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Investigation of mainstream smoke aerosol of the argileh water pipe

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Abstract

A first-generation smoking machine and protocol have been developed in order to study the mainstream smoke aerosol and elucidate thermal-fluid processes of the argileh water pipe. Results using a common *mo'assel* tobacco mixture show that, contrary to popular perceptions, the mainstream smoke contains significant amounts of nicotine, "tar" and heavy metals. With a standard smoking protocol of 100 puffs of 3 s duration spaced at 30-s intervals, the following results were obtained in a single smoking session: 2.25 mg nicotine, 242 mg nicotine-free dry particulate matter (NFDPM), and relative to the smoke of a single cigarette, high levels of arsenic, chromium and lead. It was found that increasing puff frequency increased the NFDPM but had little effect on nicotine delivery, while removing the water from the bowl increased by several-fold the nicotine, but had little effect on NFDPM. It was also found that the charcoal disk heat source contributed less than 2% of total particulate matter (TPM), and that characteristic temperatures of the tobacco varied from 450 °C nearest the heat source to 50 °C furthest away, indicating that the NFDPM is likely a result of devolatilization rather than chemical reaction, and will thus differ significantly in composition from that of cigarette smoke.

Keywords: Argileh; Shisha; Hooka; Hubble-bubble; Water-pipe; Nicotine; Tar; Tobacco

1. Introduction

A sharp increase in the use of the argileh water pipe has been noted in recent years in south-west Asia and north Africa, particularly among young people (Attah, 1997; Shediac-Rizkallah et al., 2002). The rise in popularity appears to be correlated with the advent on store shelves of an array of fruit-flavored tobacco mixtures, which list "molasses" as a primary ingredient. As the tobacco mixture is smoked, it releases an aroma of caramelizing sugar, similar to that from a cotton candy machine. In this form, the flavored tobacco mixture is popularly known as *mo'assel*, and is contrasted to the more traditional 'unflavored' tobacco, known as '*ajami* which is favored by older generations, especially men.

A widespread perception among smokers, and even physicians (Kandela, 1997), is that the water through which the smoke bubbles acts as a filter, rendering it considerably less harmful than that of cigarettes; this perception may be aided by the fact that the smoke is significantly cooled as it passes through the water bowl and long delivery pipe, adding to its 'smoother' quality. There have been few studies of the health effects on argileh smokers (Macaron et al., 1997; Zahran et al., 1982, 1985; Al-Fayez et al., 1988; Nuwayhid et al., 1998; El-Hakim and Uthman, 1999), and none to determine the chemical profile of the smoke they inhale, or the importance of the physico-chemical processes unique to the argileh. This has left researchers, public health officials and the general public with little information to rank the potential hazards of argileh smoking.

The research described here is a 'first-cut' at developing the methods to characterize the mainstream smoke and important thermal-fluid phenomena of the argileh. Preliminary results using these methods are reported.

Abbreviations: DPM, dry particulate matter; FTC, Federal Trade Commission; gTPM/gTob, grams of TPM per gram of tobacco consumed; TPM, total particulate matter; NFDPM, nicotine-free dry particulate matter; "tar", TPM − (nicotine + water).

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1.1. Smoke formation and transport in the argileh

Plate 1 illustrates the main features of the argileh water pipe. The head, body, bowl and hose are the primary 'elements' from which an argileh is assembled, and each can be purchased separately in standard sizes. The smoker typically presses the fired-clay head onto the metal body, using tissue paper or a rubber fitting at the joint to make a seal. The interface between the body and the glass water bowl, which is typically rinsed and refilled each smoking session, is similarly sealed, as is the interface between the body side-arm and hose. The flexible hose is typically made of leather or other fibrous material, with each end terminating in a hollow wood fitting.

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 tobacco smoke to bubble into the bowl. Depending on the flow rate, the static head of the water is generally the primary flow resistance in the system felt by the smoker. During each puff, air is drawn over and heated by the coals, 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, where, due to hot air convection and thermal conduction from the coal, the mainstream smoke aerosol is produced. Unlike the cigarette, there is practically no visible sidestream smoke rising from the head either during or between puffs.

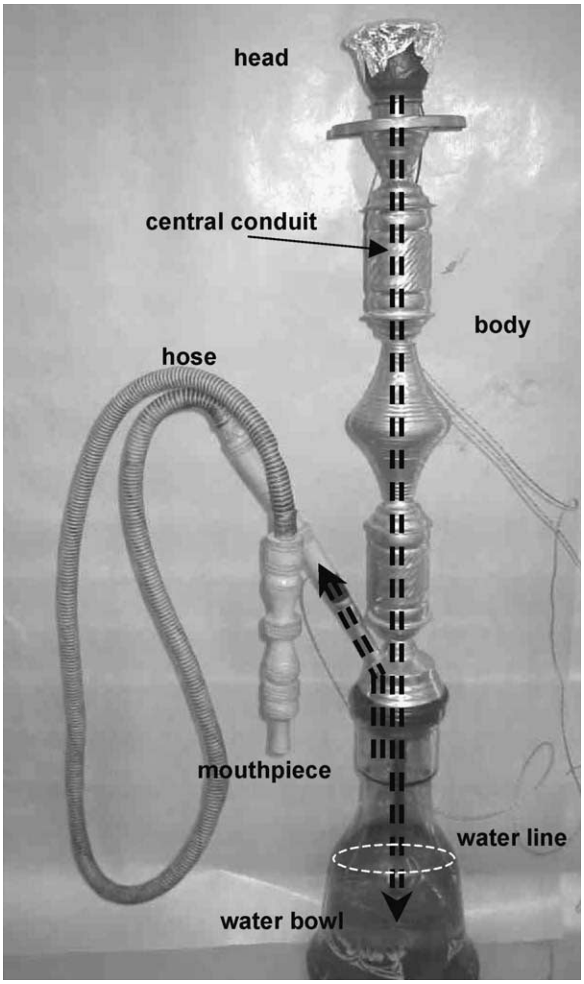

Plate 1. A typical argileh water pipe.

While the argileh body and bowl are manufactured in a variety of sizes, there are two common configurations for the clay head in which the tobacco is placed, depending on whether the smoker is using *mo'assel* or '*ajami* tobacco. When *mo'assel* is used, smokers fill a relatively deep (approximately 3 cm) head with the tobacco mixture (10–20 g), and cover it with an aluminium foil sheet that they perforate (approx. 1 mm diameter holes) for air passage. The already burning coal is placed on top of the aluminium foil, and may be changed a number of times during a particular smoking session. In the second case, that of the traditional *'ajami* tobacco, smokers mix a small amount of water with the pre-shredded and dried tobacco to make a moldable matrix which they then shape into a small mound atop a shallow head. The burning coal is placed directly on the moisturized tobacco, and both are directly exposed to the surrounding air.

In both cases flow passages are located at the base of the clay head to allow the smoke to pass into the central conduit of the body that leads to the water bowl. Owing to its high moisture content, the limited availability of air (particularly with *mo'assel* smoking), and the large heat-conducting surface of the head with which it is in intimate contact, the tobacco does not burn in a self-sustaining manner; it requires the continuous external heat source provided by the wood-derived charcoal. Products of the charcoal combustion are therefore also present in the smoke.

Because of the long path traversed by the smoke as it passes from the head, through the body, to the water bowl, and through the hose to the smoker, there are ample opportunities for gas and particulate phase deposition, diffusion, and evaporation/condensation processes to occur.

2. Materials and methods

2.1. Smoking machine development

The argileh 'puff' can be characterized as a low-resistance inhalation in which a large fraction of the smoker's chest cavity is filled with smoke, corresponding to a volume of the order of 1 l (average tidal air during quiet respiration is about 500 ml for an adult male; maximum air displaced is 3700 ml). This is an order of magnitude greater than the 35-ml puff volume specified by the FTC test method for cigarettes.

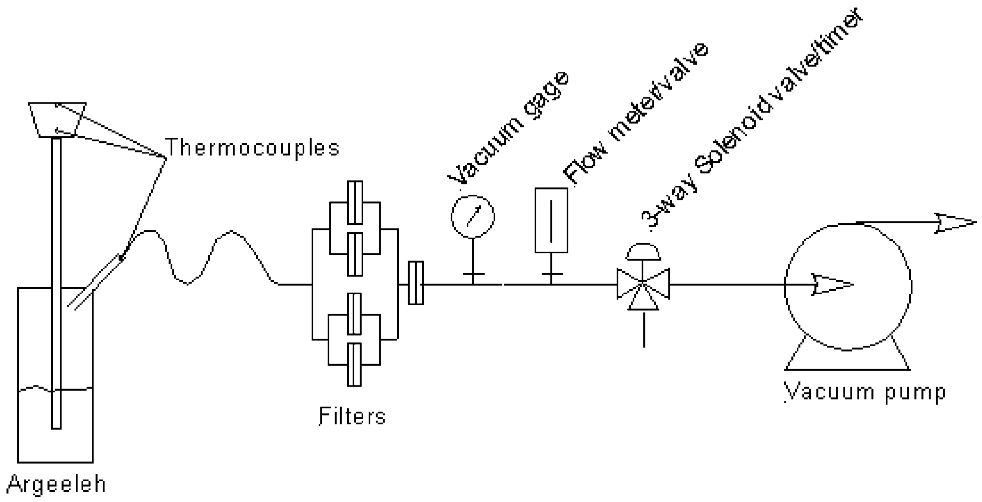

Fig. 1. Schematic of the smoking machine apparatus.

Assuming that the flow can be characterized as quasi-steady during the puff, a simple smoking machine was designed using a high flow capacity vacuum pump and direct action three-way solenoid valve and timer, as illustrated in Fig. 1. The vacuum pump was operated continuously at a flow rate of 6 l/min during each smoking run, with the suction sent either to the argileh or to atmosphere by the solenoid valve, with flow control obtained by a precise needle valve and calibrated rotameter.

As shown, the smoke aerosol was split into four streams immediately downstream of the hose outlet and each stream drawn through a single 47-mm Gelman type A/E glass fiber filter pad before being recombined. Each pad was held in a transparent polycarbonate holder, also manufactured by Gelman. The flows were split to reduce filter loading to approximately 100 mg of smoke condensate per filter for each smoking session. (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 was placed downstream of the 4-to-1 junction and weighed before and after each run to ensure that there was no break-through. All flow lines were made of $\frac{1}{4}$-inch ID transparent Tygon tubing. A vacuum gauge was installed downstream of the filters.

2.2. Temperature measurements

Rapid response Type-J thermocouples of 0.01-in. diameter were installed at several locations: (1) just below the aluminium foil, on top of the packed tobacco; (2) within the tobacco, at a depth of 2.5 cm below the tobacco surface; (3) at the flow outlet of the clay head; and (4) at the inlet to the flexible hose. The data were acquired by a PC at a rate of four sample sets per second via a Pico Technology TIC-08 data acquisition board. To verify that the thermocouples were of sufficiently rapid response to follow the relevant temperature dynamics, a 0.005-in. diameter thermocouple was used in parallel to thermocouple (1) and the signals compared for a limited number of experiments.

2.3. Smoking protocol and operating procedures

In the absence of detailed smoking topography data for argileh users, and to provide reasonable values for the number of puffs, their duration, frequency and volume, a pilot study was conducted in which 28 *mo'assel* smokers were observed anonymously in local coffee shops. Because the glass bowl of the argileh is transparent, the beginning and end of each puff could be observed visually from a distance, and event timing recorded manually with a stopwatch. In addition to recording the puff/rest interval timing, number of puffs, and total smoking session time, the amount of tobacco mixture used to pack the head, and the amount burned during the smoking session was determined with a portable digital scale by measuring the prepared head weight before and after each session, as well as the weight of the smoked head with the tobacco removed. This was done in co-operation with the service staff of the coffee shops who allowed a research assistant to weigh the argileh heads leaving and returning to the service area.

The puff and rest intervals were calculated for each smoking session by summing the respective times over the entire session and dividing by the number of puffs. Each of the 28 smoking sessions was therefore represented by average puff and rest intervals, and number of puffs, and these numbers, in turn, were averaged over the 28 sessions. The results are given in Table 1.

Based on these preliminary measurements, a standard smoking session was defined as 100 puffs, duration 3 s, with 30 s between puffs (i.e. a cycle period of 33 s). The

Table 1
Results of pilot study of argileh smokers ($N = 28$)

	Average	Range	SD
Puff duration (s)	2.77	1.6–4.6	0.6
Rest interval (s)	30.0	10.2–53.9	11.7
Session duration (min)	50.6	19.0–83.9	16.1
Total number of puffs	101.1	50–203	38.1
Tobacco loaded (g)	9.4	6.9–11.7	1.2
Tobacco consumed (g)	3.9	1.8–5.0	0.9

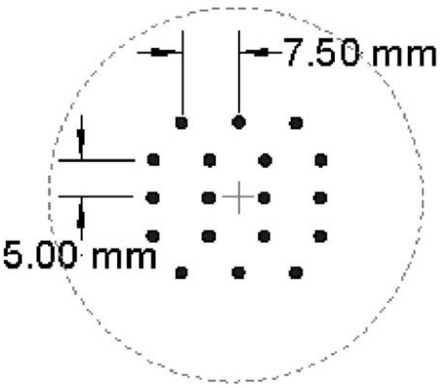

Fig. 2. Aluminium foil perforation pattern used in current study.

experimental puff volume was set to 300 ml, in order to give a similar amount of tobacco burned in 100 puffs to what was found in the field study, using the standard smoking regimen. For comparison, an "accelerated regimen" was also defined in which the interval between puffs was reduced to 15 s, all else being the same.

To standardize the experiments, self-starting charcoal disks manufactured by Three Kings Charcoal Co. (Holland) sold widely in tobacco supply shops were utilized, at a rate of one disk for each 100-puff smoking session. The disks were held by a metal tong with the radial axis of the disk in a vertical plane, and the bottom side exposed for 5 s to the flame of a butane cigarette lighter, and held for an additional 100 s in the same position to ensure that the ignition agent had been entirely consumed before placing the charcoal disk on the argileh head (the reaction front visibly traverses the entire length of the disk in roughly 45 s after lighting). The first puff was initiated 15 s after the disk was placed on the head. One disk, weighing 5.8 g, was used in each smoking session, and its weight recorded before and after each session.

Three 250-g packages of the locally most popular type of *mo'assel* tobacco mixture ("Two Apples" flavor, manufactured by Adel El-Ibiary & Co., Egypt) were mixed together, and large agglomerations and stems removed (accounting for approx. 10% of the as-purchased weight) so as to create a more homogeneous mixture for the experiments. The mixture was parceled into airtight packets of roughly 12 g each, and stored in a sealed container at 20 °C in the dark for the duration of the study. For each smoking run, an individual packet was unwrapped and 10 g of tobacco mixture was loaded into the head, essentially filling it.

A small aluminium foil sheet (approx. 9 cm×9 cm) was used to cover the head, and was perforated according to the 18-hole pattern shown in Fig. 2. Rather than wrapping the foil tautly over the head, enough slack was left to allow an approximately 2 mm depression relative to the head rim to be formed in order to help hold the coal disk in place during the smoking session. It was found that when the foil was wrapped tautly, it tended to form a "drumhead" that vibrated at the bubbling frequency, particularly in the second half of the smoking session, when the tobacco under the foil had become stiff and its vibration-damping properties reduced. This caused the coal to migrate, thereby necessitating periodic intervention during the session to prevent it from marching entirely off the head (it is quite usual for an argileh smoker to adjust the coal during a smoking session). With the depression, the need for intervention was greatly reduced or eliminated altogether, though the bubble-induced vibration remained noticeable.

After each smoking run, the water in the bowl was discarded, the bowl partially re-filled, shaken by hand for several seconds, and discarded again. The bowl was then re-filled with tap water to the water level indicator line (corresponding to a volume of 785 ml). The head was emptied, wiped dry with a paper towel, and re-packed with the prescribed 10 g of tobacco mixture. In keeping with common practice at local restaurants and coffee shops, there was no attempt to clean any of the flow passages within the argileh between runs, though some deposits in the body pipe were visible, with a thickness of the order 0.1 mm.

To further reduce variations between smoking sessions, all flow interfaces—head/body, body/bowl, and sidearm/hose—were externally sealed each smoking session with one layer of electrical tape. In addition, the body and water bowl were joined via a rubber sleeve that was originally supplied with the argileh. The ceramic head fit tightly into the body as supplied with no rubber sleeve.

The apparatus used in this study was obtained from a stock of in-use argilehs at a local popular restaurant frequented by argileh smokers. Some 40 standard smoking sessions were conducted in the lab prior to the first set of nicotine and water determinations. It is expected that aerosol deposition on the various argileh flow surfaces is greater when the apparatus is new than when it is well-seasoned, though this remains to be verified experimentally. The dimensions of the argileh used in the study are listed in Table 2.

Table 2
Argileh dimensions used in current work

Part	Dimension	Measurement
Clay head	Inner depth	3 cm
	Overall inner diameter	4.5 cm
	Number of gas outlet passages	4 cm
Body conduit tube	Length	56.5 cm
	Inner diameter	0.8 cm
	Immersion depth below water surface	4 cm
Hose	Length	155 cm
	Outer diameter	1.5 cm
Water bowl	Overall height	24.5 cm
	Water volume to fill line	785 cm

2.4. Chemical analysis

For each smoking run, the weight of the loaded, foil-wrapped head was recorded before and after each smoking run, as were the filter holders. The smoke condensates from two filter pads were extracted in ethyl acetate and toluene and analyzed by GC–MS to quantify the nicotine concentration according to standard methods (Siegmund et al., 1999). A third filter pad was analyzed for water content using Karl-Fisher titration in which the entire filter pad was introduced directly from the filter holder to the reaction vessel. In addition, for a small subset of cases a metals analysis was conducted by ICP–MS of microwave-digested filter pad in accordance with EPA Method 3051.

TPM was determined gravimetrically as the total weight increase of the filter holder assembly. The nicotine content was determined for filters 1 and 2, and the water for filter 3, and the total nicotine and water condensates collected in a given smoking session were estimated by assuming that the respective analyte scaled linearly with TPM for that session:

$$\text{Total Nicotine} = \text{TPM}_t \cdot [(\text{Nic}_1 + \text{Nic}_2)]/(\text{TPM}_1 + \text{TPM}_2)$$

and

$$\text{Total Water} = \text{TPM}_t \cdot (\text{Water}_3/\text{TPM}_3)$$

where

TPM_i	TPM collected on filter *i*
TPM_t	$\text{TPM}_1 + \text{TPM}_2 + \text{TPM}_3 + \text{TPM}_4$
Nic_i	nicotine on filter *i* as determined by GC analysis
Water_3	water contained in the condensates of filter 3, determined by KF titration

Nicotine-free dry particulate matter (NFDPM) for a given experiment was calculated as

$$\text{NFDPM} = \text{TPM}_t - \text{Total Water} - \text{Total Nicotine}$$

Because the TPM and water content were found to be three orders of magnitude greater than the nicotine, the NFDPM is essentially equal to the DPM.

3. Results

3.1. Temperature

Fig. 3 shows typical temperature profiles during a 100-puff 3/30 standard smoking session, where temperatures ranging from 450 °C closest to the coal to 50 °C at the head outlet were recorded. Each tempera-

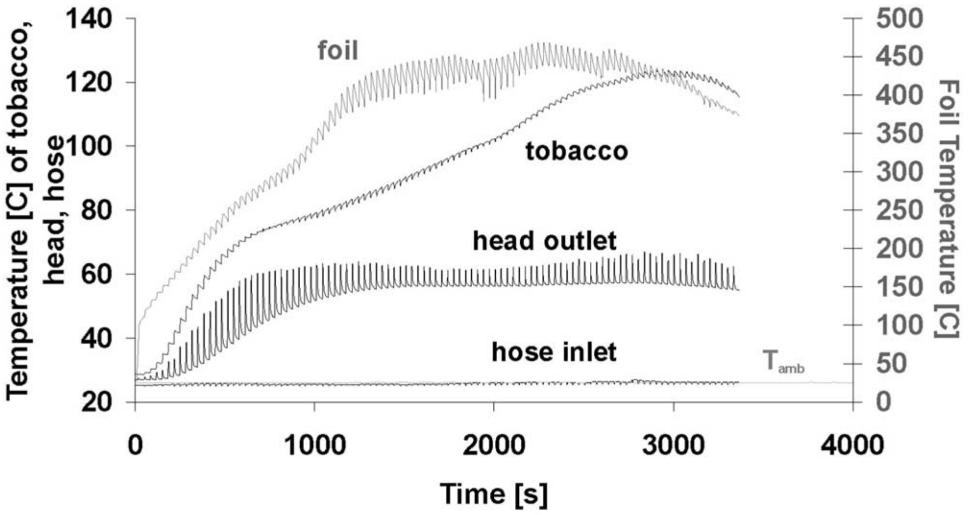

Fig. 3. Temperature profile for a standard smoking session.

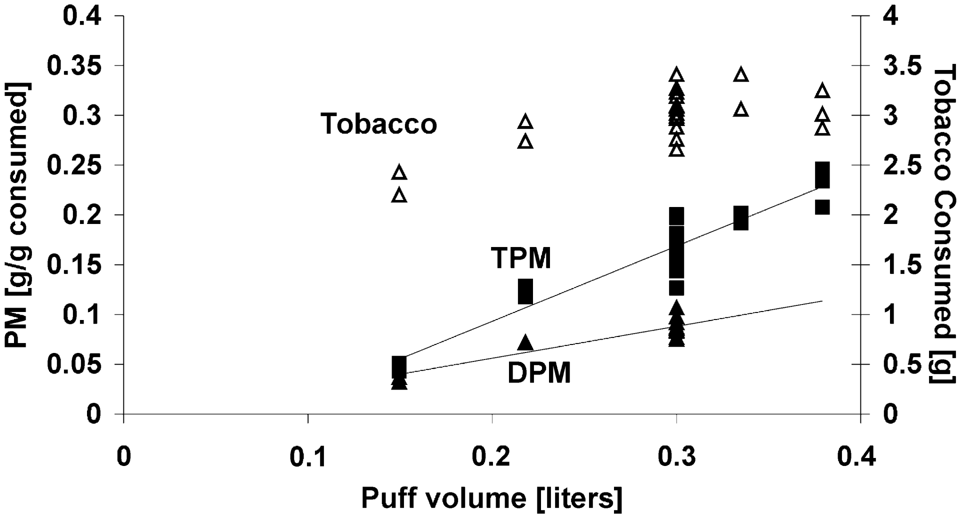

Fig. 4. Effect of puff volume on tobacco consumed and TPM for 100 3-s puffs with 30-s rest intervals. Condition with water in bowl. Lines represent

ture spike corresponds to a puff as air is drawn over the burning coal and into tobacco mixture. Owing to this convective heating, as well as the continuous heat conduction between puffs from the coal to the tobacco (as evidenced by steady-state tobacco temperature of 75 °C in a quiescent burning session with no puffs taken), the mean tobacco temperature continues to rise, peaking near the end of the smoking session, by which time the majority of the coal's chemical energy has been released. It should be noted that the head outlet temperature during puffing is represented by the peaks in the temperature signal; the off-puff temperatures between peaks simply signals the thermal environment of the head outlet while no gases are flowing through it. The puff temperature reaches approximately steady state after 700 s, while the off-puff temperature approximately stabilizes after an additional 500 s, indicating the approach of thermal equilibrium of the clay head.

The foil temperature record also illustrates the puffing cycle, with local temperature maxima resulting from the temporary increase in availability of oxygen to the burning coal, an expected phenomenon in the mixing-limited regimen characteristic of charcoal briquette combustion. Also apparent from Fig. 3 is that by the time the smoke aerosol reaches the hose inlet, it is already at a temperature essentially equal to that of the ambient air; no significant heat transfer occurs in the hose.

3.2. Tobacco mixture consumed

Fig. 4 shows the effect of puff volume on amount of tobacco mixture consumed in a single smoking session.

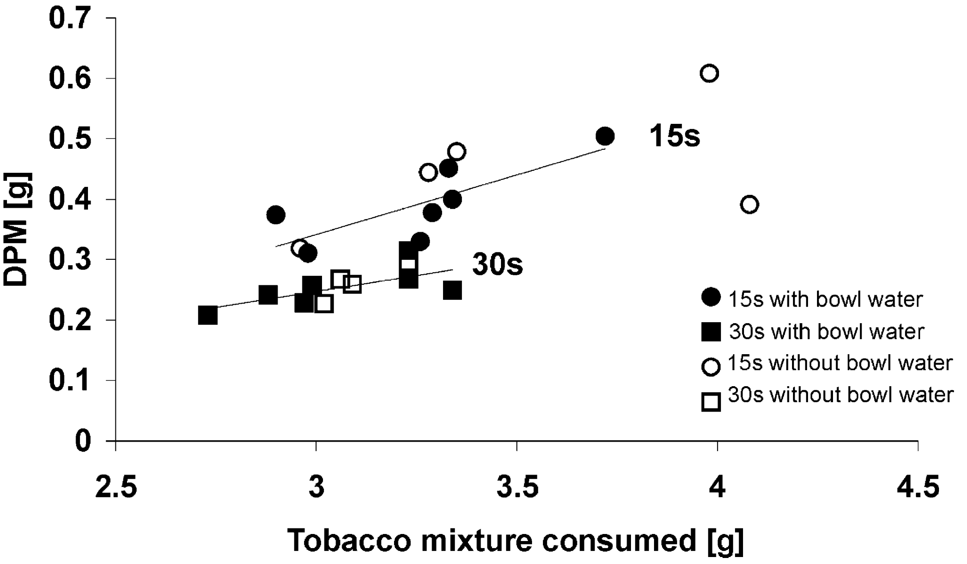

Fig. 5. Effect of bowl water and puff frequency on NFDPM. Empty symbols indicate runs without bowl water; filled symbols indicate runs with bowl water.

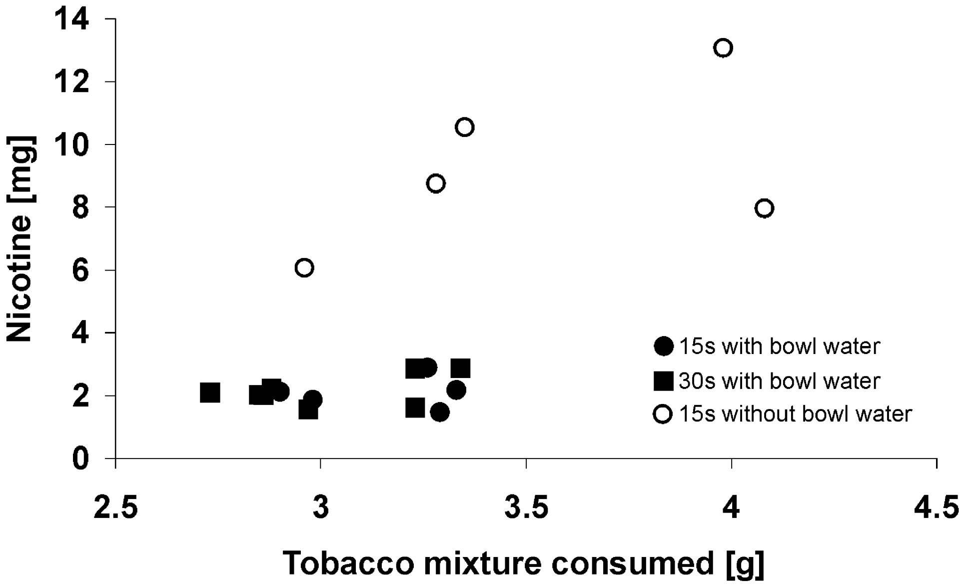

Fig. 6. Effect of bowl water and puff frequency on nicotine.

The positive correlation with puff volume can be attributed to increasing convective mass transfer from the tobacco mixture resulting from (a) the greater bulk transport of scavenging air through the head, and (b) the higher average gas temperature (observed experimentally) which results from the higher combustion rate associated with the increased oxygen availability to the coal.

Table 3
Heavy metals identified in argileh smoke condensate of a standard 100-puff smoking session (ng)

	Argileh	Cigarette
Arsenic	165	40–120
Beryllium	65	300
Nickel	990	ND–600
Cobalt	70	0.13–0.2
Chromium	1340	4–70
Lead	6870	34–85

Values found in a recent review (Hoffmann and Hoffmann, 2000) of previous cigarette smoke studies shown for comparison.

For the 15 smoking sessions run at a puff volume of 0.3 l, the average tobacco mixture consumed was 3.1 g, with a standard deviation of 0.2 g. This compares to the field study mean of 3.9 g and standard deviation of 0.9 g, a difference most likely indicating that the heat release of the single charcoal disk used in the machine smoking was somewhat less than the coals used in actual smoking conditions. The scatter in the data shown in Fig. 4 is likely indicative of irregularities in hand-packing the tobacco mixture into the argileh head, as well as differences in the burning history of the charcoal disk possibly caused by the varying degrees of coal fracture, disintegration, and migration on the head which resulted from its "drumming" at the bubbling frequency. Further, in cases where a significant fraction of the coal disk had disintegrated, some of the ashes were inducted into the tobacco mixture through the breathing holes in the aluminium foil cover of the head, and thus included in the final head weight. A comparison of the final weight of the charcoal disks that

Table 4
Summary of findings—10 g of tobacco mixture, 100 3-s puffs of 0.3 l volume each (standard deviations shown in parentheses)

Condition		Rest interval (s)		
		30	15	15 water removed
Tobacco consumed	[g/session]	3.0 (0.2)	3.3 (0.3)	3.5 (0.5)
Coal consumed	[g/session]	5.2 (0.1)	4.5 (0.1)	4.5 (0.15)
Nicotine	[mg/session]	2.25	2.11	9.29
	[mg/g consumed]	0.761 (0.071)	0.669 (0.161)	2.62 (0.61)
NFDPM ("Tar")	[g/session]	0.242	0.393	0.448
	[g/g consumed]	0.0817 (0.008)	0.120 (0.014)	0.127 (0.024)

remained intact to those that were badly disintegrated by the end of the smoking session indicates that up to 0.1 g of coal ash could be inducted into the head. The weight of the coal, its surface area, and its location on the head are also likely to impact the combustion and heat transfer dynamics.

To account for the variability in amount of tobacco consumed under a particular smoking regimen, and to distinguish this effect from others of interest, the data shown in Figs. 5 and 6 are plotted versus amount of tobacco consumed.

3.3. TPM, NFDPM, nicotine and water

Also shown in Fig. 4 is the increasing production of particulate matter with increasing puff volume. The normalized TPM concentration, calculated as the TPM per gram of tobacco consumed per unit volume of gas drawn through the filter, is approximately constant at 5.6 g TPM/g Tob/m^3, except at the smallest puff volume of 0.15 l, which yields a normalized TPM concentration of 3.2 g TPM/g Tob/m^3. This indicates that in the 0.2–0.3 l-puff volume range, the TPM is determined by how much air is made available to carry it away from the devolatilizing tobacco mixture. At the standard smoking puff volume of 0.3 l, the 5.6 g TPM/g Tob/m^3 corresponds to an average TPM concentration of 17.4 g TPM/m^3, which is of the same order of magnitude as the concentration of 9.25 g TPM/m^3 found for the 1R5F reference cigarette, representative of the "ultra-low tar" category, smoked under the FTC protocol (Bogerding et al., 1997).

In experiments carried out with no tobacco in the head it was found that the TPM collected was up to 7 mg, indicating that the coal disk provides a small contribution to the 400 mg of TPM collected under standard smoking conditions. This is not to discount its potential contribution to the risk posed by argileh smoke, since its chemical composition is unknown and may contain carcinogenic compounds not present in the particulate matter originating from the tobacco.

The effects of puff frequency and the presence of water in the bowl on NFDPM and nicotine are shown in Figs. 5 and 6. As shown in Fig. 5, the puffing frequency was found to be a significant factor with respect to NFDPM, while the presence of water showed no discernible impact at either puffing frequency. In contrast to this, Fig. 6 shows that the nicotine content is strongly affected by the presence of water in the bowl, but not by the puffing frequency. It appears that the water preferentially strips a large fraction of the water-soluble nicotine, though since the water affects not only the smoke aerosol, but also the combustion process via the previously noted bubbling-induced "drumming effect", the conclusion must remain tentative.

3.4. Metals profile

A metals analysis of the filter pads for two standard argileh smoking sessions was performed using ICP, and the results for those considered biologically active are shown in Table 3, except for mercury, which was not determined. For comparison, ranges of typical values are also given for cigarette smoke (Hoffmann and Hoffmann, 2000). As shown, the levels of chromium, cobalt and lead are orders of magnitude greater than produced by a single cigarette.

Arsenic, beryllium and chromium are listed by IARC as Group 1 (known human) carcinogens, while cobalt and lead are listed as Group 2B (possible human) carcinogens (Smith et al., 1997, 2001). Nickel, depending on its form, appears on both the Group 1 and Group 2B lists.

4. Discussion

This study was undertaken to address the dearth of information regarding the composition of argileh smoke and to highlight methods and directions for further investigation. A smoking machine was designed and smoke from an argileh fueled with charcoal and loaded with 10 g of *mo'assel* tobacco mixture was generated using puffing parameters selected to approximate those of argileh smokers. The importance of the argileh water was tested by including a condition where no water was present in the bowl. Limitations of the study include the potential that the puffing parameters may not be representative of argileh smokers and the possibility that varying the charcoal application schedule may influence the results.

The results are summarized in Table 4. While the nicotine produced in a standard smoking session is of similar magnitude to what would be found in a single cigarette, the NFDPM is one to two orders of magnitude greater; that is, a single standard argileh smoking session produces as much "tar" as 20 low-tar cigarettes. This interpretation, however, must taken with caution, as the composition of the NFDPM is likely to be quite different than that for cigarette smoke. Considering that the maximum temperatures found in the argileh head are approximately 450 °C, which is too low to sustain combustion, and considerably lower than maximum temperatures of circa 900 °C found in cigarettes (Wakeham, 1972), it would be expected that a larger fraction of the smoke condensates of the argileh are produced by simple distillation rather than by pyrolysis and combustion, and as a result, would tend to carry considerably less of the pyrosynthesized compounds found in cigarette smoke. Studies of tobacco pyrolysis condensates have demonstrated that tumorigenicity (Wynder et al., 1958) and mutagenicity (White et al., 2001) increase with pyrolysis temperature.

It is quite likely then that the detailed chemical composition of argileh smoke will differ from that of cigarette smoke that is produced at temperatures several hundreds of degrees higher. Thus a more detailed investigation quantifying compounds of biological interest present in the NFDPM of argileh smoke is needed before any conclusions can be drawn about the potential hazards presented by the high levels of NFDPM produced in a single argileh smoking session.

The result that roughly 5 g of charcoal are consumed in a smoking session also points to the need to quantify CO in the smoke, particularly given the fact that much of a charcoal briquette burns in a fuel-rich mode, and that the gases are immediately quenched as they pass from the surface of the coal into the relatively cool tobacco mixture. On the other hand, the particulate phase contribution of the charcoal is minimal on a mass basis.

While the results obtained thus far are valuable as first indications of the magnitudes of the nicotine, NFDPM and metals that can be expected in mainstream argileh smoke, considerable work remains to be done in order to assemble a more comprehensive picture. Apart from more detailed chemical analysis (particularly of the composition of the NFDPM) and CO quantification, the method outlined in this paper requires considerable tuning.

First, a model of a "standard smoking session" based on smoking topography field studies is sorely needed. As shown in this work, both the puff frequency and volume impact the measured TPM. Likewise, investigation into the fluid mechanics of the puffing event is also needed, particularly the degree to which an actual puff deviates from the quasi-steady assumption built into the simple smoking machine described above. In the event that smoking topography measurements indicate that a typical puff flow rate profile is not well represented by this assumption, the on–off solenoid valve can be replaced by a digitally controlled proportional valve that will yield whatever the desired profile, and the impact of various flow profiles at constant puff volume can be quantified.

Of obvious importance in the heat transfer-driven smoke aerosol production process would be an assessment of the role of the charcoal application schedule (mass, timing, geometric configuration), which should be measured in argileh smoking topography field studies. This may be especially important with respect to highly temperature-dependent chemical reaction pathways, and the resulting composition of the smoke aerosol. Likewise, the impact of the mass of tobacco mixture, and the effect of variations in tobacco porosity deriving from how tightly it is packed into the head is also needed. In a similar vein, the aluminium foil perforation pattern (size, number and distribution of holes) may be of significance as it will impact the path of the hot gases through the tobacco mixture.

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