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Comparison of carcinogen, carbon monoxide, and ultrafine particle emissions from *narghile* waterpipe and cigarette smoking: Sidestream smoke measurements and assessment of second-hand smoke emission factors

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The lack of scientific evidence on the constituents, properties, and health effects of second-hand waterpipe smoke has fueled controversy over whether public smoking bans should include the waterpipe. The purpose of this study was to investigate and compare emissions of ultrafine particles (UFP, $<$100 nm), carcinogenic polyaromatic hydrocarbons (PAH), volatile aldehydes, and carbon monoxide (CO) for cigarettes and *narghile* (shisha, hookah) waterpipes. These smoke constituents are associated with a variety of cancers, and heart and pulmonary diseases, and span the volatility range found in tobacco smoke.

Sidestream cigarette and waterpipe smoke was captured and aged in a 1 m^3 Teflon-coated chamber operating at 1.5 air changes per hour (ACH). The chamber was characterized for particle mass and number surface deposition rates. UFP and CO concentrations were measured online using a fast particle spectrometer (TSI 3090 Engine Exhaust Particle Sizer), and an indoor air quality monitor. Particulate PAH and gaseous volatile aldehydes were captured on glass fiber filters and DNPH-coated SPE cartridges, respectively, and analyzed off-line using GC–MS and HPLC–MS. PAH compounds quantified were the 5- and 6-ring compounds of the EPA priority list. Measured aldehydes consisted of formaldehyde, acetaldehyde, acrolein, methacrolein, and propionaldehyde.

We found that a single waterpipe use session emits in the sidestream smoke approximately four times the carcinogenic PAH, four times the volatile aldehydes, and 30 times the CO of a single cigarette. Accounting for exhaled mainstream smoke, and given a habitual smoker smoking rate of 2 cigarettes per hour, during a typical one-hour waterpipe use session a waterpipe smoker likely generates ambient carcinogens and toxicants equivalent to 2–10 cigarette smokers, depending on the compound in question. There is therefore good reason to include waterpipe tobacco smoking in public smoking bans.

1. Introduction

Exposure to second-hand smoke from cigarettes has been found to pose significant health risks due to its toxic and carcinogenic effects (USDHHS, 2006; UKDHSS, 1988; ANHMRC, 1987; NRC, 1986). On this basis, an increasing number of regulatory bodies around the world have banned most forms of tobacco smoking in public indoor spaces such as restaurants, bars, government buildings, and schools, and some have banned it in outdoor places such as public parks and beaches. Smoking bans have stirred controversy with café owners and patrons, regulatory agencies, and tobacco control advocates over whether the bans should apply to waterpipe (narghile, hookah, shisha) smoking. The lack of scientific evidence on the constituents, properties, and health effects of second-hand waterpipe smoke has left the subject open to conjecture, particularly in light of persistent beliefs in the "reduced harm" nature of waterpipe smoking (e.g. Jawaid et al., 2008; Smith-Simone et al., 2008).

While over the past decades a formidable evidence base has been built about the nature and health effects of second-hand cigarette smoke, little is known about the fumes emitted from

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tobacco smoking with the narghile waterpipe (aka “shisha”, “hookah”; see Fig. 1), a practice that uses burning charcoal in conjunction with an often heavily-flavored tobacco product to produce the desired smoke. This knowledge gap has become particularly salient in the past decade with the global rise in narghile waterpipe use (Cobb et al., 2010; Pärna et al., 2008; Baska et al., 2008; El-Roueiheb et al., 2008; Jawaid et al., 2008; Eissenberg et al., 2008; Primack et al., 2008; WHO, 2005), which commonly occurs outdoors as well as in homes, restaurants, bars, and cafés. Through “involuntary” or “passive” smoking, occupants of these spaces may be exposed to significant levels of hazardous substances issuing from the waterpipe.

It has been previously found that mainstream smoke (MS) from the narghile waterpipe delivers large quantities of nicotine, particulate matter, CO, PAH, volatile aldehydes and ultrafine particles to the user (Al Rashidi et al., 2008; Sepetdjian et al., 2008; Monn et al., 2007; Shihadeh and Saleh, 2005). It can be reasonably expected that after inhalation, some fraction of these toxicants will be exhaled into the immediate environment of the user, and, combined with sidestream smoke (SS) emitted directly from the waterpipe head (see Fig. 1), will result in an increase in ambient pollutant levels. Indeed, recent studies have found elevated pollutant levels in indoor environments where waterpipes were smoked (Fromme et al., 2009; Maziak et al., 2008; El-Nachef and Hammond, 2008).

The purpose of the current study is to quantify and compare hourly emissions of ultrafine particles (UFP, <100 nm), particulate PAH, CO, and gaseous volatile aldehydes in waterpipe and cigarette SS, and to estimate the total (SS + exhaled MS) hourly emissions of these toxicants for a typical waterpipe use session. Exposure to trace quantities of aldehydes, PAH, and CO has been linked to lung cancer, and respiratory and cardiovascular diseases. In addition, insoluble UFP are capable of translocation from the lung to other sites such as the lymph nodes, spleen, heart, and bone marrow, and their high surface area to mass ratio increases their biological activity in relation to larger particles of the same chemical composition (Oberdörster et al., 2005).

The approach taken in this study was to measure SS emissions using an environmental chamber for which a single-compartment mass or number balance model was rigorously applicable. To do so, time-resolved or total integrated smoke component concentrations were measured in an inert, well-stirred environmental chamber of known particle mass and number deposition rate while the waterpipe or cigarette was machine-smoked. Total emissions – SS plus exhaled MS (eMS) – were then estimated for each smoke component by assuming the smoker absorbs a fraction of any given inhaled MS toxicant, which can at most vary from zero to one.

Use of a smoking-machine/environmental chamber approach affords repeated measurements under highly controlled conditions, with minimal confounding variables (e.g. varying smoking behavior, other sources of airborne pollutants, unknown air change rates, uncharacterized surface deposition and reaction mechanisms). This approach has been previously employed to study second-hand smoke (e.g. Charles et al., 2007; Baek and Jenkins, 2004; Morawaska et al., 1997), and is particularly useful for comparing different smoked products.

2. Methods

SS from a waterpipe or cigarette was generated and routed to an experimental chamber which allows dilution and ageing processes characteristic of an indoor environment. The overall experimental setup is shown in Fig. 2. The waterpipe hose or cigarette is connected to an external smoking machine (see Shihadeh and Azar, 2006), while the rest of the waterpipe or cigarette is placed in a vertically-oriented cylindrical dilution tunnel (24 cm diameter, 67 cm height) fitted with a tapered cone roof. The tunnel captures the smoke coming off the head, dilutes it, and routes it into the 1 × 1 × 1 m ageing chamber. Repeated experiments showed that placement of the waterpipe inside the tunnel had no effect on the amount of tobacco burned in the head, indicating representative combustion conditions inside the tunnel.

The ageing chamber is fitted with a series of ports which are connected to external sampling pumps whose flow rates are monitored and regulated by a series of computer-controlled valves and mass flow meters. The chamber air change rate is set to 1.5 h^{-1} (1.5 ACH) using the data acquisition and control software, and is verified for every run by CO decay. The temperature, humidity, CO, and CO2 are continuously recorded using a Kanomax IAQ monitor whose sampling wand is suspended from the chamber ceiling. All internal surfaces, including the fan and IAQ wand, are coated with Teflon to minimize surface reactions.

To assure well-mixed conditions and therefore sampling location-independent emissions measurements, detailed consideration of the mixing patterns inside the chamber was made by 3-D numerical simulations of the velocity and concentration fields resulting from the inlet and outlet flows as well as various fan flow rates and placements. For this purpose, the Lagrangian discrete phase model in Fluent 6.3 was used, assuming particles of 250 nm diameter and unit density. Turbulence closure was achieved through application of the two-equation k–ε model. Results were checked at multiple grid resolutions, and second order discretization schemes were used. To check for mixing homogeneity, the simulated chamber volume was divided into 9 equidistant 1 m^2

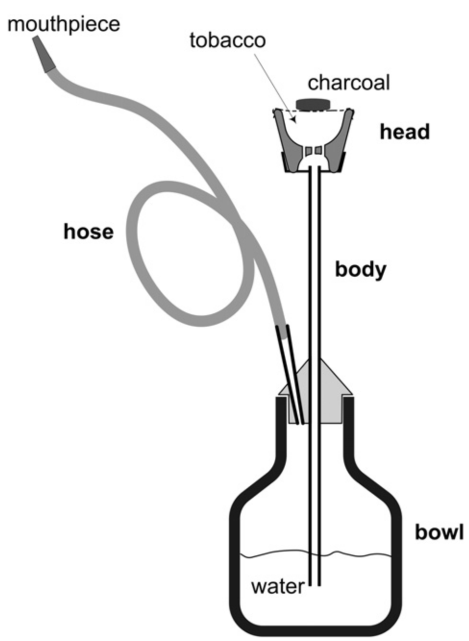

Fig. 1. Schematic of a narghile waterpipe. The head, body, water bowl, and hose are the primary elements from which the waterpipe is assembled. Tobacco is loaded into the head, and burning charcoal is placed on top of the tobacco. When a user inhales from the mouthpiece, air and hot charcoal fumes are convected through the tobacco, raising its temperature, and generating the desired smoke. The smoke exits from the bottom of the head, into the body, and through the bubbler and hose to the user. The waterpipe illustrated here, and used in this study, is configured for use with sweetened and flavored tobacco, known as ma'ssel. When ma'ssel is used, a relatively deep (approximately 3 cm) head is filled with 10–20 g of the flavored tobacco mixture and covered with an aluminum foil sheet that is perforated for air passage. Burning charcoal is placed on top of the aluminum foil to provide the heat needed to generate the smoke. Similar quantities of charcoal and tobacco mixture are consumed in a typical 1 h café use session. (Figure adapted from Monzer et al., 2008.)