Effect of electric heating and ice added to the bowl on mainstream waterpipe semivolatile furan and other toxicant yields

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ABSTRACT

Objectives We examined mainstream total particulate matter, nicotine, cotinine, menthol, pyrene, carbon monoxide (CO) and semivolatile furan yields from a commercial waterpipe with two methods for heating the tobacco, quick-light charcoal (charcoal) and electric head (electric) and two water bowl preparations: with (ice) and without ice (water).

Methods Emissions from a single brand of popular waterpipe tobacco (10 g) were generated using machine smoking according to a two-stage puffing regimen developed from human puffing topography. Tobacco and charcoal consumption were calculated for each machine smoking session as mass lost, expressed as a fraction of presmoking mass.

Results The heating method had the greatest effect on toxicant yields. Electric heating resulted in increases in the fraction of tobacco consumed (2.4 times more, $p<0.0001$), mainstream nicotine (1.4 times higher, $p=0.002$) and semivolatile furan yields (1.4 times higher, $p<0.03$), and a decrease in mainstream CO and pyrene yields (8.2 and 2.1 times lower, respectively, $p<0.001$) as compared with charcoal. Adding ice to the bowl resulted in higher furan yields for electric heating. Menthol yields were not different across the four conditions and averaged 0.16 ± 0.03 mg/session. 2-Furaldehyde and 5-(hydroxymethyl)–2-furaldehyde yields were up to 230 and 3900 times higher, respectively, than those reported for cigarettes.

Conclusion Waterpipe components used to heat the tobacco and water bowl preparation can significantly affect mainstream toxicant yields. Mainstream waterpipe tobacco smoke is a significant source of inhalation exposure to semivolatile furans with human carcinogenic and mutagenic potential. These data highlight the need for acute and chronic inhalation toxicity data for semivolatile furans and provide support for the establishment of limits governing sugar additives in waterpipe tobacco and educational campaigns linking waterpipe tobacco smoking behaviours with their associated harm.

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INTRODUCTION

Waterpipe tobacco smoking (WTS) is an emerging global health risk behaviour, particularly among youth and young adults in several countries, including the USA.[1–6] Nationally representative US data (2011–2015) showed that WTS' current use (past 30 days) among middle and high-school adolescents ranged from 14.4% to 35.9% and among young adults, ages 18–34 years, ranged from 8.4% to 15.2%.[7] WTS has been associated with increased risk for lung, oral, oesophageal and head and neck cancers, and cardiovascular and pulmonary disease.[8–11] Ever use of waterpipe by those who do not smoke cigarettes was independently associated with twice the odds of initiating cigarette smoking, as reported 1 year later.[12]

A variety of commercial components related to WTS, such as charcoal or electric devices used to heat the tobacco, and ice buckets and ice hose tips to make the smoke smoother, are available. In the USA, waterpipe components are considered tobacco products and subject to Food and Drug Administration (FDA) regulations if they are reasonably expected to (1) alter or affect a tobacco product's performance, composition, constituents or characteristics, and (2) be used with or for the human consumption of a tobacco product.[13] To determine how waterpipe components affect emissions, waterpipes can be machine smoked according to a human-derived puffing regimen, and the particulate and gas phases can be analysed. Although machine smoking cannot be used to predict human exposures or risk, it can provide useful information regarding the toxicants associated with a given component.

WTS is widely mistakenly perceived as less harmful than other forms of tobacco smoking and sometimes is not even considered smoking.[14 15] Our unpublished data indicate that some smokers minimise the harshness of tobacco smoke by adding ice to the waterpipe bowl to cool the smoke and soothe the throat during puffing. It is not known whether this practice affects the mainstream smoke emissions.

In 2012, the FDA established a list of harmful and potentially harmful constituents (HPHCs) in tobacco products and smoke.[16] Manufacturers must provide product listings and report ingredients and HPHCs to the FDA. These data can play an important role in FDA's determination of the regulations needed to protect public health, including setting product standards, such as threshold concentrations of HPHCs that cannot be exceeded. The HPHC list was developed after reviewing disease associated with smoking cigarettes and using smokeless tobacco, as those products fell under FDA's regulatory authority at that time. Four years later, FDA extended their regulatory authorities to more novel tobacco products, including waterpipe tobacco and components.[13 17] Because of the types and amounts of chemicals that manufacturers add to waterpipe tobacco and the complexity of the various components that may be used to heat the tobacco, WTS may have some unique and/or more abundant toxicant exposures that are not represented in the current HPHC list. The WHO has a similar list of priority toxicants, and both organisations intend to periodically revise the list apace with the discovery of scientific information regarding the harm of tobacco product use.[16 18] In fact, shortly after this work was accepted for publication, the FDA published a proposed update to the HPHC list that included 2-furaldehyde (or furfural), one of the semi-volatile furans we measured.[19]

Semivolatile furans, including furfuryl alcohol (FFA), 2-furaldehyde (2F), and 5-hydroxymethylfurfural (HMF), are more abundant in mainstream waterpipe smoke than cigarette smoke.[20] There are few data available regarding the toxicological implications of acute and chronic human inhalation of these compounds. In long-term inhalation studies, FFA showed carcinogenic activity in the noses of male rats and the kidneys (renal tubules) of male mice.[21] FFA is classified as an International Agency for Research on Cancer (IARC) Class 2 B carcinogen.[22] Furfural (2F) shows carcinogenicity in experimental animals via oral administration but is classified as an IARC Class 3 carcinogen due to the inadequacy of human evidence.[23] Concerningly, humans can metabolise both HMF and FFA to form genotoxic and mutagenic compounds (5-sulfoxymethyfurfural[24] and furfural sulfate,[25] respectively) in the body via sulfotransferase enzymatic activity.[26] For this reason, WHO has recommended HMF be given high priority for carcinogenic evaluation.[27]

To contribute to the body of evidence surrounding waterpipe components and emissions, we measured mainstream total particulate matter (TPM), nicotine, cotinine, menthol, benzo(a)pyrene, pyrene, tobacco-specific nitrosamines (TSNAs), carbon monoxide (CO) and semivolatile furan yields in waterpipe tobacco smoke; these data were generated by machine smoking a commercial waterpipe according to a human-derived puffing regimen. We tested two components for heating the tobacco, quick-light charcoal (charcoal) and electric head (electric) and two water bowl preparations: with ice (ice) and without ice (water).

METHODS

Waterpipe configurations

A commercial waterpipe (Hookah Egyptian Safari Shisha 22-inch, Khalil Mamoon, Amazon, USA) was equipped as follows to produce four different configurations:

1. Charcoal-water (CW): Perforated aluminium foil (Zebra Smoke, Amazon, USA) was placed over the Egyptian-style ceramic head between the lit charcoal (40 mm, Three Kings, Holland) and the tobacco (Exotic Double Apple, Starbuzz Tobacco, California, USA). The bowl was filled (470 mL) with bottled water (Water configuration, Nestlé Pure Life, Nestlé Waters North America, Connecticut, USA).
2. Charcoal-ice (CI): same head, foil, charcoal and tobacco as CW, but bowl was partially filled (293 mL) with bottled water and 15 ice cubes, prepared using the same water.
3. Electric-water (EW): same foil, tobacco and water as CW; the ceramic head had a heating element embedded in the bottom, controlled by a variable power supply with numerical settings, 1–9, where the lowest setting was a dial position below ‘1’, and the highest setting was a dial position above ‘9’(see figure 1A, Hookah-Shisha Heater, Ren Headstream, China).
4. Electric-ice (EI): same foil, tobacco and head as EW; bowl was prepared the same as CI.

Four waterpipe sets (clay heads, bowls, stems) were labelled and used in replicate smoking sessions. One electric head was used for all electric smoking sessions. The bottom of the metal stem of the waterpipe was covered with 3.8 cm of water for all configurations.

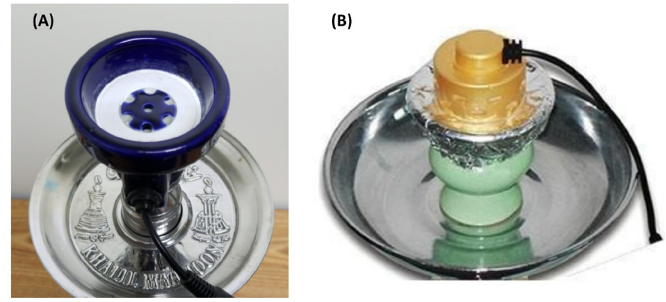

Figure 1 Two commercial components for electrically heating waterpipe tobacco: (A) ceramic heating element located inside the head, positioned underneath the foil and tobacco (this study) and (B) ceramic heating element located on the bottom and positioned above the foil and tobacco in the head.

Machine smoking and mainstream smoke yields

Stems and rocks were removed from three packages (250 g each) of a popular waterpipe tobacco purchased from one hookah supply store in Columbus, Ohio, May 2018. Tobacco was homogenised by mixing with gloved hands, stored at 6°C and brought to room temperature before machine smoking. For machine smoking, the tobacco (10.0±0.05 g) was lightly packed in the head, covered with perforated foil and heated. A disposable plastic hose (length of hose=127 cm; Fancy Hose, Zebra Smoke, Amazon, USA) was connected to the waterpipe, and platinum cured silicone tubing was used to connect the mouth-end of the hose to the smoking machine. For the CW and CI configurations, a single charcoal was placed on top of the foil-covered tobacco after sitting on an electric heater for 100 s. For the EW and EI configurations, the electric head was lined with perforated foil, and larger holes were poked through the foil into the holes in the bottom of the head. Ten grams of tobacco were lightly packed in the head and covered with perforated foil and heated for 3 min prior to the start of each smoking session. The thumbwheel on the power supply was set at ‘3’; details regarding this setting are presented in the online supplementary methods section. For each session, a smoking machine (modified Hawktech FP2000) was programmed with a two-stage puffing regimen, shown in online supplementary table S-1, derived previously from human waterpipe smoking behaviour.[28 29] Stage one includes more intense puffing (greater volume, longer duration puffs) for the first 11.2 min (32 puffs, 4.6 s duration, 16.4 s interval), followed by less intense and less frequent puffing in the remaining 22.6 min (42 puffs, 3.6 s duration, 28.7 s interval). Before each session, the puff volume drawn through the waterpipe by the smoking machine was calibrated to within 97%–103% of the true value (720 mL and 455 mL). Tobacco and charcoal were weighed before and after machine smoking, and consumption was calculated as postweight subtracted from preweight expressed as a fraction of preweight.

As shown in online supplementary figure S-1, samples were generated in 24 machine smoking sessions corresponding to the collection of wet TPM for subsequent extraction and analysis of the particle phase (n=12 sessions, 3 replicates per waterpipe configuration) and analysis of CO in the gas phase (n=12 sessions, 3 replicates per waterpipe configuration). TPM for semivolatiles analysis was collected on two parallel filters (92 mm in diameter, Cambridge, Hamburg, Germany) located at the mouth-end of the waterpipe hose. Filters were recovered immediately after smoking, and the mass of wet TPM was determined gravimetrically. Filters were placed in their cleaned extraction vessels and stored at −20°C prior to extraction. One filter was

Table 1 Consumption and mainstream yields; data presented are mean (SD) of n=3 smoking sessions unless otherwise stated

Consumption/Emissions per smoking session	Units/ Session	CW	EW	CI	EI	P value: Charcoal versus electric CW:EW	CI:EI	Water versus ice CW:CI	EW:EI
Tobacco and charcoal consumption									
Tobacco consumed	%	28.5 (2.05)	70.6 (3.71)	26.6 (4.40)	73.1 (2.07)	**<0.001**	**<0.001**	0.529	0.367
Charcoal consumed, n=9	%	66.3 (2.81)		67.4 (2.44)				0.383	
TPM, N, CO, and PAH									
Total particulate matter	g	1.08 (0.250)	0.880 (0.059)	0.583 (0.102)	0.703 (0.061)	0.115	0.330	**0.003**	0.164
Nicotine	mg	0.653 (0.173)	0.848 (0.015)	0.550 (0.086)	0.805 (0.027)	**0.040**	**0.013**	0.233	0.601
CO	mg	97.4 (0.261)	12.7 (2.88)	109 (11.7)	12.5 (1.34)	**<0.001**	**<0.001**	0.053	0.968
Menthol	mg	0.144 (0.033)	0.140 (0.008)	0.187 (0.037)	0.187 (0.008)	0.851	0.987	0.070	0.051
Cotinine	µg	0.586 (0.180)	1.09 (0.095)	0.594 (0.192)	0.910 (0.374)	**0.004**	**<0.001**	0.953	0.054
Pyrene	ng	190 (32.7)	91.7 (14.2)	192 (31.2)	90.0 (14.7)	**0.001**	**0.001**	0.924	0.936
Furans									
HMF	µg	3690 (1010)	5050 (148)	3200 (660)	4660 (265)	**0.028**	**0.021**	0.363	0.464
FFA	µg	218 (75.0)	289 (24.0)	313 (67.2)	491 (12.9)	0.134	**0.003**	0.055	**0.001**
2-FA	µg	101 (32.8)	179 (18.5)	84.7 (13.2)	171 (8.56)	**0.002**	**0.001**	0.363	0.629
2F	µg	62.0 (17.8)	149 (58.2)	60.8 (16.9)	163 (15.7)	**0.012**	**0.005**	0.965	0.592
2-FMK	µg	5.91 (2.14)	17.4 (2.52)	5.94 (1.27)	27.3 (1.16)	**<0.001**	**<0.001**	0.985	**<0.001**
5 M-2-F	µg	36.1 (13.8)	113 (24.1)	41.0 (10.5)	142 (3.32)	**<0.001**	**<0.001**	0.696	**0.044**

Bold font shows mean differences that are significant at p<0.05 level.
CI, charcoal with ice; CO, carbon monoxide; CW, charcoal with water; EI, electric with ice; EW, electric with water; 2F, furfural; FFA, furfuryl alcohol; HMF, 5-Hydroxymethylfurfural; N, nicotine; PAH, polycyclic aromatic hydrocarbon; TPM, total particulate matter.

chemically extracted and analysed for target semivolatile organic compounds using gas chromatography mass spectrometry and TSNAs using liquid chromatography with tandem mass spectrometry. The other filter was extracted and analysed for furans using reverse-phase high performance liquid chromatography with diode array detection. A final set of 12 machine smoking sessions was conducted for the quantification of CO.

Menthol, nicotine, cotinine, benzo(a)pyrene (BaP), pyrene, N′-nitrosonornicotine (NNN), 4-(methylnitrosamino)−1-(3-pyridyl)−1-butanone (NNK) and nine semivolatile furans (see online supplementary figure S-1 and table S-2) were quantified in the wet TPM, and CO was quantified in the gas phase; methodological details can be found in the online supplementary methods section.

RESULTS

Consumption and mainstream yields

Table 1 shows average consumption and mainstream yields for the four waterpipe configurations. Overall, the heating source had a bigger impact on mainstream yields than ice added to the water bowl. The electric head resulted in 2.4 times more tobacco being consumed per session ($p<0.001$) and 1.3–1.5 times higher nicotine ($ps<0.041$), 1.5–1.9 higher cotinine ($ps<0.005$) and 1.3–4.6 times higher furan yields ($ps<0.029$) as compared with charcoal. Electric heating resulted in 7.7–8.7 times lower yields of CO ($ps<0.001$) and 2.1 times lower yields of pyrene ($ps<0.002$) as compared with charcoal. There was no difference in mainstream TPM between electric and charcoal heating. Adding ice resulted in small increases (1.3–1.7X more) in some furan yields for electric heating ($ps<0.045$) and a minor reduction (1.2X less) in TPM yield ($p<0.003$) for charcoal heating, although the wide variability of the TPM data for charcoal heating is concerning. There was no difference in menthol emissions across the four configurations. 3-FM, 3F and MF were not detected in the smoke from any configuration. NNN, NNK and BaP were also not detected, which is surprising given previous reports of up to 34 ng/session for NNN, 46 ng/session for NNK and 307 ng/session for BaP.[30] Our shorter smoking session (33 vs 60 min) and splitting the sample in quarters, once during TPM collection onto two filters and once during chemical extraction when splitting the extract in half, resulted in less sensitive methodology. Table 2 shows the chemical yields measured for mainstream waterpipe versus extant yields reported for filtered cigarette smoke. Waterpipe yields were significantly higher than those reported for cigarettes for all compounds measured except nicotine, menthol and cotinine.

Table 2 Range reported in the literature for filtered cigarettes and this study's waterpipe mainstream smoke yields for a single brand

Target compound	CAS number	Filtered cigarette (mass per rod)*	Waterpipe (mass per session)†
Total particulate matter, mg	–	4.5–45	583–1080
Nicotine, mg	54-11-5	0.19–3.69	0.55–0.85
CO, mg	630-08-0	1.21–31.5	12.5–97.4
Menthol, mg	2216-51-5	0 – 3.92‡	0.14–0.19
Cotinine, µg	486-56-6	2.66–4.05	0.59–1.09
Pyrene, ng	129-00-0	49.5§	90–192
HMF, µg	67-47-0	1.3–7.4¶	3200–5050
FFA, µg	98-00-0	18–65	218–491
2-FA, µg	88-14-2	44–107	84.7–179
2F, µg	98-01-1	0.71–27.5	60.8–163
2-FMK, µg	1192-62-7	0.54**	5.91–27.3
5 M-2-F, µg	620-02-0	6–29	36.1–142

*Yields from from reference[61]. Note: Tar yields shown for total particulate matter.
†Yields from single brand of tobacco examined in this study.
‡Data estimated from rod contents reported in reference[56]; assumed 20% transfer to smoke.
§Yields reported for 1R4F and 2R4F in reference[62].
¶Yields from filtered cigarettes measured in reference[63].
**Yield taken from 0% potassium lactate cigarette reported in reference[64].

Component temperature

Temperature of the electric head ranged from 300°C to 380°C, depending on the power supply setting (see online supplementary figure S-2). Maximum tobacco temperature obtained when using electric heating (~300°C) was almost twice that obtained when using charcoal heating (~150°C), as shown in online supplementary figures S-3 and S-4. The electric head's power supply setting had little effect on the average tobacco temperature.

DISCUSSION

The study results have several policy and regulatory implications regarding waterpipe components, tobacco additives and consumer education.

Waterpipe components and toxicant yields

Both heating sources affected the mainstream smoke yields, and thus we recommend these components be regulated as tobacco products. However, a categorical statement about the harm of electric heating cannot reasonably be made, because previously we found that an electric heater (same manufacturer) designed to sit on top of the foil-covered tobacco, as shown in figure 1B, gave much lower nicotine yields compared with charcoal heating.[29] The heaters themselves achieve the same maximum temperature, but the temperature in the tobacco and corresponding nicotine yields were more than twice as high compared with charcoal heating when using the electric heater examined in this study. This is likely because thermal energy is more efficiently conducted to the tobacco when using the electric head because the surface area that gets hot (45.6 cm^2) is seven times greater than that of the top heater examined previously (6.2 cm^2). As the tobacco heats up, so does the vapour concentration of nicotine and cotinine in the head, due to their increasing volatility/vapour pressure.[31 32] The temperature of the tobacco (not necessarily the heater) drives the mainstream toxicant emission rates, and the physical design of the heating component can determine the tobacco temperature. Since these data were generated using a smoking machine, it is not known whether the increased nicotine and toxicant delivery from the electric heater studied here (figure 1A) will result in changes in human puffing behaviour and biomarkers of waterpipe smoke exposure as compared with charcoal heating. The human component of this project, not reported here, will determine the differential effects of waterpipe smoking practices on biomarkers of toxicity. There is some evidence that reduced nicotine yield in waterpipe (78% reduction) is associated with increased human exposure to toxicants because of puffing compensation.[29] Given the direct relationship between tobacco temperature and some toxicant emissions, further evidence to inform a product standard, such as setting a threshold for the maximum tobacco temperature achievable by electric heaters, is needed.

Indirect and direct harm from waterpipe tobacco additives

Mainstream waterpipe tobacco smoke yields measured here for FFA, 2F and HMF were substantially higher than cigarette yields reported in the literature for these same compounds (>12, 85 and 2500 times higher, respectively), and thus we recommend more extensive study of the toxicity of these compounds. Although we only tested one tobacco, Schubert *et al*,[20] reported similarly high levels for five other brands of waterpipe tobacco. The uniquely high semivolatile furan emissions make these chemicals distinctive exposures for this tobacco product type (waterpipe), as defined by Klupinski *et al*[33]; and more testing is needed to understand their impact on public health.

Table 3 SPI derived from extant literature for tobacco filler of combustible tobacco product types

Tobacco product type	SPI	Nicotine (mg/g)	Sugars (mg/g)
Waterpipe (Ma'assel)	290	1.2*	350†
Pipe	1.6–13	14.4‡	24–189§
Cigarettes	0.4–9.5	19¶	7–180§
Cigars	0.4–0.5	15¶	6–7.5§

*Kulak *et al*, 2017[65]
†Brinkman *et al*, 2018[35]
‡Jacob *et al*, 1999[66]
§Elson *et al*, 1972[34]
¶Lawler *et al*, 2017[67]
SPI, Starter Product Index.

The high concentrations of these furans are likely due to the fate of the sweet additives in the tobacco. Sugars like fructose, glucose and sucrose are formed during tobacco harvesting and curing at total levels of up to ~200 mg/g in cigarette tobacco.[34] However, sweetened waterpipe tobacco, or ma'assel, has much higher concentrations of these sweet chemicals, as much as 60 times higher,[34–36] indicating the tobacco is heavily fortified with these chemicals during manufacturing.

Sugar additives may increase the appeal of the smoke, making it easier for users to start smoking/initiate inhalation of nicotine. The tobacco industry adds these same sugars to cigarette tobacco to impart 'smoothness' to the mainstream smoke and has conducted human studies to determine the optimal ratio of added sugar to nicotine.[37] To emphasize the unique chemistry of waterpipe tobacco and how it may play an important role in smoking initiation, we define a similar term, Starter Product Index (SPI), as the mass of simple sugars divided by the mass of nicotine in the tobacco. Data for tobacco from four combustible product types, waterpipe, pipe, cigarettes and cigars were gleaned from the literature, the SPI was calculated, and results are summarised in table 3. Waterpipe tobacco has an SPI of 290, which is 14–725 times higher than any of the other combustible product types shown in table 3. This ratio makes waterpipe an 'ideal' nicotine starter product for youth, because sweet flavours mask the unpleasant bitter taste of nicotine[38] and can play a powerful role in tobacco product initiation.[39] Because these additives can transfer to the smoke,[40 41] they can simultaneously facilitate the transfer[35] and addictiveness[36] of nicotine while reducing the harshness and increasing the appeal of tobacco smoke.[20 42]

Sweet additives can also increase the toxicity of the smoke by chemically transforming to carcinogens and respiratory irritants when heated.[36] There is a common belief that waterpipe tobacco, or ma'assel, is sweetened by adding honey, perhaps because 'ma'assel' is taken from the Arabic 'muassel', which means 'honeyed'.[43] Given the low cost of waterpipe tobacco (as compared with cigarettes), and that the worldwide market for it exceeded $1.9B in 2017,[44] it is likely that adulterated honey, or so-called 'funny honey', that has been diluted with less expensive syrups is used.[45] Manufacturers add cheaper chemicals that are perceived as sweet, such as glycerin and molasses, and some state this practice on their websites (see online supplementary figure S-5). Beet and sugar cane molasses are inexpensive by-products of the sugar industry and are readily available at low cost.[46] Half the weight of molasses is comprised of sugars, including sucrose (34%), fructose (8%) and glucose (7%).[47] Another inexpensive, readily available sweet additive that is potentially responsible for the high furan emissions is high-fructose corn syrup (HFCS). HFCS is widely used as a sweetener in the processed food and beverage industry and can degrade during storage to form HMF.[48] The mainstream HMF levels measured here are over four orders of magnitude higher than those reported for cigarettes (table 2). Given HMF's presence at milligram levels in mainstream waterpipe smoke, and this compound's potential to form genotoxic metabolites in the lung,[24] further study is needed to inform product standards such as setting maximum thresholds for added sugars in waterpipe tobacco.

Honey, molasses and HFCS all contain simple sugars, whose molecules contain six carbon atoms, called hexoses. Hexoses can be chemically transformed via thermal dehydration into HMF.[49] Similarly, pentoses such as raffinose (also found in molasses at 1.3%–3.8%)[50] can be thermally dehydrated into 2F.

Another chemical that reduces the harshness of smoke, menthol, has also been linked to facilitating tobacco initiation in youth[51] and increased difficulty in successfully quitting cigarette smoking.[52 53] Government legislators are beginning to acknowledge menthol's power to contribute to the 2 trillion dollar (purchasing power parity) economic cost to society each year from tobacco use[54]: Brazil, Ethiopia, the European Union, Turkey and five Canadian provinces have banned the sale of menthol in tobacco products,[54] and recently the US FDA announced it will be taking similar steps with proposed rulemaking.[55] It is not known whether the menthol levels measured here are generalisable to waterpipe tobaccos that do not specify words like 'mint' or 'ice' on the label. Similar to what has been done for cigarettes,[56] future work should include characterising menthol levels for mentholated and non-mentholated waterpipe tobaccos.

Waterpipe smoking practices and toxicant yields

The practice of adding ice to the bowl resulted in direct harm in the form of minor increases to yields for some target furans when smoking at the higher temperatures achieved by the electric heater. Because of the greater variability associated with charcoal heating, the reduction in TPM when smoking with ice in the bowl requires replication. Human research is needed to understand the potential harm from this practice and how best to educate the public regarding the association between increased appeal and exposure to toxicants, and tobacco smoke/nicotine initiation and addiction.

Limitations

The data reported here have limitations. Machine smoking yield data must not be confused with valid measures of human exposure or risk.[57 58] These data were generated using one brand of commercial waterpipe, hose, electric head and tobacco and may not be generalised for the variety of commercial waterpipes and tobaccos sold worldwide. Our study focused primarily on toxicants in the particle phase plus CO; future work should examine volatile toxicants in the gas phase such as 1,3-butadiene, acetaldehyde, acrolein, benzene and furan.

CONCLUSION

Public health issues surrounding waterpipe, which include distinctive toxicants generated and mediated by the tobacco and waterpipe components, are very different from cigarette use.[59] We measured mainstream TPM, nicotine, cotinine, menthol, pyrene, CO and semivolatile furan yields from smoking a commercial tobacco and waterpipe equipped with two different components and two different water bowl preparations. Differences in nicotine yields and high concentrations of potentially carcinogenic and mutagenic furans indicate more research is needed to understand the interplay between heating components, tobacco temperature and sugar additives, smoke toxicity and tobacco product initiation, addiction potential and toxicity. To better understand waterpipe tobacco smoking behaviours, questions regarding the prevalence of use of specific components such as electric heaters and practices such as adding ice to the bowl should be included in future smoker surveillance. Smoker's behaviours can also reduce the harshness of waterpipe smoke, increasing the potential for indirect harm. Because these personal waterpipe smoking behaviours cannot be regulated, educational campaigns and other prevention strategies are needed for this unique form of tobacco use.[60]

What this paper adds

Our results have regulatory implications in that they:

- ► Demonstrate that waterpipe components such as charcoal or electric heads can alter and affect the toxicity of mainstream waterpipe tobacco smoke.
- ► Confirm that semivolatile furans with human carcinogenic and mutagenic potential are present in waterpipe smoke at significantly higher levels than cigarette smoke and highlight the need for greater understanding of the toxicity associated with acute and chronic inhalation exposure to these chemicals.
- ► Provide a theoretical rationale for the need to regulate the amount of added sugars in waterpipe tobacco.
- ► Support the need for educational campaigns surrounding user behaviours and the harm from waterpipe tobacco smoking.

Correction notice Please note that this article as been updated since it was published Online First. A typo in the Results section of the Abstract was corrected and the Acknowledgements section was expanded to include all of the Battelle study team members and their roles on the project.

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Disclaimer The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

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