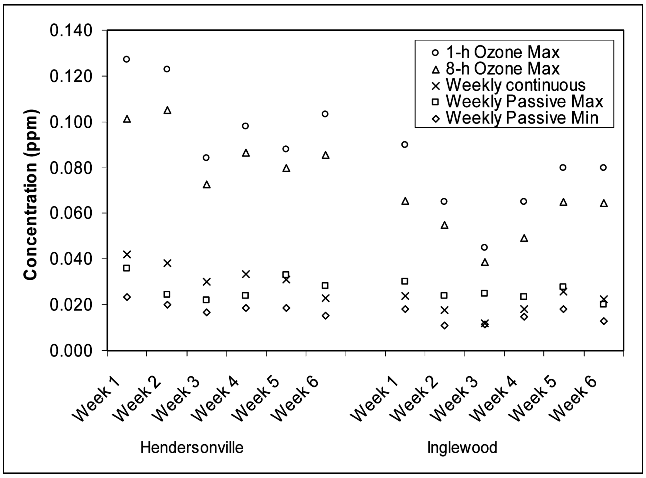

Figure 1. Ambient O_3 concentrations in Hendersonville and Inglewood.

asthma.[22,23] However, other studies did not replicate these findings.[24]

Weekly exposure estimates from the continuous monitors correlated well with passive samplers placed outside of the subjects' homes. There is particularly good agreement between the continuous Inglewood monitoring results and the average Inglewood outdoor passive sampler results. The same cannot be said, however, for Hendersonville, where the continuous monitoring results were from 8 to 67% higher than the average outdoor passive O_3 levels. While the area immediately around the Inglewood monitor is similar to the residential area studied, the Hendersonville monitor is relatively more isolated from its nearby residential area. The Hendersonville residential area, like all residential areas, contains many on-road and off-road NO_x and VOC emissions sources (cars, trucks, and lawnmowers), which expose the passive samplers to a far more dynamic chemical regime than that found at the Hendersonville continuous monitor. The Hendersonville monitoring station was located in a limited access area next to a city park on the north shore of Old Hickory Lake. The net effect of the proximity of these "fresh" emissions is to lower O_3 concentrations through chemical titration.

Descriptive statistics for weekly outdoor, indoor, and personal passive O_3 exposure estimates are shown in Table 1. All of the outdoor passive samples estimated concentrations above the minimum detection limit (MDL) of 0.0012 ppm, although 64% of the indoor passive samples and 40% of the personal samples were below the MDL. For the samplers where the concentrations were below the limit of detection, the O_3 concentration was assigned as half of the lower detection limit (i.e., 0.0006 ppm) for statistical analyses. Weekly outdoor passive O_3 measurements in Hendersonville averaged 6–24% higher than those for Inglewood, and this difference was significant for five of the six weeks ($p <$ 0.01). The regional difference in ambient O_3 exposure between Inglewood and Hendersonville demonstrated in this study is consistent with the results of a 3-yr ambient O_3 monitoring study.[19] Weekly average indoor O_3 concentrations ranged from 3 to 15% of outdoor O_3 concentrations, and average personal O_3 concentrations ranged from 7 to 31% of outdoor O_3 concentrations.

More than 60% of indoor samplers were below the MDL. Because there are very few indoor sources of O_3, and because outdoor O_3 is effectively removed by air conditioning, indoor O_3 levels are often low. In this study, the average ratio of indoor/outdoor O_3 was 0.1 with a standard deviation of 0.18. The ratio is less than ratios of 0.26 and 0.40 reported in California and Hong Kong, respectively.[25,26] Forty percent of personal samples were below the MDL. The percentage of personal samples below the MDL was lower than that for indoor samples. This is reasonable given that personal exposure depends on both indoor and outdoor levels.

When housing characteristics and indoor O_3 levels were assessed, four variables were significantly associated

Table 1. Descriptive statistics for indoor, outdoor, and personal O_3 concentration (ppm).

Week	Exposure	No.	Mean	Standard Deviation	Min	Median	Max	No. of Samples below Detection Limit (%)
1	indoor	35	0.0019	0.0035	0.0006	0.0006	0.017	30 (86)
	outdoor	35	0.0259	0.0031	0.018	0.0254	0.0356	0
	personal	34	0.0035	0.0032	0.0006	0.0023	0.013	11 (32)
2	indoor	35	0.002	0.0035	0.0006	0.0006	0.0179	24 (69)
	outdoor	35	0.0208	0.0029	0.0112	0.0209	0.0245	0
	personal	35	0.0036	0.0038	0.0006	0.0022	0.0167	13 (37)
3	indoor	35	0.0019	0.0029	0.0006	0.0006	0.0129	23 (66)
	outdoor	34	0.0189	0.0023	0.0117	0.0185	0.0247	0
	personal	32	0.0033	0.0033	0.0006	0.0022	0.0128	13 (41)
4	indoor	33	0.0016	0.0025	0.0006	0.0006	0.0133	26 (79)
	outdoor	32	0.019	0.0023	0.0147	0.0185	0.0238	0
	personal	33	0.003	0.0056	0.0006	0.0006	0.0254	22 (67)
5	indoor	32	0.0031	0.0034	0.0006	0.0018	0.0147	4 (13)
	outdoor	32	0.0235	0.0031	0.018	0.0226	0.0329	0
	personal	31	0.0045	0.0037	0.0006	0.0026	0.013	6 (19)
6	indoor	32	0.0018	0.0027	0.0006	0.0006	0.011	22 (69)
	outdoor	32	0.0186	0.0032	0.0127	0.0184	0.0284	0
	personal	33	0.0029	0.0028	0.0006	0.002	0.0103	15 (45)

with indoor O_3 levels: carpeting, air conditioning, window fans, and window opening ($p < 0.05$). The effect of carpeting is inconclusive because there were only two houses without carpet in this study. Indoor O_3 concentrations were significantly lower for houses with central air conditioning, houses that did not use window fans, and houses that did not open windows. When the one nonair-conditioned house was excluded, the three variables were not associated with each other. These three variables seem to be good predictors of lower indoor O_3 concentrations.

No housing characteristic was significantly associated with personal O_3 exposure over all six weeks. The presence of a pet was significantly associated with higher personal O_3 exposures for four of the six weeks. Subsequent analysis between variables and activity patterns indicated that children with pets tended to spend more time outdoors than children without pets. The presence of a pet appears to be a surrogate for outdoor activity, which results in higher personal O_3 exposure. When repeated measures analysis using the mixed model was used to explore models for personal exposure, the final model included three variables, 3 or more hours of time spent outdoors, the presence of a pet in the home, and the use of a window fan. None of the interaction terms between these variables were found to be significant. The 6-week average personal O_3 exposures were classified by the selected variables, as shown in Table 2.

The importance of time spent outdoors and indoors relative to personal exposure was examined. When personal O_3 exposures were stratified into three groups based on outdoor time (<25th percentile, 25–75, >75th percentile), the exposures of children spending the least amount of time outdoors were significantly lower than those of children spending the greatest amount of time outdoors (Table 3). From this, it can again be concluded that the time spent outdoors is a strong indicator of personal O_3 exposures. McConnell et al.[27] reported that the incidence of new asthma was associated with heavy outdoor exercise in communities with high ambient O_3 concentrations. This finding indirectly supports the importance of outdoor time in personal O_3 exposure. However, it was found that no housing characteristics were associated with personal exposure. This suggests that indoor levels are less important for personal exposure. The lack of correlation between housing characteristics and personal exposure may not be generalized, because such an association may be caused by very low indoor levels in this particular study.

Correlations between personal exposure and percentages of weekly indoor, outdoor, and transit times were determined. Correlations between personal/indoor ratios and personal/outdoor ratios also were made with the percentages of time spent indoors, outdoors, and in transit. The activity data were included only for times when the children wore the sampler. The Pearson correlations are shown in Table 4. Personal O_3 exposure was inversely associated with time spent indoors and positively associated with time spent outdoors. Transit time was not significantly associated with personal exposure. The relationship between outdoor time-of-day and personal exposure was similar to a daily profile of ambient O_3 concentration, as shown in Figure 2. Outdoor O_3 concentrations usually have a daily profile in which O_3 concentrations are elevated in the afternoon and low in the early morning.[19] The diurnal profile suggests that the personal O_3 exposures were affected not only by the total amount of time spent outdoors but also the time of day the child was outdoors.

Table 3. Classification of O_3 concentrations (ppm) into three groups by outdoor time from activity diary without one child living in non-air-conditioned house.

Outdoor Time	Personal	Indoor	Outdoor
<25th percentile	0.0015 ± 0.00074	0.00108 ± 0.00138	0.02141 ± 0.00194
25–75	0.002 ± 0.0016	0.00105 ± 0.00103	0.02122 ± 0.00206
>75th percentile	0.0042 ± 0.0026	0.00349 ± 0.00478	0.02106 ± 0.0023

Table 2. Six-week average personal O_3 exposure by the selected variables from repeated measures analysis using the mixed model.

Variables	Classification	Personal Exposure (ppm) ± Standard Deviation
Pet	No	1.46 ± 0.71
	Yes	3.93 ± 2.7
Window fan	Never	1.31 ± 1.96
	Occasionally	2.11 ± 1.55
	Often	4.04 ± 3.66
Outdoor time yesterday	<3 hr	1.32 ± 1.27
	>3 hr	2.63 ± 2.39

Table 4. Correlation between personal exposure and activity.

	Personal Exposure	Personal/Indoor	Personal/Outdoor
Indoor time	−0.17[a]	−0.1[a]	−0.18[a]
Outdoor time	0.19[a]	0.1[a]	0.2[a]
Transit time	−0.01	0.01	−0.02

[a] $p < 0.01$

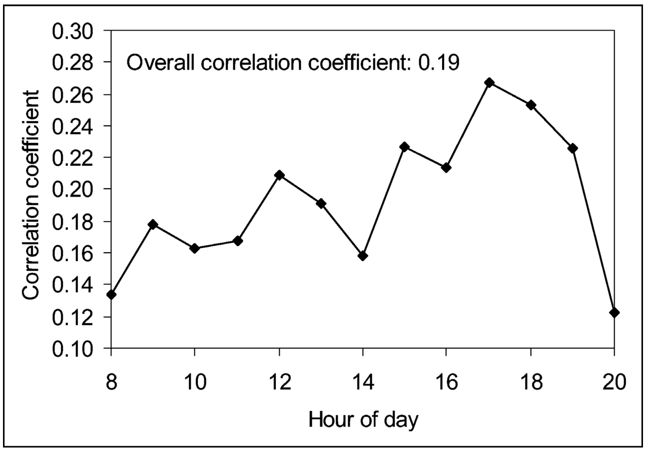

Figure 2. Correlation between personal exposure and hour of day when outdoors.

Activity patterns were collected from two groups, the 36 children participating in the O_3 monitoring study and the 99 children taking part in the telephone interview. Of the group of 99 children, activity patterns of 62 children who completed the telephone interview at least eight times were included for the analysis. Of these 62 children, 37 were female. Sixty children lived in houses with air conditioning (25 had central air conditioning and 35 had window air conditioning). The average time spent outdoors for these children was 4.1 of 13 hr, substantially higher than the average of 2.8 hr outdoors obtained from those children participating in the O_3 monitoring study.

The telephone survey group averaged 1.3 hr more time outdoors, between 8:00 a.m. and 9:00 p.m., than the group monitored for personal O_3. Figure 3 shows that ~35% of children in the monitoring group spent all 13 hr indoors, while this was true for only 5% of children in the telephone survey group. Despite these apparent differences in reported time spent outdoors, a direct comparison cannot be made between the groups because the information collection instruments were designed and used differently. It is possible that participants in the O_3 study may actually have behaved differently with respect to time spent outdoors than did other children in the Nashville area. However, it is not clear whether these results suggest a real difference in the behavior of the O_3 sampled children caused by selection criteria or a bias introduced by differences in the assessment methods. Further investigation is needed on the impact of strict participation requirements on exposure profile.

Methods of predicting personal O_3 exposures were examined using the data on microenvironmental O_3 concentrations and daily time-activity diaries. Because this study monitored only two microenvironments, indoors and outdoors at-home, two basic models were tested using an ordinary least-squares regression model:

$$C_p = \beta_1 C_i + \beta_2 C_o + \varepsilon \quad (1)$$

and

$$C_p = \beta_1 f_1 C_i + \beta_2 f_o C_o + \varepsilon \quad (2)$$

where C_p, C_i, and C_o are the personal, indoor, and outdoor O_3 concentrations, respectively; f_i and f_o are the fraction of time spent indoors and outdoors, respectively; and ϵ is the error term.

The model using unweighted O_3 concentrations (eq 1) was

$$C_p = -0.61 + 0.40\ C_i + 0.11\ C_o + \varepsilon \quad (3)$$

The model using weighted microenvironmental O_3 concentrations (eq 2) was

$$C_p = 1.20 + 0.46\ f_1 C_i + 0.34\ f_2 C_o + \varepsilon \quad (4)$$

In both models, the coefficients of indoor and outdoor O_3 levels were significant at $p < 0.01$, demonstrating that both outdoor and indoor levels affect personal O_3 exposure. Personal exposure is difficult to measure directly. This model may be useful to estimate personal exposure with indoor and outdoor O_3 levels.

Despite sample size limitations, personal exposure models were determined using microenvironmental concentrations. The objective of the modeling analysis was to investigate the feasibility of predicting personal O_3 exposures using a limited set of data. Limitations of this model

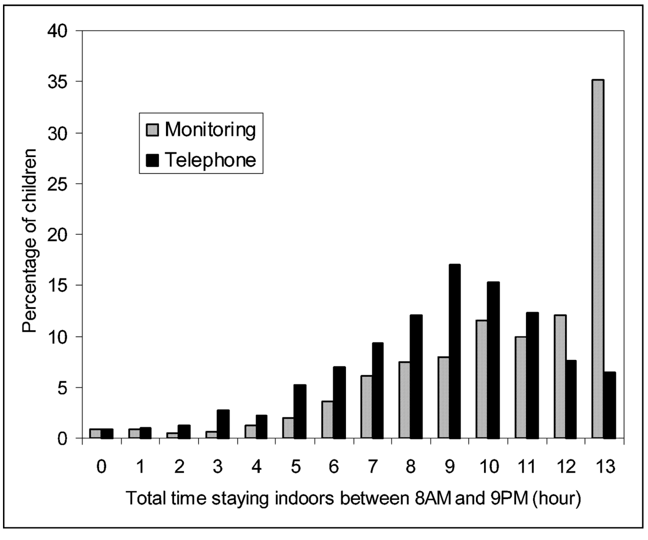

Figure 3. Comparison of total indoor times from monitoring study and telephone interview (8:00 a.m.–9:00 p.m.).

may include the fact that only two microenvironments are incorporated, as well as the short averaging time (one week), leading to a loss of resolution in the correlation between times of high outdoor O_3 and the time of day children were outdoors. Both models showed statistically significant coefficients of indoor and outdoor O_3 levels, suggesting that outdoor levels as well as indoor levels affect personal O_3 exposure. Additional measurements in other geographic locations and microenvironments may help to improve the predictive power of the exposure models.

CONCLUSIONS

This study showed that a passive sampler could be used to measure outdoor/indoor/personal O_3 exposure levels of children. Participating children (4th and 5th graders) complied with the protocol over a 6-week period. The use of passive samplers can provide complex exposure profiles with high quality but at a low cost. The measurements using continuous monitors and passive samplers showed generally good agreement. However, the association can be influenced by characteristics of the stationary monitoring location. Personal exposures of children were between lower indoor and higher outdoor concentrations. Indoor O_3 concentrations are significantly associated with several housing characteristics (i.e., central air conditioning, window fan use, and open window), rather than being associated with outdoor O_3 concentrations. Having pets and spending time outdoors were significantly associated with personal O_3 exposures. Personal exposures of children who spent more time outdoors were higher than personal exposure of those who spent less time outdoors. Personal exposures were affected not only by the total time spent outdoors but also by the time of day the children were outdoors.

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