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Particulate matter in aerosols produced by two last generation electronic cigarettes: a comparison in a real-world environment

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Abstract: The design of e-cigarettes (e-cigs) is constantly evolving and the latest models can aerosolize using high-power sub-ohm resistance and hence may produce specific particle concentrations. The aim of this study was to evaluate the aerosol characteristics generated by two different types of electronic cigarette in real-world conditions, such as a sitting room or a small office, in number of particles (particles/cm^3).

We compared the real time and time-integrated measurements of the aerosol generated by the e-cigarette types Just Fog and JUUL. Real time (10 s average) number of particles (particles/cm^3) in 8 different aerodynamic sizes was measured using an optical particle counter (OPC) model Profiler 212-2. Tests were conducted with and without a Heating, Ventilating Air Conditioning System (HVACS) in operation, in order to evaluate the efficiency of air filtration.

During the vaping sessions the OPC recorded quite significant increases in number of particles/cm^3. The JUUL e-cig produced significantly lower emissions than Just Fog with and without the HVACS in operation.

The study demonstrates the rapid volatility or change from liquid or semi-liquid to gaseous status of the e-cig aerosols, with half-life in the order of a few seconds (min. 4.6, max 23.9), even without the HVACS in operation. The e-cig aerosol generated by the JUUL proved significantly lower than that generated by the Just Fog, but this reduction may not be sufficient to eliminate or consistently reduce the health risk for vulnerable non e-cig users exposed to it.

Introduction

Electronic cigarettes (e-cigs) have become very popular worldwide in the last decade.[1,2] The 2018 report of the Centers for Disease Control and Prevention, using data from the National Youth Tobacco Survey, showed that one in five United States (US) high school students is a current e-cig user.[3] Currently JUUL is the best-selling e-cig on the US market.[4,5]

In this study we evaluated and compared real-time and time-integrated measurements of the aerosol in particle number (particles/cm^3) generated by two different types of e-cigarettes such as Just Fog and JUUL in real conditions within a specific laboratory to evaluate the health risk for vulnerable non e-cig smokers.

The e-liquid of e-cigs generally contains a mixture of nicotine, vegetable glycerin (VG), propylene glycol (PG) and flavouring chemicals, depending on the different commercial brands. It has been shown that at high temperatures both VG and PG undergo decomposition producing an aerosol that is a system of colloidal particles dispersed in a gas to low molecular carbonyl compounds, including the carcinogens formaldehyde and acetaldehyde.[6] However issues such as second-hand exposure to certain chemicals in these aerosols (e.g., nicotine, heavy metals) are still not investigated in sufficient depth.[7–9]

The design of e-cigs has evolved from the first generation of ''cigalikes'' to the ''fourth'' generation e-cigs recently marketed. The latest models aerosolize with high-power sub-ohm resistance and, as a result, they can release greater quantities of aerosol than older devices.[10,11]

Therefore, one of the major public health concerns is related to the widespread use of e-cigs and the potential impact of aerosols emitted to users and those passively exposed, what is currently known as second-hand aerosol (SHA) exposure.[12,13] Some studies indicate that emissions from e-cigs contain potential toxic compounds. While usually these compounds are at lower concentrations than those found in second-hand tobacco smoke, the results obtained contradict the popular statement that e-cig emissions are ''only water vapour,'' or that they only include glycerin and propylene glycol beyond nicotine. It has been shown that vaping is associated with a large spectrum of lung injury, defined as VAPI (vaping associated pulmonary illness).[13]

This study is a part of a larger European Union Horizon 2020 funded project, TackSHS, aimed to comprehensively study the gaps in the field of passive exposure to different tobacco product emissions.[14]

The scope of this study was to evaluate the differences in generated aerosol of two e-cigs in terms of particle number concentrations, and to measure how long SHA remains measurable in the air in a real-life indoor environment.

Materials and methods

Design and laboratory settings

We performed an experiment under controlled conditions in the laboratory of the National Cancer Institute of Milan, Italy. The laboratory is a 48 m^3 room with 0.7/0.8 Air Changes per Hour (ACH). Temperature ranged between 25.2 and 27.8 °C and the relative humidity (RH) between 45% and 55%. The laboratory contained typical home furnishings (e.g., closets, tables, and chairs) and was equipped with a specific single room Heating, Ventilating and Air Conditioning System (HVACS, model Argo AW407CL, 9000 btu and 500 m^3/h air recirculation). During the experiments, the room was occupied by one person to operate the instruments and two volunteer habitual e-cig users. The volunteers were asked to vape freely but not directly on the instrument's inlets. They were seated in the centre of the room and the instrument was on a table against a wall at 1.5 m height, about two metres away from the e-cig user. The test was repeated for three days (two days with HVACS in operation, one day with HVACS off) and each day the two volunteers smoked both types of e-cigs, alternatively. The different age and sex of the two vapers haven't influenced the tests, having repeated the tests many times and verified that this had little effect on the performance of the sessions.

A fan was kept on throughout the experiments to ensure the maximum mixing factor. Tests were performed with and without HVACS in operation, simulating a typical indoor environment, to evaluate the efficiency of HVACS devices in SHA abatement in the real-world.

Samplers

The Met One 212-2 is an optical particle counter (OPC) with 8 programmable channels: >0.3; >0.5; >0.7; >1.0; >2.5; >3.0; >5.0 and >10.0. For example: >0.3 μm means that the instrument counts all particles greater than 0.3 μm with no upper limit. The sampling frequency is 10 s. The Met One 212-2 detects and evaluate the scatter signal from suspended particulate to provide continuous real-time measurements of airborne particulate (see Metone Instruments Inc. Model 212 Profiler, Operation Manual, document 212-2800 rev. d).

The light scatter when the airborne particles intersects the laser beam is not only proportional to the cross section of the particles but also to their optical properties such as colour, morphology, which are highly correlated with the chemical composition, and RH which heavily contribute to the increase of the aerodynamic size when RH > 50/55%. Therefore the RH interference must be eliminated by heating or dehydrating the sample. The Met One 212-2 is equipped with a programmable heater, and since during all our tests the room RH never exceeded the limit of 55%, this heater was switched off to avoid evaporation of the liquid or semi liquid part of the aerosol and allow detection of the glycerol e-liquid during the few seconds when it is still in the liquid phase.[15–24]

Table 1 Comparison of the characteristics of the two types of e-cig.

CHARACTERISTICS	JUUL	JUSTFOG
Voltage	3.7 V	3.4 V
Coil resistance	1.6 Ω	1.2 Ω
Power	8.5 W	13 W
Tank size	0.7 mL	1.9 mL
PG/VG ratio	30/70	30/70
Nicotine	20 mg/mL	0 mg/mL
Flavouring	Mango	Cookies

Electronic cigarettes

For the SHA generation and measurement experiments, two different recent types of e-cigs, the Just Fog (third generation) and the JUUL were used (see Table 1).

Just Fog is a compact and portable e-cig with an integrated battery capacity of 900 mAh. The model can provide three different voltage settings (3.4, 3.8, 4.2 V) indicated with 3 LEDs located in the front of the Mod and modifiable by the only button present, the resistance goes from 1.0 to 3.00 Ω based on a 1.9 mL which can be filled with any preferred liquid.[25] E-liquid for Just Fog is available with different nicotine concentrations and in many different flavours. For this study we used a liquid without nicotine with the ''cookies'' flavour, using the minimum voltage of 3.4 V.

JUUL is an e-cig that has the form of an extended USB key pre-filled cartridges (''pods'') with solutions which contain a high concentration of nicotine, not modular, available in several flavours.[26] JUUL ''pods'' contain 0.7 mL of e-liquid, comprising nicotine benzoate salt and flavouring agents dissolved in a 30/70 ratio of propylene glycol (PG) and glycerol (vegetable glycerine, VG).[27] In each JUUL pod there is a new coil, so it is not necessary to replace it and no settings are necessary. The JUUL device is rechargeable over USB.

Experiments

The experiments with each e-cigarette were duplicated over three consecutive days (July 9–10–11th 2019). Before starting the tests with the Just Fog and the JUUL, we sampled the background particulate matter (PM) concentration and number of particles inside the laboratory for at least 15 min. On July 9th and 11th the HVACS was in operation (only indoor recirculation, without introducing changes in the air exchange rate), while on July 10th the experiment was conducted without the HVACS in operation. This was to see if the air conditioning filter could affect the tests. Three people were present in the lab during all tests, including two volunteer habitual e-ciga users and a researcher. All three tests carried out on the e-cigs in the room have always involved the same two e-cig users to minimize differences in e-cig use. The users were volunteers who were daily exclusive e-cigs users. They have been allowed to use e-cigs with and

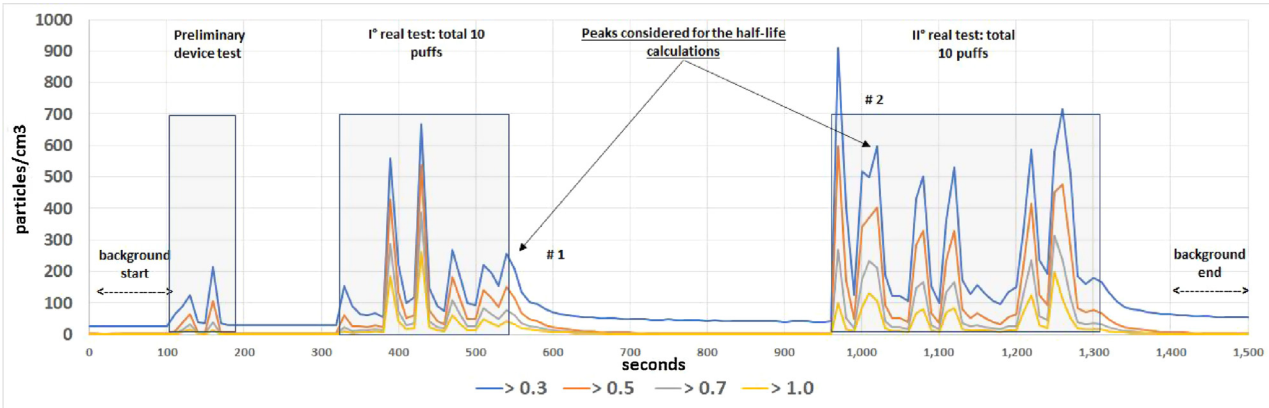

Figure 1 Example of the real time graph of one vaping session.

without nicotine freely because nicotine emission in e-cigs is mainly in the gas phase and only in a very small amount in the solid phase,[28] below the instruments detection limits. During the aerosol exposure tests the door and the windows in the room were closed and directional fans were used to homogenize the air.

On each day, the e-cig users carried out three initial tests which consisted of a single puff each minute for three minutes; subsequently, the volunteers simulated a ''real conditions'' test by performing 10 repeated puffs for each e-cig lasting about 4–6 min altogether. A typical real-time graph of one section is shown in Fig. 1. As can be seen from the graph, several puffs produced a very small number of particles and some were not recorded because of the rapid change of status of the aerosol and efficient circulation due to the fans. In Fig. 1 only peak #1 and #2 have been considered for the half-life calculation because the others were too close together or reached the background value in less than 20 s.

The Just Fog and JUUL e-cig aerosols are characterized by limited persistence in the room atmosphere since aerosol particles change state in a very short time, a time shorter than the sampling time of the Profiler (10 s) and the number of particles greater than 2.5 μm is very small and with an extremely high variability. Consequently we considered only the particle sizes from >0.3, >0.5, >0.7 and >1.0 μm in our evaluations and comparisons.

When comparing the particle counts it is necessary to take into account the environmental background PM (bckg). The bckg was measured for about 15 min before and successive stabilization after the vaping tests. These measurements were performed for each test because the bckg PM level may change during the day. With this information it is possible to deduct the bckg PM from the e-cigs emissions and to compare the aerodynamic profiles of the different e-cigs aerosols.

Statistical analysis

Student's *t*-tests for paired samples to test the null hypothesis that the mean difference between e-cigarettes for the particle sizes >0.3, >0.5, >0.7 and >1.0 μm is equal to zero, were performed. Similarly, Pearson correlations and standard deviations (SD) were calculated to compare the daily results for the two e-cigs for the particle sizes >0.3, >0.5, >0.7 and >1.0 μm. We limited the analysis to those sizes because for larger sizes the number of particles was too low and the half-life is too short. In particular we compared:

(a) the aerosol aerodynamic profiles and daily averages of the two e-cigs;
(b) the half-life.

To calculate the half-life we have been limited in accuracy by the 10 s sampling time of the OPC. During the tests it became clear that the half-life of the e-cigs aerosols was significantly lower than 10 s for the smaller aerosol sizes (<1.0 μm), particularly with the HVACS on. See an example of a vaping session in Fig. 1.

The calculation of the half-life must be considered as the best approximate result of an exponential equation applied to the first two values after reaching the maximum peak. See example in Fig. 2, where the OPC measurements in % of the maximum peak, the average half-life resulting from the exponential equation, the exponential equation factors and R^2 are reported. The maximum peak value expressed in % was selected to allow the half-life comparison of the different e-cigs types and because of the great variability of the peak maximum values.

It was not possible to extend the exponential equation to a longer period for two reasons: first because for the largest sizes (>0.7 μm) the bckgr limit was already reached after 20 s and therefore the exponential equation was not representative of the real half-life and, second, because sometimes the e-cig users inhaled at a frequency <20 s. This method was applied to all selected peaks in all tests.

Statistical analyses and graphs preparation were performed using Microsoft Excel.

Results

The Pearson correlation between the Just Fog and JUUL emission profiles from >0.3 to >1.0 μm is very similar in all tests (see Table 2). However, there is a difference between the averages of the number of particles when the tests are performed with the HVAC running or not. These differences,

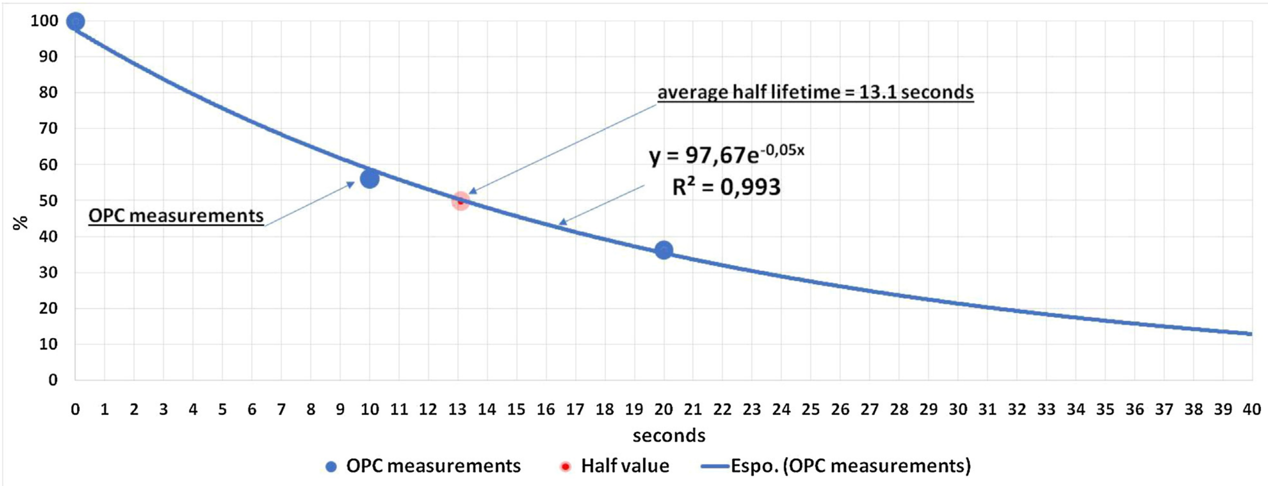

Figure 2 Example of exponential equation applied to Just Fog >0.3 size.

Table 2 Aerodynamic profiles averages and Standard Deviations.

Test performed on July 9th (HVACS on)				
Student's *t*-test *p*-value	0.065			
Pearson correlation	0.999			
Particles/cm^3 (SD)	>0.3	>0.5	>0.7	>1.0
Just Fog	38.01 (92.13)	19.75 (67.78)	10.17 (38.54)	5.31 (21.72)
JUUL	14.58 (48.37)	6.90 (24.42)	2.61 (9.51)	1.12 (3.88)
Test performed on July 10th (HVACS off)				
Student's *t*-test *p*-value	0.109			
Pearson correlation	0.999			
Particles/cm^3 (SD)	>0.3	>0.5	>0.7	>1.0
Just Fog	22.87 (49.98)	10.28 (28.67)	4.36 (13.35)	2.21 (6.85)
JUUL	8.94 (26.79)	3.63 (12.03)	1.42 (4.29)	0.67 (1.82)
Test performed on July 11th (HVACS on)				
Student's *t*-test *p*-value	0.031			
Pearson correlation	0.997			
Particles/cm^3 (SD)	>0.3	>0.5	>0.7	>1.0
Just Fog	160.36 (236.09)	96.63 (153.76)	48.37 (91.84)	25.16 (1.69)
JUUL	88.21 (210.97)	43.47 (124.16)	15.46 (53.16)	5.39 (19.38)

although considerable, are statistically significant only on the third day (July 11th, $p = 0.031$) when HVACS was on, while on the other two days they were not statistically significant.

Just Fog and JUUL half-life showed relevant differences in all sizes, with and without the HVACS in operation. Student's *t*-test resulted in $p = <0.05$ in all tests, but the Pearson correlation was always high, ranging from 0.875 to 0.990. The tests also demonstrated a relevant half-life reduction with the HVACS in operation.

As expected, the Just Fog >0.3 particles had a relevant longer half-life than the other sizes, ranging from 16.1 and 10.1 s with the HVACS off and on, respectively. The JUUL >0.3 particles half-life was relevantly longer (23.9 s) than Just Fog (16.1 s) when HVACS was in operation but lower (6.9 s) when it was off. In all tests the particles of sizes >0.7 and >1.0 μm showed similar half-lives (see Table 3).

Discussion

Two tests out of the three performed seem to confirm that the JUULs e-cigs produce a significantly lower aerosol emission than the Just Fog e-cigs tested. However between the two e-cigs there is a strong aerodynamic profile correlation. On the July 10th test all particles remained in the air of the room for a much longer time than in the other tests because it was performed without the HVACS in operation. The HVACS is equipped with a filter that holds a considerable amount of particles with a significant improvement in the removal time of the e-cigs aerosol emissions.

The reason for the significant reduction in half-life time with the HVACS on may be due to the partial deposition of the aerosol when passing through the HVACS filter, especially considering that the recirculation flow rate is 500 m^3/h.

Table 3 Half-life calculation results.

July 10th – HVACS off (no SD because one test only)		
Pearson correlation		0.875
Student's *t*-test *p*-value		0.013
Half lifetime seconds	Just Fog	JUUL
size > 0.3	16.1	23.9
size > 0.5	12.0	15.4
size > 0.7	12.2	17.4
size > 1.0	12.9	21.4
July 9th and 11th – HVACS on		
Pearson correlation		0.990
Student's *t*-test *p*-value		<0.001
Half lifetime seconds (SD)	Just Fog	JUUL
size > 0.3	10.1 (4.2)	6.9 (1.8)
size > 0.5	8.1 (3.7)	4.6 (0.9)
size > 0.7	7.8 (4.0)	4.6 (1.6)
size > 1.0	7.9 (3.7)	4.6 (1.6)

Lampos et al.[29] found similar results on the half-life of particles smaller than 1 μm emitted by e-cigs: their emissions lifetime is approximately 10–20 s in a similar room.

This very short half life is probably due to the reaction pathways of compounds that are attributed to PG and glycerol during the thermal decomposition of PG and glycerol in e-liquid solvents. The e-cigarette aerosol may be composed of a number of potentially harmful compounds in the gaseous phase such as acetone, benzaldehyde, methacrolein, acetaldehyde, 2-propenol, as well as the BTEX compounds.[16–19]

The aerodynamic profile of particles emitted by Just Fog and JUUL are mainly below 1 μm.

The day to day variation in all particles sizes, background subtracted, was very high, ranging, for the >0.3 size for example, from 75% to 85%, but the differences between the two devices were much smaller and ranging within 45–60%. The day to day variation expressed in number of particles was random regardless if the HVACS on or off because of the variability of the vaping method of the different vapers. But the differences between Just Fog and JUUL were always detectable and significant.

For the reasons described above, the use of multichannel OPCs with PM concentrations expressed in particles/cm^3, with programmable sampling time of seconds and without heating the sample have shown very positive results in evaluating the emissions of different e-cigs allowing the detection of liquid or semi liquid PM compounds and also their aerodynamic profile.

The main limitations of this study are the small number of tests and the possible variability of the vaping mode of the different volunteers. For these reasons, the described findings need to be confirmed by larger studies, characterized by suitable statistical power to achieve research objectives.

The presence of nicotine in only one of the two types of e-cig considered could not have affected the results in term of PM levels measured.[30] However, this is the first study evaluating the differences in generated aerosol of two different types of e-cigs in terms of particle number concentrations, adding important evidence to an emerging field.

The very short half-life of less than 15 s of the aerosol generated by e-cigs and the different modes of vaping of the volunteers are characterized by a non-uniform aerosol distribution within the room with consequent difficulties in the measurements. But despite these difficulties, the aerosol emission differences of the two e-cigs were evident, considering the significance of the Student's t-tests conducted between the peaks, which were almost always <0.05.

Considering this topic from a public health perspective, though both devices emit very small PM, potential harmful effects have to be taken into account, particularly for vulnerable populations, such as children, older people or chronic patients; moreover, repeated exposures to e-cig in real life conditions are still possible, especially in poorly ventilated, overcrowded enclosed spaces such as bars and discos.

Conclusions

Comparing the emissions in real-world environments, JUUL produced much lower number of PM than Just Fog. Moreover, the use of HVACS can help to reduce the half-life of the PM but not eliminate it completely.

It should be noted that aerosol is not the only health exposure risk of e-cig use: other studies[15–24] have demonstrated that several other gaseous phase compounds, some of which are carcinogenic (such as formaldehyde) may be generated. Moreover, the presence and impossibility of modulating the concentration of nicotine must be assessed among the risks, as it is the main substance that creates the strong addiction.

However, other research is needed to better evaluate the environmental pollution generated by e-cigs, not only in number of particles, but also measuring volatile organic compounds, formaldehyde, heavy metals, ultrafine particles and other pollutants.

The difference in number of particles measured by the OPC between the two models of electronic cigarettes is significant but the reduction of the environmental pollution of the JUUL may not be sufficient to eliminate or to reduce the risk to the health of users and to the people involuntarily exposed to the aerosol of e-cigs, especially in public indoor environments.

Authors' contribution

AB, AAR contributed to study conception, designed the study, performed the cross-sectional laboratory-based experiments and wrote the first draft of the paper. CVe contributed to study conception, designed the study and performed the cross-sectional laboratory-based experiments. RB, CDM, ATi, MB contributed to study conception and designed the study. ATi performed the statistical analysis. EF, OT, SG, AL, GG, GC, MJL, XC, SS, RD, LC, SK, ATz, CVa, ALN, PS, JBS contributed to write the paper. RD revised the English. All authors read and approved the final manuscript.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Specifically, they declare they did not receive, directly or indirectly, funding from tobacco manufacturers or their affiliates.

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