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Comparable Impairment of Vascular Endothelial Function by a Wide Range of Electronic Nicotine Delivery Devices

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Abstract

Introduction: Electronic nicotine delivery systems (ENDS; ie, vaping devices) such as e-cigarettes, heated tobacco products, and newer coil-less ultrasonic vaping devices are promoted as less harmful alternatives to combustible cigarettes. However, their cardiovascular effects are understudied. We investigated whether exposure to aerosol from a wide range of ENDS devices, including a new ultrasonic vaping device, impairs endothelial function.

Aims and Methods: We measured arterial flow-mediated dilation (FMD) in rats ($n = 8/\text{group}$) exposed to single session of 10 cycles of pulsatile 5-second exposure over 5 minutes to aerosol from e-liquids with and without nicotine generated from a USONICIG ultrasonic vaping device, previous generation e-cigarettes, 5% nicotine JUUL pods (Virginia Tobacco, Mango, Menthol), and an IQOS heated tobacco product; with Marlboro Red cigarette smoke and clean air as controls. We evaluated nicotine absorption and serum nitric oxide levels after exposure, and effects of different nicotine acidifiers on platelet aggregation.

Results: Aerosol/smoke from all conditions except air significantly impaired FMD. Serum nicotine varied widely from highest in the IQOS group to lowest in USONICIG and previous generation e-cig groups. Nitric oxide levels were not affected by exposure. Exposure to JUUL and similarly acidified nicotine salt e-liquids did not affect platelet aggregation rate. Despite lack of heating coil, the USONICIG under airflow conditions heated e-liquid to $\sim 77^\circ\text{C}$.

Conclusions: A wide range of ENDS, including multiple types of e-cigarettes with and without nicotine, a heated tobacco product, and an ultrasonic vaping device devoid of heating coil, all impair FMD after a single vaping session comparably to combusted cigarettes.

Implications: The need to understand the cardiovascular effects of various ENDS is of timely importance, as we have seen a dramatic increase in the use of these products in recent years, along with the growing assumption among its users that these devices are relatively benign. Our conclusion that a single exposure to aerosol from a wide range of ENDS impairs endothelial function comparably to cigarettes indicates that vaping can cause similar acute vascular functional impairment to smoking and is not a harmless activity.

Introduction

Vaping e-cigarettes (e-cigs) is viewed by many people as benign but a growing literature indicates harmful effects to multiple systems, including cardiovascular effects.^{1–7} Although e-cigarettes have been promoted as cessation aids for adults, this is debatable.^{8,9} Young adults who are not accustomed to the effects of nicotine are experimenting,^{10,11} leaving them more prone to future cigarette use.^{12,13}

It is unclear what components of vaping aerosols lead to harmful effects. Compared with smoke, aerosol from e-liquid is a less complex mixture of a small number of well-characterized major components and small amounts of any less-well-characterized chemical reaction products. E-liquid consists mainly of propylene glycol (PG) and vegetable glycerin (VG) with freebase nicotine or acidified nicotine salts. When inhaled in e-cigarette aerosol, PG/VG can harm respiratory epithelial cells and interfere with the response to

infectious challenge.¹⁴ Caporale et al.⁴ showed that vaping e-liquids lacking nicotine transiently impaired vascular endothelial function. A single vaping session in healthy adults increased endothelial cell signaling and biomarkers correlating with adverse functional vascular changes.⁶

Flavorants are another important category of potentially harmful e-liquid components. According to the National Youth Tobacco Survey, 8 out of 10 e-cig users used flavored e-cigarettes.^{15,16} However, e-cig flavorants like menthol and eugenol decrease nitric oxide (NO) production in endothelial cells.¹⁷ Moreover, while not generally included in a list of e-liquid ingredients, the specific acid used to protonate nicotine into the salt form (eg, sodium benzoate in JUUL) introduces yet another variable into the potential health effects of e-liquid aerosols, which (to our knowledge) has not been explored. Notably, both the flavorant benzaldehyde and the acidifier benzoic acid can be converted to the carcinogen benzene under some aerosolization conditions.¹⁸

Nicotine delivery technology has evolved substantially in the last several years with the advent of nicotine salts and ultrasonic delivery approaches. E-cigarettes came into market in 2007 but the introduction of more palatable nicotine salts and sleek, easily concealable design by JUUL Labs in 2015, led to a tremendous increase in youth vaping.^{19,20} A more recent innovation is the introduction of ultrasonic vaping devices such as those from USONICIG, which use ultrasonic vibrations to produce aerosol without a heating coil. The ultrasonic chip in the USONICIG Zip operates at 3 000 000 vibrations/s to aerosolize e-liquid. This device uses a refillable e-liquid pod, a fiberglass tube, cotton, and an ultrasonic chip over a battery (1200 mAh) connector. The lack of heating coil presumably avoids the chemical reaction products from e-liquid components and the liberation of free metals from the coil, making them potentially safer than other vaping devices. While JUUL devices are designed to deliver nicotine more efficiently by using nicotine salts, USONICIG devices are advertised to maintain high nicotine delivery by avoiding breakdown of nicotine using lower temperature. The health benefits of using ultrasonic vaping devices instead of traditional vaping devices remain relatively unexplored.

Acute exposure to smoke/aerosol from combusted cigarettes and e-cigarettes causes endothelial dysfunction in humans^{1,21–23} measured as arterial flow-mediated dilation (FMD), a validated measure for overall cardiovascular health.^{24–26} Using our established rat model²⁷ that employs micro-ultrasound to measure femoral artery FMD similarly to how brachial artery FMD is measured clinically, we previously showed in rats that acute exposure to sidestream smoke from combusted tobacco products^{28,29} or from marijuana,³⁰ or aerosol from e-cigarettes,⁷ heated tobacco products,³¹ or cannabis vaporizers,³² all similarly impair endothelial function. We now have comprehensively examined the effects on FMD of acute exposure to aerosol from a wide range of electronic nicotine delivery systems (ENDS) including both free-base nicotine and nicotine salt e-liquids of several flavors, a heated tobacco product, and an ultrasonic device, along with PG and VG alone. As short-term exposure to e-cigs increases platelet aggregation in mice,^{33,34} we measured platelet aggregation after exposure and determined whether different nicotine acidifiers influenced aggregation or nicotine absorption. Finally, as it is known that serum from chronic smokers³⁵ and vapers³⁶ impairs release of NO from cultured endothelial cells, we also evaluated the effects of postacute exposure rat serum on endothelial NO release.

Methods

Animals

We used Sprague-Dawley rats, 9–11 weeks old, $n = 8$ rats/group (4 male, 4 female), 233 ± 7 g, the standard condition for our previous studies on inhalational exposures.^{7,28–31} Based on standard deviation within groups, $n = 8$ /group was sufficient to detect FMD changes of 3.5 percentage points (absolute values) at power of 0.8 and significance levels of 0.05. Rats were anesthetized with intraperitoneal injection of ketamine (100 mg/kg) and xylazine (5 mg/kg). To maintain temperature at 37.5°C and prevent hypothermia during the experiment, rats were kept on a thermal pad. Frequency and depth of respiration were continuously monitored to ensure full anesthesia; supplemental intramuscular anesthetic was

given if necessary. All procedures were approved by the UCSF Institutional Animal Care and Use Committee.

Measurement of Endothelial Function

FMD was measured as described previously.²⁷ After anesthetizing the rat, we made a 1-cm incision in the groin to expose the common iliac artery. We then placed an arterial loop occluder consisting of a 4-0 Prolene filament under the artery and passed it through a 15-cm PE-90 tubing enabling transient occlusion of blood flow after suturing the skin. The ultrasound probe was positioned parallel to the femoral artery to obtain the artery image, and the optimal portion between the proximal and distal end was selected for the arterial diameter measurements. A series of femoral artery images and accompanying Doppler blood flow images were recorded using a Vevo3100 LT ultrasound system with a 550 MHz transducer (VisualSonics, Toronto, Canada). After capturing the baseline internal diameter image, we induced a transient occlusion for 5 minutes followed by release of the snare to reestablish perfusion with a rush of blood flow (hyperemia), with ultrasound measurements of femoral artery diameter performed every 30 seconds for 3 minutes with additional measurements at 4 and 5 minutes.

FMD was measured before and after exposure. We used an automated program (Brachial Analyzer Version 6.11.9; Medical Imaging Applications, Coralville, IA) to measure baseline artery diameter and peak postischemia diameter during diastole. The investigator was blinded to exposure conditions during FMD procedure, analysis of ultrasound images, and subsequent calculations. FMD was calculated as % change: $(\text{peak diameter}_{\text{postischemia}} - \text{diameter}_{\text{baseline}}) / \text{diameter}_{\text{baseline}} \times 100$.

Smoke/Aerosol Generation and Exposure

For generating aerosol from devices representative of previous generation e-cigs, we used a Nautilus Aspire tank (33% VG and 67% PG by volume, 12 mg/mL freebase nicotine (MyFreedomSmokes). Freebase nicotine e-liquid was unflavored. The Nautilus tank was also used to aerosolize 100% PG and 100% VG or a nicotine-free combination of the two. A JUUL starter kit (Batch: G0811CG-1) with “5% nicotine” JUUL Virginia Tobacco pods (listed percent nicotine is by weight but corresponds to 59 mg/mL; JUUL e-liquid is 60% VG and 30% PG by volume) and Menthol flavor pods were purchased from local California gas stations. Mango pods were purchased anonymously from the manufacturer. For generating JUUL-like aerosol from e-liquids without nicotine, we used refillable pods compatible with JUUL devices purchased from ShopMVG. A USONICIG Zip device was purchased from the manufacturer and unflavored e-liquid consisting of 60% PG and 40% VG with 12 mg/mL freebase nicotine was used. An IQOS 3 multidevice was obtained in Germany and Marlboro HeatSticks (Batch: 975000) were purchased in Atlanta, GA. Cigarettes were Marlboro Red brand (Batch: 283572).

We exposed anesthetized rats via nose cone to the ENDS aerosols and the cigarette smoke, and clean air as a negative control. Our pulsatile exposure regimen consisted of a series of consecutive 30-second cycles, each consisting of 5-second exposure to smoke/aerosol followed by 25 seconds of clean air, over 5 minutes. To generate the aerosol and mainstream smoke, we used a Gram Universal Vaping Machine version 5.0 (Gram Research, Oakland, CA).^{7,31} The system generated 35 mL of aerosol or smoke over 2 seconds, following the

ISO standard 3308:2012 smoking regimen for each draw but the push for exposure was over 5 seconds to ensure at least one inhalation, and the frequency of cigarette smoking was doubled to remain directly comparable to the e-cig exposure timing.

We did not control particle levels because we used whatever mainstream aerosol or smoke was generated by a simulated inhalation through these products. Separate syringes, valves, and tubing segments were used for each product to avoid cross-contamination of different aerosols and smoke.

Rats from each group were exposed in a random order and arterial diameter measurements were obtained by an investigator unaware of the experiment condition.

Composition of Acidifier Solutions

One experiment involved rats exposed to lab-produced e-liquids based on 60% VG and 30% PG with the remaining 10% consisting of freebase nicotine at a final concentration of 59 mg/mL (as in “5%” JUUL pods), acidified with equimolar amounts of the acid of choice. Those acids were benzoic acid (45 mg/mL final concentration), malic acid (49.5 mg/mL), or salicylic acid (51 mg/mL).

Whole Blood In Vitro Platelet Aggregation

Whole blood was collected from the left ventricle of the still-anesthetized rat in a terminal procedure with a 21G BD Safety-Lok Butterfly Blood Collection Needle (BD, Franklin Lakes, NJ) in Vacutainer PST Tubes with spray-coated lithium heparin (BD) 10 minutes after end of exposure. Blood was incubated at room temperature for 30 minutes following collection.

To assess the effect of different exposures on platelet aggregation, we used a Whole Blood Impedance model 810 Aggregometer (Chrono-log Corporation, Havertown, PA) following manufacturer’s instructions. After setting up the baseline, 10 μ L adenosine diphosphate (ADP) was added to the cuvette with diluted blood (10 μ M final concentration) and the impedance was measured for 6 minutes. Area under the curve and amplitude of the platelet aggregation curve were measured and calculated by AGGRO/LINK for Windows Software version 5.1 (Chrono-log). Each sample was measured twice, and the replicate values were averaged for analysis.

Measurement of Serum Nicotine

To determine the amount of nicotine absorbed, we performed cardiac puncture in rats to collect whole blood after completing postexposure FMD imaging. Serum was prepared and was sent out for quantitative nicotine analysis at the UCSF Tobacco Biomarker Core facility.

Measurement of NO Levels

To determine if exposure of rats to smoke or aerosol caused changes in serum that could exert inhibitory effects on endothelial NO release in vitro, we measured the levels of NO species both directly in postexposure serum, and in culture medium accumulated from rat primary aortic endothelial cells (RAECs; Cell Biologics, Chicago, IL) that had been incubated in the postexposure serum. RAECs were cultured in a T-75 flask (Corning, Corning, NY) and used at passages 4–6. Confluent cells were trypsinized and centrifuged at 320g for 5 minutes, and the cell pellets were isolated and resuspended in fresh culture media. 400 μ L of media containing 50 000 RAECs was plated in each well of a 24-well culture dish. After 24 hours for the cells to attach, the supernatant

was replaced with 2:3 (vol/vol) postexposure rat serum and cell media. Before the cell treatment, the serum samples were heated at 55°C to inactivate complement. RAECs were incubated for 12 hours, and the supernatants were collected to measure unstimulated NO levels. The cells were then washed twice with phosphate-buffered saline. After the wash, media containing 50 ng/mL recombinant human vascular endothelial growth factor (VEGF) (Sigma-Aldrich, St. Louis, MO) was added and the cells were stimulated for 30 minutes. At the end of the stimulation, the supernatants were collected. Cell viability was assessed by 0.4% trypan blue stain (Thermo Fisher Scientific, Waltham, MA) each time and the proper dosage of serum to cell media for cell viability was determined by CCK-8 (Sigma-Aldrich).

The NO levels in serum and culture supernatants were measured as nitrite plus nitrate by the chemiluminescence method using a Liquid NO nCLD 88 Analyzer (Eco Physics, Switzerland). The levels of NO measured in culture supernatants were normalized to the cell count of each well.

Measurement of USONICIG Temperature

USONICIG e-liquid temperature was measured using a rapid response Type-K thermocouple of 0.25 mm diameter as previously described.³⁷ The thermocouple was inserted in the e-liquid pod to touch the base and the device was activated to measure the rising temperature both in the absence of airflow and during aerosol generation using a syringe similar to that in the Gram system described above. Data were logged using the HOBOWare, graphing, and analysis software package.

Statistics

To evaluate differences in FMD or baseline diameter versus time or exposure conditions, we fit a two-factor (exposure condition and time) repeated measures analysis of variance to all data using a linear mixed model estimated with restricted maximum likelihood estimation, then tested for differences over time and across exposure conditions using contrasts and pairwise comparisons, adjusted for multiple comparisons using the Šidák method using STATA 13.1. For platelet aggregation, statistical analyses and graphs were generated using GraphPad Prism 9 (San Diego, CA). Data were compared between the different groups with parametric and nonparametric forms of one-way analysis of variance after the normality test. For in vitro experiments, biological group means were compared by analysis of variance with nonparametric analysis.

Results

FMD Was Impaired by Exposure to Aerosol From All ENDS Tested, Regardless of Nicotine or Heating Coil

To determine effects of acute ENDS exposure on FMD, we exposed rats to aerosol from PG alone, VG alone, PG + VG combination without nicotine, previous generation e-cig, USONICIG, JUUL (Virginia Tobacco, Mango, Menthol), or IQOS; or to Marlboro Red cigarette smoke or clean air as controls. As shown in [Figure 1](#), FMD was impaired by aerosol from PG ($7.8 \pm 2.1\%$ pre-exposure vs. $3.4 \pm 2.2\%$ postexposure, $p = .0004$), VG ($12.8 \pm 2.9\%$ vs. $7.5 \pm 3.9\%$, $p = .007$), combination of PG and VG without nicotine ($10.9 \pm 2.0\%$ vs. $6.2 \pm 2.0\%$, $p = .002$), previous generation e-cig ($9.8 \pm 2.9\%$ vs. $5.4 \pm 1.4\%$, $p = .006$), USONICIG Zip ($11.2 \pm 2.2\%$ vs. $6.1 \pm 2.3\%$, $p = .0002$), JUUL Virginia Tobacco ($10.9 \pm 3.5\%$

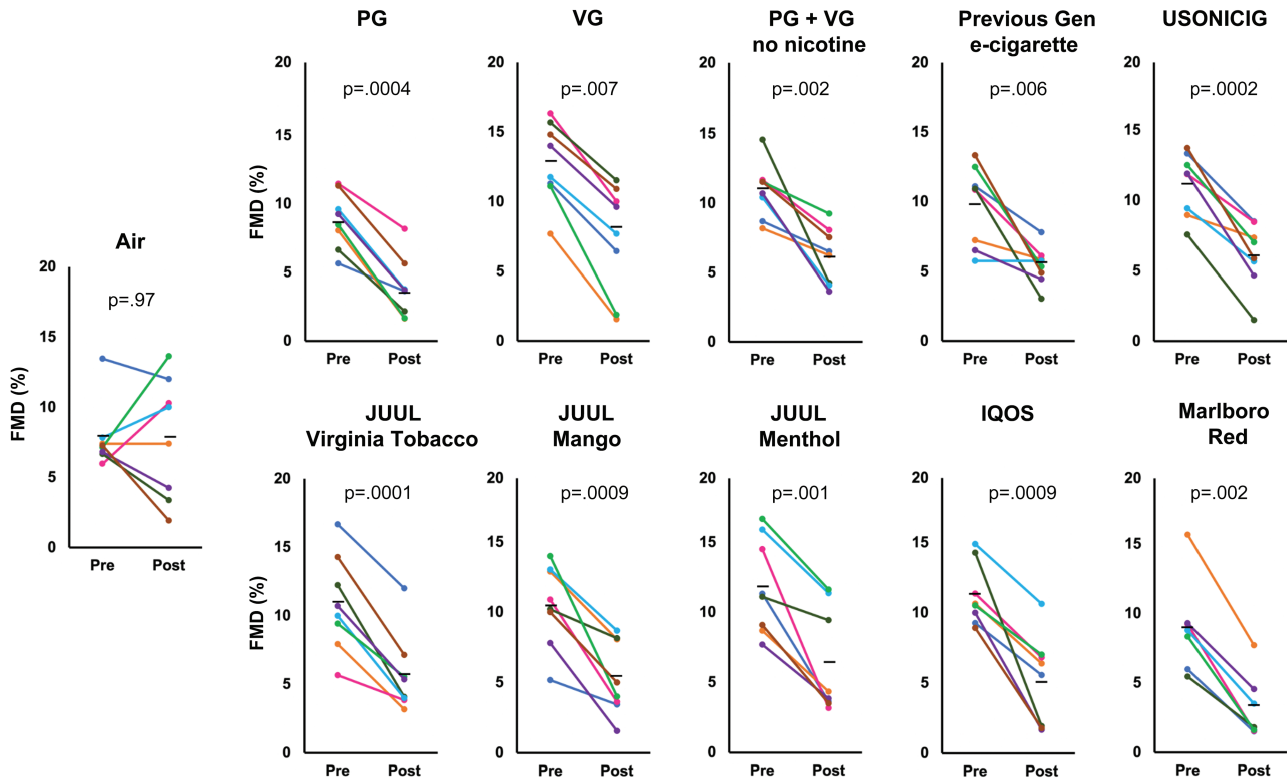


Figure 1. FMD was significantly impaired by exposure to aerosol from all groups except air. Each graph denotes FMD after 5 minutes of exposure. Colored lines denote individual rats. Horizontal bars denote mean of respective groups; see text for individual SDs. *p* values are derived from paired two-tailed *t* tests. FMD = flow-mediated dilation.

vs. $5.6 \pm 2.9\%$, $p = .0001$), JUUL Mango ($10.5 \pm 2.9\%$ vs. $5.3 \pm 2.7\%$, $p = .0009$), and JUUL Menthol ($11.9 \pm 3.4\%$ vs. $6.4 \pm 3.7\%$, $p = .001$), IQOS ($11.2 \pm 2.2\%$ vs. $5.2 \pm 3.2\%$, $p = .0009$), and Marlboro Red cigarette smoke ($9.0 \pm 3.3\%$ vs. $3.2 \pm 2.3\%$, $p = .002$). No significant impairment of FMD was seen in the air group ($7.8 \pm 2.3\%$ vs. $7.9 \pm 4.3\%$, $p = .98$).

The extent of FMD impairment ranged from 40% to 60% but did not significantly differ between the groups other than the air control ($p = .97$; [Supplementary Figure 1](#)). No significant differences were observed in the baseline femoral artery diameter pre- and postexposure to aerosol/smoke ([Supplementary Figure 2](#)). Frequency and depth of respiration did not noticeably change during exposures.

Serum Nicotine Was Highest in Rats That Were Exposed to IQOS Aerosol

Serum nicotine levels were highest in rats exposed to aerosol from IQOS (61.4 ± 30.9 ng/mL), followed by JUUL Mango flavor (40.5 ± 12.9 ng/mL), JUUL Virginia Tobacco flavor (38.7 ± 11.1 ng/mL), JUUL Menthol flavor (37.1 ± 15.4 ng/mL), and Marlboro Red cigarettes (22.5 ± 5.0 ng/mL). Low levels of serum nicotine were found in rats exposed to previous generation e-cig (8.4 ± 1.9 ng/mL) and USONICIG (7.0 ± 1.0 ng/mL). As expected, nicotine was undetectable in serum from rats exposed to PG, VG, PG + VG without nicotine, and clean air ([Figure 2](#)).

Nicotine Absorption Was Not Influenced by Choice of Nicotine Salt Acidifier, But Was Higher From JUUL E-Liquid Than From Laboratory-Mixed E-Liquids

JUUL nicotine salts are produced by acidifying nicotine with benzoic acid, but commercial nicotine salt e-liquids vary with

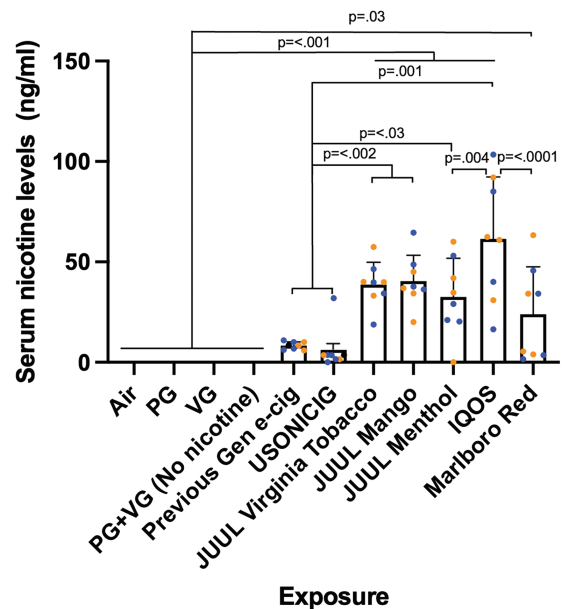


Figure 2. Serum nicotine (ng/mL) from sera collected 20 minutes after end of exposure to different aerosols or smoke. Colored dots denote gender of rats: blue = females and orange = males. Most *p* values not shown here were all $>.1$; except for JUUL Virginia Tobacco versus IQOS, which was borderline significant at $p = .057$. Bars = SD.

respect to the acid used. We filled JUUL-like pods with a similar PG/VG ratio to JUUL's with comparable nicotine concentration using benzoic acid as acidifier. The rats exposed to the JUUL e-liquid had substantially higher serum nicotine levels than those exposed to the lab-mixed benzoic acid

e-liquid (39.3 ± 19.1 vs. 15.3 ± 4.2 ng/mL, $p < .001$; Figure 3, A). However, there were no significant differences between nicotine levels in the rats exposed to the lab benzoic acid e-liquid aerosol and those exposed to aerosols with malic acid (6.5 ± 3 ng/mL) and salicylic acid (10.7 ± 2.5 ng/mL) ($p > .1$).

Platelet Aggregation Rate Was Not Affected by Acute Exposure to JUUL or Similar Aerosols With Different Nicotine Acidifiers

We measured platelet aggregation in rats exposed to aerosols from JUUL Virginia Tobacco and from nicotine salt e-liquid produced using the different nicotine acidifiers (benzoic acid, malic acid, and salicylic acid). Clean air was used as negative control. No significant difference in aggregation rate was observed between the groups using two different types of measurements: amplitude ($p = .74$; Figure 3, B), and area under the curve ($p = .43$; Figure 3, C).

Serum NO Levels and Serum Effects on NO Release From Cultured Endothelial Cells Were Not Affected by a Single Session of Aerosol Exposure

To determine if exposure of rats to smoke or aerosol caused changes in vascular endothelial NO release, we evaluated NO levels in two different relevant scenarios after exposure to a subset of products that have consistently been observed to impair FMD in previous experiments (Marlboro Red cigarettes, IQOS, and JUUL Virginia Tobacco flavor, with air control; Figure 4). First, we measured NO directly in the serum, and observed no differences between groups of rats exposed to the different products ($p = .19$). Second, we incubated commercially available RAECs in the serum samples, under both unstimulated and VEGF-stimulated conditions, and measured NO released from the cells into the culture medium, with results normalized to cell numbers in the wells. We did not observe any significant difference in the amount of NO levels from unstimulated ($p = .80$) or stimulated conditions ($p = .69$).

USONICIG Heats E-Liquid Despite Lack of Heating Coil

While USONICIG lacks a heating coil, the ultrasonic vibrations may still heat the e-liquid; but this information was

unavailable from the manufacturer. Therefore, we measured the temperature of the e-liquid during use. In the absence of the airflow to generate aerosol, the device caused elevation of temperature ranging from 100°C to 254°C . However, under realistic use conditions of pulsatile airflow, the e-liquid temperature did not exceed 77°C (Figure 5).

Discussion

We examined how acute exposure to different ENDS influences rat vasodilatory function, platelet function, nicotine absorption, and endothelial NO release. Although there have been many studies that investigated the role of acute ENDS exposure in impairing endothelial function,^{1,7,17,31,38–41} our study has its novelty in exploring endothelial functional and serum nicotine level from different types of ENDS with diverse aerosol generation mechanisms (heating coils vs. vibrations), and multiple flavors or lack thereof (JUUL flavors were Mango, Menthol, and Virginia Tobacco; the other ENDS were unflavored). There are no unflavored JUUL pods, but Virginia Tobacco flavor was reported to have the lowest level of flavorants of the 8 flavors on the market as of August 2019 when these were obtained.⁴² Moreover, we investigated whether different nicotine acidifiers in e-liquid (benzoic acid, malic acid, and salicylic acid) affect nicotine absorption and platelet aggregation in exposed animals.

Regardless of flavors, nicotine concentration of e-liquid, and heating mechanisms, we found that all acute exposures to aerosol from different ENDS impaired FMD comparably to each other and to smoking. We have previously shown that when FMD is impaired by tobacco or marijuana sidestream smoke, endothelium-independent vasodilation induced by nitroglycerin remains intact, indicating that impaired FMD reflects an impaired endothelial function.^{28,30} Our results in the rodent FMD model indicate that the known consequences of cigarette smoke on vascular function^{21,22,43} are not avoided by using these products even at the low exposure level of a single session of 10 cycles of pulsatile 5-second exposure over 5 minutes. Furthermore, Caporale et al.⁴ showed that vaping nicotine-free e-cigarettes transiently impacts vascular function, consistent with our results that the e-cigarette aerosol

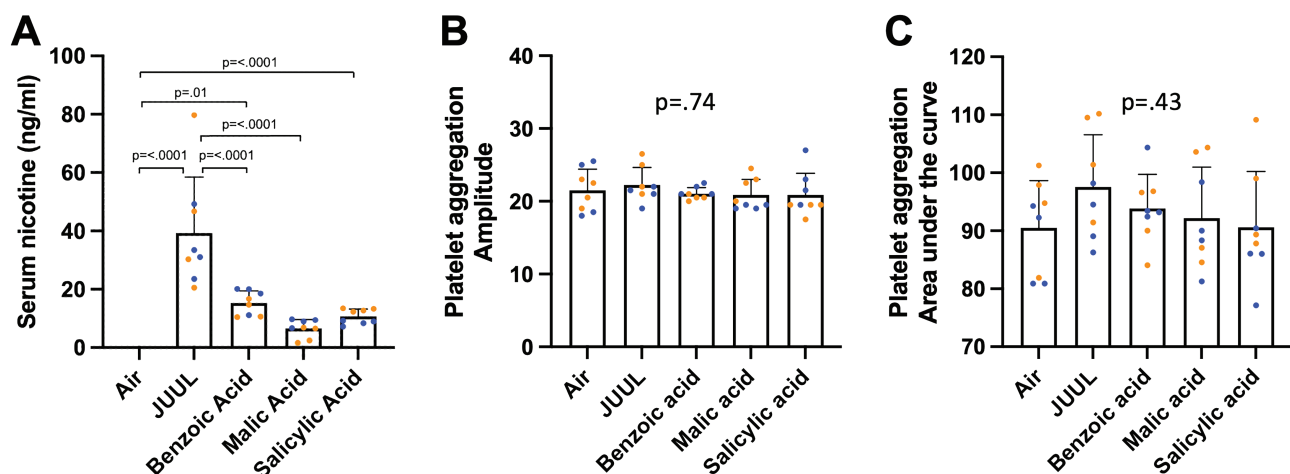


Figure 3. Choice of nicotine acidifier did not significantly modulate nicotine absorption or ADP-induced platelet aggregation. (A) Serum nicotine levels after exposure did not vary significantly with acidifier, but were higher with JUUL e-liquid than with e-liquids produced in the laboratory. (B, C) Platelet aggregation was not significantly changed by JUUL or lab-produced e-liquids. Colored dots denote gender of rats: blue = females and orange = males. Bars = SD.

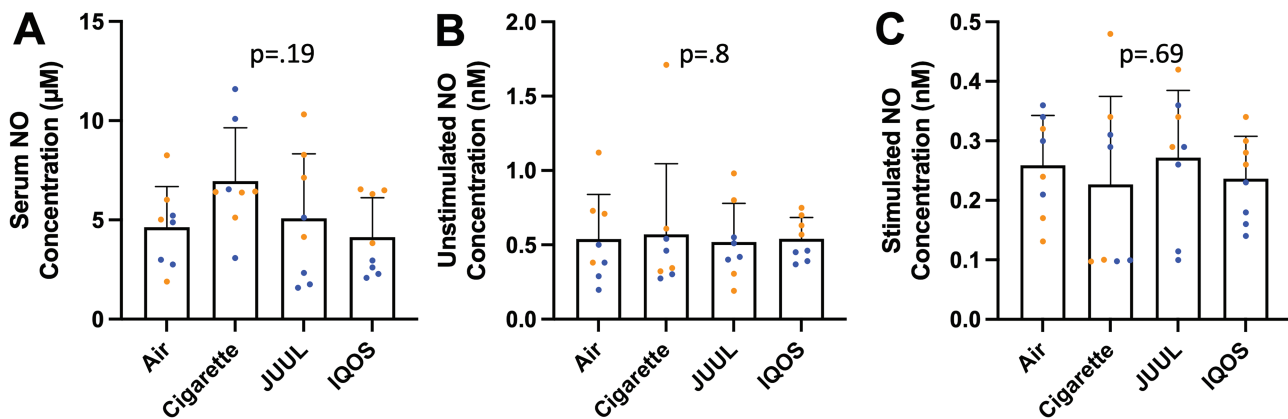


Figure 4. A single session of exposure to aerosol from JUUL, IQOS, and Marlboro Red cigarettes did not affect endothelial NO release. (A) Graph denotes serum NO concentration levels; no significant differences between groups. (B) Graph denotes unstimulated accumulated NO levels in culture supernatants from cells incubated for 12 hours in serum samples from representative groups; no significant differences were observed. (C) Graph denotes NO levels in similar culture supernatants after 30 minutes stimulation with VEGF; no significant differences between groups. Colored dots denote gender of rats: blue = females and orange = males. Bars = SD. NO = nitric oxide.

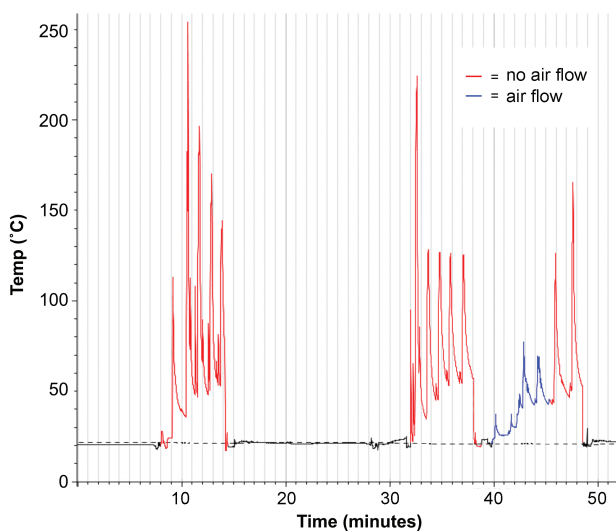


Figure 5. Temperature of e-liquid in USONICIG during successive device activations. Three pulsatile sessions are shown; each peak corresponds to an activation. The first two sessions consist of one activation per minute with no airflow. The third session consists of two pulses with airflow and aerosol generation, followed by two more pulses without airflow to confirm comparable readings to the previous sessions.

with or without nicotine or flavors impaired endothelial function comparably to cigarettes. While this study and comparable human studies have focused mainly on transient effects of acute exposures, previous studies of chronic human active and passive smokers have indicated that repeated transient impairments ultimately lead to chronic dysfunction.^{21,22}

Serum nicotine levels in rats exposed to IQOS were significantly higher than all other groups, which is consistent with our earlier results.³¹ Levels in previous generation e-cig and USONICIG groups were significantly lower than in JUUL groups (Virginia Tobacco, Mango, Menthol), which aligns with the fact that JUUL e-liquid delivers much higher concentrations of nicotine salts compared with the USONICIG and the freebase nicotine of previous generation e-cigs. Another reason for these observations could be due to the differences in particle sizes or inhalation tidal volume in response to products of varying levels of irritation. However, the lower nicotine absorption also suggests that the users may engage in

compensatory puffing to get enough nicotine for a sufficient hit. We observed that the difference in e-liquid nicotine content and serum nicotine concentration do not correlate with the degree of FMD impairment in acute exposure settings, which appears to involve a threshold effect. However, while USONICIG Zip probably avoids production of many chemical reaction products common to standard coil-based vaping devices,⁴⁴ using USONICIG Zip to get equal amounts of nicotine in the body may pose higher risks of exposure to other harmful properties of smoke and aerosols.

Our inclusion of the ultrasonic USONICIG device was informative, because many of the harmful constituents of e-cigarette aerosol include chemical reaction products resulting from the heating process⁴⁵ and metals derived from the heating coil,⁴⁴ neither of which are expected to be in aerosol from the coil-less USONICIG devices. Our measurements indicated that the 3 MHz vibrating chip does heat the e-liquid to some extent during realistic use with airflow (~70°C–77°C; Figure 5). In contrast, when tested without airflow, the measured temperatures fell into the range of those measured for a heating-coil-based e-cig, which have been measured as varying from 110°C to 334°C under a range of realistic coil wetness conditions.³⁷ It should be noted that this thermocouple measurement provided only a quick one-point temperature assessment. More research is needed to fully understand the spatial temperature distribution at a given instant. Nonetheless, it is notable that aerosol from the USONICIG impaired FMD as much as the other ENDS and smoke exposures did.

Chronic smoking⁴⁶ and acute exposure to e-cig aerosol^{33,34,47} are known to lead to an increase in platelet aggregation. However, the amount of exposure in these publications was high, lasting several hours/week or for multiple weeks, whereas our study involved only a single 5-minute pulsatile session of exposure. We observed no significant difference in platelet aggregation after the acute exposure with JUUL and other e-cigarettes with different nicotine acidifiers. Therefore, although published literature shows a clear link between vaping and increased platelet aggregation, a longer duration of exposure may be necessary to alter the platelet behavior and increase platelet aggregation.

We were surprised that nicotine absorption was higher for JUUL e-liquid compared with laboratory-mixed e-liquids, given that one of them used benzoic acid and should be similar

in composition to JUUL. This could have been a result of the differences in the age of the relatively fresh lab-made versions of JUUL e-liquid, and the actual JUUL pods that had been produced at least several months before the experiment. Alternatively, the difference may have been due to the presence of 10% water in our laboratory-mixed e-liquid, as it is not clear from JUUL's description of its e-liquid how much of the remaining 10% ascribed to benzoic acid and nicotine is aqueous. A subsequent measurement of aqueous dilutions revealed a pH of 6.0 in JUUL and 6.3 in our corresponding benzoic acid e-liquid, a slight difference that may have resulted in varying absorption due to varying protonation states.

We opted to not measure FMD after exposure to e-liquids with various nicotine acidifiers, because the consistent response of FMD impairment to the wide variety of aerosols makes it unlikely that the choice of acidifier would influence that property. As we found that acute exposure to cigarette smoke and JUUL aerosol did not affect platelet aggregation, and acute exposure to aerosol/smoke from JUUL, IQOS, and cigarettes did not affect NO levels, we did not extend these studies to the other ENDS devices. Relevant limitations of our study are that (1) we stimulated NO release with VEGF, which works well in human cells³⁶ but is less physiologically relevant than acetylcholine and may have missed a subtle stimulated effect; and conversely (2) we induced platelet aggregation with 10 μ M ADP, which is a strong stimulant of aggregation and that may have saturated the effect and missed subtle differences.

We conclude that a wide range of ENDS, including multiple types of e-cigarettes with and without nicotine, a heated tobacco product, and an ultrasonic vaping device devoid of heating coil, all impair FMD after a single vaping session comparably to combusted cigarettes.

Supplementary Material

A Contributorship Form detailing each author's specific involvement with this content, as well as any supplementary data, are available online at <https://academic.oup.com/ntr>.

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Declaration of Interests

None declared.

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Data Availability

All functional data will be available at https://datadryad.org/stash/share/qHD_J-Ru3mqL_LIUJKDQA1QnG6nr_Sce2hBjlmWRJw, doi:10.7272/Q63F4MW3.

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