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A Multiple-Smoker Model for Predicting Indoor Air Quality in Public Lounges

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A mathematical multiple-smoker model for predicting the minute-by-minute indoor time series and time-averaged pollutant concentrations from environmental tobacco smoke (ETS) was developed and tested during 10 visits to glass-enclosed public smoking lounges at two international airports in the San Francisco Bay Area. The model is based on the mass balance equation and uses counts of active smokers as input. Its predictions were compared with the time series measurements of carbon monoxide (CO) and respirable suspended particles (RSP). The experimental time series for RSP was determined by averaging the readings (2-min averages) from monitors at three widely-spaced locations in the lounge. At 8 out of the 10 visits, instantaneous CO concentrations also were measured every 2−3 min from a single monitor at the center of the room. The average emission rates per cigarette for CO and RSP for two visits in which the air exchange rates were measured were found to be 11.9 and 1.43 mg/min, respectively, which are consistent with values reported elsewhere in the literature. There was excellent agreement (0−12% error) between the observed RSP and CO concentration time series average and average concentrations predicted by the model for all study visits. Regression results between observed and predicted time series were also excellent. The average difference between the time-averaged RSP concentrations measured at the three widely spaced locations in the room and the average concentration across the room was about 12%. These results suggest that the model can be used by human exposure assessors and smoking lounge designers to predict the average exposures that people will experience for visits of typical duration.

Introduction

Environmental tobacco smoke (ETS) has been characterized as an environmental and occupational carcinogen (*1, 2*) and may contribute to mortality from heart disease (*3*). To reduce the exposures of nonsmokers in indoor settings, many building owners have restricted smoking indoors, and some have established smoking lounges with their own ventilation systems that operate separately from the building air handling system. Little information is available on the relationship between pollutant concentrations in these lounges, smoking activity, and physical parameters such as the volume and air exchange rate.

This paper develops a mathematical model for predicting indoor pollutant concentrations in smoking lounges and then tests the performance of this model for carbon monoxide (CO) and respirable suspended particles (RSP) by conducting experiments with monitoring instruments in 10 visits to the public smoking lounges in two international airports. The verified model can provide design criteria for other lounges. Because pollutant concentrations in smoking lounges show a great range, models that perform accurately in these lounges should also perform well at other locations where multiple smokers are present (auditoriums, bus terminals, bingo parlors), provided that the air at these locations is sufficiently well-mixed. Mage and Ott (*4*) report that the model works satisfactorily in a 521-m^3 tavern because convection and mechanical mixing caused air in the tavern to be sufficiently well-mixed to give uniform concentrations throughout the tavern at any instant of time.

The San Francisco Airport (SFO) and the San Jose International Airport (SJC) terminals each have provided airport visitors with large, glass-enclosed rooms that are set aside for smokers. These large smoking lounges are ideally suited for testing and validating an indoor air quality model because (1) the rooms are rectangular, facilitating accurate calculation of their volumes; (2) all the smokers can be observed visually, and cigarette smoking activity—the number of cigarettes being smoked each minute—can be recorded with high accuracy; (3) the concentrations are relatively high and can be measured with portable monitoring instruments; (4) no other major sources of CO and RSP are present besides those derived from smoking; and (5) smoking activities vary greatly from hour-to-hour (and minute-to-minute), allowing time series models and measurements to be compared.

Development of the Model

Smoking Activity Pattern Time Series *n(t)*. A precise determination of the cigarette activity pattern $n(t)$ in smoking lounges requires an observer to record the beginning and ending times of every cigarette smoked in the lounge. To illustrate this concept, Figure 1 (a) shows a hypothetical case of seven persons in a room, each lighting up their cigarettes at different times and smoking their cigarettes for different arbitrary time durations. Each person's cigarette, while it is actively burning, is represented by a horizontal line. At time $t = 0$, no one is smoking. At $t = 20$ s, person D ignites the first cigarette, which lasts for 7 min and 10 s, ending at $t = 7$ min and 30 s. Person A lights up a cigarette at $t = 30$ s, or 10 s after person D's first cigarette began. Person F's first cigarette begins at $t = 1$ min and 10 s. Thus, there are zero cigarettes being smoked in the room from $t = 0$ to $t = 20$ s; one cigarette from 20

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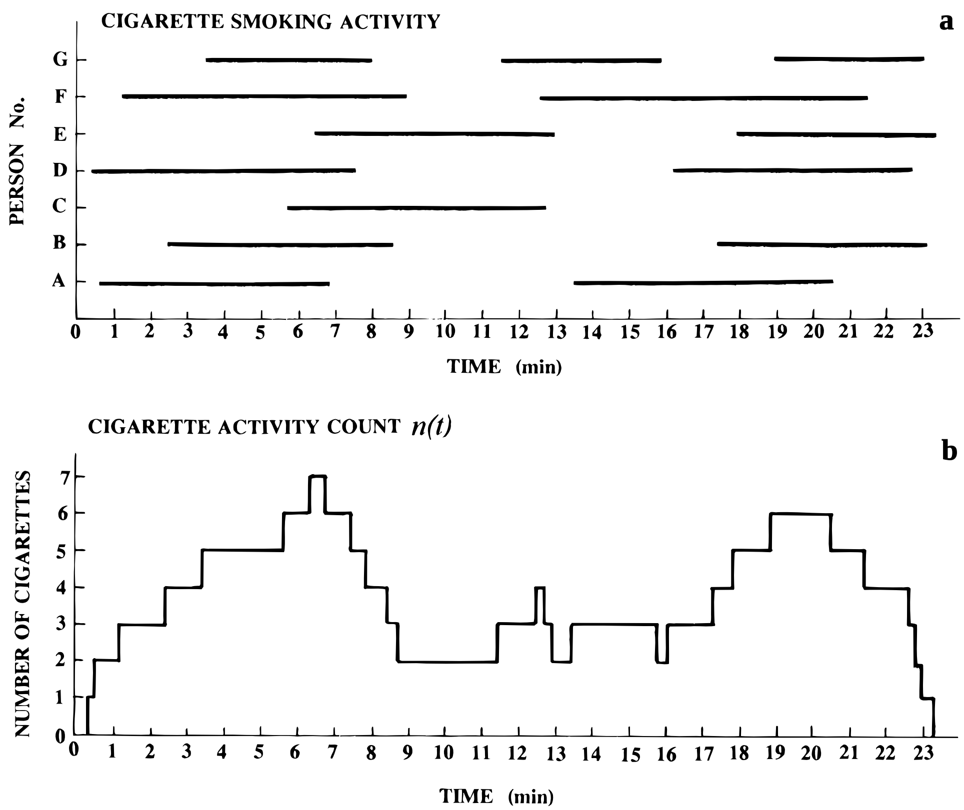

FIGURE 1. (a) Illustrative smoking activity pattern showing a hypothetical example with 7 smokers (A–G). Horizontal lines show the time for which a smoker is active with gaps showing the time the person is not smoking. Each smoker has a unique smoking frequency and duration. (b) The instantaneous cigarette activity count time series *n(t)* derived from the number of active smokers at time *t* in the multiple-smoker activity pattern shown in panel a. Notice the piecewise-constant nature of the cigarette count *n(t)*.

to 30 s (person D); two cigarettes from $t = 30$ s to $t = 1$ min and 10 s (person A + person D together); three cigarettes after $t = 1$ min and 10 s (person A + person D + person F together); etc. The total cigarette activity pattern $n(t)$ is obtained by summing the active cigarettes for any time t (Figure 1b). The exact function $n(t)$ shows discrete integer jumps at arbitrary times and is "piecewise-constant" over continuous time intervals.

A simpler method of estimating $n(t)$ is to record instantaneous values of the cigarette activity pattern every minute. This approximation generates a piecewise-constant time series $n_1, n_2, ..., n_i$ at times $t = \delta, 2\delta, ..., i\delta$ where $\delta = 1$ min. For the example in Figure 1, the time series between $t = 0$ and $t = 10$ min would give the following sequence of cigarette counts: 0, 2, 3, 4, 5, 5, 6, 6, 4, 2, and 2. The peak count of 7 cigarettes occurring between $t =$ 6 and $t = 7$ min would be missed by this simplified minute-by-minute cigarette counting approach because this peak lasts only 20 s and comes between the evenly spaced minutes, but the overall error is small.

Mass Balance Equation. Using the mass balance equation, Switzer and Ott (*5*) show that, if the piecewise-constant concentration time series in a well-mixed room is described only at discrete times $\delta, 2\delta, 3\delta, \ldots, i\delta$, then the concentration entering from outside y_i can be related instantaneously to the concentration z_i inside the room by the following recursive formula:

$$z_i = y_i(1 - \alpha) + z_{i-1}\alpha \tag{1}$$

where y_i is the outdoor concentration at time segment i; z_i is the indoor concentration at time segment i; $i = 1, 2, ...$; $\alpha = e^{-\phi\delta}$; δ is the duration of each equally spaced time interval [T]; and ϕ is the air exchange rate [$1/T$]. This equation applies only if there are no indoor sources. The air exchange rate ϕ in eq 1 can be either an "effective" (ϕ_P) or a "ventilatory" (ϕ_V) air exchange rate. Ott et al. (*6*) show that the effective air exchange rate ϕ_P consists of the sum of the ventilatory air exchange rate ϕ_V and a term ϕ_D, the deposition rate, accounting for the deposition of material onto surfaces and other removal mechanisms. Some indoor air quality models (*7*) use the notation of $a = \phi_V$, $k = \phi_D$, and $a + k = \phi_P$. These decay parameters all have the units of air changes per unit time [1/T].

Ott et al. (*6*) also show that if, instead of assuming that y_i is a piecewise-constant concentration entering the room from outside through air infiltration, the source is located inside the chamber, then y_i in eq 1 is replaced by the source strength (emission mass per unit time) divided by the product of the air exchange rate ϕ and the mixing volume v. As discussed above, the continuous multiple-smoker activity pattern $n(t)$ can be treated as a discrete time series of cigarette counts n_i. The source strength is the product of n_i and the single-cigarette emission rate g_c and consists of piecewise-constant steps that are equally spaced by the time interval δ. Thus, substituting $n_i g_c/\phi v$ for y_i in eq 1, we obtain the following recursive expression for the case in which multiple-smoker sources are located inside the room:

$$z_i = \frac{(1 - \alpha)}{\phi v} n_i g_c + z_{i-1}\alpha \tag{2}$$

where z_i is the concentration inside the room at time segment i [M/L^3]; $\alpha = e^{-\phi\delta}$; ϕ is the air exchange rate [$1/T$]; v is the room volume [L^3]; n_i is the count of active cigarettes at time segment i [cigarettes]; $i = 1, 2, ...$; g_c is the average emission rate per cigarette of all cigarette brands [M/T].

Ott et al. (*6*) show mathematically that, if the averaging time is sufficiently long, then the average concentration over the visit $\bar{z}$ is a function of the average number of cigarettes $\bar{n}$ as follows:

$$\bar{z} = \frac{g_c \bar{n}}{\phi v} = \frac{g_c \bar{n}}{\omega} \qquad (3)$$

where ω is the air flow rate [L^3/T].

Equation 2 does not explicitly include a term for air outside the smoking lounge that infiltrates indoors. Because the mass balance equation follows the principles of a linear system, the outdoor concentration that infiltrates indoors can be treated as a background concentration that is added to z_i by the law of superposition. In this study, background concentrations were determined from the lowest concentration measured either inside or outside the lounge for a given study visit.

The model that is applied to airport smoking lounges in the present study (eqs 2 and 3) can be used equally well to predict minute-by-minute time series and time-averaged concentrations. Ott et al. (*6*) show that ϕ_P and ϕ_V can be estimated experimentally if a strong source is present but then suddenly stops, allowing the interior CO and RSP concentrations to decay exponentially at their natural rates. Since CO is not adsorbed onto surfaces, the exponential decay constant of the CO concentration decay curve gives the ventilatory air exchange rate ϕ_V. Conversely, the decay constant of the RSP concentration decay curve gives the effective air exchange rate ϕ_P, including the effect of particle deposition.

Smoking Lounge Experiments

Experiments to evaluate the performance of the model were carried out in the realistic settings of public smoking lounges in two airports: the San Francisco Airport (SFO) and the San Jose International Airport (SJC). Each lounge had its own ventilation system that maintained a slightly negative pressure relative to that of the airport terminals. The lounge at the SFO airport was a rectangular room containing 84 seats and had a volume of 28357 ft^3 or 803 m^3 with a floor area of 2498 ft^2 or 232 m^2. The lounge at the SJC airport contained 66 seats with a volume of 8410 ft^3 or 238 m^3 with a floor area of 758 ft^2 or 70.4 m^2.

In the experiments, one investigator carefully observed the persons present in the lounge each minute and counted the number of people who were actively smoking. Another investigator measured RSP concentrations using three Model 8510 piezobalances (ThermoSciences, Inc. (TSI) St. Paul, MN) with 3.5-μm size-selective impactors on their inlets giving 2-min averaged readings. The performance of this instrument has been investigated in previous studies (*8*−*10*), and the instrument has been used in carefully controlled experiments (*6, 11*) and in ETS field studies (*12, 13*). The principles of operation of this monitor along with its precision and performance characteristics are reviewed in another paper (*14*). CO concentrations were measured with an electrochemical Model L15 CO personal exposure measurer (Langan Products, San Francisco, CA), which is capable of giving instantaneous readings (*15, 16*). This monitor is equipped with a chemical filter and has been used to measure CO in animal experiments on cigarette smoking conducted in a chamber (*6*). The piezobalances were placed at chair height at either end and in the center of each lounge, and the investigator operated each one manually and wrote down the concentration readings approximately every 2 min. CO measurements were read simultaneously from a Langan monitor at the center location at the same time that the piezobalance readings were recorded.

The time series of the number of smokers and the RSP concentration were recorded for five study visits inside the San Francisco airport smoking lounge (SFO 1−SFO 5) and for five study visits inside the San Jose airport smoking lounge (SJC 1−SJC 5) in the spring and early summer of 1993. The CO time series was measured at every study visit except SFO 3 and SJC 1.

For the SFO 5 and SJC 5 study visits, when the number of smokers in the airport smoking lounges was at or near zero because almost no people were present, a "cigar test" was conducted to measure the CO ventilatory air exchange rate ϕ_V and the RSP effective air exchange rate ϕ_P of the lounge. The cigar test consisted of smoking several cigars and measuring the exponential decay of CO and RSP concentrations.

Results

The time period of each of the 10 study visits at the San Francisco and San Jose airport smoking lounges was between 60 and 146 min (Table 1). The average number of persons actively smoking during each study visit time period ranged from 2.8 to 13.5. Often, children—including infants and toddlers—were observed inside the smoking lounges accompanied by an adult. All measured concentrations were adjusted by subtracting the appropriate background concentration (usually the lowest concentration measured inside or outside the lounge during each study visit; Table 1). The average RSP concentration over all visits ranged from 46 to 156 μg/m^3, with an overall average of 100 μg/m^3 (Tables 1 and 2). All CO concentrations were converted from their measured units of ppm into gravimetric units of μg/m^3 (1 ppm = 1145 μg/m^3 at 25 °C and 1 atm). The average CO concentration over all visits ranged from 472 to 1364 μg/m^3, with an average of 854 μg/m^3 (Tables 1 and 2). An example of the RSP time series for study visit SJC 5 shows reasonable agreement among RSP concentrations at three locations in the room (Figure 2a), which when averaged are associated with the minute-by-minute counts of smoking activity (Figure 2b).

Obtaining Model Parameters. The four basic parameters in the mathematical model are the air exchange rate (ventilatory ϕ_V or effective ϕ_P), the cigarette source strength $n_i g_c$, the room volume v, and the initial concentration z_0 (see eq 2). Since the initial concentration is simply the concentration observed in the lounge at the start of each study visit, and n_i is the cigarette count time series measured every minute, the only parameters left to determine are the air exchange rate and the single-cigarette emission rate g_c.

The air exchange rate ϕ (ventilatory for CO or effective for RSP) was determined by least-squares fitting (*17, 18*) the decay of the pollutant concentration z_i at time t_i (after the cigar tests) to the following equation (Table 1 andFigure 3):

$$z_i = z_0 e^{-\phi t_i} + b \qquad (4)$$

where i = 1, 2, ...

The data points z_i were collected in 2-min intervals during the decay period (i = 1 ... 7 for San Francisco at SFO

TABLE 1

Summary of RSP and CO Measurements and Model Predictions for Each Study Visit with Predicted−Observed Regression Results and Least-Squares Fits to Cigar Test Data Collected at SFO 5 and SJC 5 Study Visits

study visit[a]	study visit date	time period (min)	av no. of smokers	no. of smokers sample size	obs av concn (μg/m^3)[b]	obs concn sample size	av back concn (μg/m^3)[c]	pred emission rate (mg/min)[d]	pred av concn (μg/m^3)[e]	pred concn sample size	av diff[f]	av diff (%)[g]	regression[h] R^2	regression[h] slope	regression[h] y-intercept (μg/m^3)
RSP															
SFO 1	4/25/93	104	5.23	30	60.0	59	5	2.380	60.6	30	0.6	1.0	0.85	1.20	−23.8
SFO 2	5/4/93	76	6.57	76	62.7	36	10	2.018	63.6	76	0.9	1.4	0.84	1.21	−12.8
SFO 3	5/14/93	107	10.58	107	88.1	49	23	1.759	87.2	107	−0.9	−1.0	0.91	1.24	−20.4
SFO 4	6/23/93	104	13.50	104	127.3	47	19	1.992	126.1	104	−1.2	−1.0	0.31	0.70	38.0
SFO 5	7/15/93	146	6.77	146	46.2	65	20	1.439	46.9	146	0.7	1.5	0.67	1.25	−13.0
SFO 5 cigar test: $z_i = 291\ \mu\text{g/m}^3)e^{(-0.263\ \text{min}^{-1})t_i} + 20\ \mu\text{g/m}^3$; $n = 7$; $R^2 = 0.98$															
SJC 1	5/23/93	88	5.56	88	128.9	40	6	1.176	125.3	88	−3.6	−2.9	0.83	1.30	−38.1
SJC 2	6/2/93	118	6.79	117	125.6	53	10	0.938	128.6	117	3.0	2.3	0.90	1.21	−26.6
SJC 3	6/9/93	60	2.82	60	64.8	27	6.7	1.167	70.3	60	5.5	7.8	0.78	0.86	4.18
SJC 4	6/21/93	121	6.69	120	155.5	55	21	1.178	155.7	55	0.2	0.1	0.81	1.15	−24.2
SJC 5	7/1/93	140	5.12	140	144.0	62	13	1.426	151.8	140	7.8	5.1	0.91	0.98	−6.75
SJC 5 cigar test: $z_i = (476\ \mu\text{g/m}^3)e^{(-0.213\ \text{min}^{-1})t_i} + 13.3\ \mu\text{g/m}^3$; $n = 10$; $R^2 = 0.98$															
CO															
SFO 1	4/25/93	101	5.31	29	562.4	42	561	18.455	538.6	29	−23.8	−4.4	0.88	1.48	−30.8
SFO 2	5/4/93	79	6.42	79	771.0	47	767	20.935	818.7	79	47.7	5.8	0.70	1.10	10.8
SFO 3	5/14/93														
SFO 4	6/23/93	104	13.50	104	696.6	47	698	8.984	691.6	104	−5.0	−0.7	0.40	1.10	−72.6
SFO 5	7/15/93	146	6.77	146	472.1	64	469	12.145	485.1	146	13.0	2.7	0.59	1.12	−68.2
SFO 5 cigar test: $z_i = (1.86\ \text{ppm})e^{(-0.217\ \text{min}^{-1})t_i} + 0.80$ ppm; $n = 7$; $R^2 = 0.98$															
SJC 1	5/23/93														
SJC 2	6/2/93	118	6.79	117	981.8	55	927	6.163	1018	117	36.2	3.6	0.82	1.56	−567.4
SJC 3	6/9/93	60	2.82	60	622.5	30	595	9.415	710.2	60	87.7	12.3	0.90	1.0	−68.7
SJC 4	6/21/93	121	6.69	120	1363	55	1360	8.676	1366	120	3.0	0.2	0.91	1.17	−232.2
SJC 5	7/1/93	134	5.00	134	1364	55	1360	11.622	1471	134	107.0	7.3	0.94	1.0	−204.4
SJC 5 cigar test: $z_i = (3.23\ \text{ppm})e^{(-0.179\ \text{min}^{-1})t_i} + 0.74$ ppm; $n = 10$; $R^2 = 0.96$															

[a] The effective air exchange rate was determined by cigar test at the SFO 5 and SJC 5 study visits. The cigar test data were least-squares fit to eq 4 in the text (see Figure 3). [b] Observed RSP averages for SFO 5 and SJC 5 reflect the period before each cigar test was begun. CO concentrations were not collected at the SFO 3 and SJC 1 study visits. CO concentrations were converted from ppm to μg/m^3 (1 ppm of CO = 1145 μg/m^3 at 25 °C and 1 atm) except for data from cigar tests. [c] Quantities in this table reflect the subtraction of an average background concentration from all observed concentrations except for concentrations collected during cigar tests. [d] Predicted emission rates were calculated (using eq 5) for all study visits in each lounge using the air exchange rates determined at either the SFO 5 or SJC 5 study visit. [e] Predicted CO and RSP concentrations were calculated (using eq 2) for the minutes during which a smoker count was recorded. [f] This column contains the difference between the predicted and observed average concentrations for each study visit: pred av−obs av. [g] This column contains the percentage difference between the predicted and observed average concentrations for each study visit: 100 × (pred av−obs av)/(pred av). [h] Regression statistics were calculated between the predicted and observed concentration time series at each study visit (sample size is the same as for the observed concentration time series). Abbreviations: obs, observed; pred, predicted [by the model]; back, background; diff, difference.

5 and $i = 1 \ldots 10$ for San Jose at SJC 5), with z_0 as the initial value just before the decay began. The background concentration b in the equation was determined from the asymptotic value measured inside the smoking lounge at the end of the decay curve. Although the numbers of data points were small, the R^2 values are all greater than 0.95 (Table 1). The plots of the observed and predicted exponential decay also appear to have no systematic residual values, and the fitted curve decays asymptotically to the background level (Figure 3).

The difference ϕ_D between the ventilatory air exchange rates ϕ_V determined from the decay of CO (0.217 min^{-1} at SFO and 0.179 min^{-1} at SJC) and the effective air exchange rates ϕ_P from RSP (0.263 min^{-1} at SFO and 0.213 min^{-1} at SJC; including all removal terms) is about 0.046 min^{-1} for San Francisco and 0.034 min^{-1} for San Jose. A ventilatory air exchange rate of 0.217 min^{-1} is equivalent to $\phi_V = (0.217\ \text{min}^{-1})(60\ \text{min/h}) = 13.0$ air changes per hour (ach). Although ϕ_D incorporates the effect of all RSP removal mechanisms other than ventilation (deposition, evaporation, agglomeration, etc.), deposition onto surfaces may predominate, implying that surface deposition increments the natural ventilation rate from 10.7 to 12.8 ach in the San Jose lounge and from 13.0 to 15.8 ach in the San Francisco lounge. Overall, the removal of RSP from surface deposition in both the smoking lounges was found to be about 19−21% of the ventilatory removal from air flow ($100 \times \phi_D/\phi_V$). Because the deposition rate ϕ_D is obtained by subtracting two larger numbers, it does not have great precision. However, values in the literature (*7*) show a wide range, and few measurements in locations similar to smoking lounges are available.

The single-cigarette emission rate can be obtained by rearranging eq 3:

$$g_c = \frac{\bar{z}\phi v}{\bar{n}} \tag{5}$$

Here, g_c is the *average* single-cigarette emission rate (measured in mass emitted per unit time) for all cigarette brands, types, and smoking styles encountered for a given study visit. The RSP and CO background concentrations (Table 1) were estimated from the lowest measurements observed either inside or outside the lounges, and the observed RSP and CO time series were adjusted by subtracting background values before calculating $\bar{z}$ and $\bar{n}$ for the entire visit inside each smoking lounge (omitting portions of the visits used for air exchange rate studies). Thus, the calculated emission rates reflect only the pollutants emitted from the cigarettes and not from infiltration into the lounges from outside sources.

TABLE 2

Selected RSP and CO Statistics for the 10 Study Visits at the San Jose (SJC) and San Francisco (SFO) Airport Smoking Lounges[a]

statistic	time period (min)	av no. of smokers	obs av concn (μg/m^3)	av back concn (μg/m^3)	predicted emission rate (mg/min)	regression R^2	regression slope	regression *y*-intercept (μg/m^3)
RSP								
av SFO	107	8.5	76.9	15	1.920	0.72	1.1	−6.4
SD SFO	25	3.4	32.0	7.6	0.348	0.24	0.2	25.3
$n = 5$								
av SJC	105	5.4	123.8	11	1.180	0.85	1.1	−18.3
SD SJC	32	1.6	35.1	6.1	0.173	0.06	0.2	16.8
$n = 5$								
av overall	106	7.0	100.3	13	1.550	0.78	1.1	−12.3
SD overall	27	3.0	40.2	6.8	0.468	0.18	0.2	21.2
$n = 10$								
av SFO 5 & SJC 5 only	143	5.9	95.1	16.5	1.430	0.79	1.1	−9.9
SD SFO 5 & SJC 5 only	4	1.2	69.2	4.9	0.0092	0.17	0.2	4.4
$n = 2$								
CO								
av SFO	108	8.0	625.5	499	15.100	0.64	1.2	−40.2
SD SFO	28	3.7	133.8	302	5.520	0.20	0.2	38.8
$n = 4$								
av SJC	108	5.3	1083	850	8.970	0.89	1.2	−268.2
SD SJC	33	1.9	355.7	574	2.250	0.05	0.3	211.9
$n = 4$								
av overall	108	6.7	854.2	613	12.000	0.77	1.2	−154.2
SD overall	28	3.1	348.8	490	5.110	0.19	0.2	186.4
$n = 8$								
av SFO 5 & SJC 5 only	140	5.9	918.1	916	11.900	0.77	1.1	−136.3
SD SFO 5 & SJC 5 only	9	1.3	630.7	632	0.370	0.25	0.1	96.3
$n = 2$								

[a] See the footnotes in Table 1. SD, standard deviation.

Because the lounges used a mechanical forced-air ventilation system, the air exchange rates at SFO 5 and SJC 5 study visits may not have differed too much from those at the other study visits. Therefore, eq 5 and the air exchange rates measured at SFO 5 and SJC 5 study visits were used to calculate the emission rates (mg/min) for each visit (Table 1). The emission rates calculated for SFO 5 and SJC 5 study visits are considered the most accurate: 12.1 and 11.6 mg/min, respectively, for CO with an average of 11.9 mg/min (Tables 1 and 2), and about 1.4 mg/min for RSP at both SFO 5 and SJC 5 with an average of 1.43 mg/min (Tables 1 and 2). The similarity of these results for the two lounge visits is impressive, because it implies that average cigarette emission rates may be fairly constant between different smoking lounges. The much greater variability observed in the emission rates calculated for SFO 1−4 and SJC 1−4 study visits (6.2−20.9 mg/min for CO and 0.9−2.4 mg/min for RSP; Table 1) is probably a result of differences in the air exchange rates from SFO 5 and SJC 5 study visits.

Comparison of Observed and Predicted Concentration Time Series. The time series model (eq 2) was used with the emission rates determined for each study visit to calculate the predicted RSP and CO concentration time series. The same CO air exchange rate and effective RSP air exchange rate (determined from the SFO 5 and SJC 5 study visits) were used for the predictions at each location. The initial concentration z_0 was set equal to the first concentration reading taken on each visit. If the model is valid, we expect good agreement between the predicted and observed time series averages, since we have used the model to obtain average emission rates that best predict the observed time series averages (eq 5). An alternative to using this approach would be to either (1) use the emission rates determined from the SFO 5 and SJC 5 study visits or (2) vary the model parameters until the best agreement between the predicted and observed time series for each visit is obtained, *i.e.*, an "optimization" procedure. The latter option will be explored by the authors in a future paper.

Regression analysis was used to compare the predicted RSP and CO minute-by-minute time series for each visit with the observed time series (Table 1). The results for most of the study visits are excellent for both CO and RSP, with R^2 values between 0.59 and 0.94, slopes near unity, and near-zero *y*-intercepts. The average slope over all study visits is 1.1 for RSP and 1.2 for CO; the average R^2 over all the study visits is 0.79 for RSP and 0.77 for CO (Table 2). The agreement between the predicted and observed time series *averages* is excellent for all study visits: the percentage difference between the predicted and observed time averages ranges from −4.4% to 12.3% for all the study visits. The poor agreement between the predicted and observed time series for the SFO 4 study visit ($R^2 = 0.40$ for CO and $R^2 = 0.31$ for RSP) contrasts with the excellent agreement between the predicted and observed time series averages for the same study visit (error within 1%). Much of the error between the observed and predicted time series for study visits such as SFO 4, where there is a discrepancy between regression results and the comparison of averages, probably arises because the model assumption of uniform mixing is not perfectly satisfied.

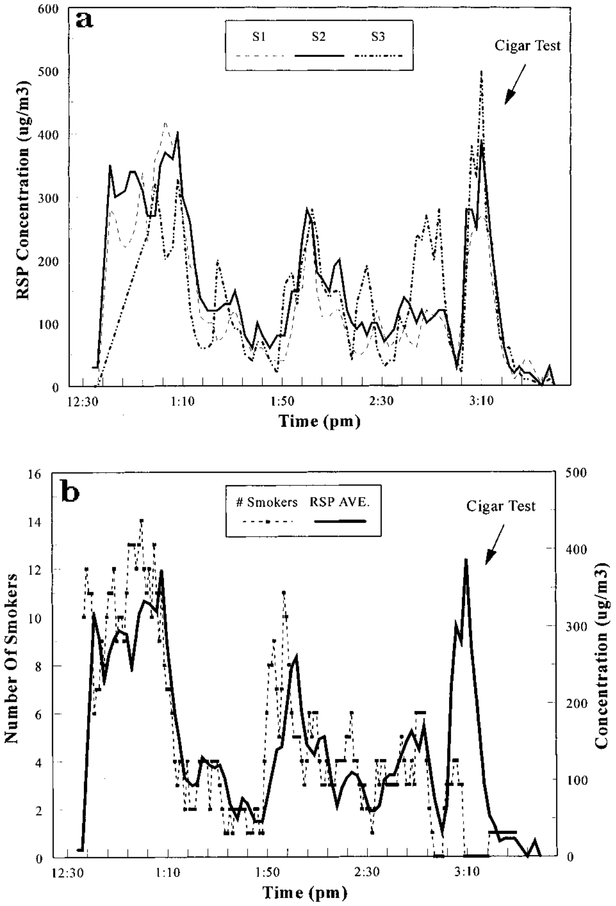

FIGURE 2. (a) RSP concentration time series measured by piezobalances (labeled S1, S2, and S3) at three widely-spaced locations in the smoking lounge at the SJC 5 study visit. The large decay curve at the end of the trace is for the cigar test conducted to determine the air exchange rate after all persons had departed. (b) The cigarette count time series and the *mean* RSP concentration time series from the three piezobalances at the SJC 5 study visit.

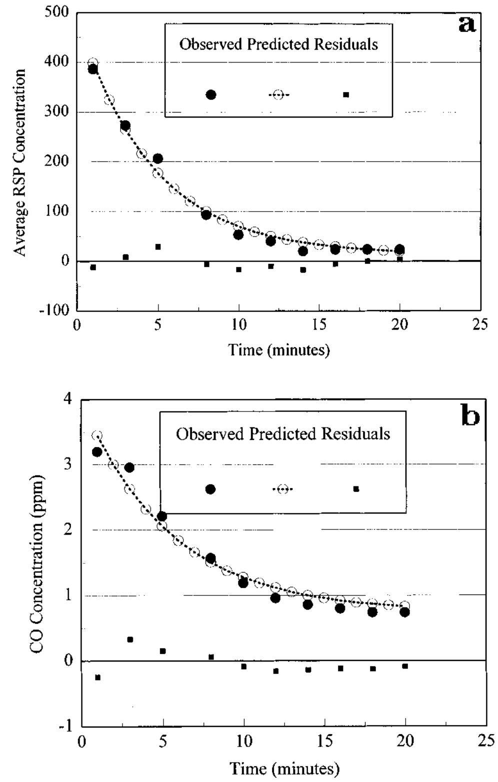

FIGURE 3. Plots of concentrations predicted by the exponential decay model in eq 4 (smooth curve), along with observations measured in the smoking lounge at San Jose International Airport (study visit SJC 5) for RSP (a) and CO (b). The residual values are shown at the bottom of each graph, and the decay models for each visit are given in Table 1, where the exponential decay constants correspond to air exchange rates (ventilatory for CO and effective for RSP).

Discussion

Major sources of error in the model's predictions of each study visit's RSP and CO concentration time series are: (1) uncertainty about the air exchange rate; (2) uncertainty about the emission rate; and (3) turbulence and streamflow in that room which may prevent perfectly-uniform mixing. The model uses an average emission rate, although the emission rate may actually vary according to (1) the brand and/or type of tobacco product smoked by each visitor to the lounge; (2) the rate at which cigarettes are smoked; (3) the degree to which cigarettes are actively smoked (mainstream emissions) or allowed to smolder (sidestream emissions); and (4) the amount of smoke absorbed by the smoker's lungs. In addition, the accuracy of the predicted emission rate depends on the accuracy of the observed air exchange rate (eq 5). The low variability in emission rates calculated for the two study visits in which the air exchange rate was accurately determined (SFO 5 and SJC 5) and the differences in emission rates calculated for the other study visits suggest that the air exchange rate may have changed slightly between visits. The most accurate estimates of the emission rates for our study—obtained by averaging those from the SFO 5 and SJC 5 study visits—are 1.43 mg/min for RSP and 11.9 mg/min for CO (Table 2).

Despite sources of error that include our use of average cigarette emission rates calculated using spatially-averaged RSP measurements from three widely-spaced RSP monitors and measurements from one centrally-located CO monitor, we have obtained excellent agreement between predicted and observed time series averages for all study visits, and excellent regression results between the predicted and observed minute-by-minute time series for most study visits. These results suggest that the model is useful for designing smoking lounges and understanding their ventilation requirements.

Comparison with Other Source Strengths. Indoor air quality models for ETS require the source strength to be expressed as an emission rate—mass emitted per unit time (*e.g.*, mg/min)—which takes into account how fast the cigarettes are smoked. Unfortunately, most studies reported in the literature (*19–33*) do not give source emission rates based on realistic smoking activity patterns. Rather, these published studies report either the total emissions (in which the entire cigarette is consumed) or emissions per length (or mass) of tobacco product consumed; for example, mg of RSP per mm of cigarette consumed. Usually these source strengths are derived from controlled experiments in chambers and not from realistic smokers in actual settings. The present study provides average RSP and CO emission rates for the mix of cigarette brands and smoking activities for groups of smokers found in two visits (SFO 5 and SJC 5) to two different public lounges where the effective air exchange rate was accurately measured (1.43 mg/min for RSP and 11.9 mg/min for CO). These lounges were studied under normal conditions with realistic smoking patterns.

TABLE 3

Variation in Mean RSP Concentration of Observed Time Series Measured by Each of Three Piezobalances at Widely-Spaced Locations in Each Lounge[a]

study visit	av RSP concn: monitor 1 (X_1)	av RSP concn: monitor 2 (X_2)	av RSP concn: monitor 3 (X_3)	overall av (X)	no. of obs (n)	absolute difference from av: monitor 1 ($X - X_1$)	absolute difference from av: monitor 2 ($X - X_2$)	absolute difference from av: monitor 3 ($X - X_3$)	av abs diff av ($X - X_i$)	av abs diff (%) $100 \times$ av ($X - X_i$)/X
SFO 1	65.61	51.43		58.98	60	6.63	7.55		7.09	12.02
SFO 2	54.29	71.39	64.00	62.73	37	8.44	8.66	1.27	6.12	9.76
SFO 3	75.31	76.94	112.04	88.10	50	12.79	11.16	23.94	15.97	18.12
SFO 4	114.5	131.23	125.80	127.30	47	12.82	3.93	1.50	6.09	4.78
SFO 5	61.38	44.77	32.66	46.15	68	15.23	1.38	13.49	10.04	21.75
SJC 1		121.08	136.75	128.90	40		7.82	7.85	7.83	6.08
SJC 2	106.01	131.88	142.35	125.60	53	19.59	6.29	16.65	14.18	11.29
SJC 3	53.70	80.00	60.74	64.81	27	11.11	15.19	4.07	10.12	15.62
SJC 4	120.88	195.23	150.81	155.50	55	34.61	39.73	4.69	26.34	16.94
SJC 5	133.39	149.84	135.18	144.00	62	10.61	5.84	8.82	8.42	5.85
av				100.21		14.65	10.75	9.14	11.22	12.22
SD				40.28		8.38	10.86	7.60	6.25	5.77

[a] Concentrations measured during cigar tests and concentrations measured outside the smoking lounge were omitted from all averages. Background concentrations were subtracted from the concentration readings of all three monitors (see text). Abs, absolute.

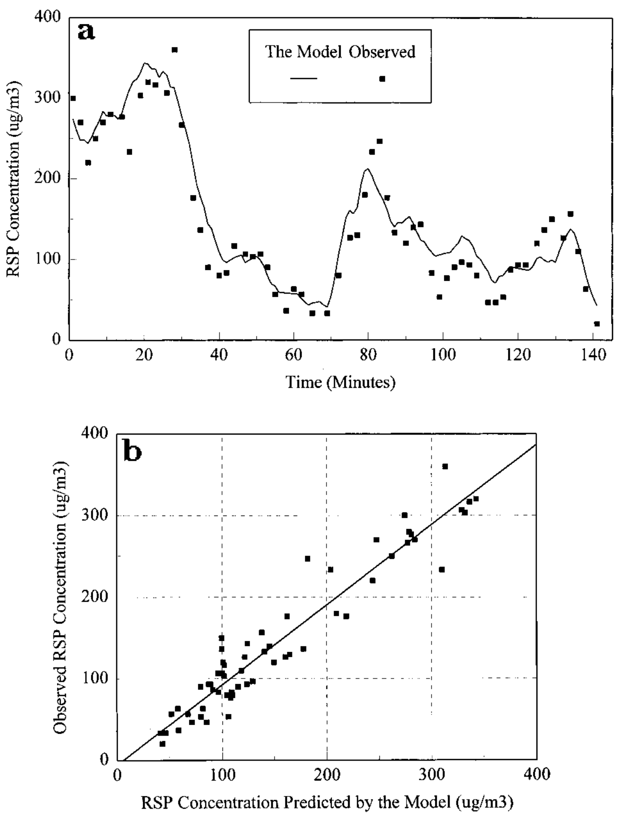

FIGURE 4. (a) Time series of RSP (averaged over the three locations in the room) concentrations predicted by the model and concentrations observed in the smoking lounge at San Jose International Airport for the SJC 5 study visit. (b) Scatter plot of the model vs observed RSP for the SJC 5 study visit (regression results for RSP and CO at all study visits are given in Table 1).

Even when published source strengths are derived from larger-scale population field studies, they usually are expressed in total emissions per cigarette rather than an emission rate. For example, Ozkaynak *et al.* (*26*) applied the model of Koutrakis et al. (*22*) to the Particle Total Exposure Assessment (PTEAM) data and determined an average RSP cigarette source strength of 11.4 mg. If people smoke cigarettes on the average for 8.0 min, then the average source RSP emission rate would be 11.4 mg/8.0 min = 1.43 mg/min, which is identical to our result for the two smoking lounges. Rosanne and Owens (*33*) report a CO cigarette source strength of 86 mg if mainstream and sidestream smoke are combined. With an average smoking duration of 8.0 min, the average CO source strength would be 86 mg/8.0 min = 10.8 mg/min, which is close to our value of 11.9 mg/min. In these calculations, our use of 8.0 min as the average cigarette duration is intended only as an example. Because of the different ways in which source strengths are reported in the literature (total emissions vs emission rates), comparability with other studies is difficult to establish, and our values seem reasonable (and sufficiently consistent with those in the literature) to use in other smoking lounges where groups of people are present.

Spatial Variation in RSP Concentrations. Like other indoor air quality models (*5*, *6*, 11), our model assumes that the room volume is uniformly mixed, implying that, at any instant of time, every place in the room has the same pollutant concentration. The assumption of uniform mixing was evaluated by comparing the time series collected at each of the three monitor locations in the room.

Overall, the average absolute difference between all three monitors and the mean room concentration (Table 3) was 11 μg/m^3 (ranging from 6 to 26 μg/m^3) or 12% of the overall average RSP concentration (ranging from 5 to 22%). Thus, in estimating the mean room concentration, the average error one makes by using just one monitor versus the average of three monitors across the room is about 12%. A person spending time near smokers at one end of the room could experience an exposure (concentration at one monitor) that is approximately 5−22% different (higher or lower) than our estimate of the average room exposure (concentrations averaged over all three monitors) for the same visit. This study did not examine the vertical profile of concentrations in the lounge; the good fit of the exponential decay of concentrations during the cigar test and the agreement between most of the predicted and observed concentration time series suggest that the lounges may be reasonably uniformly-mixed in both the horizontal and vertical directions.

Design Considerations for Air Quality in Smoking Lounges. Given the air exchange rate, room volume, average emission rate, and number of persons actively smoking in a room, the model predicts the CO and RSP time series averages with good accuracy (0−12% error; Table

1). For a given average number of smokers, the model equations can be used to determine (1) the resulting air quality for a given effective air flow rate (room volume multiplied by effective air exchange rate) or (2) the effective air flow rate needed to achieve acceptable air quality. The average emission rates determined from the SFO 5 and SJC 5 study visits (1.43 mg/min for RSP and 11.9 mg/min for CO) are our best estimates of typical emission rates per cigarette for the smoking-lounge microenvironment.

For any visit to a smoking lounge of sufficiently long duration, eq 3 predicts the average pollutant concentration. For example, the effective RSP air flow rates at the SFO 5 and SJC 5 study visits were approximately $\omega = \phi_P v = 200$ m^3/min ($\sim$0.263 $min^{-1} \times 803\ m^3$) and $\omega = \phi_V v = 50\ m^3$/min ($\sim$0.213 $min^{-1} \times 238\ m^3$), respectively. If, on the average, there were 10 persons actively smoking in each lounge for an extended time period, then the average predicted RSP concentrations would be 71.5 and 286 $\mu g/m^3$ for the San Francisco and the San Jose smoking lounges, respectively (assuming an average RSP emission rate per cigarette of 1.43 mg/min).

For another example, suppose that a building owner wants to build a 500-m^3 smoking lounge and does not want the average concentration of RSP to exceed 150 $\mu g/m^3$. If the owner knows that an average of 20 people smoke in the lounge during the 8-h work day, then assuming the average cigarette emission rate for RSP is 1.43 mg/min, the lounge would require an effective air flow rate of at least 191 m^3/min ($\phi_P = 22.9$ effective ach) to maintain an average RSP concentration below 150 $\mu g/m^3$.

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