RESEARCH PAPER

Ultrafine particle emissions from waterpipes

Ch Monn, Ph Kindler, A Meile, O Brändli

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Objectives: Ultrafine particle emissions from waterpipes and their impact on human health have not been extensively studied. The aim of this study was to characterise the inhalation pattern of waterpipe smokers, and (a) construct apparatus to simulate waterpipe smoking in the laboratory, and (b) characterise mainstream emissions from waterpipes under different smoking conditions.
Methods: Real life waterpipe smoking patterns were first measured with a spirometer. The average smoking pattern was then mechanically simulated in apparatus. Total particle number concentrations were determined with a condensation particle counter (CPC) for particles between 0.02 μm and 1 μm (P-Trak UPC, Model 8525, TSI) and the particle size fraction was determined with a differential mobility analyser (DMA) for particles from 0.01 μm to 0.5 μm. This instrument was coupled with a laser particle spectrometer for particles between 0.35 μm and 10 μm (Wide Range Particle Spectrometer, Model 1000XP, MSC Corp). Carbon monoxide levels were determined with an electrochemical sensor (Q-Trak monitor, Model 8554, TSI).
Results: The tidal volume of an average waterpipe breath of 5 seconds was found to be 1 (SD 0.47) litre. The intervals between breaths on average were 25.5 (SD 10.2) seconds. Particle number concentrations of ultrafine particles in mainstream smoke during waterpipe smoking ranged up to 70×10^9 particles per litre. The median diameter of the particles in a full smoking set with charcoal, tobacco and water was 0.04 μm. Smoke from the heated tobacco contributed to particles in the size range between 0.01 μm and 0.2 μm. The glowing piece of charcoal only contributed to particles smaller than 0.05 μm.
Conclusions: Waterpipe smoking emits large amounts of ultrafine particles. With regard to particle emissions, smoking waterpipes may carry similar health risks to smoking cigarettes.

See end of article for authors' affiliations

Correspondence to: Dr Christian Monn, State Secretariat for Economic Affairs (SECO), Work and Health, Stauffacherstrasse 101, 8004 Zürich, Switzerland; christian.monn@seco.admin.ch

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In Swiss restaurants, lounges and bars, cigarette and tobacco smoking is very common. Despite the fact that the majority of the population are non-smokers, smoking in these venues is determined by local laws and individual policies. Generally this involves providing a smoke-free area and smoke-free tables. Federal labour legislation requires employers to protect their employees from secondhand smoke at the workplace "if the circumstances offer such opportunities." So far, only two counties in Switzerland have banned smoking in restaurants.

The health effects of cigarette smoking have been characterised in a large number of studies over the past decades.[1 2] Smoking is a very significant source of indoor fine and ultrafine particles.[3] Several studies have shown that particulate matter ($PM_{2.5}$) levels in homes of smokers are higher than in homes of non-smokers.[4] Moreover, a strong relation between $PM_{2.5}$ levels in the air and the number of cigarettes smoked was found.[5] In the past decade, more sophisticated instruments have been applied to monitoring real time concentrations of ultrafine particles. Interest has shifted from mass per volume of air to particle numbers per volume of air in specific particle size ranges—mainly in the range of ultrafine particles smaller than 0.1 μm. The principle of light scattering coupled with a condensation counter allows these instruments to detect particles down to sizes of 0.01 μm.

In Switzerland, waterpipe smoking has become popular in recent years, especially among 18–30-year-olds. A large number of lounges and bars now have waterpipes available to smoke. In the Middle East and Africa waterpipe smoking has a long tradition. However, scientific data about the emissions and risks from waterpipe smoking are sparse. Shihadeh *et al* assessed the chemical composition of waterpipe particles for the first time.[6–8] This group also studied breathing patterns of waterpipe smokers. Some health consequences of smoking waterpipes are also addressed by Knishkowy.[9] An important difference between cigarette and waterpipe smoking is the combustion: in a cigarette, tobacco burns at several hundred degrees Celsius, while in a waterpipe, tobacco is heated by a piece of ember beneath it at temperatures less than 200℃. In addition, a filtration and cooling of smoke takes place in the waterpipe.

This study aimed to characterise mainstream smoke emissions from waterpipes during different smoking settings. Of primary interest was obtaining information about the particle number concentrations and the particle sizes. Therefore, we constructed smoking apparatus that simulated waterpipe smoking mechanically according to real smoking patterns of waterpipe users.

METHODS

Set-up of a waterpipe

Figure 1 shows the set-up of a waterpipe. The head consists of a piece of charcoal, a piece of metal sieve, flavoured tobacco, a clay bowl and a tray. The air connections consist of a metal stem and a flexible hose with a mouthpiece. A water bowl is filled with water.

Spirometer

Breathing patterns of waterpipe smokers were measured during real smoking sessions. A spirometer (Vitalograph Compact, Series 42.000) was connected to the outlet hose of the waterpipe to detect breathing patterns. The instrument was modified in order to record the air flows continuously on a graphical writer. Measurements of the air flow could be performed without a significant resistance to the air stream and without disturbance to the waterpipe smokers.

Abbreviations: CPC, condensation particle counter; DMA, differential mobility analyser; PM, particulate matter; WPS, wide range particle spectrometer

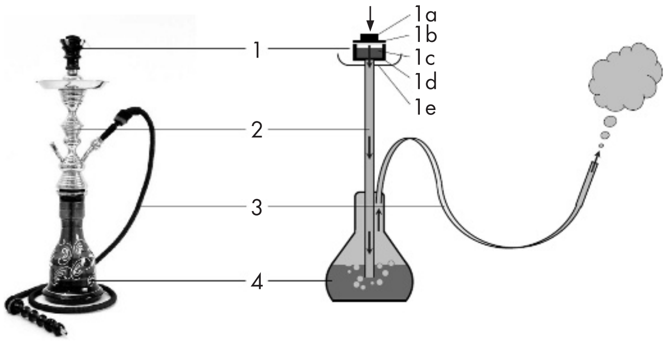

Figure 1 Set-up of a waterpipe: (1) head, (1a) charcoal, (1b) metal sieve, (1c) flavoured tobacco, (1d) clay bowl, (1e) tray; (2) metal stem; (3) flexible hose with mouthpiece; (4) water bowl.

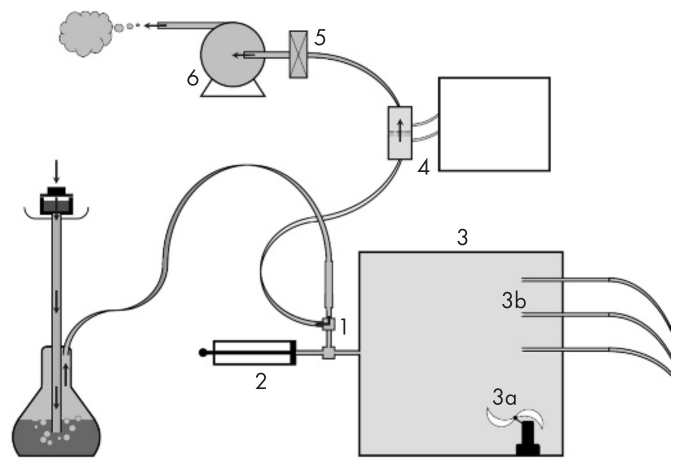

Figure 2 Experimental set-up of the mechanical smoking apparatus and the chamber. (1) Hose connection piece with manifold. (2) Hand syringe (volume 1 litre). (3) Chamber (113 litres) (a) ventilator, (b) sensors. (4) Flow meter, (5) filter, (6) pump.

Analysis of smoke in a chamber and smoking procedures (fig 2)

An identical smoking procedure was used in all experiments. The waterpipe was prepared by placing a glowing piece of charcoal onto the metal sieve above the tobacco in the clay bowl. Then, air was sucked through the pipe by two mechanisms (by turning the manifold (1) into the appropriate position): (a) A mechanical (automatic) pump sucked air through the waterpipe and the extracted air was exhaled into the laboratory exhaust, and (b) a volume of 1 litre was extracted manually from the pipe with a hand syringe. (2) This air was immediately injected into the chamber (3) for analysis. During analysis in the chamber, procedure (a) continued to smoke the waterpipe. Using this procedure, every tenth breath of the pipe was analysed during a waterpipe session.

Detailed protocol of the procedure:

- Tobacco was placed into the clay bowl and apparatus was prepared for smoking
- A piece of charcoal was ignited in a separate laboratory hood, the glowing piece (ember) was then placed onto the metal sieve (1a, 1b) on the head of the waterpipe.
- In the first 3 minutes, the mechanical pump ''smoked'' the pipe by sucking air through the pipe every 30 seconds (with a duration of 5 seconds). Exhaled air was directly transferred into the laboratory exhaust and therefore removed from the laboratory.
- After 3 minutes, a volume of 1 litre was extracted from the pipe with a hand syringe (duration 5 seconds); this air parcel was immediately injected into the chamber for analysis (duration of the entire procedure: 10 seconds). The air in the chamber was well mixed by a ventilator. Monitoring sensors detected the concentrations continuously.
- The mechanical pump continued to take breaths through the pipe every 30 seconds. The air volume drawn through the pipe was directly exhaled into the laboratory exhaust. After 2 minutes, the air in the chamber was removed by opening the roof of the chamber. During this time, particle and carbon monoxide (CO) sensors recovered and pollutant levels inside the chamber decreased to background levels. After 2 minutes, the chamber was closed again and was ready for the next air injection. Additional injections into the chamber would have resulted in concentrations above the upper detection limits.
- Again, a volume of 1 litre was extracted from the waterpipe by the hand syringe and transferred into the chamber. In the meantime, the mechanical apparatus kept on ''smoking'' the pipe, as described above.
- After 50 minutes, the waterpipe session ended.

All experiments were repeated at least three times. Different smoking sets were tested: a full smoking set (with charcoal, tobacco, water), and a set without tobacco (with charcoal and water). In the experiments with the wide range particle spectrometer (WPS), the repeatability between the same setting of experiments was $\pm$18% (first experiments) and $\pm$13% (second experiments). For the total particle number (determined with a condensation particle counter CPC, P-Trak) the standard deviations between the experiments are indicated in table 2.

Tobacco and charcoal

Tobacco with a double apple aroma was commercially bought from Naklha Tobacco Company. It is the most popular tobacco for waterpipes in Switzerland. Tobacco for waterpipes contains glycerol. In the experiments, 8 g of tobacco were placed on the clay bowl. The consistency of the tobacco is uneven and rough. Charcoal used was of the Swift Lite type. The diameter was 3.3 cm.

Monitoring equipment

Ultrafine particles were measured with a CPC for particles between 0.02 μm and 1 μm (P-Trak UPC, Model 8525, TSI). Particle size distributions were determined with a Differential Mobility Analyser for particles between 0.01 μm and 0.5 μm, connected to a laser particle spectrometer for particles between 0.35 μm and 10 μm (WPS Model 1000XP, MSC Corp). Carbon monoxide concentration was determined with an electrochemical sensor (Q-Trak monitor, Model 8554, TSI).

Table 1 Spirometery data obtained from analysis of real life smoking pattern

	Tidal volume of an inhalation breath (litres)	Duration of a breath (seconds)	Interval duration between breaths (seconds)
Median	1.0	5.0	25.5
SD	0.47	2.4	10.2
Number	565	565	565

Table 2 Comparison between waterpipe and cigarette particle emissions (number of total particles and carbon monoxide per breath)

	Total number of ultrafine particles (0.02 to 1 μm)	Carbon monoxide (mg)
Waterpipe	$74.4\ (16.3)\times10^9$	1.79 (0.61)
Cigarette	$9.24\ (-1.2)\times10^9$	1.06 (0.50)

Mean values (SD). Differences between waterpipes and cigarettes were significant for particles (*t* test, $p<0.001$) and CO (*t* test, $p<0.01$).

RESULTS

Real life smoking patterns in a restaurant of waterpipe smokers were analysed with a spirometer linked to a waterpipe hose. The tidal volume of inhalation breaths and the temporal sequences of smokers were recorded (table 1). A total of 565 breaths from the 11 smokers was statistically analysed. An average tidal volume of 1.0 litre (SD 0.47) was found. The duration of one breath was, on average, 5 seconds. The interval between breaths was 25 seconds. Eleven smokers (eight males, three females) were included in this study. On average, they were 26 years old.

All further protocols of the experiments with apparatus were based on these observations. The tidal volume of the breaths was set at 1 litre, the duration at 5 seconds and the intervals between breaths was set at 25 seconds.

Total particle numbers and CO in mainstream smoke during a waterpipe session

Table 2 depicts a comparison between the total number of particles (0.02–1 μm) and CO in one breath from a waterpipe and in one breath of a cigarette. Note that the breathing volume of the waterpipe is 1 litre and for the cigarette only 0.045 litres.[10] A full session of a waterpipe consists of about 100 breaths (most often smoked by more than one person) compared to about 11 breaths of a cigarette.[10] The total number of ultrafine particles was higher in a 1 litre breath from a waterpipe than in one breath from a cigarette (with a volume of 45 ml only)—but the particle number concentration was higher in the cigarette. For CO, the amount in each breath was of a similar scale. A waterpipe session lasts about 50 minutes—with a total of almost 100 inhalations. In most cases, waterpipes are shared between several people, so that the number of inhalation breaths is smaller.

Figure 3 depicts the temporal profile of the total number of particles in 1 litre of air in a breath over a waterpipe session. The points represent mean values from the three sessions.

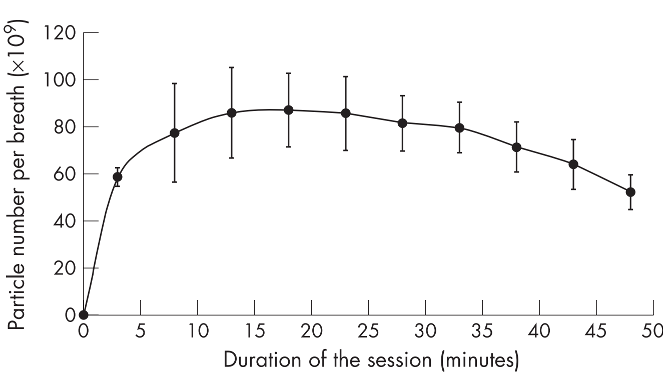

Figure 3 The average of the total number of particles ($\times10^9$) in the air volume of individual breathes (1 litre) is shown on the y axis. Each tenth inhalation was analysed. Measurements were performed with a P-Trak for particles between 0.02 μm and to 1 μm (average of three sessions).

A maximum particle number of 8.5×10^{10} particles were observed in the fourth breath analysed. The particle number per breath remained stable over the next 15 minutes and then decreased by the end of the session after 50 minutes. A similar shape of the curve was found in all other experiments. These experiments show that maximum particle emission occurs after 15 minutes of a session. A temperature profile measured inside the clay bowl indicated that the temperature rose from 20℃ to 100℃ in the first 10 minutes. After 25 minutes a maximum of 160℃ was recorded, while at the end of the session the temperature fell to 140℃. Overall, the tobacco was heated to temperatures between about 100℃ to 160℃.

Particle size distribution in the mainstream smoke of waterpipes

Particle size distributions of mainstream smoke from different experiments are shown in figure 4. In experiments with a full smoking set (including charcoal, tobacco, water) a particle size range between 0.01 μm and 0.2 μm was observed. The median particle size (geometric mean of different experiments) was 0.04 μm. In independent experiments with charcoal and water only, mainly particles smaller than 0.05 μm were observed. This indicated that the ember contributed mainly to emission of particles in the very finest particle fraction. The contribution of the heated tobacco covered a wider size range up to 0.2 μm. In order to compare waterpipe smoke with emissions from a cigarette, mainstream cigarette smoke was extracted from a burning cigarette and injected into the chamber (volume of the extraction: 0.045 litre). The particle size profile is also included in figure 4. It shows that the size range was between 0.15 μm and 0.5 μm, being larger than the particle sizes of the waterpipe experiments.

DISCUSSION

Our experiments showed that waterpipe smoking emits large number of ultrafine particles. Three factors are involved in particle emissions: the charcoal with its igniting and glowing process, the heating of the tobacco (including the melting of glycerols) and the effect of water. The ember mainly contributed to particle emissions of sizes smaller than 0.05 μm, while the melting process of the tobacco contributed to particles between 0.02 μm and 0.2 μm. Additional experiments showed that ignition of the charcoal is a major source of ultrafine particles. In comparison with particles emitted from cigarettes, waterpipe particles were even smaller in size.

Some important differences in the breathing patterns of waterpipe smokers between smokers in the Middle East and in our study were found. In the study from Shidadeh *et al* the tidal volume of smokers was 0.53 litres, the duration was 2.6 seconds and the interval between breaths was 17 seconds.[6] In our study the volume was 1 litre, the duration 5 seconds and the interval between breaths was 25 seconds (see table 1). Waterpipe smoking has been a cultural tradition in the Middle East for much longer than in Europe and therefore the smoking patterns are different. Breathing patterns in the study from Shidadeh were shorter and the tidal volumes were smaller—but the interval between breaths was also shorter. Overall, in considering these differences, the inhaled volume per minute was quite similar in both studies (2.09 litres in Shidadeh, 2.0 litre in this study). With respect to the particle deposition in the respiratory tract, such differences have to be considered in risk assessments.

A limitation of our experiments was that mainstream air was transferred into a chamber for analysis. Technical circumstances (for example, upper detection limit) did not allow direct in situ detection of the smoke. Therefore, coagulation, deposition and settling processes occurred in the chamber and

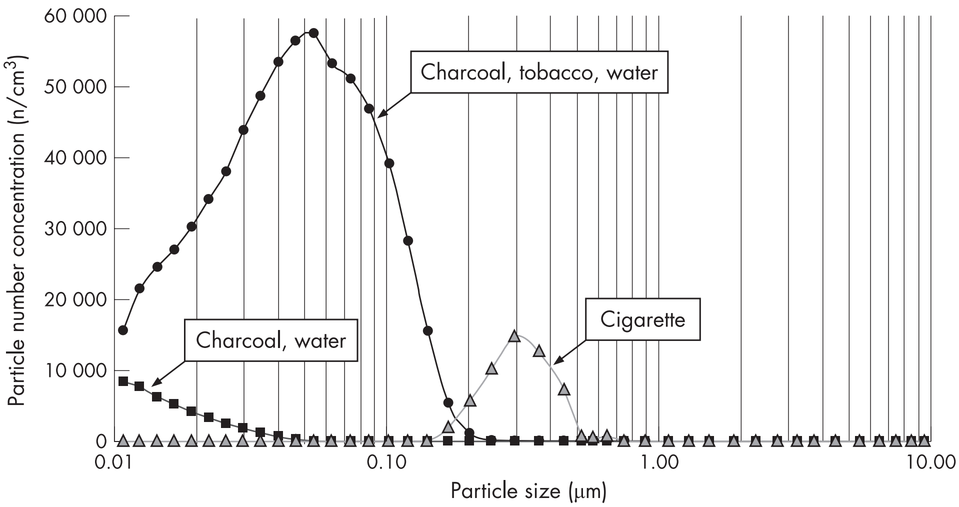

Figure 4 Particle size fractions (x-axis) and the particle number concentration (number per cm^3) (y-axis) for different smoking settings: full set experiments (charcoal, tobacco and water) (circles), experiments with charcoal and water only (squares) and for a cigarette (triangles). Note that the extracted volume was 1 litre for the waterpipe and 0.045 litre for the cigarette. (Measurements were performed with the WPS instrument.)

What this paper adds

- Mainstream waterpipe smoke contains a very large number of ultrafine particles.
- The median particle size was 0.04 μm (smaller than that of cigarettes).
- With respect to particle uptake, waterpipes pose as much risk as cigarette smoking.
- For the protection of non-smokers, similar measures as for rooms with cigarette smoking should be implemented.

syringe. Potential effects of pressure differences and humidity may have interfered with the measurements as a result of water droplet formation.[11] However, all our experiments were based on the same settings and therefore, any potential bias might have influenced all experiments of the same setting in a similar manner.

With respect to particle exposure, smoking waterpipes poses as many risks for the smoker as cigarette smoking. Besides particles, smoking waterpipes bears additional risks such as an uptake of chemicals, nicotine and microbial exposure while sharing waterpipes.

In this project additional experiments with the waterpipe were performed. One finding was that that particles were not washed out by the water. Moreover, measurements of room concentrations indicated large amounts of secondhand smoke particles indoors.[12 13]

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Authors' affiliations

Ch Monn, A Meile, State Secretariat for Economic Affairs (SECO), Work and Health, Stauffacherstrasse 101, 8004 Zürich, Switzerland
Ch Monn, Ph Kindler, Centre for Organizational and Occupational Sciences (ZOA), ETH Zürich, Leonhardstrasse 25, 8092 Zürich, Switzerland
O Brändli, Zürcher Höhenklinik Wald, 8639 Faltigberg, Wald, Switzerland

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