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The effect of cigar smoking on indoor levels of carbon monoxide and particles

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To provide new information on environmental tobacco smoke (ETS) levels from cigars, we conducted three types of experiments: (1) Measurements of carbon monoxide (CO) during 15 controlled experiments in an office where several cigar brands were machine-smoked; (2) Measurements of CO or respirable suspended particles (RSP) and particle-bound polycyclic aromatic hydrocarbons (PAH) in a residence where two cigars were smoked by a person; and (3) Measurements of CO during two studies at cigar social events (where there were up to 18 cigars being smoked at a time) in which an investigator wore a concealed personal exposure monitor. Average concentrations of CO at the cigar social events were comparable to, or larger than, those observed on a freeway during rush hour traffic. A mass balance model that has been used successfully to predict ETS from cigarettes is used in this paper to obtain CO, RSP, and PAH emission factors (emission rate [mg/min], total mass emitted [mg], and emissions per mass smoked [mg/g]). The calculated emission factors show that the cigar can be a stronger source of CO than the cigarette. In contrast, the cigar may have fewer emissions of RSP and PAH per gram of consumed tobacco than the cigarette, but its size and longer smoking time results in greater total RSP and PAH emissions than for a single cigarette.

Keywords: *carbon monoxide, cigar emissions, cigars, environmental tobacco smoke, human exposure, indoor air quality, polycyclic aromatic hydrocarbons, respirable suspended particles.*

Introduction

In recent years, there has been much concern about exposure to environmental tobacco smoke (ETS), and the U.S. Environmental Protection Agency (USEPA) has classified ETS as a human carcinogen. Indoor cigarette smoking has been the widely accepted source of ETS exposure, and the cigar has received relatively little attention. Consequently, there are difficulties in estimating the health risks of second-hand cigar smoke due to a shortage of air quality and exposure data. Our purpose in the current research is to expand the database of indoor air quality levels from cigars for places where ordinary cigar smokers or aficionados congregate.

In this paper, we characterize the effect of the cigar on indoor air quality by measuring carbon monoxide (CO) concentrations in a variety of indoor settings and using the mass balance model to determine cigar emission factors for CO, respirable suspended particles (RSP), and particle-bound polycyclic aromatic hydrocarbons (PAH). We present results from 16 cigar studies where CO was measured in an office and a residence, and two cigar studies where CO or RSP and PAH were measured in a residence. CO levels measured at two cigar social events (a "cigar smoker" and a "cigar banquet") are also presented in this paper.

1. Abbreviations: USEPA, United States Environmental Protection Agency; ETS, environmental tobacco smoke; RSP, respirable suspended particles; CO, carbon monoxide; ppm, parts per million; PAH, particle-bound polycyclic aromatic hydrocarbons; ϕ, effective air exchange rate ($=\phi_V+\phi_D$) [1/T]; ϕ_V=ventilatory air exchange rate [1/T]; ϕ_D=particle deposition rate [1/T]; τ, residence time (the time required for $z(t)$ to reach 1/e times the original level) [T]; ach, air changes per hour [1/T]; acm, air changes per minute [1/T]; mg, milligrams (10^{-3} g); μm, micrometers (10^{-6} m) [L]; μg, micrograms (10^{-6} g); g, grams [M]; m, meters [L]; l, liters [L^3]; s, seconds [T]; min, minutes [T]; h, hours [T]; $PM_{3.5}$, particulate matter with a diameter of 3.5 μm or less; $PM_{2.5}$, particulate matter with a diameter of 2.5 μm or less; T, duration or averaging time of a given exposure or experimental study [T]; $z(t)$, room concentration at time t [M/L^3]; $n(t)$, number of active sources at time t; v, room volume [L^3]; $\bar{z}$, time-averaged average pollutant concentration [M/L^3]; $g(t)$, total emission rate at time t [M/T]; $\bar{g}$, time-averaged emission rate [M/T]; $\bar{g}_c$, average emission rate per source [M/T]; $\bar{n}$, time-averaged number of sources; T_c, duration of cigar smoking [T]; q, total emissions [M]; q_m, emissions per unit mass smoked [M/M]; g_{eq}, equilibrium emission rate [M/T]; z_{eq}, equilibrium pollutant concentration [M/L^3]; t_{eq}, time required to reach equilibrium [T]; [T^n]=time units; [M^n]=mass units; [L^n]=length units; n=unit dimension (1, 2, or 3).

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Methods

Instrumentation

As part of our experiments in an office, a residence, and at two cigar social events, we measured instantaneous CO concentrations using a Langan L15 CO Personal Exposure Measurer attached to a Langan DataBear™ digital data logger (Langan Products, San Francisco, CA), which stored concentrations in intervals as short as 10 s. The monitor is equipped with a chemical filter and has been evaluated in previous research (Langan, 1992; Ott et al., 1995).

For the residential study, 2-min averages of RSP concentrations were measured with a TSI Model 8510 piezobalance with a 3.5-μm size-selective inlet (Thermo-Sciences, Inc., TSI, St. Paul, MN). The features and performance characteristics of this instrument are described in the literature (Daley and Lundren, 1975; Sem and Tsurubayashi, 1975; Sem et al., 1977).

Particle-bound ($PM_{2.5}$) PAH were measured in the residence using the EcoChem Model 1002i PAH monitor (West Hills, CA). This monitor is a new instrument designed to measure total PAH on a real-time basis with extremely rapid time response (Burtscher and Schmidt-Ott, 1984; Neissner and Walendzik, 1989; McDow et al., 1990; Chuang and Ramamurthi, 1992; Steiner et al., 1992; Wilson et al., 1994; Agnesod et al., 1996; Ramamurthi and Chuang, 1997a,b). It measures larger molecular weight PAH (above four rings) based on the photoelectric ionization of PAH absorbed on the surface of particles using a mercury vapor lamp with 222 nm ultraviolet wavelength. Neissner and Walendzik (1989) have used the method as a fast-responding and sensitive detection system for cigarette smoke analysis. Wilson et al. (1994) used the EcoChem Model 1002i to measure particle-bound PAH from tobacco smoke (cigarettes). They report that the monitor responds only to fine particles and not to gas-phase PAH, and they obtained reasonably good agreement with chemically based methods when a conversion factor of 1000 ng m^{-3} pA^{-1} was used. Ott et al. (1994) report that PAH monitor readings measured with this same model were highly correlated with RSP concentrations for several types of cigarettes. Buckley and Ott (1996) also used a conversion factor of 1000 ng/m^3=1 pA for PAH concentrations in traffic. In the current study, we report PAH data using a conversion factor of 1000 ng/m^3=1 pA, as suggested by Chuang (1998).

Determining Decay Rates

The present study and previous studies in a tavern (Ott et al., 1996), a residential bedroom (Ott et al., 1995), and two public smoking lounges (Klepeis et al., 1996) have used the cigar as a convenient source of tracer pollutants such as CO and RSP. With appropriate monitoring devices, the overall decay rate ϕ, the ventilatory air exchange rate ϕ_V, and the particle deposition rate ϕ_D can be determined for

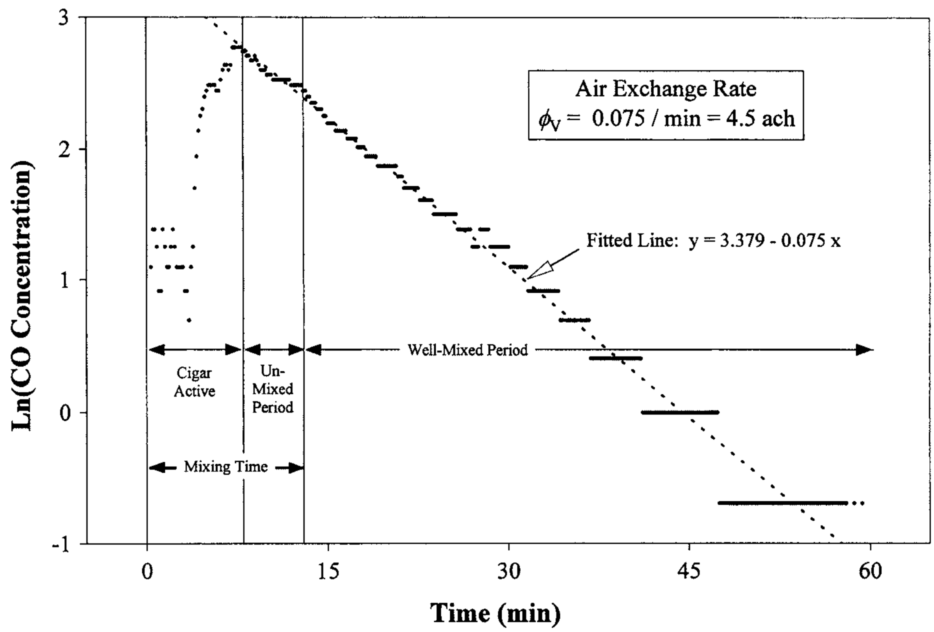

Figure 1. Experimental results from a cigar experiment in an office (experiment O-2) showing how the pollutant decay rate ϕ is determined (in this case, for carbon monoxide). Notice that the unmixed time period (estimated at 5 min) is under 10% of the source-off time period, suggesting that the room can be considered to be well-mixed.

Table 1. Summary of CO emission factors[a] from 15 machine-smoked cigar experiments in a 49.6 m^3 office.

ID	Experiment description[b]	Study duration, T [min]	Cigar duration, T_c [min]	Average CO concentration, $\bar{z}$ [ppm]	Peak CO concentration[c], $z(T_c)$ [ppm]	Average CO emission rate[d], $\bar{g}_c$ [mg/min]	CO emissions per cigar[e], q	Mass smoked[f], m [g]	CO emissions per mass smoked[g], q_m [mg/g]
O-1	1 Sante Fe Fairmont cigar (4/5/96); var ϕ_V	424 (7.1 h)	18	3.6 (4.1 mg/m^3)	14	–	–	6.2	–
O-2	Sante Fe Fairmont cigar (4/6/96); ϕ_V=4.5 ach; see Figures 1 and 2	157 (2.6 h)	7.8	1.7 (2.0 mg/m^3)	16	140	1.1 g	6	190
O-3	1 Sante Fe Fairmont cigar (4/7/96); ϕ_V=0.12 ach	1284 (21 h)	24	7.5 (8.6 mg/m^3)	19	46	1.1 g	6.1	180
O-4	1 Sante Fe Fairmont cigar (4/8/96); ϕ_V=2.1 ach	339 (5.7 h)	20	1.8 (2.1 mg/m^3)	15	61	1.2 g	6	200
O-5	1 Imported Ashton cigar (4/9/96); ϕ_V=1.8 ach	275 (4.6 h)	28	2.5 (2.9 mg/m^3)	15	42	1.2 g	14.3	82
O-6	1 Swisher Sweets cigar (4/22/96); var ϕ_V	167 (2.8 h)	20	4.4 (5.0 mg/m^3)	16	–	–	5.3	–
O-7	1 Swisher Sweets cigar (4/23/96); ϕ_V=0.96 ach	450 (7.5 h)	42	2.4 (2.8 mg/m^3)	9.5	23	980 mg	5.6	180
O-8	1 Dutch Masters El Presidente cigar (4/24/96); ϕ_V=1.9 ach	220 (3.7 h)	15	5.7 (6.5 mg/m^3)	18	–	–	6.4	–
O-9	1 Dutch Masters El Presidente cigar (4/25/96); ϕ_V=2.4 ach	240 (4.0 h)	54	2.1 (2.4 mg/m^3)	7.5	–	–	6.8	–
O-10	1 Dutch Masters El Presidente cigar (4/26/96); ϕ_V=0.06 ach	1440 (24 h)	9	9.2 (11 mg/m^3)	18	84	750 mg	6.6	114
O-11	1 AyC Grenadiers cigar (4/27/96); ϕ_V=0.12 ach	1539 (25.65 h)	10	4.9 (5.6 mg/m^3)	13	86	860 mg	4.9	180
O-12	1 AyC Grenadiers cigar (4/28/96); ϕ_V=3.0 ach	130 (2.2 h)	17	1.7 (2.0 mg/m^3)	7.0	37	630 mg	5.0	130
O-13	1 AyC Grenadiers cigar (4/29/96); ϕ_V=4.5 ach	195 (3.25 h)	12	0.94 (1.1 mg/m^3)	8.0	65	780 mg	4.9	160
O-14	1 AyC cigar (4/29/96); var ϕ_V	87 (1.5 h)	17	0.89 (1.0 mg/m^3)	4.5	–	–	5.1	–
O-15	1 AyC cigar (4/30/96); ϕ_V=0.72 ach	630 (10.5 h)	11	1.3 (1.5 mg/m^3)	8.0	–	–	5.3	–

[a]Calculations of emission factors are based on a single-compartment mass balance model, which assumes uniform mixing.
[b]Experiment descriptions include the type of cigar or cigarette source, the location where smoking took place, the room volume, and the air exchange rate and/or effective air exchange rate, which includes all removal mechanisms (both are in units of ach).
[c]Peak concentrations are the measured concentrations occurring just after the cigar was extinguished (where the theoretical maximum is supposed to occur for the given emission rate, volume, and air exchange rate); however, it is possible that higher concentrations occurred while the cigar was being smoked because of non-uniform mixing.
[d]Average emission rate is the average emission rate over the time the cigar was on; only one cigar was ever active.
[e]Emissions per cigar is the total mass emitted by the cigar (only one cigar was ever active).
[f]Mass smoked is the measured difference between the mass of the unsmoked cigar or cigarette source and the mass after smoking.
[g]Emissions per mass smoked is emissions per cigar divided by mass smoked. 1 ppm=1.145 mg/m^3 at 25°C and 1 atm. Missing cells indicate that conditions were not suitable for the calculation of emission factors (e.g., varying air exchange rate, non-uniform mixing/transient peaks). Constant backgrounds between 0 and 1 ppm were subtracted from each CO time series prior to making calculations. The time interval between all CO measurements was 10 s. See Figure 2 for the O-2 CO time series.

any room. The decay rate ϕ is equal to ϕ_V when obtained from the decay of CO (no surface sorption) and equal to $\phi_D+\phi_V$ when obtained from the decay of RSP, which adheres to surfaces.

In real situations, the room will have a characteristic mixing time τ_{mix}, which is the time it takes for the pollutant to become well-mixed after the cigar is ignited. The decay rate ϕ (sometimes called the effective air exchange rate) is taken as the absolute value of the slope of a least-squares fitted line through the natural logarithm of the pollutant concentration versus time starting after time $t=\tau_{mix}$ (see Figure 1). The background concentration for the levels in the room from sources besides the cigar must be subtracted from each concentration prior to taking its logarithm.

Office Experiments

We conducted 15 experiments (referenced as O-1 through O-15; see summary in Table 1) using single cigars of different types in a vacant, two-person office (volume of 49.6 m^3 and a floor area of 17.0 m^2). CO concentrations were logged in time intervals of 10 s. Background CO concentrations — the levels present in the absence of any cigars — ranged from 0 to 1 ppm. The former occupant of the office regularly smoked cigars during work hours when the office was occupied. The office had a desk but no other furniture. The ventilatory air exchange rate ϕ_V of the office varied from about 0.1 air changes per hour (ach) to about 4.5 ach; it was highest when both the transom over the door and window were open or only the window was open (0.36–4.5 ach), and it was smallest when both the transom and window were closed (about 0.1 ach). There were no forced-air mechanisms or other ventilating systems opera-ting in the office. However, during some experiments when the window was open, the air exchange rate fluctuated widely due to light winds. The duration T of the 15 experiments in the office (Table 1) ranged from 87 min (1.45 h) to 1444 min (24.1 h); for most experiments, concentrations were measured from the time just before the cigar was lighted ($t=0$) until after the time the concentrations decayed to the background level ($t=T$).

Five different, commercially available brands of cigar were used in the office experiments (Sante Fe Fairmont, Imported Ashton, Swisher Sweets, Dutch Masters El Presidente, and Antonio y Cleopatra (AyC) Grenadiers). See Table 2 for the physical characteristics of each cigar. Each cigar was smoked by a smoking machine for between 7 and 40 min (with a mean of 19 min). The smoking machine operated at the center of the room at approximate breathing height; it consisted of a series of tubes that fit snugly around one end of the cigar and a plastic bellows with a small valve from which the mainstream smoke was emitted into the room as the cigar was smoked. Sidestream smoke coming from the burning end of the cigar was also freely emitted into the room. The cigar was smoked by squeezing the bellows at different intervals, and after the cigar was almost completely smoked, it was extinguished by dousing it in a glass of water.

Residential Experiments

Two cigar experiments and one cigarette experiment (referenced as R-1 through R-3; see summary in Table 3) were conducted on two separate days in the 97 m^3 parlor of a San Francisco residence in which a veteran cigar smoker volunteered to smoke two single cigars (a Santona and a Paul Garmirian) and a second volunteer smoked a Marlboro Regular cigarette. The parlor of the residence

Table 2. Physical characteristics of seven different cigars[a] and Marlboro cigarettes[b].

Cigar brand	Experiment(s)	Length [mm]	Mass[c] [g]	Diameter [mm]
Santona	R-1	150	13.2	17
Paul Garmirian	R-2	175	15.4	19
Sante Fe Fairmont	O-1–O-4	152	8.4	16
AyC Grenadiers	O-11–O-15	166	5.9	13
Todo El Mundo (equivalent for Ashton)[d]	O-5	186	16.7	19
Dutch Masters	O-8–O-10	139	7.6	15
Swisher Sweets	O-6–O-7	143	6.0	13
Marlboro (cigarette)	R-3	78 (with a 19 mm filter)	0.83 (with filter); 0.55 (without filter)	6

[a]Cigar characteristics are based on measurements of one cigar (unsmoked).
[b]The mass of an unsmoked Marlboro cigarette (both with and without the filter) was determined by weighing 10 identical cigarettes together and then dividing the total mass by 10; there remained a 10-mm "butt" of tobacco after the filters were cut off.
[c]Measurement errors are about ±0.1 g for cigar masses and about ±0.01 g for cigarettes masses.
[d]A Todo El Mundo cigar of similar size as the Ashton was used for measurements of physical characteristics.

Table 3. Summary of CO, RSP, and particle-bound PAH emission factors[a] from two cigar experiments and one cigarette experiment in a 97 m^3 parlor of a residence.

ID	Experiment description[b]	Study duration, T [min]	Source duration, T_c [min]	Average concentration, $\bar{z}$	Peak concentration[c], $z(T_c)$	Average emission rate[d], $\bar{g}_c$	Emissions per cigar[e], q	Mass smoked[f], m [g]	Emissions per mass smoked[g], q_m
R-1	1 Santona cigar smoked by a person (3/1/97); ϕ=2.0 ach	300 (5 h)	76 (1.3 h)	0.96 ppm CO (1.1 mg/m^3)	3.0 ppm CO	14 mg CO/min	1.1 g CO	8.8	130 mg CO/g
R-2	1 Paul Garmirian cigar smoked by a person (3/9/97); ϕ_v=0.9 ach; ϕ=1.2 ach for RSP; ϕ=1.5 ach for PAH	285 (4.75 h)	90 (1.5 h)	0.16 mg/m^3 RSP; 0.55 $\mu g/m^3$ PAH	0.35 mg/m^3 RSP	0.98 mg RSP/min; 0.0042 mg PAH/min	88 mg RSP; 0.38 mg PAH	10.8	8.2 mg RSP/g; 0.035 mg PAH/g
R-3	1 Marlboro cigarette smoked by a person (3/9/97); ϕ=1.3 ach for RSP; ϕ=2.0 ach for PAH	127 (2.75 h)	9	0.065 mg/m^3 RSP; 0.33 $\mu g/m^3$ PAH	0.16 mg/m^3 RSP	1.9 mg RSP/min; 0.015 mg PAH/min	17 mg RSP; 0.14 mg PAH	0.4	43 mg RSP/g; 0.34 mg PAH/g

See footnotes under Table 1. See Figure 3 for the RSP and PAH time series from experiments R-2 and R-3.

contained a sofa, chairs, a piano, carpets, drapes, and a fireplace (no fire was lit). See Table 2 for a description of the cigar and cigarette characteristics.

For the first experiment, CO concentrations were measured in 15-s intervals. RSP (2-min averages every 2–3 min) and PAH concentrations (15-s intervals) were measured for the second and third experiments. The cigar experiments lasted 300 and 285 min, respectively, and the volunteer smoked the cigars for 1.3 and 1.5 h, respectively. For the third experiment, which lasted a total of 127 min, the volunteer smoked the cigarette for 9 min in the same parlor. He began smoking the cigarette after elevated particle concentrations caused by the cigar had fallen approximately to background levels (illustrated in Figure 3). The smoking of the cigarette permitted a comparison of cigar and cigarette RSP and PAH levels under the same conditions.

The air exchange rates for the first two experiments were about ϕ=2.0 and ϕ=0.9 ach, respectively, and the RSP decay rate (i.e., the ventilation air exchange rate plus the particle deposition rate) was 1.2 ach for the second experiment (Paul Garmirian cigar) and 1.3 ach for the third experiment (Marlboro cigarette). The parlor doors and windows were closed during all three experiments.

Measurements at Cigar Social Events

In two field experiments, an investigator wearing a concealed CO personal exposure monitor attended social events that featured cigar smoking. The monitor was carried in the inside pocket of a formal dinner jacket so as to not attract the attention of the other guests. Measurements were logged every minute in the first experiment and every 15 s at the second event. The monitor was carried for several hours while traveling to and from each event, so that in-vehicle and outdoor CO concentrations could be compared with those measured during the events.

The first event, a "Cigar Smoker," was held in an elegant private club in suburban San Francisco. This party included food, wine, music, and an author signing his book on cigars. Four different types of cigars were available at the entrance door. The private club was a large house with two adjoining rooms (a large reception hall with a balcony and a food preparation area) measuring 1560 ft^2 (155 m^2) in area, with a volume of 570 m^3. The event's sponsors opened all the doors and windows completely to allow the maximum flow of outdoor air, and the resulting air exchange rate may have exceeded 10 ach. The investigator secretly wearing the monitor smoked the first cigar only partially and then mingled with the other guests in the room and engaged in conversation.

The second concealed monitoring field study took place at a downtown San Francisco restaurant. This particular "Cigar Banquet" (featuring three Cuban cigars per person) was held regularly about every 3 months. The guests received the first cigar when they entered the door. After gathering around the bar to socialize for about an hour prior to being seated for dinner, they were served a second imported cigar. A third cigar was distributed just before dessert.

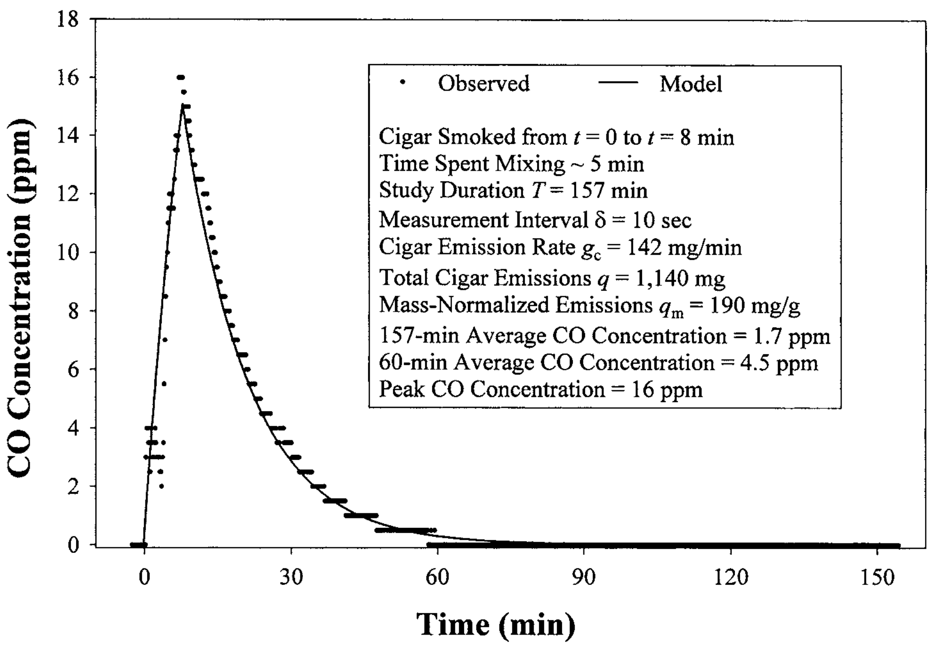

Figure 2. Observed CO concentrations and those predicted by a mass balance model during and after a cigar smoking experiment in a 49.6 m^3 office (experiment O-2). CO emission factors calculated using the model are shown.

Indoor Air Quality Model

Several books discuss the derivation and application of the mass balance equation to predicting indoor air pollutant concentrations (Wadden and Scheff, 1983; Nagda, 1993; Ott, 1995). A variety of scientific papers also discuss its use in determining source emissions and predicting indoor air pollution levels (Alzona et al., 1979; Dockery and Spengler, 1981; Traynor et al., 1982a,b; Repace, 1987). Previous investigators have applied the mass balance equation to predicting ETS from cigarette smoking in indoor settings (Jones and Fagan, 1974; Repace, 1987; Repace and Lowrey, 1980, 1982; Repace et al., 1998; Ott et al., 1992, 1996; Switzer and Ott, 1992; Klepeis et al., 1996), and the results from this modeling usually show good agreement between observed and predicted indoor concentrations due to smoking. A similar mass balance model is used in this paper to calculate emission factors and theoretically predict pollutant concentrations (both time-

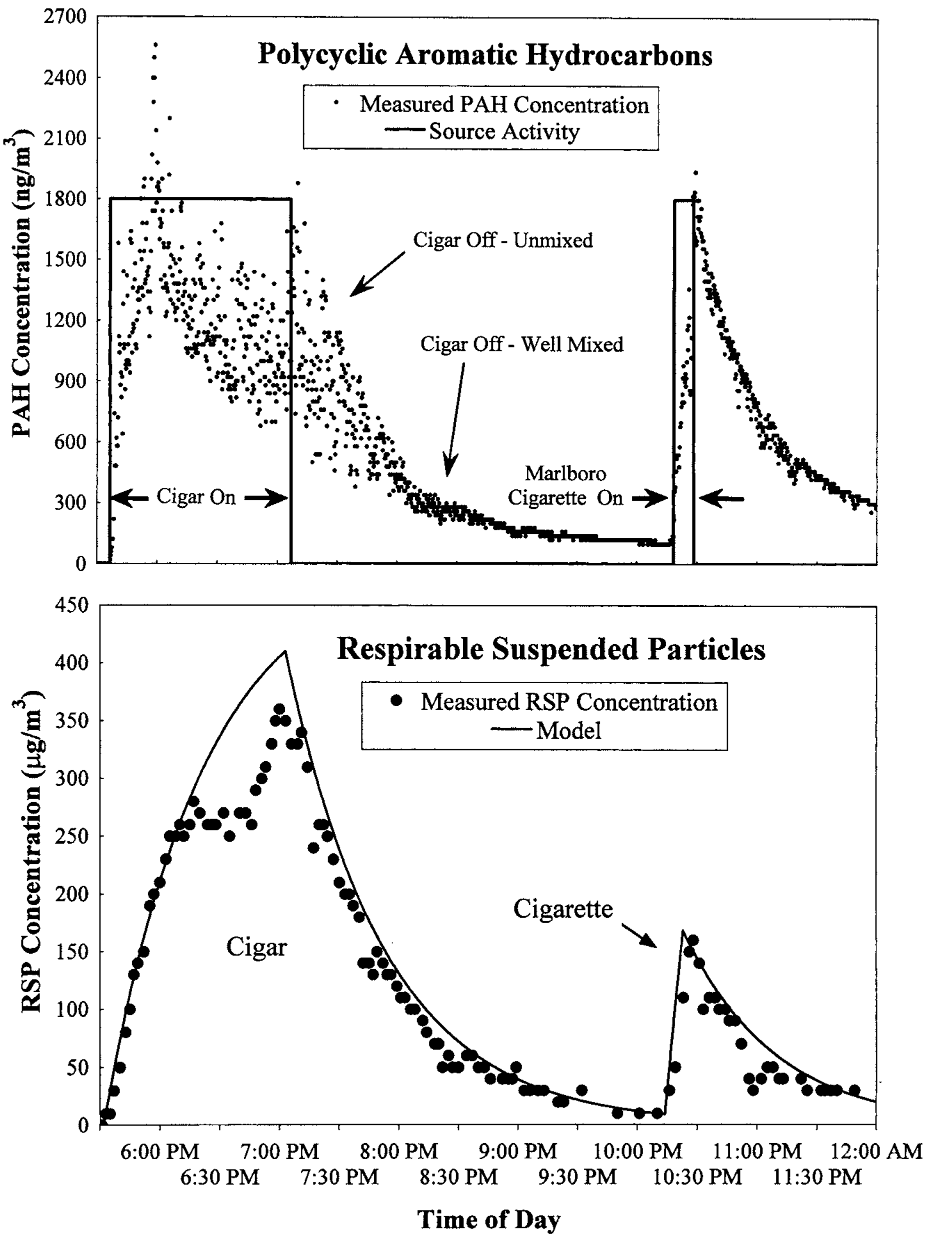

Figure 3. The simultaneous particle-bound PAH and RSP time series measured in the 97 m^3 parlor of a San Francisco residence after a Paul Garmirian cigar and a Marlboro cigarette were smoked one after another by two different persons. The top plot shows the source activity pattern and the bottom plot shows the time series predicted by a model (Experiments R-2 and R-3).

evolving concentrations — i.e., the times series — and time-averaged concentrations).

The model assumes that the air in each location is approximately well-mixed. In a reasonably well-mixed room, the pollutant concentration is uniform across all points in the room at any instant of time. Mage and Ott (1996) propose, based partly on experimental data by Baughman et al. (1994), the classifying of room pollutants as well-mixed if the proportion of time spent in an unmixed state is small in comparison to the overall duration of the study (e.g., the time it takes ETS pollutants to decay to background levels). Several other experimental investigators have demonstrated that reasonably uniform mixing can be achieved for typical exposure time periods under realistic conditions (Drescher et al., 1995; Klepeis et al., 1996; Ott et al., 1996, 1998) such as those under which we performed the experiments described in this paper. For example, Figure 1 shows a visually-estimated unmixed time period of 5 min (for experiment 0–2), which is small compared to the well-mixed time period of over 50 min.

Important emission factors for use in exposure models and in direct comparisons between tobacco and other sources include: (1) the average pollutant emission rate (mass of pollutant emitted per unit time); (2) the total emissions (total mass emitted into the air over some time T); and (3) the mass-normalized emissions (mass of total pollutant emitted per mass of tobacco smoked). Formulae for these three quantities, respectively, are as follows:

$$\bar{g}_c = \bar{z}\phi\nu/\bar{n} \quad (1)$$

$$q = \bar{g}\,T = \bar{g}_c\,\bar{n}\,T = \bar{z}\phi\nu\,T \quad (2)$$

$$q_m = q/m \quad (3)$$

where $\bar{g}_c$ is the average pollutant emission rate [mg/min], $\bar{z}$ is the average pollutant concentration [mg/m^3], ϕ is the effective air exchange rate or decay rate [ach], ν is the volume of the room [m^3], $\bar{n}$ is the average number of sources over T [sources], T is the experimental study duration equal to the time period starting when the tobacco source is lit and ending when the pollutant concentration decays to the background level [min], q represents the total emissions from the tobacco source [mg], q_m represents the mass-normalized total emissions [mg/g], and m is the total mass of tobacco smoked [mg]. We calculate per-cigar and per-cigarette emission factors in this paper using Equations 1–3. However, we do not calculate emission factors for

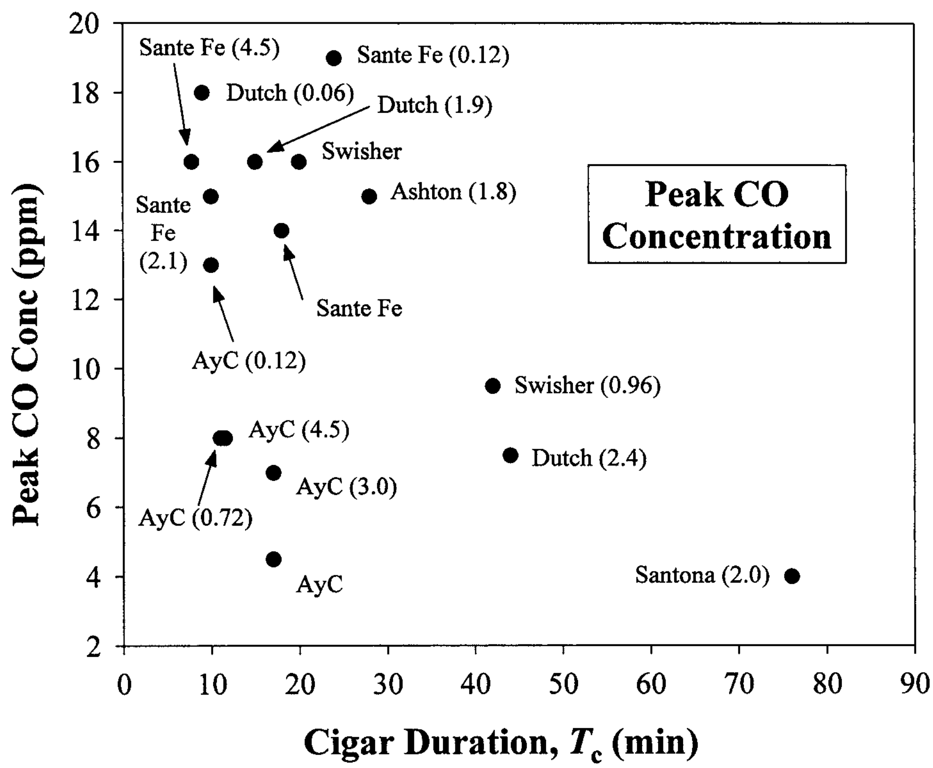

Figure 4. Plot of peak CO concentration versus cigar duration for 16 experiments where CO was measured. Each point is labeled with the cigar brand and the air exchange rate in units of air changes per hour (for experiments where the air exchange rate was determined). Notice that except for the AyC cigars, which have lower total emissions than most of the other cigars, there is a trend towards lower peak CO concentration as the cigar duration increases.

those experiments where conditions were unsuitable, such as when the air exchange rate could not be determined accurately or there appeared to be a large degree of non-uniform mixing.

Figures 2 and 3 (bottom panel) compare the model time series (Ott et al., 1992; Switzer and Ott, 1992; Klepeis et al., 1996) with observed pollutant concentration data for experiments O-2 (CO) and experiments R-2 and R-3 (RSP). Figure 2 also presents CO time series statistics and emission factors determined from the observed CO data. The time-series model requires, as input, the pollutant decay rate ϕ (see above discussion), the room volume v, and the average pollutant emission rate, $\overline{g}_c$, as calculated from the observed pollutant concentration data using Equation 1.

Results and discussion

In the current work, we have not carried out a complete survey of cigar types and smoking situations, but our 16 CO experiments and preliminary experiments with PAH and RSP provide insight into the effect that cigar-smoking can have on indoor air quality. The most useful results are the calculated emission factors (emission rate, total emissions, and emissions normalized by mass smoked), which allow one to gauge the relative strength of different tobacco products and to predict pollutant levels for different smoking scenarios. We also report peak and average concentrations of CO or RSP and PAH in each of the three locations that were studied (office, residence, and social events). Unless stated otherwise, background concentrations were subtracted from all measurements before being used in the calculation of descriptive statistics or emission factors.

Trends in CO Levels

Statistics that are often used in exposure assessment are the average, peak, and steady-state pollutant concentration. A principal difference between cigars and cigarettes is that while a single cigar can be smoked for a very long period (up to an hour or more), cigarettes rarely last more than about 10 min. Different cigar durations T_c affect the peak and average room pollutant concentrations, and it is also possible that smoking the cigar more quickly or more slowly will change its emissions. Two other factors affecting the peak, average, and steady-state concentrations are the physical features of the room (e.g., the volume and the ventilation rate) and the cigar source strength (i.e., the pollutant emission rate).

Since transient peaks sometimes occurred while a cigar was being smoked, we determined the maximum CO concentration at the time when the cigar ended (or just afterwards), which is the time that the theoretical maximum concentration should occur. In Figure 4, the peak CO concentration (3–19 ppm) from the 16 cigar experiments where CO was measured (O-1 through O-15 and R-1) is plotted against the cigar duration (T_c=8–76 min). There is

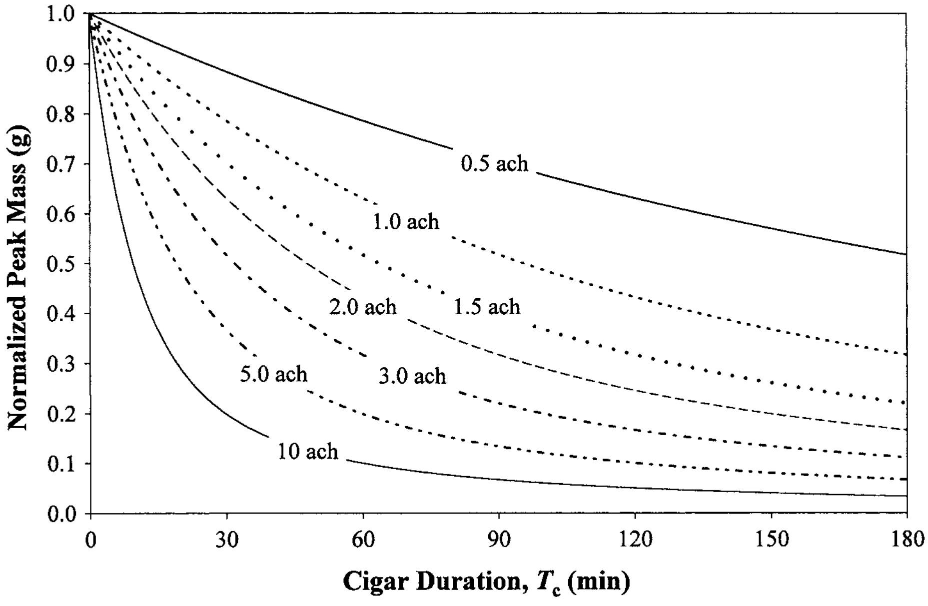

Figure 5. Theoretical curves demonstrating how the pollutant peak airborne mass is affected by the cigar duration T_c and pollutant decay rate ϕ. The total mass emitted by the cigar is held constant and has been normalized to 1 g. Dividing masses by the room volume gives concentrations. The source duration can substantially affect the peak mass, although this effect is non-linear and can sometimes be relatively small for a low decay rate and/or short cigar duration.

a trend toward lower peaks as the cigar duration increases, excluding the AyC brand cigars, which, as we discuss below, have somewhat lower total emissions than most of the other cigars. The low peak for the Santona cigar is probably a result of both the long cigar duration and the larger room volume (97 m^3 for the parlor experiments versus ~50 m^3 for the office experiments). Figure 5 shows, theoretically, how the peak airborne mass changes with both the decay rate (ϕ=0.5–10 ach) and the cigar duration (T_c=1–180 min) when a total of 1 g of pollutant is emitted. The airborne mass, if considered to be distributed in a 1 m^3 room, can be equated to concentration units of grams per cubic meter. For a cigar duration of 30 min, the peak mass ranges from about 90% of the total emitted mass at 0.5 ach to about 20% of the total emitted mass at 10 ach. Obviously, if the mass is emitted nearly instantaneously (e.g., over 1 min or less), then the peak mass will be equal to the total mass emitted.

In contrast with the observed peak concentrations, which ranged from 3 to 19 ppm, the 60-min time-averaged CO concentrations (calculated from when the cigar was first ignited) seem to depend in a more distinct way on the decay rate, but do not depend as strongly on cigar duration. When the air exchange rate is greater than or equal to 2 ach, the observed average CO concentrations are all below 8 ppm (Figure 6; unfilled circles), whereas for air exchanges below 2 ach, all except one of the observed average CO concentrations are above 8 ppm (Figure 6; filled circles). The theoretical pollutant time series in Figure 7, calculated for constant pollutant decay rates ϕ and 1 g of total emissions, shows that the 180-min average airborne pollutant mass does not change much even when the cigar duration is increased from 1 to 120 min. Regardless of the value of T_c, the average airborne mass is around 30% of the total mass emitted at 1 ach and 7% of the total mass emitted at 5 ach.

When a cigar is smoked for an extended period of time, it is possible to reach a characteristic equilibrium concentration for a given emission rate and pollutant decay rate. Unless the cigar is smoked for a very long time, the concentrations may never quite reach this level, but it provides an upper-bound to the maximum pollutant concentration for the given room conditions and pollutant emission rate. The modeled equilibrium concentration equals the equilibrium emission rate g_{eq} divided by the volume and the decay rate: $z_{eq}=g_{eq}/v\phi$. However, the time, t_{eq}, that it takes to reach 99% of the equilibrium concentration depends only on the pollutant decay rate: $t_{eq}=-\ln(0.01)/\phi$. For a pollutant decay rate of 1 ach (fairly typical for a residence), t_{eq}=4.6 h.

Calculated Emission Factors

The cigars that were studied have average CO emission rates $\bar{g}_c$ ranging from 14 to 140 mg/min and total emissions

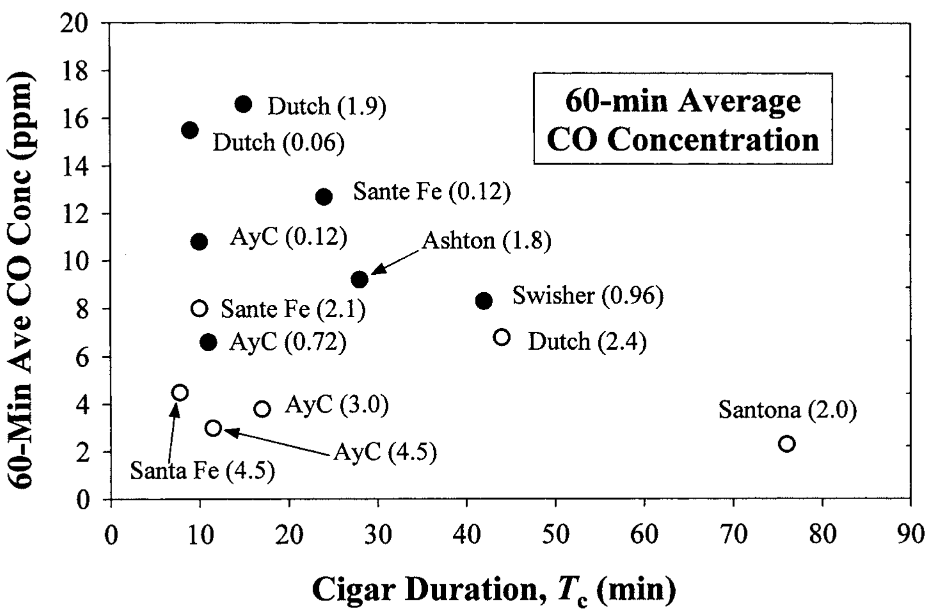

Figure 6. Plot of the 60-min average CO concentration (calculated from the time the cigar begins) versus cigar duration for 13 experiments where CO was measured and the air exchange rate was determined. The unfilled circles designate data from experiments with an air exchange greater than or equal to 2 ach and filled circles designate data for experiments with an air exchange rate less than 2 ach. Notice that all of the average CO concentrations at higher air exchange rates are below about 8 ppm, whereas six of seven of the average CO concentrations at lower air exchanges rate are above 8 ppm. Averages over the entire study duration T (87–1440 min) are given in Tables 1 and 3.

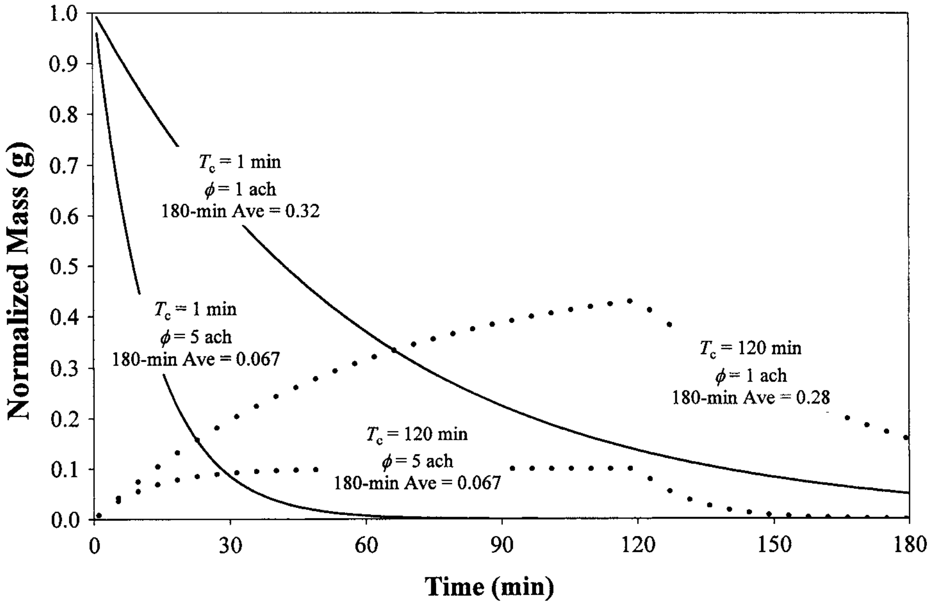

Figure 7. Theoretical curves demonstrating how the average airborne pollutant mass is affected by the cigar duration T_c and pollutant decay rate ϕ. The total mass emitted by the cigar is held constant and has been normalized to 1 g. Dividing masses by the room volume gives concentrations. Notice that for a given time period ($T = 180$ min) and decay rate ($\phi = 1$ or 5 ach), the cigar duration does not greatly affect the average room concentration.

between 630 and 1200 mg/cigar, with the Santona having the lowest emission rate (14 mg/min) and the AyC and Dutch Master cigars having the lowest total emissions (630–860 mg/cigar). See Tables 1 and 3 for summaries of emission factor results. The Sante Fe cigars have the greatest mass-normalized emissions at 180–200 mg/g, and the Ashton (82 mg/g) and the Dutch Masters (114 mg/g) have the smallest. Although the Ashton has one of the lowest emission rates and the smallest mass-normalized emissions, its large (unsmoked) mass (14.3 g) causes its total emissions to be as high as any of the other cigars that were studied (1.2 g).

The Paul Garmirian cigar, which was smoked for 90 min, emitted a total of 88 mg of RSP and 0.38 mg of PAH (Table 3). The emission rates for RSP and PAH were 0.98 and 0.0042 mg/min, respectively, and the RSP and PAH mass-normalized emissions q_m were 8.2 and 0.035 mg/g, respectively. In contrast, the Marlboro cigarette that was smoked under identical conditions had RSP and PAH mass-normalized emissions that were five and ten times higher (43 and 0.34 mg/g), and RSP and PAH emission rates that were two and four times as large as the cigar (1.9 and 0.015 mg/min). However, the total RSP and PAH emissions of the cigar are five and three times higher, respectively, than those of the cigarette (17 and 0.14 mg), which is not that large a difference considering that the mass of cigar tobacco smoked is about twenty-seven times larger than the mass of cigarette tobacco that was smoked.

Comparison to Published Cigarette Emission Factors

As reported in the literature (Rosanne and Owens, 1969; Rickert et al., 1984; Ott et al., 1992), total CO emissions from cigarettes are typically between 40 and 70 mg for sidestream smoke. If the mass of tobacco smoked is about 0.4 g (as it was for one of our experiments), then, neglecting mainstream emissions, the CO emissions per mass smoked would be 100–175 mg/g. If more of the cigarettes were smoked (e.g., 0.55 g; see Table 2), then the CO emissions per mass smoked could be as low as 70–130 mg/g. Our results show that CO emissions per mass smoked for cigars are between about 100 and 200 mg/g (Table 1) and Ott et al. (1992) report an average CO emission rate of 9.4 mg/min per cigarette, which is lower than the 14–140 mg/min average emission rates that we found for cigars. Thus, cigars can be a much stronger source of CO than cigarettes.

For RSP, our results show that mass-normalized emissions can be five times larger for cigarettes than for cigars (40 versus 8 mg/g), and the PAH emissions for a cigarette can be about ten times that of a cigar (0.34 versus 0.035 mg/g). Leaderer and Hammond (1991) report 48 mg/g of RSP emitted from a cigar (a cigarillo according to Leaderer, personal communication) and 23–35 mg/g emitted from 12 different cigarettes — suggesting that some types of cigars may have larger RSP mass-normalized emissions than cigarettes. Daisey et al. (1994) report average RSP ($PM_{2.5}$) emissions of 12.4 mg/g over six types of machine-smoked cigarettes, a result which is closer to our value for a cigar.

CO Levels at Two Cigar Social Events

At the Cigar Smoker (the first cigar-smoking event that we studied), about 50 persons were present (12 women and 38 men), and indoor CO concentrations ranged between 5 and 11 ppm, giving an indoor average of about 6 ppm (see Figure 8a). The highest CO concentrations occurred on the upstairs balcony of the main hall, suggesting that CO concentrations were higher near the ceiling than at the floor. If we adjust the observed CO concentrations by subtracting the ambient CO levels of 1.5 ppm measured outside the building while walking on sidewalks, then about 18 active smokers in the hall contributed 4.5 ppm, approximately the same level as measured on the freeway while driving to the event. The high air exchange rate caused by the wide-open doors and windows probably reduced the CO concentrations in the building considerably.

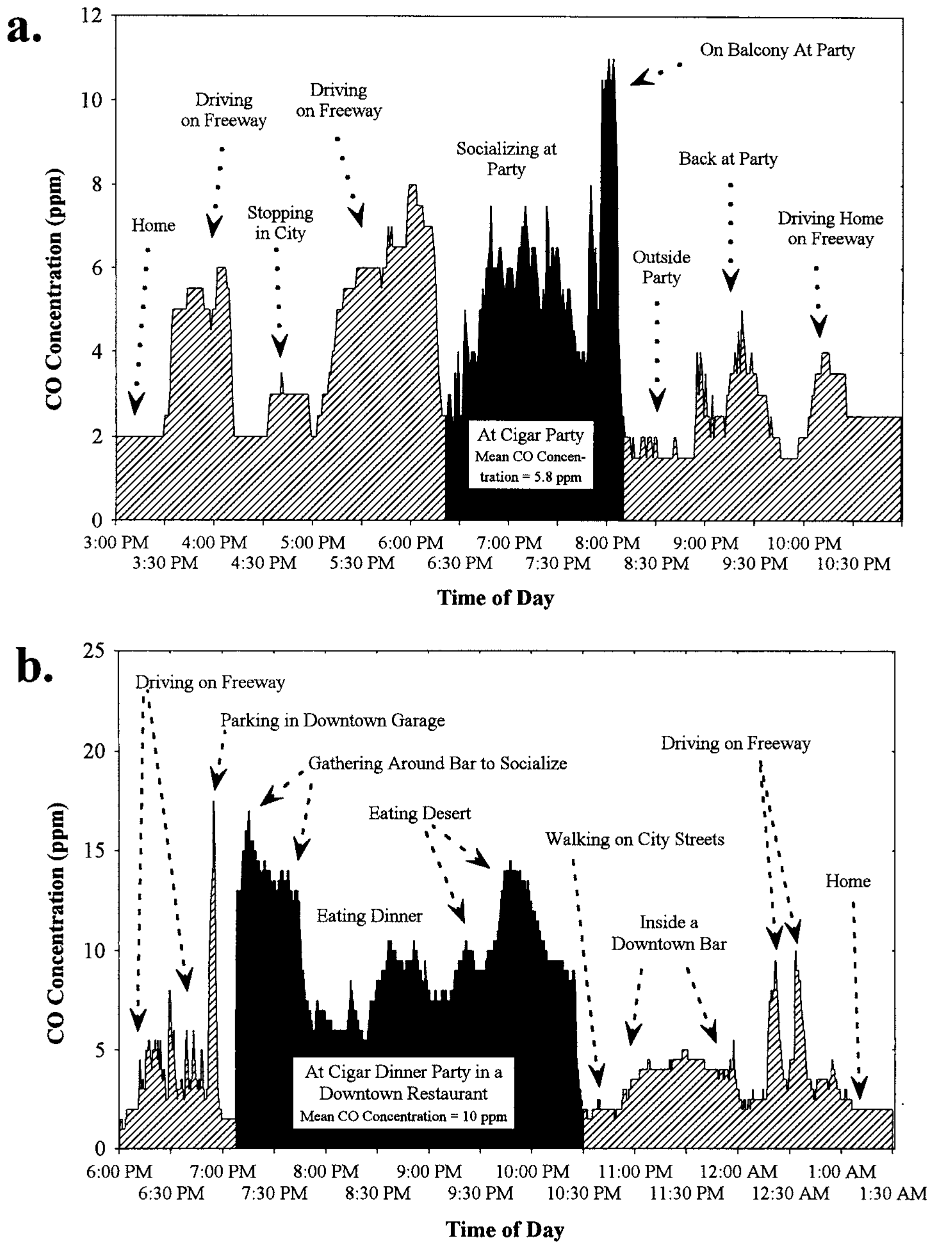

Figure 8. CO concentrations measured using a concealed personal exposure monitor before, during, and after (a) a "cigar smoker" in a San Francisco club and (b) a "cigar banquet" in a San Francisco restaurant. Background levels have not been subtracted from the CO levels shown in the figure.

At the Cigar Banquet (the second event that we studied), the outdoor ambient CO concentration was about 1 ppm, and indoor levels during the first hour when about 24 smokers were at the bar were 13–17 ppm (see Figure 8b). At 7:45 pm h, the patrons were seated for dinner at individual tables of four to six persons each for a three-course dinner, which included cigars. The investigator was seated with five other persons, all of whom smoked cigars during dinner. Overall, more than 100 cigars were smoked during the dinner party. The indoor CO concentration averaged over the 3-h-and-20-min visit was 10 ppm, and about 75% of the 40 persons present was smoking cigars at any instant of time. Based on measurements outdoors on downtown sidewalks before and after the event, ambient CO concentrations were found to be about 1 ppm, so the indoor CO concentration caused by cigar smoking in the restaurant was about 9 ppm. If the cigar dinner had lasted more than 8 h, then indoor CO concentrations might have exceeded the USEPA National Ambient Air Quality Standard (NAAQS) designed to protect public health (9 ppm for 8 h). After leaving the restaurant where the cigar banquet was held, the investigator walked to a San Francisco bar where several cigarettes were being smoked but no cigars were present; indoor CO levels were much lower than at the cigar banquet (Figure 8b).

CO concentrations recorded on the freeway while driving to and from both cigar social events averaged approximately 4.5 ppm. This level is approximately the same as the average in-traffic CO concentration of 4.6 ppm measured on 96 trips during a year-long study of an urban arterial highway in the Bay Area (Ott et al., 1993).

Conclusions

This paper reports cigar emission factors and peak and average concentrations for CO, RSP, and PAH from 17 new cigar experiments. From our results, it appears that for a given mass smoked, cigars can emit larger amounts of CO than cigarettes. This point is illustrated from the CO levels we measured at two cigar social events that are comparable to CO levels on a busy freeway. Cigar smoking can elevate indoor CO concentrations in a restaurant considerably, even when the doors are wide open and the ventilation system is fully operating. Even though cigars appear to emit either less or comparable amounts of RSP and PAH per given mass than cigarettes, cigars are more massive than cigarettes, and they are smoked for much longer periods of time (10 min or less for a cigarette versus as much as an hour or more for cigars). Thus, total emissions from a fully smoked cigar can be two to three times that of a cigarette for PAH, five times that of a cigarette for RSP, and nine to thirty times that of a cigarette for CO (630–1200 mg CO/cigar versus 40–70 mg CO/cigarette). A bystander who is present during the smoking of a cigar receives a much higher exposure to CO, RSP, and PAH than would likely occur for a single cigarette.

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