

# A portable, low-resistance puff topography instrument for pulsating, high flow smoking devices

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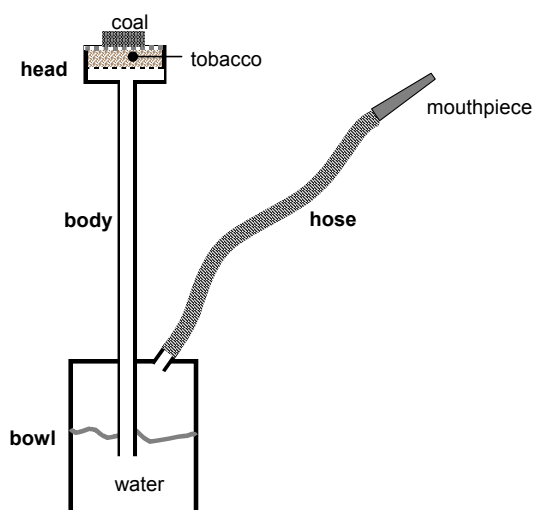
**Abstract** – A smoking topography instrument appropriate for pulsating high flow rate smoking devices such as the narghile water pipe has been developed and tested. Instrument precision and repeatability was determined using a digitally controlled smoking machine, and the added draw resistance due to the topography instrument was measured over the range of expected puff flow rates. The maximum error in any topography variable was found to be less than 5%. The instrument was successfully demonstrated in a pilot field study of 30 volunteer narghile smokers. The pilot study yielded an average smoker puff volume, duration, and interpuff interval of 0.53 l, 2.47 s, 16.28 s, respectively.

**Abbreviations:** slpm = standard liters per minute, STI = smoking topography instrument

This work was born from our study of the toxicology of the “narghile” water pipe, a tobacco smoking device indigenous to Southwest Asia whose use has reached beyond its traditional physical and social borders to include young women and men across the Arabic-speaking world and beyond. Recent smoking machine studies (Shihadeh, 2003) at the AUB Aerosol Research Lab showed that the quantities of “tar” and nicotine delivered to the narghile smoker are strongly dependant 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 accurate models of smoking behavior based on studies of smokers. For similar and other reasons, cigarette smoking topography instruments have been previously developed and deployed to study cigarette smoking (Guyatt et al. 1989; Guyatt and Baldry 1988; Puustinen et al. 1987), but these are inappropriate for the pulsating high-flow rates which characterize water-pipe smoking. This report documents the development of a smoking topography instrument which can be used with the narghile and other pulsating, high flow smoking devices in field studies of smokers in their natural settings.

Conventional cigarette smoking topography instruments utilize an obstruction-type differential pressure flow sensor incorporated into a cigarette holder which is attached to the filter end of the cigarette. As the smoker draws a puff, a pressure differential is generated in the mouthpiece, and the pressure signal is converted to a voltage which is digitized and recorded for subsequent statistical analysis. Common topography measures include puff volume, puff duration, and interpuff interval.

Figure 1 illustrates the main features of the narghile water pipe. When a smoker inhales through the hose, a vacuum is created in the water bowl sufficient to overcome the small static head above the inlet pipe, causing the tobacco smoke to bubble into the bowl.



**Figure 1.** Argileh water pipe schematic

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During each puff, air is drawn over and heated by the coals, some of it participating in the coal combustion. Several large holes in the base of the clay head allow the smoke to pass into the central conduit of the body that leads to the water bowl. The characteristic flow passage diameter throughout the narghile is approximately 1 cm. Unlike the cigarette, there is no well defined point at which the narghile has been consumed; in general, the smoker simply stops when the smoke is no longer appealing, whether due to a change in flavor as the tobacco is consumed, or due to a sense of satiation, or a change in social setting.

From a fluid mechanics perspective, cigarette puffing differs qualitatively from narghile puffing in that the former possesses a relatively low volume/high resistance character. For cigarette topography, this factor facilitates the design of a pressure differential meter because the large existing flow resistance masks any additional flow resistance imposed by a flow sensor. In the case of the water pipe, puffing is akin to a free inhalation, meaning that the smoker can tolerate less of an artificially imposed flow resistance. This compounds the difficulty of obtaining a high signal-to-noise ratio in flow measurement, since the pressure perturbations caused by bubbling can be of the order of magnitude of the pressure differential available for flow measurement.

## METHOD

### Device description

A detailed design and experimental study was undertaken to balance the opposing requirements of a high-flow, low draw resistance sensor, and a high signal-to-noise ratio. Early experiments with hot-wire type mass flow sensors (Honeywell AWM series) showed excellent signal response, insensitivity to pressure pulsations, and low flow resistance, but these were unable to withstand more than 2 smoking sessions before the sensor failed due to the buildup of smoke particulate matter. As an alternative, the traditional pressure differential obstruction meter was pursued, using pulsation dampers to remove the fluctuating components of the signal. The final design utilizes a polycarbonate medical research differential pressure flow sensor (Novamatrix Medical neonatal sensor) in a 50% bypass flow configuration. This bypass ratio provides a workable tradeoff between a higher signal to noise ratio and added flow resistance. The pressure ports of the flow sensor are connected by 1/8-inch flexible Tygon® tubing to a pair of 1280 cc glass pulsation-damping bottles which in turn are connected to an analog differential pressure transducer. The signal output of the pressure transducer feeds to a 22-bit analog to digital data logger, and the logged data can be periodically downloaded through a serial port to a PC. A rechargeable battery and voltage regulators provide the power for the data logger and for pressure transducer excitation. The entire set up fits in a small tool box, and weighs approximately 2 kg. Miscellaneous flow fittings were fabricated from polypropylene. This design was found to be robust, with no required replacement of any of the components for the duration of the pilot study.

As shown in Figure 2, the sensor is incorporated into a typical narghile hose at its point of connection with the water-pipe, far from the mouthpiece. A typical hose is approximately 1 m in length. As such, attachment of the sensor does not impose any modification in smoking method. Unlike the cigarette holder-utilizing topography systems now

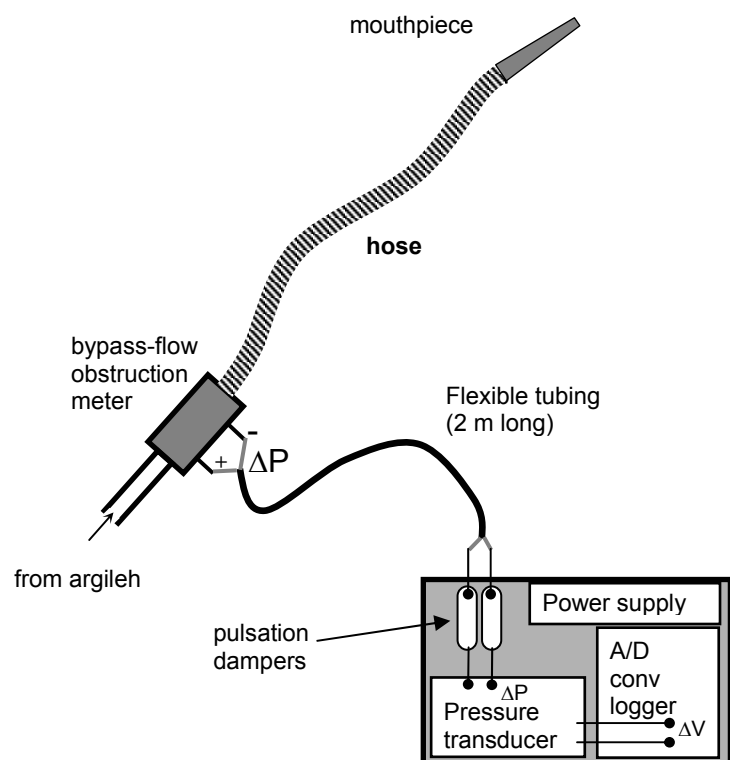


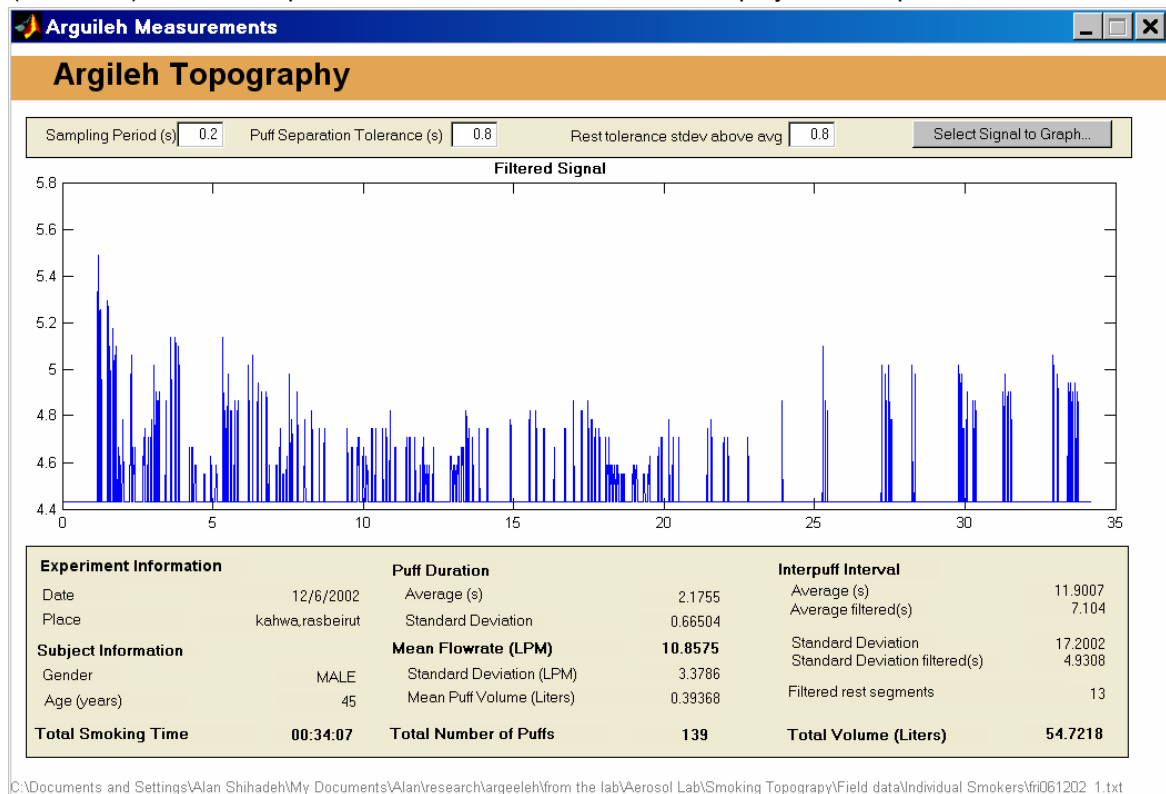
Figure 2. Prototype topography unit (not to scale)

in use, the taste and feel—both in the fingers and on the lips—of the smoking device remain unchanged. It has been found that cigarette holders can influence smoking behavior due to varied sensory effects (Hoefler et al, 1991).

Because the flow sensor is attached to the hose, field data collection requires replacement of the smoker's original hose with the topography unit hose at the beginning of the smoking session. The set-up time is under one minute, making it convenient for field studies of randomly approached smokers.

The logged data, consisting of transducer voltage versus elapsed time, is processed using a Matlab<sup>®</sup> based code which reads the pressure transducer signal and locates the timings corresponding to the beginning and end of each puff. Puff events are defined by deviation of the pressure transducer signal from the zero flow voltage plus a threshold setting to eliminate noise from registering as a puff. In this case the threshold was set equal to the data logger accuracy of 0.039 volts, which corresponds to a sensor flow rate of 1.6 lpm. Other user-input tolerances include a minimum time separation between two puffs to ensure that a stray zero voltage is not read as the end of a puff when it occurs in the midst of one. Negative voltages which occasionally occur at the end of a puff due to transducer bounce are re-assigned to zero. The software includes a graphical user interface (Figure 3) to facilitate use by field workers.

Having determined the beginning and end timings of a given puff, the software calculates the instantaneous puff flow rate  $\dot{q}(t)$  using an experimentally-derived input calibration curve of transducer voltage versus flow rate. Figure 4 shows the highly correlated ( $R^2 > 0.99$ ) flow versus pressure data fitted to a second order polynomial equation.



**Figure 3.** STI graphical user interface. Sample data shown, with each puff appearing as a vertical line whose height is proportional to flow rate. Smoking session statistics are indicated.

The volume of each puff  $i$  is defined as the integral of the volumetric flow rate with

respect to time:  $v_i = \int_{t_{sop(i)}}^{t_{eop(i)}} \dot{q}_i(t) dt$ , where  $t_{sop(i)}$  and  $t_{eop(i)}$  are respectively the times at the start and end of puff  $i$ . The integral is evaluated numerically from the recorded data using the trapezoidal rule, and the mean flow rate for puff  $i$  is then calculated as  $\bar{q}_i = \frac{v_i}{t_{eop(i)} - t_{sop(i)}}$ .

The data from the puff events are stored in an array from which the total number of puffs, the mean puff volume, duration, and inter-puff interval are calculated for a given smoking session.

**Instrument performance testing**

The STI was laboratory tested to determine the additional flow resistance imposed by it on the smoker, as well as its accuracy in terms of several smoking topography parameters: total number of puffs, average puff volume and duration, and average interpuff interval.

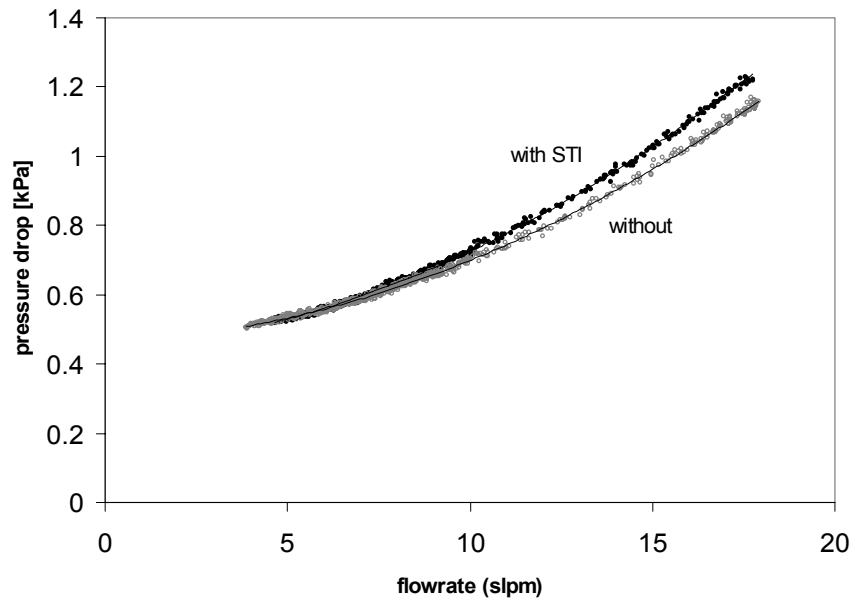
In addition to the laboratory testing, the unit was field tested for its ease of use and volunteer acceptance.

The laboratory tests were carried out using a previously described smoking machine (Shihadeh, 2003), which was upgraded by the incorporation of digital control of the puffing regimen (previously controlled by a solenoid valve and timer) and by the use of a calibrated, analog output electronic mass flow meter (Omega Engineering Model FMA-1608) and data acquisition system. This allowed simultaneous acquisition and subsequent comparison of the STI signal and the smoking machine flow rate. A single smoking machine puffing regimen was made using a constrained random number generator to determine the duration of each puff and rest interval for one hundred consecutive puff cycles. Each puff was randomly assigned a duration ranging from 1.5-4 seconds, followed by a rest time which could range from 5-30 s, in accordance with the values found in the pilot field study. Using this numerically generated puffing regimen, 11 tests were made in which the only variant was the flow rate; it was varied from 6 -18 slpm (nominal) to correspond to the range observed in the pilot study.

The snap-action of the smoking machine solenoid valve gave a nearly instantaneous zero-to-full flow rate (and vice-versa) puffing regimen, and provided a difficult test of STI responsiveness and ability to follow the smoker. Transient response is an issue because the pulsation damping bottles used to smooth the pressure perturbations act in an analogous manner to an RC filter, introducing a system response time constant proportional to their volume. If the bottles are too large, they will introduce an excessive lag, causing an over-estimation of the puff duration; if they are too small, the damping effect will be insufficient to reduce the ratio of fluctuating to mean pressure, and accuracy will be sacrificed.

To determine the additional draw resistance imposed by the STI, a static pressure tap and transducer were fitted to the mouthpiece of the hose, which in turn was attached to a standard size narghile which had been prepared for smoking in accordance with the procedures specified in Shihadeh (2003). The pressure transducer and mass flow meter signals were acquired to a PC as the flow rate was varied from 5 to 20 slpm. The test was conducted with and without the STI installed in order to determine the added draw resistance.

The pilot field study was conducted at a café near the American University of Beirut where the narghile is commonly served. When a café 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 informed consent was obtained, the STI was attached to the narghile upon its delivery by the food server. The STI was then left with the smoker for approximately 40 minutes of unsupervised smoking in the café. Because it is physically unobtrusive (placed



**Figure 4.** Draw pressure versus flow rate for standard argileh with and without the flow sensor attached.

under the table, out of sight), it is expected that the recorded smoking sessions closely resembled the “natural” smoking behavior of the smokers in this common setting. A total of 30 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.

## RESULTS

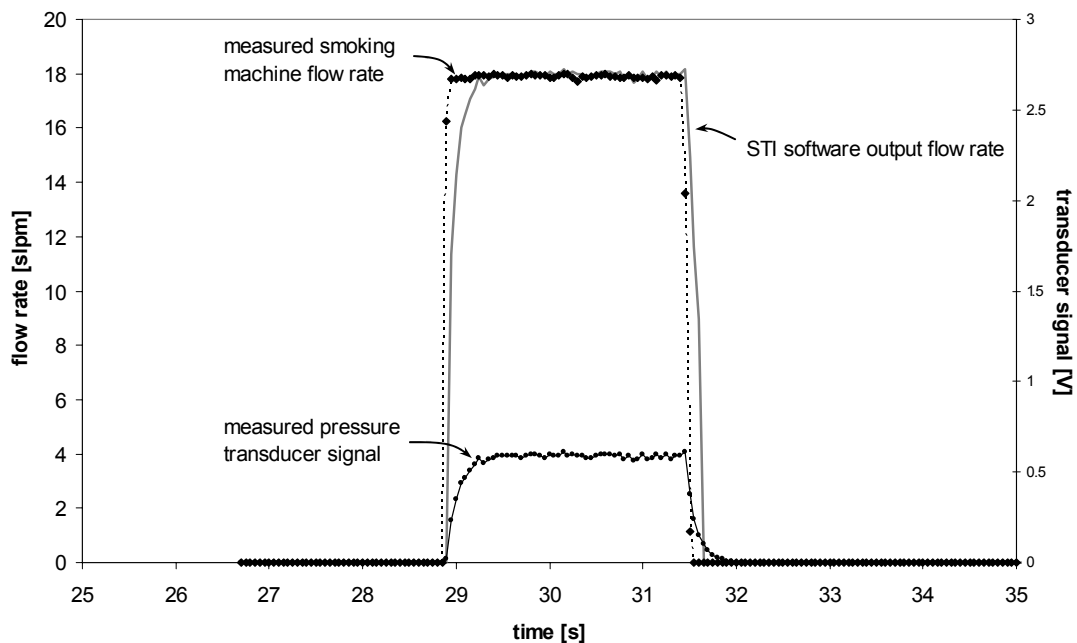
### Flow resistance

As shown in Figure 4, the pressure drop through the narghile with the STI installed was only slightly greater than the base case, with an additional draw pressure of 0.04 kPa (a 5% increase) at the average 13 slpm field-measured flow rate. At the highest flow rate of 20 slpm, the added draw resistance is 0.1 kPa (an 8% increase).

The measurement confirmed that the draw resistance through the narghile is far less than through a cigarette. Tip-ventilated cigarettes at a standard testing flow rate of 1.05 lpm demonstrated pressure drops of approximately 1.2 kPa (Guyatt et al, 1989); at this pressure drop, the narghile provides more than 17 times the flow rate of the cigarette.

### Dynamics and accuracy

Figure 5 shows the smoking machine flow rate, the STI pressure transducer signal, and STI output versus time for a single sample puff recorded in the laboratory using the smoking machine. As shown, the pressure transducer signal exhibits a lagging step response characteristic of first-order systems, and has a characteristic time constant of approximately 100 ms. This is an expected effect of the pulsation dampers, which introduce a large capacitance in the pressure domain. This response lag, in turn, leads to over-estimating the puff duration (particularly the time corresponding to the end of puff), and under-estimating the flow rate in the early portion of the puff, as can be seen by comparing the “smoking machine” and “software output flow rate” curves. Fortunately, the two effects tend to cancel when calculating the puff volume.



**Figure 5.** Smoking machine, STI, and pressure transducer output signals for a single puff.

Also noticeable in Figure 5 is the relatively large signal-to-noise ratio of the transducer, providing reasonable accuracy in calculating the instantaneous flow rate from the

flow calibration equation. Without the dampers, the pulsating and mean pressure signals were found to be indistinguishable.

Table 1 shows the tabulated results of the random machine smoking sessions at varying flow rates. The STI showed a maximum absolute error of 4.5% in puff volume and duration. The puff volumes, durations, and interpuff intervals of the repeated tests 4 through 10 yielded a coefficient of variation of less than 1%.

### Pilot field study

More than 85% of the approached candidate volunteer smokers were willing to have the STI attached to their narghile and participate in the study. On two occasions volunteer smokers complained of a strong residual flavor in the pipe from a previous smoking session, and aborted the test shortly after starting. It was noted that the previous smoking sessions had used a rose-flavored tobacco, which apparently produces a discordant aroma when followed by the more common fruit-flavors (apple, cherry, and strawberry). According to the café food servers, this is a common complaint which is normally resolved by replacing the narghile hose. The data from these sessions was 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 smoking sessions were recorded, the STI was left overnight connected to a compressed air line to reduce build up of the aromatic smoke particulates from day to day.

**Table 1.** Comparison of smoking machine and STI determined smoking parameters for thirteen smoking sessions. Shading indicates repeated trials. The same stochastic puffing routine was utilized for all tests except 2 and 3.

| Test | Puff volume, l |      |         | Puff duration, s |      |         | Interpuff interval, s |       |         |
|------|----------------|------|---------|------------------|------|---------|-----------------------|-------|---------|
|      | machine        | STI  | error % | machine          | STI  | error % | machine               | STI   | error % |
| 0    | 0.23           | 0.23 | 0.0     | 2.50             | 2.52 | 0.8     | 19.10                 | 19.09 | -0.5    |
| 1    | 0.39           | 0.40 | 2.6     | 2.48             | 2.59 | 4.4     | 19.13                 | 19.02 | -0.6    |
| 2    | 0.41           | 0.42 | 2.4     | 2.53             | 2.49 | -1.6    | 17.65                 | 17.69 | 0.2     |
| 3    | 0.54           | 0.55 | 1.9     | 3.45             | 3.37 | -2.3    | 17.70                 | 17.80 | 0.6     |
| 4    | 0.55           | 0.54 | -1.8    | 2.51             | 2.55 | 1.6     | 19.09                 | 19.06 | -0.2    |
| 5    | 0.55           | 0.55 | 0.0     | 2.53             | 2.55 | 0.8     | 19.08                 | 19.06 | -0.1    |
| 6    | 0.55           | 0.55 | 0.0     | 2.52             | 2.56 | 1.6     | 19.09                 | 19.06 | -0.2    |
| 7    | 0.55           | 0.55 | 0.0     | 2.51             | 2.55 | 1.6     | 19.10                 | 19.06 | -0.2    |
| 8    | 0.56           | 0.55 | -1.8    | 2.54             | 2.55 | 0.4     | 19.07                 | 19.06 | -0.1    |
| 9    | 0.55           | 0.54 | -1.8    | 2.53             | 2.54 | 0.4     | 19.08                 | 19.06 | -0.1    |
| 10   | 0.56           | 0.55 | -1.8    | 2.54             | 2.55 | 0.4     | 19.07                 | 19.06 | -0.1    |
| 11   | 0.67           | 0.64 | -4.5    | 2.55             | 2.53 | -0.8    | 19.06                 | 19.09 | 0.2     |
| 12   | 0.77           | 0.75 | -2.6    | 2.61             | 2.51 | -3.8    | 19.01                 | 19.09 | 0.4     |

Results from the pilot study are given in Table 2. While the mean puff duration of 2.47 s is comparable to the 1-2.4 s range previously reported for cigarette smokers (USDHHS 1988), the mean puff flow rate of 12.9 lpm (215 ml/s) is more than one order of magnitude greater than the FTC method's 17.5 ml/s, resulting in a mean puff volume 16 times larger. The mean interpuff interval of 16.4 s falls just under the previously reported range of 18-64 s for cigarette smokers (USDHHS 1988). The large interpuff interval standard deviation is indicative of the sporadic nature of the smoking ritual. Inspection of the session recorded in Figure 3, for example, reveals long rest periods punctuated by closely spaced puffing events.

It is interesting to note that at the mean smoker peak flow rate of 20.9 lpm, the expected narghile draw pressure is 1.3-1.4 kPa based on extrapolation from the data given in Figure 4, approximately the same as that measured in previous cigarette puff topography experiments. This could indicate some intrinsic limit, across smoking delivery methods, in the maximum smoker draw pressure.

**Table 2.** Pilot study results. *N=30 smokers, each sampled for approximately 40 minutes of unsupervised smoking in a local café. Smoking time and number of puffs reflect those measured during the 40 minute trial; most smokers continued smoking after STI was removed. All participants were smoking in the mo'assel narghile configuration (see Shihadeh 2003 for narghile typologies).*

| Parameter                                 | mean  | min   | max   | st. dev. |
|---|-------|-------|-------|----------|
| Smoking time, m:s                         | 39:20 | 29:54 | 53:33 | 5:21     |
| Number of puffs                           | 137.1 | 44    | 226   | 51.7     |
| Smoker mean puff duration, s              | 2.47  | 1.22  | 4.52  | 0.77     |
| Smoker mean puff volume, l                | 0.53  | 0.15  | 1.11  | 0.22     |
| Smoker mean puff flow rate, lpm           | 12.9  | 5.57  | 16.16 | 2.58     |
| Smoker peak flow rate, lpm                | 20.31 | 10.47 | 28.98 | 4.28     |
| Smoker mean interpuff interval, s         | 16.28 | 7.06  | 34.11 | 8.28     |
| Smoker interpuff interval standard dev, s | 23.49 | 6.95  | 70.83 | 15.53    |

## DISCUSSION

A portable smoking topography unit appropriate for high flow rate water pipe smoking has been demonstrated in laboratory and field testing. The additional draw resistance of 0.1 kPa at the peak flow rate of 20 lpm imposed by the STI on the smoker is within the range of draw resistances resulting from normal variations in water pipe design and preparation which are routinely tolerated by smokers. For example, water height in a given narghile can vary by 2 cm from one smoking session to another, causing a change in draw resistance of 0.2 kPa. Other factors such as the degree to which the tobacco is packed in the head, the geometry of the flow passages, and the method of application of coals to the head are also expected to provide variations in draw resistance from one smoking session to another.

The instrument demonstrated a degree of precision and overall accuracy acceptable for use in field studies of water pipe smokers, and demonstrated a reasonable trade-off between responsiveness and accuracy. The maximum recorded error was 4.5% in any smoking parameter. Some improvement in detecting the end of a puff (and therefore in the puff volume and duration calculations) may be realized by sensing the end of the puff by the slope of the pressure transducer signal rather than its magnitude.

The pilot study showed a high acceptance rate among approached candidate volunteers, indicating that the device was not overly cumbersome as configured and packaged. Smokers indicated that they sensed no difference when smoking through the STI. The tabulated results from the field study showed that narghile smoking involves much higher flow rates and puff volumes than cigarette smoking and differs to a lesser degree in interpuff interval and puff duration.

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