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Towards a topographical model of narghile water-pipe café smoking: a pilot study in a high socioeconomic status neighborhood of Beirut, Lebanon

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Abstract

A pilot study of narghile water-pipe smokers in a cafe in the Hamra neighborhood of Beirut, Lebanon, was conducted to develop a preliminary model of narghile water-pipe smoking behavior for use in laboratory smoking machine studies. The model is based on data gathered from smoking sessions of 30 min or longer duration from 52 smoker volunteers using a differential pressure puff topography instrument, as well as anonymous visual observations of 56 smokers in the same cafe. Results showed that the "average" water-pipe cafe smoking session consists of one hundred seventy-one 530-ml puffs of 2.6-s duration at a frequency of 2.8 puffs/min. The implications of this comparatively high-intensity puffing regimen on the production of toxic smoke constituents are discussed.
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Keywords: Topographical model; Narghile water-pipe; Smoking; Beirut

1. Introduction

A sharp rise in the popularity of the narghile water-pipe has been noted in recent years (Chaaya et al., 2004). National and local surveys in Kuwait (Memon et al., 2000), Egypt (Israel et al., 2003), Syria (Maziak et al., 2004), and Lebanon (Shediac-Rizkallah et al., 2002; Jabbour, 2003) have found that 20–70% and 22–43% of the sampled populations has ever smoked or currently smokes the narghile, respectively. Anecdotal evidence in the form of newspaper reports (e.g., McNicoll, 2002; Barnes, 2003; Landphair, 2003; Edds, 2003; Gangloff, 2004) and "hookah bar" advertisements in college papers suggests that narghile smoking is catching on in North America and Europe as well.

The new appeal of the narghile water-pipe, until recently considered the domain of older men in Southwest Asia and North Africa, appears to be correlated with the marketing of an array of fruit-flavored tobacco mixtures, which list "molasses" as an ingredient, and which burn with a strong aroma of caramelizing sugar. Cafes and restaurants offering narghile water-pipes as a form of entertainment to young women and men have mushroomed in recent years in the Middle East and North Africa and come in the context of a broad commercialized revival of regional customs. In these cafes, and in printed and televised ads, wait staff can often be seen wearing costumes that purport to conjure the authentic atmosphere of the past, in which narghile smoking presumably flourished.

Fig. 1 illustrates the main features of the 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 H_2O) static head of the water above the inlet pipe, causing the smoke to bubble into the bowl. At the same time, air is drawn over and heated by the coals, with some of it participating in the coal combustion, as evinced by the visible red glow that appears during each puff. It then passes through the tobacco mixture (typically, 10–20 g are loaded), where due to hot air convection and

Abbreviations: STI, smoking topography instrument.

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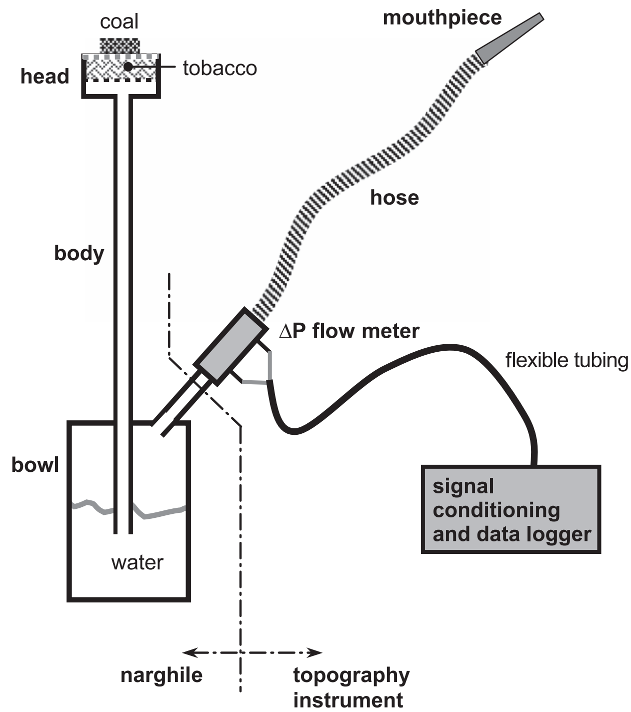

Fig. 1. Schematic of the narghile water-pipe, shown with the topography instrument attached. The hose and mouthpiece of the topography instrument are identical to the originals. Not to scale.

thermal conduction from the coal, the mainstream smoke aerosol is produced.

Despite its long history and recent revival, there have been few studies on narghile smoking, and recognized methods and instruments specific to its study have yet to be developed. Recent smoking machine studies (Shihadeh, 2003) at the AUB Aerosol Research Lab have shown that the quantities of tar and nicotine delivered at the mouthpiece strongly depend on the puffing parameters used, even when the total drawn volume is held constant. It was found, therefore, that toxicological assessment of narghile smoking requires models of smoking behavior based on studies of smokers. To the best of our knowledge, no previous detailed smoking topography data have been collected from which a model can be derived.

The objectives of this study were to provide data that can be used to guide the design of smoking topography studies and to derive a first approximation of "average" narghile smoking parameters, such as puff volume, duration, and frequency for the purpose of programming laboratory smoking machines used in toxicological assessments, as is commonly done with cigarette testing, where a fixed frequency, duration, and puff volume smoking regimen is used to generate the smoke sample. To do so, we conducted a field study using a portable smoking topography instrument (STI) at a busy cafe near the American University of Beirut (Beirut, Lebanon), where the narghile is served. Our work has focused on the cafe because it provides a convenient natural setting for making topographical measurements for many smokers and likely represents a large fraction of narghile consumption, particularly for the young narghile smokers, who have taken up the habit in recent years. Other smoking settings, such as the home and public outdoor places, also likely account for a large fraction of narghile consumption, possibly with varied smoker characteristics (e.g., gender, age, and prior smoking experience), which could affect topography. These settings are not covered in the present study.

2. Methods

2.1. Study design and procedures

The study was conducted in two phases. In the first, a portable STI was attached to the narghiles of 52 smokers in a cafe, prior to commencement of smoking, and measurements of flow rate versus time were made for typically 30–40 min of unsupervised smoking. A limited number of measurements were made in which the entire smoking sessions were sampled. Using the data compiled from the first 30 min of smoking, a time-resolved smoking model was derived from which a whole smoking session of a given duration could be inferred. We assumed that the 30-min minimum sampling duration would provide a sufficiently representative data sample to determine the mean puff duration, flow rate, and frequency for a given smoker, while also allowing a greater number of smokers to be sampled in the time available for this pilot study.

This assumption was tested by tracing the cumulative and moving averages of each topographical parameter over time for the first 30 min of smoking, averaged over the 52 smokers. In this way, we could (1) elucidate temporal patterns of the smoking ritual, (2) directly assess how the results would have differed had we sampled each smoker for a shorter time, and (3) extrapolate trends in time to predict cumulative mean puff parameters for sessions longer than 30 min in duration. Item 3 was tested by comparing the extrapolated and recorded data for those smoking sessions sampled longer than 30 min. Nemeth-Coslett and Griffiths (1984) and Morgan et al. (1985) followed a similar approach of tracking the evolution of group mean puffing parameters for cigarette smokers in a laboratory and natural setting, respectively.

When a cafe customer ordered a narghile, the food server notified the field worker, who then proceeded to recruit the customer as a volunteer in the study. If consent was obtained, the field worker attached the STI upon delivery of the narghile. The methods used were in compliance with the Declaration of Helsinki and involved no additional risk to the smoker. Smokers were instructed to smoke as they normally would and informed that the field worker would return after some time to pick up the STI, although the field worker could be summoned earlier through the food server. The STI was left with the smoker for typically 30–40 min of unsupervised smoking in the cafe. In most cases, the smoker had still not finished smoking, and the collected data thus represented partial smoking sessions. Because the STI was physically unobtrusive (placed under the table, out of sight) and did not require any modification in smoking method, we expected that the recorded smoking sessions closely resembled the "natural" smoking behavior of the smokers in this common setting. A total of 52 smokers were sampled in this fashion. In addition to age and gender, volunteers were asked whether they sensed any differences in smoking or had any complaints in connection with the use of the STI.

The second phase of the study was conducted to determine the mean total smoking session duration by visually observing 56 smokers in the same cafe. Following the approach of Chapman et al. (1997), observations were conducted randomly without the smokers' knowledge. Using a stopwatch and a table map of the cafe, the times corresponding to the first and last puff of each smoker were recorded with an estimated accuracy of 2 min by two field workers observing the same smokers from a distance. Typically, 3–5 smokers were tracked simultaneously. No contact was made with the smokers before or after the smoking sessions, and the age and gender of the smokers were therefore assessed by best estimate of the field workers. Combined with the detailed puff topography statistics of the first phase, a complete description of the average smoking session could thus be attained from this preliminary work.

2.2. Instrumentation

The STI was designed for the pulsating, high flow rate of the narghile. It utilizes a differential pressure obstruction meter (Novametrix Medical Neonatal Sensor) and pressure transducer. Pressure transducer voltage is digitized and recorded on a portable data logger at a rate of 5 Hz and is periodically downloaded to a PC for processing. The entire apparatus fits in a small tool box and weighs approximately 2 kg.

As shown in Fig. 1, the sensor is incorporated into a typical narghile hose at its point of connection with the water-pipe, far from the mouthpiece. As such, attachment of the sensor does not impose any modification in the smoking method. Unlike the cigarette-holder-utilizing topography systems now in use, the taste and feel—both in the fingers and on the lips—of the smoking device remain unchanged. Because the flow sensor is attached to the STI hose, field data collection requires replacing the smoker's original hose at the beginning of the smoking session. Except for the presence of the flow sensor, the STI hose and mouthpiece are identical to those in use in the cafés.

The logged data, consisting of transducer voltage versus elapsed time, is processed using software that reads the pressure transducer signal and locates the timings corresponding to the beginning and end of each puff. Puff events are defined by deviation from the zero voltage plus a tolerance value (usually equal to the resolution of the data logger), and various user-input tolerances (e.g., minimum time separation between two puffs greater than 0.1 s) exclude artifacts.

Having determined the beginning and end timings of a given puff, the instantaneous and mean flow rate between these times are calculated using an experimentally derived calibration curve of transducer voltage versus flow rate. The calibration is performed by acquiring data from the topography instrument while it is attached to a typical argileh that has been prepared for smoking, in accordance with the methods given in Shihadeh (2003). The transducer voltage is plotted against the output signal of a calibrated digital mass flow meter ($\pm$ 1% accuracy), while sweeping a range of flow rates from 2 to 20 standard liters per minute.

Each individual puff's volume is then calculated as the mean flow rate during the puff multiplied by the elapsed time from puff beginning to end. The data from the puff events are stored in an array from which the total number of puffs, the mean puff volume, duration, and puff frequency are calculated for a given smoking session. Maximum error for any topography parameter is less than 5% of the reading. The STI and its testing are described in more detail in Shihadeh et al. (2004).

2.3. Calculation procedures and data analysis

To derive a fair representation of smoking session dynamics from STI recordings of differing lengths, the first 30 min of each recorded session were used to calculate the cumulative and moving average puff volume, duration, and frequency. The first 30 min were discretized into 18 time intervals for this purpose, and the puff parameters calculated for each interval and smoker were then averaged over the 52 smokers to arrive at a time-resolved aggregate model of the first 30 min of smoking.

For each of the 18 time intervals, the arithmetic average puff volume, puff duration, and puff frequency were calculated for each smoker, in accordance with the equations given in Appendix A. The average flow rate in each time interval was calculated as the total drawn volume during that interval, divided by the sum of the puff durations over the interval. It should be noted that this definition of mean flow rate is not necessarily equal to the mean of the individual puff flow rates. The former is a preferable definition because it weighs the mean flow rate by puff volume, rather than treating all puffs equally.

2.4. Participants and setting

The field study was conducted from December 2002 through May 2003 at a busy cafe adjacent to the American University of Beirut in Beirut, Lebanon. The cafe has an estimated capacity of 150 persons and is frequented predominantly by young adults, male and female. Along with light food, it offers narghiles of various tobacco flavors on the menu, for a price of 8000–10,000 LL (approximately US$5–7). The great majority of narghiles served are of the common *mo'assel* type (see Shihadeh, 2003, for narghile typology). The relatively high price of the narghile at this cafe, as well as its proximity to the American University of Beirut, an exclusive private university whose yearly tuition is comparable to the average yearly family income in Lebanon, suggests that the population sample was likely skewed towards the upper income stratum of Beirut.

Both phases of the study were carried out between 2000 and 0100 h, in the same cafe, and usually on the weekend (Friday–Sunday).

3. Results

3.1. Participant pool

The 52 volunteers in the puff topography study consisted of 14 female and 38 male smokers, with a median age of 21 years and an interquartile range of 4.75 years. More than 85% of the approached candidate volunteer smokers were willing to have the STI attached to their narghiles and participate in the study. On three occasions, volunteer smokers complained of a residual flavor in the pipe from a previous smoking session and aborted the test shortly after starting. The data from these sessions were not tabulated. Other than these instances, no volunteer smoker noted any sensory difference from normal narghile smoking, and none aborted the test. After each day of data collection, during which typically 4–5 smoking sessions were recorded, the STI was left overnight connected to a filtered compressed air line to reduce build up of the smoke particulates from day to day.

Those anonymously observed for the total smoking time consisted of 16 female and 38 male smokers, based on visual appearance to the field workers. Because no contact was made with the smokers, we cannot be certain that the age group for this phase of the study matched that of the STI study group, although by best estimate of the field workers, the age distribution appeared to be the same. The observations were conducted in the same cafe and during the same hours as the measurements with the STI, but on different days.

3.2. Aggregate puff parameter statistics

Table 1 shows the 52 smoker cumulative mean puffing parameters for the first 30 min of smoking. The mean puff duration of 2.6 s is comparable with the range of 1–3 s, while the mean puff volume of 530 ml is an order of magnitude greater than the range of 42–70 ml previously reported for cigarette smokers over a wide range of smoking conditions and cigarette types (Djordjevic et al., 1997; McBride et al., 1984; Kolonen et al., 1991, 1992a,b). The puff volumes associated with the narghile are so much greater than those of cigarettes that a single narghile puff draws, a volume comparable to the cumulative volume of 335–1235 ml for an entire cigarette (Kolonen et al., 1991, 1992b; Corrigall et al., 2001). The mean interpuff interval (IPI) of about 15 s falls just under the previously reported range of 15.4–24.4 s for cigarette smokers (McBride et al., 1984; Kolonen et al., 1991). Differences in puffing parameters between male and female smokers were not statistically significant at the 90% confidence level.

Table 1
Smoker-averaged puffing parameters averaged over the first 30 minutes of smoking

N=52	Mean	Range	S.E.M.
Puff volume (l)			
Mean	0.53	0.15–1.22	0.03
Maximum	1.06	0.27–1.86	0.05
Minimum	0.14	0.03–0.63	0.01
S.D.	0.19	0.04–0.42	0.01
Flow rate (lpm)			
Mean	12.46	5.61–23.79	0.48
Minimum	6.43	3.06–22.03	0.43
Maximum	20.00	7.94–28.98	0.64
Puff duration (s)			
Mean	2.60	1.21–4.74	0.12
Minimum	0.85	0.60–2.00	0.04
Maximum	5.00	1.80–10.60	0.25
S.D.	0.83	0.28–1.86	0.05
Interpuff interval (s)			
Mean	15.48	6.94–54.30	1.24
S.D.	19.60	6.96–55.74	1.66
Puff frequency (puff/min)			
Mean	3.95	1.07–6.64	0.21

The large IPI standard deviation is indicative of the highly sporadic nature of the smoking ritual. This likely results from the social nature of cafe smoking: Smokers are normally in the company of others and are engaged in conversation, as well as eating.

3.3. Time-resolved aggregate puff parameters and effect of sampling period

The dynamics of the 52-smoker mean smoking session are illustrated in Fig. 2, where the aggregate averages (Eq. (A5)) of various puffing parameters for 18 successive time intervals are plotted over the first 30 min of smoking. As shown, the early part of the smoking session is characterized by relatively high flow rate, rapid succession puffs of short duration, which appear to correspond to a "light-off" period. The puffing frequency and the flow rate decay, while the puff duration rises to approximately steady values in approximately 8 min. It is notable that the decrease in flow rate is offset by the increase in puff duration in such a manner that the puff volume remains approximately constant from the beginning of the smoking session.

The approximately steady state reached after 8 min indicates that a significantly reduced sampling time could have been used without introducing error in the aggregate mean puff volume, duration, and flow rate. Analysis of time-truncated data showed that the cumulative mean puff parameters, except puff frequency, would have been the same as those reported in Table 1 had the sampling period been reduced to 10 min.

Cumulative aggregate mean puff frequency was found to decay monotonically with sampling period and, for a smoking session of duration $T \geq 8$ min, is well represented by a linear fit

$$\bar{f} = c_0 + c_1 T \qquad \text{p/min} \qquad (T \geq 8 \text{ min}) \tag{1}$$

where $c_0 = 4.78$ (4.64, 4.92), $c_1 = -0.0322$ (-0.0395, -0.0250), and the parenthesis indicate the 95% confidence bounds on the fitted parameter.

3.4. Comparison of 30-min aggregate and longer smoking sessions

Inspection of the smoking sessions that were sampled longer than 30 min showed that there was no qualitative change from the picture presented by the first 30 min of smoking. Puff frequency continued to decay, while the cumulative mean puff volume and duration remained invariant with time ($R^2 < .01$).

We found that extrapolating Eq. (1) beyond $T = 30$ min yielded results that are consistent with the cumulative puff frequencies found for the longer smoking session recordings. It can be seen in Fig. 3 that Eq. (1) falls within the 95% confidence limits of the best linear fit for cumulative puff frequency calculated for the entire duration of each smoking session of length greater than 35 min. It should be stressed that the equation represents the cumulative puff frequency calculated at various elapsed times, for the sample set of 52 smokers, up to $T = 30$ min; it thus represents the evolution of the aggregate mean puff frequency for the entire set of smokers. The linear fit of the data shown in Fig. 3, on the other hand, is derived from the cumulative puff frequency for each smoker, calculated at the end of the STI recording, whose duration varied from one smoker to the next.

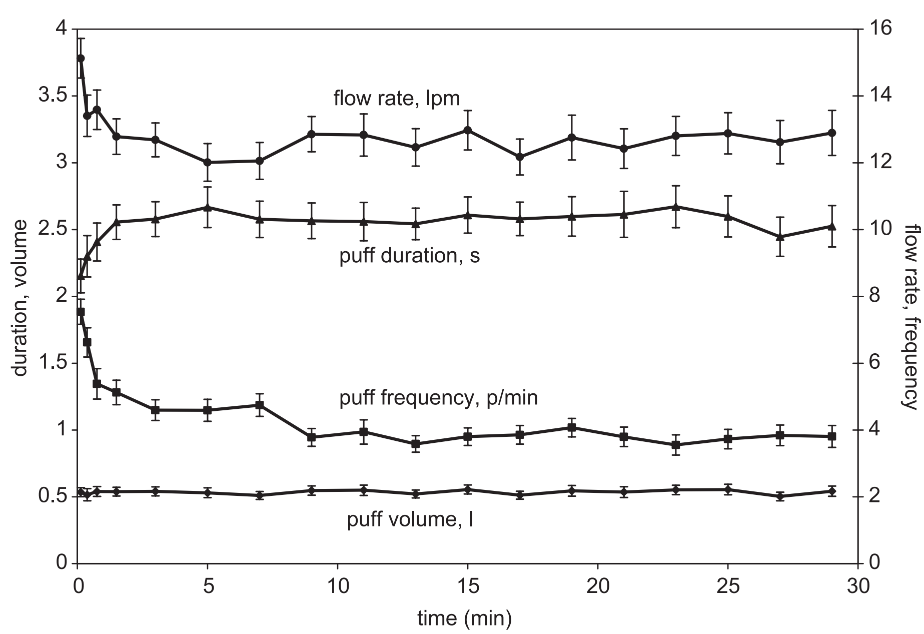

Fig. 2. Interval average aggregate puff parameters (error bars ± S.E.M.) for 52 smokers.

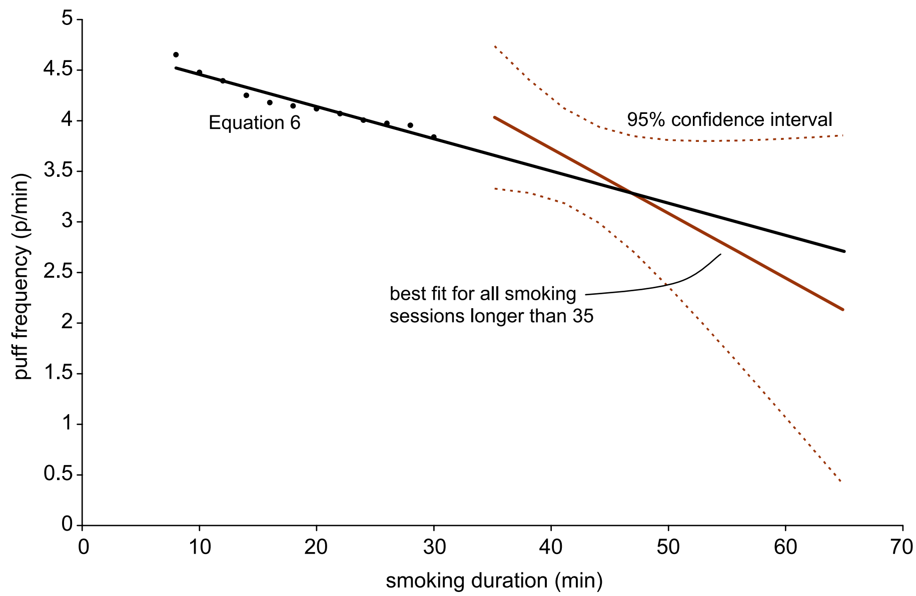

Fig. 3. Comparison of extrapolated trend in puff frequency (Eq. (1)) and best linear fit of cumulative puff frequency evaluated at the end of the STI recording vs. time for all recorded smoking sessions longer than 35 min in duration ($n=40$). Dashed lines indicate 95% confidence interval for the best linear fit.

3.5. Minimum sample size

Using the *t* distribution to estimate the true standard deviation of the means, the number of smoker samples required to achieve a 95% confidence interval, whose magnitude is no greater than 10% of the mean, was calculated, and the results are given in Table 2. As shown, the IPI is the limiting parameter that dictates the minimum number of smokers required to achieve a given precision interval.

The minimum sampling time per smoker needed to achieve these confidence intervals is also given in Table 2. These numbers represent the median of the minimum needed sampling times calculated for each smoker to achieve a 95% confidence with a precision of 10% of the mean value of the parameter under question. As shown, it is impossible to meet the 10% precision criterion for the IPI because the required sampling time of 181 min exceeds the characteristic duration of an entire smoking session.

3.6. Total smoking time

The anonymous observation of 58 smokers yielded a mean smoking session duration of 61 min, with a 4-min S.E.M. This is comparable with the mean smoking duration of 51 min previously determined by the same technique for 28 smokers in coffee shops in Ramallah, Palestine (Shihadeh, 2003).

4. Discussion

This study provides a picture of smoking behavior in a particular setting, a Beirut cafe frequented by university students, derived from STI recordings of partial smoking sessions and extrapolated to an average smoking session duration, which was determined by visual observation. Its limitations include the fact that the smoking sessions were not sampled in their entirety, which would have eliminated the need to extrapolate the puff parameters. Furthermore, possible linkages to observed puffing behavior of such variables as frequency of smoking ("heavy" vs. "light" smokers), nicotine dependence, prior smoking deprivation, use of other forms of tobacco, tobacco flavor, time of day, socioeconomic status of smokers, among others, were not explored. In these respects, we do not know whether the smokers visiting the cafe in this study are representative of cafe smokers, in general, or whether, for example, our sample is skewed by disproportionate numbers of "chip-

Table 2
Samples needed for 10% precision interval at a 95% confidence level for individual smoker and aggregate puffing parameters

Puffing parameter	Puff cycles per smoker	Sampling time per smoker (min)	Required number of smokers
Volume	46	12.5	58
Duration	38	11.0	43
Interpuff interval	722	181.3	129

Median data for 52 smokers.

pers'' or, conversely, nicotine-dependant smokers, whose puffing practices may differ from that of the average cafe smoker. The results of this study should therefore be taken as a snapshot of how narghiles were used in a particular place, time, and population, rather than as a general model of café smoking.

The interval- and cumulative-average puff parameters were found to be remarkably continuous in time and characterized by narrow confidence intervals, as indicated by the error bars of Fig. 2. Together, they provide a well-articulated picture of narghile smoking dynamics described by rapid succession, high flow rate puffs of short duration for the first few minutes, followed by nearly steady puffing afterwards, with a slight but continual decline in puff frequency. Except for puff frequency, all cumulative average smoking parameters would have been the same had the topography sampling time been reduced to 10 min.

Pending a wider study, the results can be used to derive a preliminary model to guide laboratory smoking machine studies of narghile toxicology, keeping the previously mentioned caveats in mind. Using Eq. (1) and the mean session smoking time of 61 min, a mean puff frequency of 2.82 puffs/min is calculated, yielding a session total of $\bar{n} = \bar{f}T = 171$ puffs. For a whole smoking session of duration T, the effective IPI can be inferred as $\overline{\mathrm{IPI}} = \frac{T - \bar{n}\bar{d}}{\bar{n}} = \frac{1}{\bar{f}} - \bar{d}$, where $\bar{d}$ is the aggregate mean puff duration. Utilizing the aggregate mean puff duration and volume given in Table 1, an average smoking session is specified and is given in Table 3.

As noted above, this model signifies a dramatic departure from that of cigarette smoking, with its more than one order of magnitude greater puff volumes, number of puffs, and smoking session duration. It also represents a more intensive smoking regime than that used in the previously cited narghile smoking machine study, which utilized smoking sessions consisting of one hundred 0.3-l puffs of 3 s duration, over a 60-min smoking session. A single smoking machine test was conducted using the current smoking model given in Table 3, in accordance with the methods specified in the cited study, and the total particulate matter (TPM) collected was found to be 1.10 g. This is considerably higher than the 0.40 g previously measured using the original 100 puff smoking protocol, indicating that the current model will likely yield considerably greater tar and nicotine from a single smoking session than previously reported.

Table 3
Representative model of narghile café smoking for laboratory smoking machine studies

Puffing parameter	Recommended value
Number of puff cycles	171
Session smoking time (min)	61
Puff volume (l)	0.53
Puff duration (s)	2.6
Interpuff interval (s)	17

While the proposed narghile smoking model can be used in a manner analogous to the FTC method for cigarette testing, it remains to be shown that programming a smoking machine with a periodic rectangular waveform representation of a real, irregular smoking session yields representative toxicological data. The FTC smoking machine puff protocol for cigarette testing has been widely criticized in the tobacco research community as an unrealistically low-intensity puffing regimen (in terms of puff volume, duration, and frequency) that results in a significant underestimate of the delivery of various toxins to the smoker; but whether adjusting the puff parameters is enough to correct the machine studies is another question. The implications of modeling a real, irregular smoking session as one with uniform puff volume and spacing have not been thoroughly investigated. This question may be particularly important with narghile smoking because its relatively long overall duration and many puffs could lend to significant cumulative errors. We are currently investigating this question by comparing the composition of smoke generated by ''playing back'' the actual recorded smoking sessions to that generated when the smoking machine is programmed with the equivalent periodic (fixed frequency, duration, and volume) sessions.

5. Nomenclature

Variables

d	Puff duration (s)
f	Puff frequency (puffs/min)
IPI	Interpuff interval (s)
n	Number of puffs
N	Number of smokers
$\dot{q}$	Volumetric flow rate (l/min)
SEM	Standard error of the mean
t	Time
T	Sampling period

Subscripts

i	Smoker index
eop	End of puff
sop	Start of puff

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Hewlett Foundation, and the Research for International Tobacco Control Secretariat of the Canadian International Development Research Centre.

Appendix A. Equations used to calculate interval average puff parameters

Mean puff parameters for smoker i over the time interval t_1, t_2 were calculated as follows:

$$\bar{v}_i(t_1,t_2) = \frac{\sum_{n(t_1)}^{n(t_2)} v_{i,j}}{n(t_2)-n(t_1)} \quad \text{puff volume} \tag{A1}$$

$$\bar{d}_i(t_1,t_2) = \frac{\sum_{n(t_1)}^{n(t_2)} d_{i,j}}{n(t_2)-n(t_1)} \quad \text{puff duration} \tag{A2}$$

$$\bar{q}_i(t_1,t_2) = \frac{\sum_{n(t_1)}^{n(t_2)} v_{i,j}}{\sum_{n(t_1)}^{n(t_2)} d_{i,j}} \quad \text{flow rate} \tag{A3}$$

$$\bar{f}_i(t_1,t_2) = \frac{n(t_2)-n(t_1)}{t_2-t_1} \quad \text{frequency} \tag{A4}$$

where for puff j and smoker i, $d_{i,j} = t_{\mathrm{eop}(j,i)} - t_{\mathrm{sop}(j,i)}$ is the puff duration, and $v_{i,j} = \int_{t_{\mathrm{sop}(j,i)}}^{t_{\mathrm{eop}(j,i)}} \dot{q}_i(t)\mathrm{d}t$ is the puff volume. It should be noted that the definition of mean flow rate given by Eq. (A3) is not necessarily equal to the mean of the individual puff flow rates. Eq. (A3) is a preferable definition of mean flow rate because it weighs the mean flow rate by puff volume, rather than treating all puffs equally. For cumulative parameters, the time interval (t_1, t_2) over which the parameter of interest was calculated began at $t_1 = 0$.

Any aggregate mean puff parameter $\bar{p}$ for N smokers was calculated as

$$\bar{p}(t_1,t_2) = \frac{\sum_{i}^{N} p_i(t_1,t_2)}{N} \tag{A5}$$

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