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A Closed-Loop Control "Playback" Smoking Machine for Generating Mainstream Smoke Aerosols

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ABSTRACT

A first generation smoking machine capable of reading and replicating detailed puffing behavior from recorded smoking topography data is presented. Unlike standard smoking machines, which model human puffing behavior as a steady periodic waveform with a fixed puff frequency, volume, and duration, this novel machine generates a mainstream smoke aerosol by automatically "playing-back" puff topography recordings. Because combustion chemistry is highly non-linear, representing real smoking behavior with a smoothed periodic waveform may result in a tobacco smoke aerosol with a significantly different chemical composition and physical properties than that generated by a smoker. The machine presented here utilizes a rapid closed-loop control algorithm coded in Labview® to generate smoke aerosols for toxicological assessment and inhalation studies. To illustrate its use, dry particulate matter and carbon monoxide yields generated using the playback and equivalent periodic puffing regimens are compared for a single smoking session by a 26-year-old male narghile water-pipe smoker. It was found that the periodic puffing regimen yielded 20% less carbon monoxide (CC) than the played-back smoking session, indicating that steady periodic smoking regimens, which are widely used in tobacco smoke research, may not produce realistic smoke aerosols.

Key words: argileh, FTC, hooka, narghile, shisha, smoke analysis, smoking machine, smoking regimen, smoking topography, tobacco smoke, waterpipe

INTRODUCTION

STUDIES ON THE CHEMICAL COMPOSITION, respirability, toxicity, and carcinogenicity of cigarette smoke generated using a smoking machine have been widely used to predict and understand health effects of smoking, and to compare effects of varied tobacco blends, delivery methods, and puffing behavior. To allow for comparisons across cigarette products, a standard testing protocol has been adopted by the U.S. Federal Trade Commission (FTC), which specifies smoking machine characteristics and a steady periodic puffing regimen of one 35-mL puff of 2-sec duration per minute. The FTC method has been criticized for specifying an unrealistically low-intensity puffing regimen (in terms of puff volume, duration, and frequency), which can result in a significant underestimate of the delivery of various toxicants to the smoker, especially for "light" cig-

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arettes for which smokers have been shown to increase smoking intensity (e.g., puff volume) to achieve nicotine satisfaction.(1–3) When smoked using a higher intensity puffing regimen derived from smoking topography measurements of real smokers, Djordjevic et al.(3,4) found significantly higher yields of toxicants than when the cigarettes were smoked using the FTC method.

Both the FTC method and its higher intensity alternatives, however, rely on a steady periodic puffing regimen in which the puff frequency, duration, and volume are held constant over the duration of a machine smoking session. In fact, standard ISO-compliant smoking machines are not set up to smoke in any other way. In reality, puff topography measurements of cigarette smokers reveal puffing profiles that are characterized by varying puff durations, spacing, and flow rates within a given smoking session.(5–7) These intrasession puffing variations may result in varying combustion, pyrolysis, and devolatilization conditions, which can render a significantly different net smoke composition and particle size distribution than would be the case for the steady periodic smoking session in which these variations have been smoothed by averaging.

To illustrate, temperature and oxygen concentration in the combustion zone of a cigarette are dependent on the instantaneous air flow rate during puffing, as can be noticed by the glowing of the cigarette coal during each puff. Given that elementary chemical reaction rates are exponential functions of temperature, it would be fortuitous if, for a given real smoking session, the integrated average smoke composition matched that produced by a steady periodic smoking session in which all the local peaks and valleys in instantaneous flow rate have been eliminated. That is, even if the average puff duration, frequency, and volume were representative for some real smoker, there is no guarantee that these representative smoking parameters yield a representative smoke composition. For a description of the coupled chemistry, heat transfer, and mass transfer phenomena involved in tobacco smoke production, see previous work.(8–10)

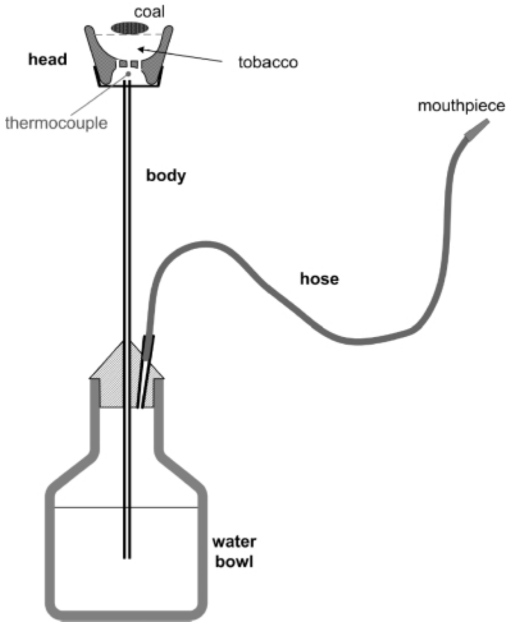

FIG. 1. Schematic of a narghile water-pipe. The head, body, bowl, and hose are the primary "elements" from which a narghile is assembled. When a smoker inhales through the hose, a vacuum is created in the headspace of the water bowl sufficient to overcome the small (typically 3 cm of H_2O) static head of the water above the inlet pipe, causing the smoke to bubble into the bowl. Simultaneously, air is drawn over and heated by the coal, with some of it participating in the coal combustion, as evidenced by the visible red glow that appears during each puff. It then passes through the tobacco moisture, where due to hot air convection and thermal conduction from the coal, the mainstream smoke aerosol is produced. (Thermocouple is shown for experimental setup only.)

F1

The questions arose in our ongoing study of the narghile water-pipe (Fig. 1), a tobacco smoking device popular in North Africa, West Asia, and increasingly in Europe and the United States. The narghile is commonly smoked using a heavily flavored and hydrated, shredded tobacco known as *ma'assel*, and it relies on burning charcoal placed on top of the tobacco to provide the heat needed to produce the aerosol, since unlike cigarette tobacco, the *ma'assel* is incapable of self-sustained combustion.(11) A field study in which smoking topography measurements were made for 52 narghile smokers in a café in Beirut(12) showed that narghile smoking sessions are of the order of 1 h in duration, during which hundreds of puff cycles are executed in a highly non-periodic fashion. For example, the median relative standard deviation for inter-puff interval *for a single smoking session* was 114%. Combined with the fact that "tar" production and tobacco temperature in narghile machine smoking are highly sensitive to inter-puff interval,(11) we concluded that the many puff cycles involved with narghile smoking could lead to significant cumulative errors when steady periodic machine smoking is used to estimate smoker exposure to various toxicants or to generate smoke aerosols for inhalation studies.

With this motivation, a digital smoking machine was developed for the narghile water-pipe in which the recorded smoking topography signal of a real smoker could be "played back" through the smoking machine, thus replicating in detail the smoker's puffing behavior. This paper documents the design and testing of the "playback smoking machine," and demonstrates its use in comparing a real recorded smoking session to its periodic analog in terms of carbon monoxide and total dry particulate matter yields (total particulate matter minus water), as well as the smoke aerosol temperatures attained in the narghile head. We were able to locate only one previous study in which an attempt was made to reenact a real smoking sequence using a smoking machine. In that study, Hinds et al.$^{(13)}$ used a manually controlled syringe smoking machine to produce sequential sinusoidal or square-wave puffs whose duration, volumes, and spacing matched those measured using smoking topography measurements of real smokers. The goal of that study was to calculate respiratory deposition during smoking by comparing inhaled and exhaled particulate matter concentrations. The inhaled particulate matter was estimated by measuring particulate matter produced by machine smoking the cigarettes in the same sequence as measured using a puff topography device. The machine described here, in contrast, is fully automatic and follows the exact time varying flow signal produced by a smoker in its detail, without resort to assuming a particular puff waveform.

METHODS

Smoking machine description

The smoking machine can be thought of as a device that communicates a vacuum signal to the smoking device (narghile) in a controlled manner. To play back a smoking session, the smoking machine controller must generate a time-varying control signal that yields the desired instantaneous flow rate (also known as "puff velocity" in the tobacco smoke research literature), which ranges from zero between puffs to the maximum flow attained during a given smoking session. As shown in Figure 2, this is accomplished by sending a varying DC voltage to a rapid response (20 msec closed to fully open) pro-

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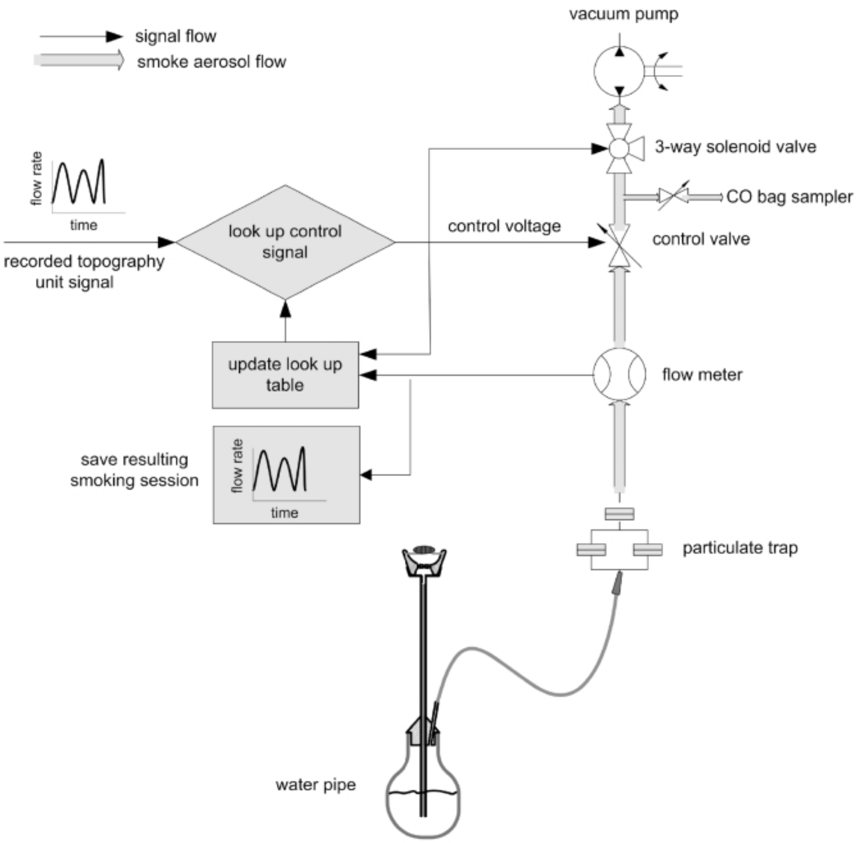

FIG. 2. Schematic of playback smoking machine.

portional control valve (Omega Engineering PV-101) located between a continuously running vacuum pump and the narghile. When a command is issued to begin a puff, a three-way solenoid valve diverts the vacuum from the lab atmosphere to the smoking machine, and a flow is induced through the narghile. A 10-msec response time digital mass flow meter (Omega Engineering FMA-1609A), located upstream of the control valve, provides feedback to the controller.

This control valve signal is generated by a PC-based data acquisition and control (DAQ) system (National Instruments 6040E PCI card with SCB-68 signal conditioner) that is coded in the Labview® graphical programming language. During operation, the controller executes the following algorithm: (1) Read from the smoking session recording the desired flow rate during the next time interval (varying from 100 to 200 msec, depending on the resolution of the recording which is being played back). (2) Look up the control valve voltage expected to produce the desired flow rate. (3) Send that voltage to the proportional control valve. (4) Read the actual flow rate produced by that voltage. (5) Update the look-up table. (6) Read the next required flow rate, and so on until the end of the smoking session.

The look-up table is initialized prior to a playback session by a calibration program that increments the valve control voltage from zero to 10 V in 0.1-V steps while recording the resulting flow rates. Each initial entry of voltage in the table defines the center of a "neighborhood," whose width is 0.05 V. As the playback smoking session proceeds and new flow versus voltage data is acquired, the program searches the voltage domain for the appropriate neighborhood for each new data point. Having found the neighborhood, the program arithmetically averages the previous and current data pairs, and updates the table with this new average value. When looking up the control voltage for a flow rate that falls between two table entries, the program interpolates linearly between them.

Because the table is updated at the sampling frequency of the DAQ, changes in the flow resistance of the narghile or smoke sampling trap (which occur on the time scale of several puffs) as the smoking session proceeds are continuously accounted for and should not affect the accuracy of the playback session. One advantage of the adaptive look-up table approach is that no transfer function is needed to relate control valve voltage and flow rate for the smoking machine and narghile; changes to the physical set-up, for example, by using a narghile of different flow geometry or a different type of particulate trap, does not require any new knowledge of the system's dynamic response to the control signal.

Smoke sampling and analysis

As configured for this work, the smoking machine was equipped to capture the smoke particulate phase for dry particulate matter (DPM) determination, and to sample a fraction of the vapor phase for carbon monoxide (CO) determination. As shown in Figure 2, the smoke aerosol is split into two streams via a 30-degree Y-junction immediately downstream of the narghile hose outlet and each stream is drawn through a single 47-mm Gelman type A/E glass fiber filter pad. Each pad is held in a transparent polycarbonate holder, also manufactured by Gelman. This two parallel-filter configuration typically requires eight sets of filters (i.e., seven filter changes during each smoking session) to limit the particulate loading to circa 100 mg per filter. (ISO 4387:1991 specifies that up to 150 mg of tobacco smoke condensates may be collected on a 47-mm glass fiber filter pad.) A secondary filter is placed downstream of the second Y-junction and weighed before and after each smoking session to ensure that there is no breakthrough. The total particulate matter (TPM) was determined by weighing the filters before and after each smoking run. DPM was found by subtracting the mass of water on the filters from the TPM. To determine water mass, the 16 filter pads were combined in a 250-mL bottle and stirred for 20 min with 50 mL of ethanol. Five milliliters of the resulting solution was then added to the reaction chamber of a modified KF apparatus (Aquametry II, Barnstead-Thermolyne). Using filter blanks with known quantities of water, we found that this extraction procedure was quantitative to the accuracy of the KF instrument.

For CO determination, a fraction of the smoke aerosol flow is sampled from the main flow path through a critical orifice by a miniature sealed diaphragm pump that exhausts into a 10-L tedlar grab sample bag (SKC, Inc., no. 232-08). The pump is activated during each puff by the DAQ system via a digital solid state relay. Carbon monoxide was quantified using a calibrated electrochemical CO analyzer (Monoxor II, Bacharach Inc.) that was connected to the grab sample bag after the smoking session was terminated. A limited number of experiments were made with a non-dispersive infrared CO analyzer (Emission Systems Inc., model no. 4001) to validate the measurement. Measured volume concentrations of CO were reported in units of mass by multiplying by the total drawn smoke volume and the density of the CO at ambient temperature and pressure. The initial dead volume between the sampling point and grab bag was negligible to the accuracy of the CO instrument, and was therefore excluded from analysis. Additional details regarding particulate and gas phase sampling set-up are given elsewhere.(14)

Performance testing

Smoking machine performance was tested by comparing original and played-back recordings. The testing was conducted in two phases. Phase I was undertaken to test the ability of the controller and flow hardware to follow the records of the most challenging smoking behavior morphologies recorded in the aforementioned 52 smoker field study. The most challenging behavior for the smoking machine to reproduce is one where flow conditions change rapidly, for example when many short duration puffs are taken in rapid succession. Accordingly, seven smoking sessions (labeled A–G) were selected from the pool of 52 according to the criteria given in Table 1. Sessions A–G span the flow rates and puff volumes observed in the field study, and also correspond to the smoking sessions with the minimum puff durations, minimum interpuff intervals, and maximum variability in all smoking parameters (as indicated by standard deviation). Sessions A–G were recorded from three female and four male smokers who ranged from 21 to 33 years of age. The first 30 min of these recorded smoking sessions were re-played, with the narghile connected but not lit. The original and played-back smoking session flow signals were compared in terms of the session-averaged parameters given in Table 1.

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TABLE 1. CRITERIA USED TO SELECT RECORDED SMOKING SESSIONS FOR PLAYBACK TESTING

Smoking parameter	*Minimum*	*Maximum*
Interpuff interval		
Mean	A	
Standard deviation		B
Puff duration		
Mean	C	
Standard deviation		D
Puff volume		
Mean	E	F
Standard deviation		D
Mean flow rate	E	G

Each letter represents a particular smoker that met the given category (e.g., smoker A had the minimum interpuff interval of the 52 smokers sampled, while smoker B had the maximum interpuff interval standard deviation).

In the second phase of testing, a single smoking session was chosen and played back in its entirety with the narghile in the lit condition. This was repeated five times. In the lit condition, the ability of the controller to adapt to the changing flow resistance as the filters are loaded with particulate matter and are replaced periodically during the playback session is tested. When a fresh filter replaces a loaded one, the smoking machine experiences a step decrease in flow resistance, and the controller must learn the new relationship between flow rate and control valve voltage. During the phase II testing, the original and played back smoking sessions were compared on a puff-by-puff basis as well as in terms of the total session-integrated parameters given in Table 1.

Comparison of playback and periodic smoking aerosol components and temperatures

To illustrate potential use of the playback machine, DPM and CO yields, as well as smoke temperature and tobacco consumption were compared for a playback smoking session and its steady periodic analog. These diagnostics were chosen for their relative ease of measurement and because they broadly characterize differences which may arise in the composition of the gas and vapor phases of the aerosol as a result of the smoking regimen chosen. In particular, CO is primarily formed by the incomplete combustion of the charcoal, whose chemical kinetics are exponentially dependant on local temperature; differences in CO yields are therefore indicative of varying combustion chemistry arising from the varying puffing regimen, with potentially important effects on the yields of other pyrosynthesized compounds such as polycyclic aromatic hydrocarbons. DPM, on the other hand, is an aggregate representation of the aerosol particulate formation in the narghile head, resulting primarily from distillation of the tobacco mixture.(11)

This distillation process is primarily controlled by the net thermal energy provided by the charcoal to the tobacco. Differences in DPM between playback and periodic smoking would thus indicate differences in the aggregate delivered energy, and the net transfer of material from the tobacco to the aerosol. This would be important for nicotine and tobacco specific nitrosamines, both of which are delivered to the smoker by distillation from the tobacco.

The mean puff volume, duration, and interpuff interval were calculated (see Shihadeh et al, 2004 for equations) for a smoking session recorded from a 26-year-old male smoker, and these values were used to generate a steady periodic smoking regimen. The periodic regimen consisted of 182 puffs, each of 1020-mL volume and 3.9 sec duration, speed 15.3 sec apart. The playback and periodic smoking sessions were each replicated five times. Procedures for coal, tobacco, and narghile type, storage, and preparation, filter replacement schedule, and DPM and CO yield determinations were as presented elsewhere.(11,14)

To compare smoke aerosol temperatures resulting from playback and periodic smoking sessions, the head outlet temperatures measured using a K-type thermocouple (Fig. 1) were plotted against the cumulative drawn volume. To characterize overall differences in smoke aerosol temperature, the volume-weighted mean smoke temperature, $\bar{T}$, was calculated as

$$\bar{T} = \frac{\int \dot{Q}(t)\ T(t)dt}{\int \dot{Q}(t)dt}$$

where $\dot{Q}(t)$ is the instantaneous volume flow rate and $T(t)$ is the instantaneous temperature measured at the head outlet. The integrals were evaluated numerically using the trapezoidal rule.

RESULTS AND DISCUSSION

Phase I (unlit) smoking machine performance

Figure 3 shows recorded and played-back flow rate traces for the first 30 sec of a playback smoking session. It can be seen that the smoking machine reproduces the flow profiles in fine detail. Figure 4 shows the originally recorded and played-back session-averaged puffing parameters listed in Table 1 for the seven unlit selected smoking sessions. As shown, the session-average puff parameters were re-produced with an average error (deviation from a slope of unity) of less than 1%, indicating that the smoking machine is capable of following the range of smoking behaviors, including the most stochastic (large standard deviations) and dynamic (short puff durations and interpuff intervals), found in the 52-smoker pilot field study.

Phase II (lit) performance

Figure 5 compares the field-recorded and machine-attained puff-resolved volume, duration, and interpuff interval for one of the five repeated smoking sessions with the narghile lit. The other four sessions provided essentially the same plots, and are not shown, though the slopes and coef-

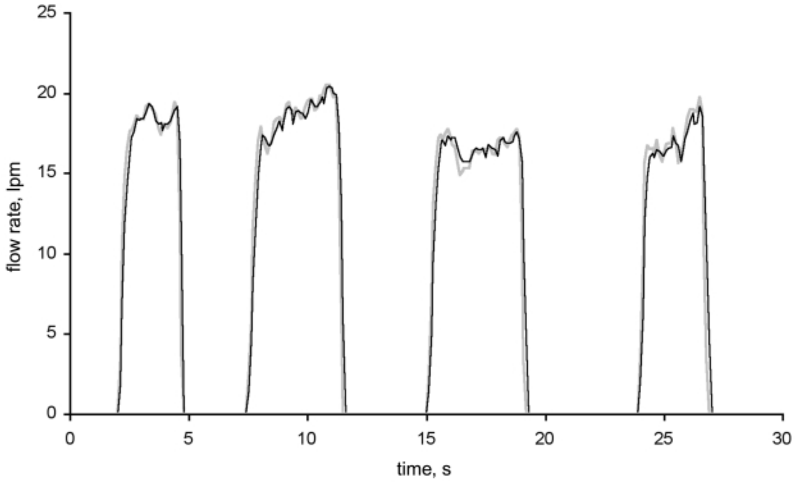

FIG. 3. Original and played-back flow rate traces for the first 30 sec of a 182-puff session. The original flow signal is shown in gray.

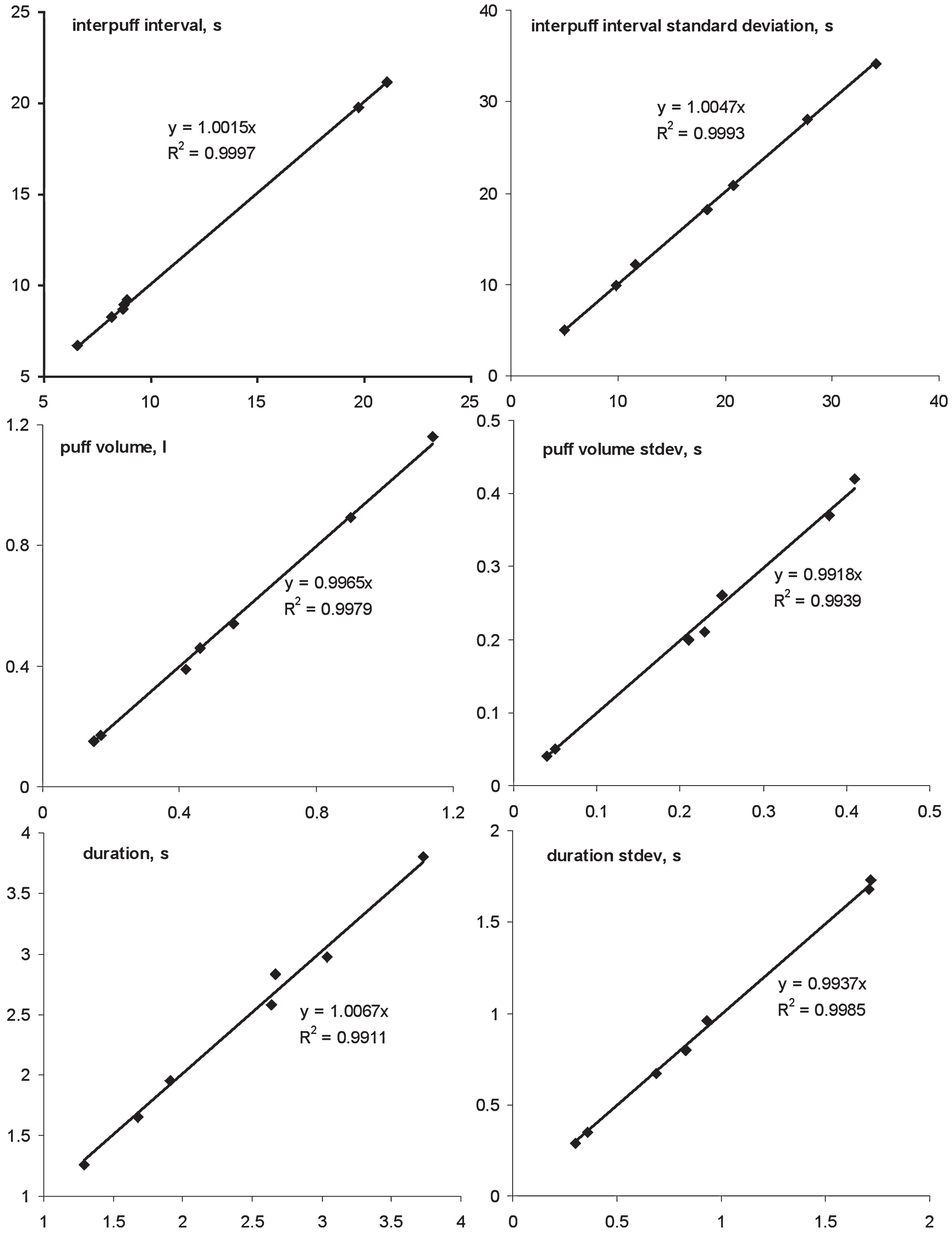

FIG. 4. Comparison of originally recorded and playback session-averaged puff parameters for smokers A–G. Horizontal and vertical axes correspond to original and playback data, respectively.

T2

ficients of determination for the best linear regression relating the original and playback puffing parameters for the five sessions are given in Table 2. The slopes indicate the bias error, whereas the correlation coefficients indicate the precision at the individual puff level. A low correlation coefficient, for example, would signify scatter about the mean. Variation from one test to another indicates smoking machine repeatability.

As shown in Table 2, the bias error is greatest for the puff volume, ranging from −2% to 3% for the five smoking sessions. The puff volume is the

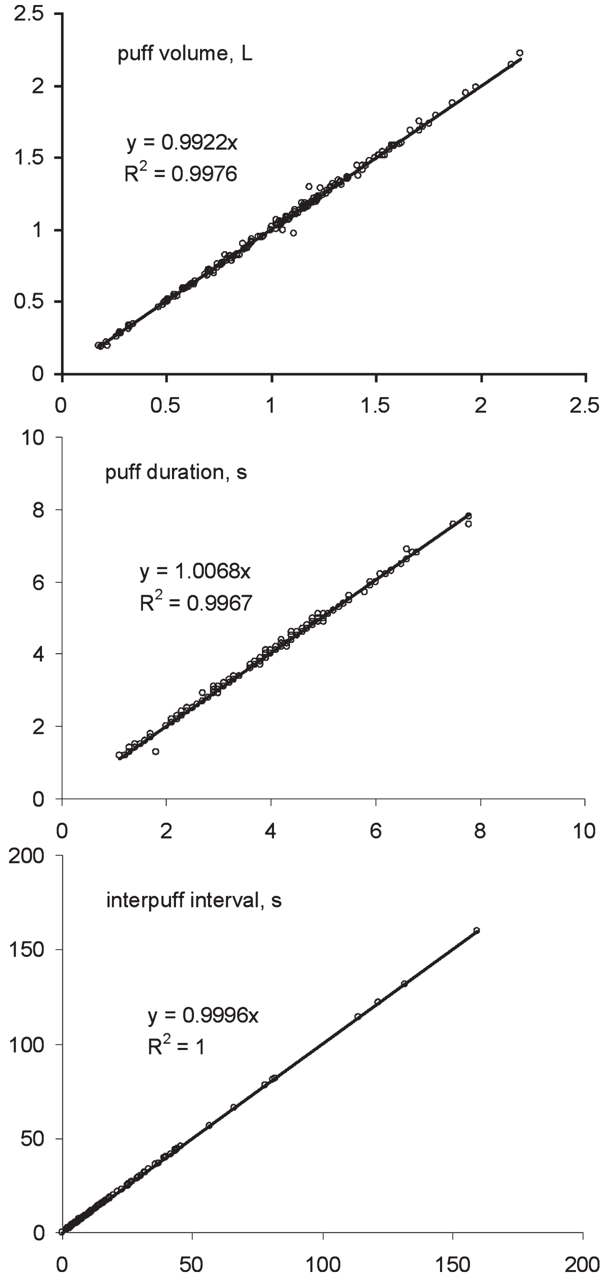

FIG. 5. Individual puff playback versus originally recorded volume, duration, and interpuff interval for lit smoking condition (test 1 in Table 3). Horizontal and vertical axes correspond to original and playback data, respectively.

most challenging parameter to reproduce because it is a product of the instantaneously varying flow rate and puff duration. The former depends on the accuracy of the look-up table and the response times of the control valve and flow meter as well as the inertia of the flow. The puff duration and interpuff intervals are accurate to less than 1% error, and the correlation coefficients for the three puff parameters are all better than 99%. As a whole, the data in Table 2 indicate that the playback machine is capable of reproducing with fidelity the detailed puff-by-puff behavior of a real smoker for the normal, lit condition during which the flow resistance is changing.

The session-average smoking parameters for the five tests above are given in Table 3 along with those of the original field-recorded session. Whereas the previous table indicated puff-by-puff performance, the data shown in Table 3 represents the integrated error over each entire smoking session. As shown, the average error for the five sessions is under 1% in any of the measured parameters, though the 95% confidence interval includes possible errors as large as 4.43% (mean error in puff volume standard deviation is 0.98 ± 3.45%).

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Tobacco consumed, DPM, CO, and smoke aerosol temperature for playback and periodic smoking

The mean and standard error of the mean (SEM) for tobacco consumed, DPM and CO yields, and smoke temperature for five replicate periodic and five replicate playback smoking sessions are provided in Table 4. The difference in mean CO between the playback and periodic sessions is significant at the 95% confidence level, and shows that the steady periodic smoking regimen results in a 20% under-estimate of the CO delivered to the smoker. The DPM yields, on the

T4

TABLE 2. SLOPE AND CORRELATION COEFFICIENTS FOR THE RELATIONSHIP BETWEEN RECORDED AND PLAYED BACK PUFF-BY-PUFF VOLUME, DURATION, AND INTERPUFF INTERVAL FOR FIVE REPEATED TESTS WITH LIT NARGHILE

Test	*Volume*	*Duration*	*Interpuff interval*
1			
Slope	0.9922	1.0068	0.9996
R^2	0.9976	0.9967	1
2			
Slope	1.0217	1.0115	0.9992
R^2	0.9980	0.9972	1
3			
Slope	0.9839	1.0050	0.9997
R^2	0.9923	0.9980	1
4			
Slope	1.0069	1.0138	0.9990
R^2	0.9946	0.9970	1
5			
Slope	1.0301	1.0078	0.9995
R^2	0.9972	0.9972	1

TABLE 3. COMPARISON OF RECORDED AND PLAYED BACK SESSION FOR INTEGRATED SMOKING PARAMETERS

		Repeated playback sessions					*Error %*	
Smoking parameter	*Original recording*	*1*	*2*	*3*	*4*	*5*	*Mean*	*95% CI*
Total drawn volume, L	185.6	183.9	189.9	182.5	187.2	191.0	0.70	±2.46
Interpuff interval, sec								
Mean	15.32	15.29	15.27	15.30	15.26	15.29	−0.25	±0.13
Standard deviation	23.07	23.08	23.08	23.07	23.07	23.07	0.02	±0.03
Puff duration, sec								
Mean	3.93	3.96	3.98	3.95	3.99	3.96	0.97	±0.52
Standard deviation	1.34	1.34	1.34	1.34	1.34	1.35	0.15	±0.41
Puff volume, L								
Mean	1.02	1.01	1.04	1.00	1.03	1.05	0.59	±2.52
Standard deviation	0.41	0.41	0.42	0.41	0.40	0.43	0.98	±3.45
Mean flow rate, L/min	15.25	14.96	15.37	14.88	15.07	15.52	−0.59	±2.23

The 95% confidence interval (CI) for the mean error is given in the last column, as calculated using the *t*-test distribution ($n = 5$).

other hand were essentially the same for both types of smoking, and while the average tobacco consumed was almost 15% greater for playback smoking, the large relative SEM meant that the difference was not significant at the 90% confidence level.

F6

The volume weighted mean smoke temperature exiting the narghile head was approximately the same for both types of smoking, though, as shown in Figure 6, the temperature fluctuates more for the playback smoking sessions, resulting in significantly higher peaks and lower minima. Since the hot combustion gases of the coal are measured after they have passed through the tobacco (and generated the smoke aerosol), the measured temperature fluctuations are actually damped by the thermal inertia of the moist tobacco paste. Temperature fluctuations in the combustion zone are expected to be considerably higher. We found that the data was very repeatable across periodic smoking sessions, while it varied considerably for the playback smoking sessions. The two playback temperature traces shown in Figure 6 are representative of the variations across repeated playback smoking sessions.

CONCLUSION

Steady periodic machine smoking protocols have long been used to estimate yields of various toxicants and to generate tobacco smoke aerosols for physical characterization and inhalation studies. This study has demonstrated a smoking machine and methodology for examining the implications of following a steady periodic versus actual smoking profile with the narghile waterpipe. It has been shown that the adaptive look-up table control approach provides good accuracy for playing back a wide range of puffing behavior morphologies, and is capable of tracking the desired flow signal even when the draw resistance in the smoking device or particulate

TABLE 4. DRY PARTICULATE MATTER, CO, TOBACCO CONSUMED, AND VOLUME-WEIGHTED MEAN (SEM) SMOKE TEMPERATURE FOR FIVE REPEATED PLAYBACK AND FIVE REPEATED PERIODIC SMOKING SESSIONS WITH THE SAME NUMBER OF PUFFS AND MEAN PUFF PARAMETERS

	Playback	*Periodic*	*Single cigarette*[15]
DPM, mg	1004 (138)	1047 (140)	1–29
Co, mg	342 (21)	274 (13)	1–22
Tobacco consumed, g	7.0 (0.6)	6.0 (0.6)	—
Volume-weighted mean smoke temperature (°C)	110 (6.8)	103 (2.4)	—

CO, carbon monoxide; SEM, standard error of the mean; DPM, dry particulate matter; FTC, Federal Trade Commission.

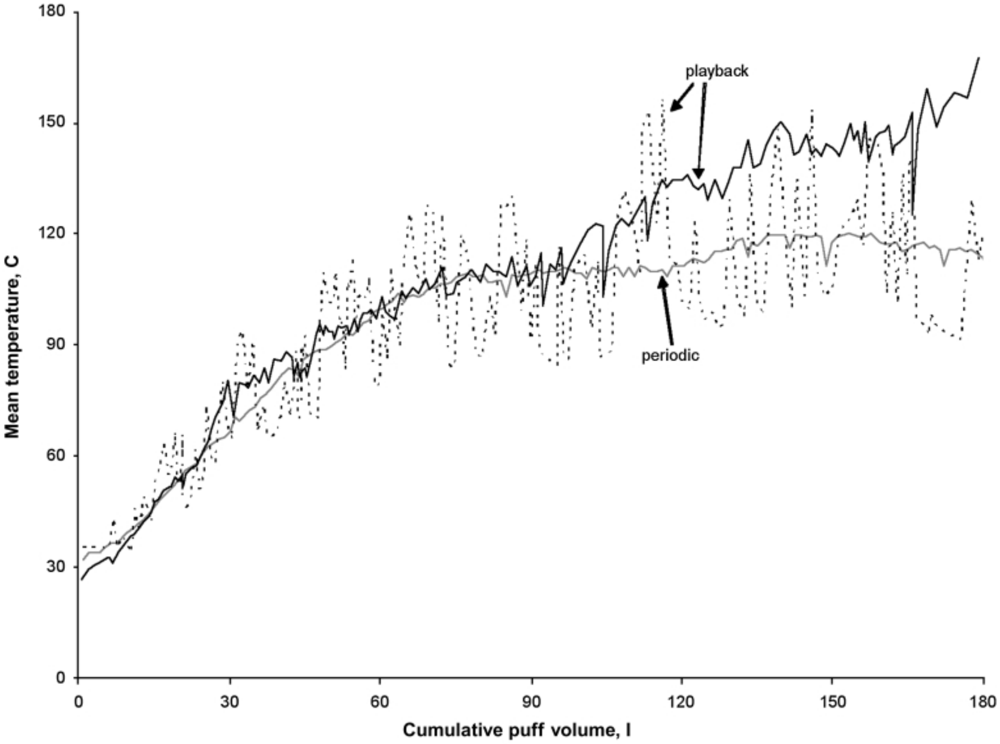

FIG. 6. Aerosol temperature (°C) at head outlet versus cumulative puff volume. Solid gray line shows typical data for periodic smoking sessions, whereas dashed and solid black lines show typical data for playback smoking.

sampling system is changing. For the smoking session examined, we found that the periodic smoking regimen results in a 20% under-prediction of the actual CO delivered to the smoker, while the DPM content and mean aerosol temperature were approximately the same. Further investigation is warranted to determine the generality of these results, as well as to compare other toxicologically significant measures such as polycyclic aromatic hydrocarbons (PAH), nicotine, and particle size distribution.

It should be highlighted that, because the control algorithm requires no draw resistance model of the smoking device or sampling system, the playback machine is equally capable of generating smoke aerosols for cigarettes, pipes, and hand-rolled marijuana cigarettes in a playback mode using prior smoking topography recordings. The only modification needed for these relatively low-flow smoking devices would be the replacement of the flow meter used in this study with one of a lower flow range. We would expect slightly higher smoking machine accuracy with these smoking devices, because they are not accompanied by pressure perturbations generated by a water bubbler, and because the smaller stored volume and flow path length in the devices (relative to the waterpipe) will reduce characteristic response times between the vacuum applied at the mouthpiece and the resulting smoke flow rate. Given the greater role of tobacco combustion (rather than distillation as with the narghile) to the formation of the mainstream aerosol, we speculate that differences in chemical composition between playback and periodic smoking may be even more important than with the narghile. Apart from playback smoking, the use of a continuously running vacuum pump modulated by a digitally controlled flow valve, rather than the conventional use of a piston-cylinder device to generate a Gaussian puff profile, affords the specification of any smoking waveform desired, and generally at lower cost.

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