E-cigarettes emit very high formaldehyde levels only in conditions that are aversive to users: A replication study under verified realistic use conditions

Konstantinos E. Farsalinos [a, b, c, *], Vassilis Voudris [a], Alketa Spyrou [a], Konstantinos Poulas [b]

[a] Department of Cardiology, Onassis Cardiac Surgery Center, Sygrou 356, Kallithea 17674, Greece
[b] Department of Pharmacy, University of Patras, Rio-Patras 26500, Greece
[c] National School of Public Health, Greece

ABSTRACT

Purpose: In 2015, a study identified 5—15-fold higher levels of formaldehyde emissions from an old-generation e-cigarette tested at 5.0 V compared to tobacco cigarettes. We set to replicate this study using the same e-cigarette equipment and e-liquid, while checking for the generation of dry puffs.
Design: Experienced e-cigarette users (n = 26) took 4 s puffs at different voltage settings and were asked to report the generation of dry puffs. Formaldehyde emissions were measured at both realistic and dry puff conditions.
Results: Dry puffs were detected at ≤ 4.2 V by 88% of participants; thus, 4.0 V was defined as the upper limit of realistic use. Levels ranged from 3.4 (SE = 2.2) μg/10 puffs at 3.3 V to 718.2 (SE = 58.2) μg/10 puffs at 5.0 V. The levels detected at 4.0 V were 19.8 (SE = 5.6) μg/10 puffs. At 4.0 V, the daily exposure to formaldehyde from consuming 3 g of liquid with the device tested would be 32% lower compared to smoking 20 tobacco cigarettes.
Conclusions: The high levels of formaldehyde emissions that were reported in a previous study were caused by unrealistic use conditions that create the unpleasant taste of dry puffs to e-cigarette users and are thus avoided.

1. Introduction

Electronic cigarettes (e-cigarettes) were introduced in the last decade as smoking alternatives. A growing body of evidence suggests that, although less harmful than smoking, they are not risk-free (Farsalinos and Polosa, 2014). Research has focused, among others, on the levels of toxic aldehyde emissions. Thermal degradation of the main ingredients of e-cigarettes, propylene glycol and glycerol, can result in the formation of formaldehyde (Bekki et al., 2014). Formaldehyde is also emitted in tobacco cigarette smoke (Counts et al., 2005). Goniewicz et al. (2014) reported that the levels of formaldehyde in e-cigarette aerosol were approximately 9 times lower compared to tobacco cigarettes. However, Jensen et al. (2015) measured formaldehyde emissions from an old-generation e-

cigarette atomizer and reported that the levels emitted were much higher than from tobacco cigarettes at high power (high voltage) settings, resulting in 5—15-fold higher formaldehyde-attributed cancer risk compared to smoking. The media release (Portland State University, 2015) received worldwide media attention (e.g. http://www.dailymail.co.uk/wires/afp/article-2920762/Formaldehyde-e-cigarettes-boost-cancer-risk.html). The authors tested two voltage settings (3.3 V and 5.0 V) and found formaldehyde emissions at 5.0 V only, but they did not control for the development of dry puffs, an unpleasant aversive taste resulting from overheating of the liquid, which the users avoid (Farsalinos et al., 2015a).

The dry puff phenomenon, first described in the scientific literature in 2013 (Farsalinos et al., 2013; Romagna et al., 2013), is common knowledge and experience among e-cigarette users and has been presented in detail elsewhere (Farsalinos et al., 2015a). In brief, it represents an unpleasant change in the taste of the e-cigarette puff and is related to overheating and thermal degradation of e-cigarette liquid ingredients. It results from too much

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* Corresponding author. Onassis Cardiac Surgery Center, Sygrou 356, Kallithea 17674, Greece.
  E-mail address: kfarsalinos@gmail.com (K.E. Farsalinos).

energy delivered to the atomizer, too much power and/or long puff duration or when not enough liquid is present in the atomizer. Since this is an organoleptic parameter, it is by definition subjective and can only be detected when reported by e-cigarette users. One study showed substantially elevated formaldehyde emission from e-cigarettes under dry puff conditions compared to realistic use settings (Farsalinos et al., 2015a).

The study by Jensen et al. generated some controversy and several letters to the editor suggested that the findings of very high levels of formaldehyde emissions could be explained by overheating the liquid (Bates and Farsalinos, 2015; Kershaw, 2015; Nitzkin et al., 2015). However, until now experimental evidence substantiating that dry puffs were the reason for the high formaldehyde emissions was lacking. Therefore, the purpose of the current study was to clarify this issue by measuring formaldehyde emissions using the same e-cigarette device, atomizer and liquid at different voltage settings after verifying and differentiating between realistic and dry puff conditions. Additionally, the levels of formaldehyde emitted from the e-cigarette tested were compared with data on formaldehyde emissions from tobacco cigarettes.

2. Methods

2.1. Equipment and participants

After contacting the authors of the original study, we obtained the same e-cigarette equipment and liquid. The equipment used was CE4 top coil atomizer, Innokin iTaste VV V3.0 variable voltage battery device and Halo Café Mocha liquid with 6 mg/mL nicotine concentration. The CE4 atomizer represents an outdated design which, to the best of our knowledge, is not currently available in Europe. Thus, it was purchased from China.

Twenty six adult experienced daily nicotine-containing e-cigarette users were recruited to identify the generation of dry puffs. All participants were former smokers and were using e-cigarettes for at least 2 months. When asked, they all knew the phenomenon of dry puffs which was described by them as an unpleasant "burning" taste related to liquid overheating. For the experimental session, they took 5–7 puffs of 4 s duration and 30 s interpuff interval at varying voltage settings and reported whether the characteristic change in taste associated with dry puffs was detected. A preliminary assessment by two members of the research team (experienced e-cigarette users) identified the upper limit of realistic puffing conditions at approximately 4.0 V. To make the duration of the experiment acceptable and limit total nicotine intake, participants tested the devices starting at 3.6 V and with increments of 0.2 V until the time they identified dry puffs. Each session was accompanied by 5–10 min resting period, during which the participants did not use their own e-cigarette. Participants were blinded to the power setting and the e-cigarette battery screen was covered with black tape. The device was not tested in random order of voltage settings because experienced e-cigarette users would easily identify the increased or decreased aerosol yield associated with substantial increases or decreases in voltage. When dry puffs were identified, each participant retested the device after 15–20 min of resting time. Initially, the same voltage that resulted in dry puffs was applied; if dry puffs were detected, then they tested the device at 0.2 V lower setting, while if dry puffs were not detected they retested the device at 0.2 V higher setting. Findings from this session were used to determine the voltage associated with dry puffs. Each participant used a different atomizer unit since the mouth piece of the atomizer was non-removable. The study conforms to the Declaration of Helsinki for research involving human subjects and was approved by the institutional review board. Written informed consent was signed by the volunteers before participating to the study.

2.2. Aerosol collection and formaldehyde measurements

Aerosol collections were performed at different voltage settings using a smoking machine and 2 impingers (connected in series) containing a solution of 2,4-dinitrophenylhydrazine (2,4-DNPH) and acetonitrile. The puffing regime used was 60 mL puff volume, 4 s puff duration and 30 s interpuff interval. In total, 50 puffs were collected per sample. Three unused CE4 atomizers were used and two collections per atomizer were performed at each voltage setting (total of six repetitions per voltage setting). Blank air samples were simultaneously collected in different impingers to measure environmental (room air) levels of formaldehyde; these levels were subtracted from the levels in the collected aerosol. Formaldehyde was measured by High Performance Liquid Chromatography using a previously validated protocol with slight modifications (Farsalinos et al., 2015a; Cooperation Centre for Scientific Research Relative to Tobacco, 2013).

3. Statistical analysis

Formaldehyde levels were expressed as μg/10 puffs, with mean value and standard error (SE) reported. Liquid consumption per puff was expressed as mg/puff. Voltage settings were reported in the study by Jensen et al. (2015). However, as explained previously (Farsalinos et al., 2015a), power settings are more appropriate when assessing the energy delivered to the atomizer; thus, both voltage and power settings are presented here. Comparison in liquid consumption per puff and formaldehyde levels between different voltage settings was performed by one-way analysis of variance (ANOVA) with post-hoc Bonferroni correction. Analyses were performed with SPSS v22.0. A P value of <0.05 was considered statistically significant.

4. Results

4.1. Liquid consumption and formaldehyde emissions

Dry puffs were identified at 4.0 V (7.3 W) by 8 participants, 4.2 V (8.0 W) by 15 participants and at 4.4 V (8.4 W) by 3 participants. None of the participants was willing to try the device at power settings higher than those generating dry puffs, explaining that the expected taste would be really aversive. During the testing, some atomizer units were either non-functional or were generating dry puffs at low voltage settings, indicating that they were defective. These atomizers were replaced by new units. Given that most e-cigarette users (88%) experienced the dry puff taste at 4.2 V, we consider 4.0 V as the maximum level associated with realistic use conditions. Based on this, aerosol collections for formaldehyde measurements were performed at the following voltage (power) settings: 3.3 V (5.0 W), 3.6 V (5.9 W), 4.0 V (7.3 W), 4.2 V (8.0 W), 4.6 V (9.6 W), 4.8 V (10.5 W) and 5.0 V (11.4 W).

The amount of liquid consumption per puff at each voltage setting is displayed in Fig. 1. Liquid consumption ranged from 3.7 (0.3) mg at 3.3 V to 8.0 (0.5) mg at 5.0 V. The differences between liquid consumption at different voltage settings were statistically significant (one-way ANOVA: F = 17.1, P < 0.001). While a linear increase in liquid consumption per puff was observed from 3.3 V to 4.0 V, the pattern was erratic at higher voltage settings.

The levels of formaldehyde emissions are presented in Fig. 2 together with the results by Jensen et al. Formaldehyde levels ranged from 3.4 (2.2) μg/10 puffs at 3.3 V to 718.2 (58.2) μg/10 puffs at 5.0 V. The differences between formaldehyde levels at different voltage settings were statistically significant (one-way ANOVA: