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Use of electronic cigarettes (e-cigarettes) impairs indoor air quality and increases FeNO levels of e-cigarette consumers

Wolfgang Schober[a,*], Katalin Szendrei[a], Wolfgang Matzen[a], Helga Osiander-Fuchs[b], Dieter Heitmann[c], Thomas Schettgen[d], Rudolf A. Jörres[e], Hermann Fromme[a]

[a] Bavarian Health and Food Safety Authority, Department of Chemical Safety and Toxicology, Pfarrstrasse 3, 80538 Munich, Germany
[b] Bavarian Health and Food Safety Authority, Department of Cosmetics and Tobacco Products, Veterinärstrasse 2, 85764 Oberschleissheim, Germany
[c] Bavarian Environment Agency, Bürgermeister-Ulrich-Strasse 160, 86179 Augsburg, Germany
[d] Institute for Occupational and Social Medicine, Medical Faculty, RWTH Aachen University, Pauwelsstrasse 30, 52074 Aachen, Germany
[e] Institute and Outpatient Clinic for Occupational, Social and Environmental Medicine, Inner City Clinic, University Hospital of Munich, Ziemssenstrasse 1, 80336 Munich, Germany

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ABSTRACT

Despite the recent popularity of e-cigarettes, to date only limited data is available on their safety for both users and secondhand smokers. The present study reports a comprehensive inner and outer exposure assessment of e-cigarette emissions in terms of particulate matter (PM), particle number concentrations (PNC), volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), carbonyls, and metals. In six vaping sessions nine volunteers consumed e-cigarettes with and without nicotine in a thoroughly ventilated room for two hours. We analyzed the levels of e-cigarette pollutants in indoor air and monitored effects on FeNO release and urinary metabolite profile of the subjects. For comparison, the components of the e-cigarette solutions (liquids) were additionally analyzed.

During the vaping sessions substantial amounts of 1,2-propanediol, glycerine and nicotine were found in the gas-phase, as well as high concentrations of $PM_{2.5}$ (mean 197 $\mu g/m^3$). The concentration of putative carcinogenic PAH in indoor air increased by 20% to 147 ng/m^3, and aluminum showed a 2.4-fold increase. PNC ranged from 48,620 to 88,386 particles/cm^3 (median), with peaks at diameters 24–36 nm. FeNO increased in 7 of 9 individuals. The nicotine content of the liquids varied and was 1.2-fold higher than claimed by the manufacturer.

Our data confirm that e-cigarettes are not emission-free and their pollutants could be of health concern for users and secondhand smokers. In particular, ultrafine particles formed from supersaturated 1,2-propanediol vapor can be deposited in the lung, and aerosolized nicotine seems capable of increasing the release of the inflammatory signaling molecule NO upon inhalation. In view of consumer safety, e-cigarettes and nicotine liquids should be officially regulated and labeled with appropriate warnings of potential health effects, particularly of toxicity risk in children.

Introduction

Environmental tobacco smoke (ETS) is by far the most significant indoor air quality issue, bearing a health risk by inducing lung cancer and cardiovascular disorders in non-smokers (IARC, 2004; US, 2006). It is also considered as important risk factor for asthma, respiratory infections and sudden infant death syndrome in children (EPA, 1992, 1997; Raupach et al., 2008). National regulators in USA and Europe have progressively banned tobacco smoking from public buildings, bars, cafés and restaurants which led to improved indoor air quality in these buildings (Bohac et al., 2010; Gleich et al., 2011). The smoke-free policies and constantly surging tobacco prices prompted consumers to look for alternatives to conventional smoking. New products, especially electronic nicotine delivery systems also known as electronic cigarettes or e-cigarettes, have become popular in spite of insufficient data on their safety for both users and secondhand smokers (Etter et al., 2011).

E-cigarettes do not burn tobacco but produce a respirable aerosol without smoke or flame from a battery-powered heater and liquid-containing cartridges (Trtchounian et al., 2010).

Abbreviations: DNPH, 2,4-dinitrophenylhydrazine; e-cigarette, electronic cigarette; eCO, exhaled carbon monoxide; FeNO, exhaled nitric monoxide; GC, gas chromatography; HPLC, high-performance liquid chromatography; 3-OH-cotinine, trans-3′-hydroxycotinine; 3-HPMA, 3-hydroxypropylmercapturic acid; LOD, limit of detection; MS, mass spectrometry; PAH, polycyclic aromatic hydrocarbons; PM, particulate matter; PNC, particle number concentrations; VOC, volatile organic compounds.

* Corresponding author. Tel.: +49 09131 6808 4242; fax: +49 09131 6808 4297.
E-mail address: wolfgang.schober@lgl.bayern.de (W. Schober).

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Depending on the brand, the liquids usually contain nicotine in different concentrations (8.5–22.2 mg/ml) (Cameron et al., 2013), humectants to produce the vapor (especially 1,2-propanediol) and flavors (e.g. tobacco, vanilla, cherry). Despite the growing popularity of e-cigarettes, consumers do not have valid information on the chemical content of liquids or on their safety. In particular, liquids labeled as nicotine-free may contain low levels of nicotine (FDA, 2009), and the risk of impurities (e.g. nitrosamines) is of major concern to health care authorities (FDA, 2009). There is not only a lack of internationally certified manufacturing sites, and liquids freely available via the Internet are not subject to official quality control.

Because e-cigarettes are marketed for delivering nicotine and sometimes other substances, there is a need for regulation, as for other drug delivery devices. Thus far there has been a wide range of responses across countries and states, ranging from no regulation to complete bans (Etter et al., 2011). The empirical basis for these decisions is uncertain, and more research on the health effects of and risks from e-cigarettes must be conducted to ensure that the decisions of regulators, health care providers and consumers are based on scientific evidence.

The aim of our study was to perform a comprehensive exposure assessment by analyzing the indoor air concentration of e-cigarette emissions in terms of particulate matter (PM), particle number concentrations (PNC), volatile organic compounds (VOC), polycyclic aromatic hydrocarbons (PAH), carbonyls, and metals. For this purpose, we simulated a real-world scenario (café-like setting) in an environmentally controlled room with predetermined occupancy density and air exchange rate. Before and after the vaping sessions, the concentrations of exhaled carbon monoxide (eCO) and nitric oxide (FeNO) were measured to reveal acute effects of e-cigarette use on physiological parameters. FeNO has already been used in a previous study on e-cigarettes (Vardavas et al., 2012) and is sensitive to a number of factors including eosinophilic inflammation, airway caliber, mucus production, oxidative stress, and enzyme activity, all of which might be affected by e-cigarettes. Additionally, the uptake of nicotine and other VOC was investigated by analysis of urinary nicotine metabolites and mercapturic acids. To support consumer protection, we furthermore analyzed the chemical composition of the e-cigarette liquids and checked for the presence of impurities (nitrosamines).

Materials and methods

Study design

The study was carried out in a room in the office building of the Bavarian Health and Food Safety Authority in Munich, Germany. Room size was 18 m^2 and its volume 45 m^3. The room contained three tables and a wardrobe (café-like setting), and was operated at an average air exchange rate of 0.56 h^{-1}. The measurements were taken on seven days in July 2012 at the same time of the day. On the first day (control day) the air was monitored without vaping activities and on the following six days with e-cigarette consumption. Before the measurements, the room was thoroughly ventilated, and the window was kept tilted during the measurement periods. Subjects were asked to give spot urine before each exposure, and eCO and FeNO were measured using established monitoring devices (BreathCO, Vitalograph, Hamburg, Germany; NIOX MINO, Aerocrine, Bad Homburg, Germany); FeNO was assessed at the standard expiratory flow rate of 50 ml/s. During each vaping session three study subjects took a seat around a table and consumed an e-cigarette filled with a tobacco-flavored nicotine-free liquid (Liquid 1) from 10 am to 12 pm, while recording their individual number of puffs. This procedure was repeated on five consecutive days for the nicotinic variant of Liquid 1 and for another two other tobacco-flavored liquids (Liquid 2 and 3), each of these with and without nicotine (overall six experiments with three volunteers at each session). The equipment for sampling and monitoring was placed on 2 tables at the side of the room about 1 m above floor level and 1 m away from the e-cigarette consumers. After exposure eCO and FeNO were measured again to determine acute effects of e-cigarette use on these measures. For metabolite analysis subjects were asked to collect urine for another 24 h.

Liquids (with and without nicotine, all with tobacco flavor) and e-cigarettes were commercially available (Red Kiwi, Seevetal, Germany). The nicotine content of the liquids was 18 mg/ml according to the manufacturers' declarations. The e-cigarette contained a rechargeable lithium-ion battery, an electronic circuit, a vaporizer, and a mouthpiece with a refillable tank. Batteries were charged before the study and between study days to ensure their correct operation.

Subjects

Nine adult volunteers (all males, 20–30 years old, mean age 24.7 ± 4.2 years, size 173–198 cm, weight 63–85 kg) were recruited for participation in the study. In each vaping session three of them consumed first a nicotine-free and on the day after a nicotinic e-cigarette for two hours. All subjects judged themselves as healthy and were not under medication for at least 15 days before biomonitoring. In particular there was no evidence for pulmonary disease or other chronic conditions (e.g. renal or liver disease) that might influence FeNO and nicotine metabolism. All subjects were occasional smokers with a cigarette consumption of <10 cigarettes per week (no e-cigarettes) and capable of nicotine abstinence 48 h prior to each vaping session. Before taking part in the study, the subjects were familiarized with the device by vaping one e-cigarette under the instruction of the laboratory staff. Thereafter, each subject was given a test set including an e-cigarette and a non-nicotinic liquid to freely practice vaping for one week at home. Participants were asked to refrain from cigarette smoking for at least 48 h prior to their scheduled session. The ethical committee of the Bavarian Medical Association approved the study, and volunteers were enrolled in the study after giving written informed consent. The investigation was conducted according to the Declaration of Helsinki.

Chemical characterization of liquids

1,2-Propanediol, glycerine

To 0.3 g of each liquid 0.1 g internal standard (1,3-propanediol) were added. This mixture was dissolved in 5 ml isopropanol and diluted 1:5 with isopropanol. The GC analysis was carried out on an Agilent 6890 gas chromatograph with flame ionization detector (GC-FID). Separation was performed on an Agilent DB-WAXetr (polyethylene glycol) capillary column with following dimensions: 30 m length, 0.32 mm inner diameter and 1 μm film thickness. The GC oven temperature was programmed from an initial temperature of 150 °C for 2 min, followed by a ramp to 220 °C at 5 °C/min with a hold time of 20 min. 1-μl-samples were injected into the GC inlet at a 40:1 split ratio with helium carrier gas flow rate of 1 ml/min. Temperatures of injector and detector were 240 °C. The analytes were positively identified by comparison of their retention times with those of standards. Quantification followed the internal standard quantification method. The limit of detection (LOD) for 1,2-propanediol was 0.5%. The results were confirmed by analysis via a second GC-column (Agilent HP 5 capillary column) and in the case of glycerine by enzymatic analysis.

Nicotine

Samples were prepared by adding 100 μl internal standard solution (heptadecane, 25 mg/ml isopropanol) to 0.3 g of each liquid. This mixture was diluted with 2 ml isopropanol. The gas chromatograph instrument was an Agilent 6890 equipped with a flame ionization detector (GC-FID). Separation was carried out on an Agilent HP 5 (5% phenylmethyl polysiloxane) capillary column with following dimensions: 30 m length, 0.32 mm inner diameter and 0.25 μm film thickness. The GC oven temperature was programmed from 140 °C (held 5 min) to 210 °C at 20 °C/min with a hold time of 25 min. 1-μl-samples were injected into the GC inlet at a 20:1 split ratio with helium carrier gas flow rate of 1 ml/min. Temperatures of injector and detector were 250 °C and 280 °C, respectively. Nicotine was positively identified by comparison of retention time with that of the standard. Quantification again followed the internal standard quantification method. The LOD for nicotine was 0.1%. The results were confirmed by analysis on a second GC-column (Agilent DB-WAXetr capillary column).

Other organic compounds

Gas chromatography–mass spectrometry (GC/MS) was carried out with a Shimadzu QP2010 instrument equipped with an AOC-20i injector and a mass selective detector operated in the single-ion monitoring mode. A 1-ml-aliquot of each liquid was diluted with 10 ml chloroform and subjected to GC/MS analysis. Analyte separation was performed using helium as carrier gas with constant flow at 35 cm/sec and a 20 min temperature program composed as follows: 95 °C for 2 min, then 12 °C per min to 250 °C, then 10 °C per min to 280 °C, then held for 2 min at 280 °C. The MS transfer line temperature was 275 °C. A three-point calibration curve was prepared for both the respective analyte and its internal standard, and quantification was performed using the ratio of peak areas under a single ion chromatogram.

Nitrosamines

For analysis of tobacco-specific nitrosamines, a 1-ml-aliquot of each liquid was spiked with 10 μl internal standard (NNK-d_4) in preparation for LC/MS/MS analysis. N′-nitrosonornicotine (NNN), N′-nitrosoanatabine (NAT), N-nitrosoanabasine (NAB), and 4-(methylnitrosamino)-1-(3-pyridyl)-1-butanone (NNK) were analyzed by tandem mass spectrometry using selected reaction monitoring (SRM) detection. The LOD ranged from 0.22 ng/ml (NAB) to 0.38 ng/ml (NNK).

Analysis of indoor air parameters

Particle mass, particle number concentration

Continuous measurements of particle mass (PM_{10}, $PM_{2.5}$, $PM_{1.0}$) were made using an optical laser aerosol spectrometer (LAS) (Dust monitor 1.108 operated with factory default settings, Grimm Technologies, Ainring, Germany). This spectrometer works by constantly drawing air via a volume-controlled pump (1.2 l/min) through a flat beam of laser light. The scattered signals generated while particles cross the beam are detected with a high-speed photo diode, analyzed by an integrated pulse height analyzer and counted. The LAS measures particle concentrations in 15 size ranges from 0.300 to 20 μm. For our purposes the continuous measurements were stored minute-by-minute on a data logger. PNC were measured using a Wide Range Aerosol Spectrometer (WRAS, Grimm Technologies, Ainring, Germany). The WRAS comprises two particle counters and sizers: GRIMM 5.403 SMPS + C and GRIMM 1.108 LAS (described above), combined via software to one unit. The GRIMM 5.403 consists out of a high-resolution particle counter (CPC) attached to a "Vienna Type" electrostatic classifier (M-DMA). The complete WRAS covers the size range from 0.005 to >20 μm.

Volatile organic compounds

Indoor air samples were collected with a constant flow of 0.2 l/min with Tenax GR as adsorbent and analyzed using a thermodesorption unit (Gerstel, Mülheim, Germany) coupled to GC/MS (gas chromatograph 6890A coupled to MSD 5973N, Agilent, Waldbronn, Germany). The desorption temperature was 230 °C. The LOD for a single compound was 0.04 $\mu g/m^3$ using a sample volume of 24 l.

Aldehydes/ketones

Airborne concentrations of aldehydes and ketones were determined by DNPH method according to NIOSH Method 2018 (DNPH, 2,4-dinitrophenylhydrazine). Air was sampled on LpDNPH H10 Cartridges (Supelco, Bellefont, USA) with a constant flow rate of 0.1 l/min for 120 min. Elution of aldehyde derivatives was performed by 5 ml acetonitrile (LiChrosolv, Merck, Germany). A Dionex HPLC system UltiMate 3000 containing of sampler, degaser, gradient pump, column oven, and UV detector was used to carry out the measurements. Aldehyde derivatives were separated by a binary gradient (water/acetonitrile) on a reversed-phase column SUPELCOSIL LC-18 (250 mm × 4.6 mm, particle size 5 μm). UV detection wavelength was 360 nm. The LOD was 0.033 mg aldehyde per sample, resulting in 0.03 mg/m^3 aldehyde in air sample. Formaldehyde, acetaldehyde, butyraldehyde, acrolein, and acetone were analyzed.

Polycyclic aromatic hydrocarbons

Gaseous and particle-bound PAH were determined by collecting indoor air with a medium volume sampler equipped with a sampling unit consisting of a $PM_{2.5}$-inlet, a quartz fiber filter and a polyurethane foam. Filter and PU foam were extracted with toluene after addition of deuterated PAH standards, purified on a silica column and analyzed by GC/MS. Naphthalene, acenaphthylene, acenaphthene, phenanthrene, fluorene, anthracene, fluoranthene, pyrene, benzo[*a*]anthracene, chrysene, benzo[*b*]-+benzo[*k*]fluoranthene, benzo[*a*]pyrene, dibenzo[*a,h*]anthracene, indeno[1,2,3-*cd*]-pyrene, and benzo[*ghi*]perylene were determined as single PAH compounds. Additionally, the sum of these 16 PAH according to US-EPA was calculated. The LOD was 0.1 ng/m^3 using a sample volume of 10 m^3.

Metals/elements

Samples were collected on 47 mm quartz fiber filters (Pieper, Bad Zwischenahn, Germany) using a medium volume sampler equipped with a $PM_{2.5}$ sampler as sample inlet which operated at a constant flow of 2.3 m^3/h over a 2-h sampling period parallel to e-cigarette vaping. Before use, the filters (coming from the same production lot) were analyzed for their heavy metal blank values. After a closed-vessel microwave decomposition of the filter samples using nitric acid and hydrogen peroxide as oxidizing agents, the target analytes were measured using inductively coupled plasma-mass spectrometry (ICP-MS).

Indoor climate

Indoor carbon dioxide (CO_2) was measured using a continuously monitoring infrared sensor (Testo 435) (Testo, Vienna, Austria). The instrument was programmed for a 1-min data logging interval and values were averaged over the 2-h period of each vaping session. Indoor humidity, temperature and air pressure were measured simultaneously with a separate sensor connected to the Testo instrument. Indoor carbon monoxide (CO) was measured using a Fourier transform infrared (FTIR) spectrometer (Ansyco, Karlsruhe, Germany).

Determination of urinary nicotine metabolites by LC/MS/MS

Internal exposure to nicotine was determined by the quantification of urinary nicotine and its metabolites cotinine and

trans-3′-hydroxycotinine using a slightly modification of a LC/MS/MS-method (Xu et al., 2004). Shortly, 400 μl of urine was buffered to pH 4.5 using 400 μl of 0.1 M ammonium acetate buffer, 10 μl of the isotopically labeled internal standards (d_3-nicotine, d_3-cotinine and d_3-trans-3′-hydroxycotinine, 10 mg/l) were added and 10 μl of this solution were directly injected in the LC/MS/MS-system. The analytical column was a Phenomenex Fusion RP (150 mm × 4.6 mm) with 2 mM ammonium acetate (pH 4.5) in water and 2 mM ammonium acetate (pH 4.5) in acetonitrile as eluents at a flow rate of 0.4 ml/min. Between-series precision was determined using a native smokers' urine sample that was analyzed with every batch ($n = 12$); it was 4.4% for urinary nicotine ($c = 886$ μg/l), 4.2% for urinary cotinine ($c = 1464$ μg/l) and 3.3% for urinary trans-3′-hydroxycotinine ($c = 1614$ μg/l). The accuracy of this method is assured by regular successful participation of our laboratory in round robins for the determination of nicotine and cotinine in urine (www.g-equas.de). Urinary creatinine concentrations were determined photometrically using a 96-well-plate photometer (Larsen, 1972).

Determination of urinary mercapturic acids by LC/MS/MS

Urinary mercapturic acids were determined as described previously (Schettgen et al., 2008). The mercapturic acids of benzene (S-PMA), benzylalcohol/toluene (S-BMA), styrene (PHEMA), 1,3-butadiene (DHBMA and MHBMA) and acrylonitrile (CEMA and CHEMA) were determined using specific automated column-switching LC/MS/MS-methods. Sample preparation and clean-up was carried out automatically by online-enrichment of the analytes on a Restricted-Access-Material column (RAM). After transfer of the analytes to the analytical column, they were further separated from matrix compounds and finally quantified by tandem mass-spectrometry using isotopically labeled analogs of the analytes as internal standards. The LOD of the methods was determined to be 0.05 μg/l urine for S-PMA, 0.5 μg/l urine for S-BMA, 0.3 μg/l urine for PHEMA, 10 μg/l and 2 μg/l urine for DHBMA and MHBMA, as well as 1 μg/l urine for both CEMA and CHEMA; this is sufficient to determine a background excretion of these mercapturic acids in urine within the general population. The mercapturic acid of acrolein (3-HPMA) was enriched and cleaned up from urinary matrix using an offline solid phase extraction on a SPE-column (ENV+, 100 mg from Separtis GmbH, Grenzach-Wyhlen, Germany). The acid was subsequently separated and quantified by LC/MS/MS using isotopically labeled 3-HPMA as internal standard. Accuracy of the determination of S-PMA in human urine is assured by regular successful participation of our laboratory in round robins (www.g-equas.de). For the other analytes, round robins were not available during the study period.

Statistical analysis

Data are described by mean values and standard deviations or by median values and percentiles, depending on the purpose and distribution. Wilcoxon matched-pairs signed-ranks test was employed to compare values of eCO, FeNO and urinary metabolites before versus after e-cigarette consumption. A p value < 0.05 was considered statistically significant.

Results

Table 1 gives the results of the liquid analysis in terms of humectants, nicotine, and other (volatile) organic compounds. All liquids consisted to >90% of the humectants 1,2-propanediol (mean ± SD, 559.2 ± 51.5 g/l) and glycerine (480.3 ± 41.0 g/l). Nicotine levels (22 ± 0.8 mg/ml) were on average 22% above the manufacturers' declaration of 18 mg/ml, but liquids labeled as nicotine-free had no nicotine present. All e-cigarette solutions contained small amounts of sensitizing chemicals including benzylalcohol, menthol, vanillin, and L-limonene, which were mainly present in Liquid 1. None of the liquids comprised the tobacco-specific nitrosamines NNN, NAT, NAB, and NNK (data not shown).

The results of particle measurements and major climate parameters during the six vaping sessions and on the control day are presented in Table 2. Overall, the amount of PM was markedly higher on the vaping days than on the control day, with generally the highest values on the vaping days without nicotine. Overall, mass concentrations showed a mean value of 197 μg/m^3 (control 6 μg/m^3) for $PM_{2.5}$ (90th percentile: 373 μg/m^3 vs. 8 μg/m^3), with the maximum during the 5th vaping session (Liquid 3 without nicotine: 514 μg/m^3). PNC also reached high median values ranging from 48,620 to 88,386 particles/cm^3, with peaks at diameters 24–36 nm. Indoor concentrations of CO and CO_2 showed no difference between control and vaping periods.

Table 3 summarizes the results for VOC and aldehydes/ketones. A distinct increase versus control was found for 1,2-propanediol (mean ± SD, 199.2 ± 93.2 μg/m^3 vs. <0.04 μg/m^3), glycerine (72.7 ± 6.9 μg/m^3 vs. <0.04 μg/m^3) and nicotine (2.2 ± 1.7 μg/m^3 vs. <0.04 μg/m^3). Formaldehyde, benzene and the pyrolysis products acrolein and acetone did not exceed background concentrations. Only during vaping session 4 (Liquid 2 with nicotine) the level of formaldehyde was higher than on the control day (55 μg/m^3 vs. 25 μg/m^3). Indoor concentrations of the sensitizing chemicals vanillin and benzylalcohol were only slightly increased in comparison to control values (0.3 ± 0.2 μg/m^3 vs. <0.04 μg/m^3; 5 ± 3 μg/m^3 vs. 4 μg/m^3).

The sum of all measured 16 PAH was approximately 30–90% higher during the vaping sessions (Table 4) compared to the control day. The total concentration of PAH was dominated by the more volatile substances naphthalene, acenaphthene, fluorene and phenanthrene. With regard to the seven PAH classified as probable carcinogens by the IARC (IARC, 2002, 2010), the concentration increased on average by 20% from 122.8 ng/m^3 (control) to 147.3 ± 26.2 ng/m^3 (vaping sessions). The concentrations of elements and metals found in indoor air (Table 5) showed a 2.4-fold increase for aluminum (482.5 ± 158.6 ng/m^3 vs. 203.0 ng/m^3). The rare-earth elements lanthanum and cerium, the concentrations of which are usually elevated by conventional tobacco smoking (Böhlandt et al., 2012), exhibited no increase and were in the range of outdoor air levels of below 0.5 ng/m^3 and 1 ng/m^3, respectively. Moreover, no significant increase was observed for the toxic and potentially carcinogenic elements cadmium, arsenic and thallium.

The mean ± SD puff rate over all subjects and sessions was 1.1 ± 0.4 puffs per minute. Before and after e-cigarette consumption eCO and FeNO in the subjects' exhaled air were measured. As illustrated in Fig. 1, 7 of 9 individuals showed a slight but statistically significant ($p = 0.030$) rise of FeNO after vaping a nicotinic e-cigarette. The effect was not statistically significant ($p = 0.554$; increase in 3 of 9 subjects), when nicotine-free liquids were used. eCO levels which are known to be strongly elevated by conventional cigarette smoking were not significantly influenced by e-cigarette consumption (data not shown).

The results of metabolite analysis of urine samples are depicted in Fig. 2. On average, vaping e-cigarettes with nicotine resulted in a significant increase of urinary nicotine and cotinine, but not 3-OH-cotinine levels. Interestingly, 3-HPMA, the mercapturic acid metabolite of the pyrolysis product acrolein, was also elevated after nicotinic vaping, while the other analyzed mercapturic acids showed no increase in the urine of the subjects (data not shown). Nicotine-free vaping had no statistically significant impact on all

Table 1
Component analysis (mg/l) of liquids[a] vaporized during the vaping sessions.

Compounds	CAS	Liquid 1		Liquid 2		Liquid 3	
		− nicotine	+ nicotine	− nicotine	+ nicotine	− nicotine	+ nicotine
1,2-Propanediol	57-55-6	547,000	529,000	546,000	529,000	673,000	531,000
Glycerine	56-81-5	497,000	507,000	485,000	498,000	390,000	505,000
Nicotine	54-11-5	0.0	23,000	0.0	22,000	0.0	21,000
Sabinene	3387-41-5	0.0	1.5	0.0	0.0	0.0	0.0
Trimethylpyrazine	14667-55-1	12.1	12.4	0.3	0.3	0.5	0.5
Benzylalcohol[b]	100-51-6	59.4	60.5	0.5	3.1	0.9	2.7
Phenylethylalcohol	60-12-8	3.1	3.3	0.8	0.8	2.6	3.0
p-Dimethoxybenzene	150-78-7	14.7	15.6	0.9	1.1	0.7	0.9
Menthol[b]	1490-04-6	1.3	1.1	4.1	4.2	2.9	8.8
Ethylmaltol	4940-11-8	47.0	46.0	0.0	0.0	253.2	0.5
2-(2-Butoxyethoxy)ethanol	112-34-5	3.2	3.9	3.3	5.5	1.8	117.0
Anisaldehyde	123-11-5	9.6	9.4	0.8	1.0	0.6	0.7
p-Propenylansiole	104-46-1	11.4	13.4	0.0	0.0	0.0	0.0
γ-Dodecalactone	2305-05-7	0.0	0.5	0.6	0.6	0.0	0.0
Furaneol	3658-77-3	323.9	522.2	2207.1	7622.7	0.0	0.0
β-Pinene	127-91-3	1.6	2.5	0.0	0.0	0.0	0.3
Corylon	80-71-7	774.4	691.2	0.0	0.0	234.2	4.2
Ethylvanillin	121-32-4	59.2	54.8	0.0	0.0	0.0	0.0
Dihydrocoumarin	119-84-6	72.3	60.8	1.3	1.7	0.9	1.1
Vanillin[b]	121-33-5	135.3	140.4	0.0	3.1	22.8	167.1
Acetophenone	98-86-2	5.5	5.7	3.2	2.5	0.7	0.7
Ethylphenylacetate	101-97-3	7.5	4.1	0.5	0.0	0.0	0.0
Camphor	76-22-2	3.8	4.9	0.0	0.0	0.0	0.0
δ-Undecalactone	710-04-3	0.0	0.0	1.0	0.7	7.0	5.9
ι-Limonene[b]	5989-27-5	2.4	2.2	1.6	1.9	1.8	2.2

[a] All liquids were labeled as tobacco-flavored.
[b] Known contact allergens. CAS: Chemical Abstracts Service number.

urinary metabolite levels measured in this study. Only nicotine was found slightly but significantly elevated possibly due to passive exposure to cigarette smoke prior to the nicotine-free vaping session (Benowitz et al., 2009).

Discussion

Since tobacco smoking is being progressively banned from public places worldwide, electronic cigarettes (e-cigarettes) show a

Table 2
Statistical characteristics of the distributions of particulate matter[a] and room climate parameters in indoor air during the 2-h vaping sessions and the control period.

	No vaping[b]	Liquid 1		Liquid 2		Liquid 3	
		− nicotine	+ nicotine	− nicotine	+ nicotine	− nicotine	+ nicotine
10th percentile							
$PM_{1.0}$ (μg/m³)	2	105	9	11	11	127	9
$PM_{2.5}$ (μg/m³)	3	126	13	17	16	169	16
PM_{10} (μg/m³)	34	158	31	41	31	198	46
PNC (N/cm³)[c]	4140	68,867	46,444	29,733	44,287	65,805	33,485
90th percentile							
$PM_{1.0}$ (μg/m³)	3	521	64	244	72	577	244
$PM_{2.5}$ (μg/m³)	8	636	79	290	90	819	324
PM_{10} (μg/m³)	61	683	115	304	116	866	363
PNC (N/cm³)[c]	4943	92,673	58,490	66,124	57,886	100,656	55,307
Median							
$PM_{1.0}$ (μg/m³)	2	242	13	62	22	421	31
$PM_{2.5}$ (μg/m³)	6	296	18	74	30	561	49
PM_{10} (μg/m³)	45	332	40	93	57	604	85
PNC (N/cm³)[c]	4365	85,724	53,552	56,441	53,068	88,386	48,620
Mean							
$PM_{1.0}$ (μg/m³)	2	293	28	98	40	376	80
$PM_{2.5}$ (μg/m³)	6	353	35	121	51	514	110
PM_{10} (μg/m³)	47	398	63	141	74	555	145
PNC (N/cm³)[c]	4466	82,800	52,568	51,385	51,321	85,446	46,572
Geometric diameter (nm)	43	31	27	24	28	36	33
Air exchange rate (1 h^{-1})	0.76	0.39	0.56	0.37	0.40	0.74	0.74
Temperature (°C)	24	25	26	26	27	27	27
Relative humidity (%)	48	48	53	57	56	48	44
Air pressure (hPa)	964	956	954	957	955	958	958
CO (ppm)	0.00	0.02	0.04	0.00	0.00	0.00	0.00
CO_2 (ppm)	1380	1710	1486	1665	1606	1239	1216

[a] Calculated PM in accordance to VDI 4300-11.
[b] Determined without e-cigarette the day before first vaping session.
[c] PNC, particle number concentrations; size range 5 nm to > 20 μm.

Table 3
Indoor air concentrations (μg/m³) of volatile organic compounds and aldehydes/ketones measured during a 2-hour use of e-cigarettes containing different liquids[a] with (+) or without (−) nicotine, or at the control day.

Compounds	CAS	No vaping[b]	Liquid 1		Liquid 2		Liquid 3	
			− nicotine	+ nicotine	− nicotine	+ nicotine	− nicotine	+ nicotine
Formaldehyde	50-00-0	25.0	24.0	28.0	27.0	55.0	28.0	21.0
Acetaldehyde	75-07-0	20.0	19.0	22.0	19.0	25.0	162.0	16.0
Butyraldehyde	123-72-8	<10	<10	<10	<10	<10	<10	<10
Acetone	67-64-1	<10	<10	<10	<10	<10	<10	<10
Acrolein	107-02-8	<10	<10	<10	<10	<10	<10	<10
Benzene	71-43-2	0.2	0.2	0.3	0.2	0.3	0.2	0.3
Benzaldehyde	100-52-7	3.7	1.7	2.2	2.9	5.0	3.1	2.3
Benzylalcohol[c]	100-51-6	4.0	4.4	1.9	4.9	11.0	2.5	2.9
Benzylbenzoate	120-51-4	<0.04	<0.04	<0.04	<0.04	<0.04	0.3	<0.04
2,5-Dimethylfuran	625-86-5	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
3-Ethenylpyridine	1121-55-7	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04
Glycerine	56-81-5	<0.04	72.0	77.0	71.0	81.0	76.0	59.0
L-Limonene[c]	5989-27-5	2.2	0.8	0.9	2.4	3.1	0.5	1.4
Menthol[c]	1490-04-6	0.4	0.4	0.7	1.1	1.3	0.6	0.7
Nicotine	54-11-5	<0.04	<0.04	0.6	0.9	1.3	–[d]	4.6
1,2-Propanediol	57-55-6	<0.04	160.0	140.0	110.0	175.0	395.0	215.0
Vanillin[c]	121-33-5	<0.04	0.2	0.1	0.2	0.4	0.6	0.3

[a] Each of the six liquids was vaporized by three e-cigarette consumers during an individual vaping session.
[b] VOC background concentrations were determined without any e-cigarette exposure the day before first vaping session.
[c] Known contact allergens.
[d] Not determinable.

rapidly growing market share, although data on their safety for users and secondhand smokers are limited. The present study offers a comprehensive exposure assessment by analysis of the effects of e-cigarettes on indoor air quality in terms of PM, PNC, VOC, PAH, carbonyls, and metals. FeNO levels of the subjects were measured to determine acute effects of e-cigarette consumption on a physiological read-out. The uptake of nicotine and other VOC by the e-cigarette consumers was investigated via urinary nicotine metabolites and mercapturic acids. We also analyzed the chemical composition of the liquids and checked for the presence of nitrosamines.

The nicotine content of e-cigarette solutions varies by manufacturer (Cameron et al., 2013; Goniewicz et al., 2013b) and can sometimes be markedly higher than declared (FDA, 2009). Such differences were also observed in our study, as the nicotine content of liquids was 1.2-fold higher than claimed by the manufacturer. Still, liquids labeled as nicotine-free had no nicotine present, in contrast to previous findings (FDA, 2009). Nicotine is a potent parasympathomimetic alkaloid and psychoactive drug that acts on the nicotinic acetylcholine receptors in the central nervous system to induce the release of several neurotransmitters (Tweed et al., 2012). Increased levels of dopamine in the reward circuits of the brain

Table 4
PAH concentrations (ng/m³) measured during the 2-h e-cigarette vaping sessions and at the control day.

PAH (IARC group)[a]	No vaping[b]	Liquid 1		Liquid 2		Liquid 3	
		− nicotine	+ nicotine	− nicotine	+ nicotine	− nicotine	+ nicotine
Acenaphthene (3)	51.0	41.0	100.0	83.0	120.0	70.0	63.0
Acenaphthylene (n.c.)	1.0	1.4	3.0	2.1	2.8	3.3	9.5
Anthracene (3)	2.0	<0.2	<0.2	3.6	7.8	3.7	8.3
Benzo[*a*]anthracene (2B)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Benzofluoranthenes[c] (2B)	2.3	2.5	2.7	2.6	3.2	3.7	4.1
Benzo[*a*]pyrene (1)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.4
Benzo[*ghi*]perylene (3)	0.5	<0.2	0.4	0.3	0.4	0.4	0.5
Chrysene (2B)	0.5	<0.2	0.5	0.4	0.5	0.5	0.4
Dibenzo[*a,h*]anthracene (2A)	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Fluoranthene (3)	12.0	6.0	11.0	13.0	17.0	17.0	16.0
Fluorene (3)	32.0	28.0	69.0	60.0	100.0	70.0	91.0
Indeno[1,2,3-*cd*]pyrene (2B)	<0.2	<0.2	0.4	0.3	0.3	0.5	0.6
Naphthalene (2B)	120.0	120.0	170.0	110.0	150.0	130.0	180.0
Pyrene (3)	8.6	4.6	8.3	7.8	11.0	9.6	8.9
Phenanthrene (3)	120.0	73.0	180.0	170.0	250.0	220.0	240.0
Sum of all PAH	349.9	276.5	545.2	453.1	663.0	528.8	622.6
Sum of 1/2A/2B-PAH	122.8	122.5	173.6	113.4	154.0	134.7	185.4

[a] Assessment of the PAH carcinogenicity by the International Agency for Research on Cancer (IARC):

- carcinogenic to humans (IARC group 1)
- probably carcinogenic to humans (IARC group 2A)
- possibly carcinogenic to humans (IARC group 2B)
- no evidence to their carcinogenicity in humans (IARC group 3)
- n.c., not classified

[b] PAH background concentrations were determined without any e-cigarette exposure the day before first vaping session.
[c] Sum of benzo[*b*]fluoranthene and benzo[*k*]fluoranthene.

Table 5
Concentrations of metals/elements (ng/m³) measured during the 2-h e-cigarette vaping sessions and at the control day.

	No vaping[a]	Liquid 1		Liquid 2		Liquid 3	
		− nicotine	+ nicotine	− nicotine	+ nicotine	− nicotine	+ nicotine
Al	203.0	709.0	667.0	269.0	434.0	351.0	465.0
As	0.8	1.5	1.7	<0.2	1.3	0.4	<0.2
Bi	0.1	1.1	1.2	0.1	0.3	0.2	0.2
Ca	<2000.0	3142.0	2161.0	<2000.0	<2000.0	<2000.0	<2000.0
Cd	<0.1	1.2	0.2	<0.1	0.2	<0.1	<0.1
Ce	<0.2	0.5	0.5	2.4	0.7	0.2	0.3
Co	4.4	1.7	1.9	0.6	2.7	<0.5	<0.5
Cr	1376.0	476.0	475.0	236.0	655.0	65.3	113.0
Cu	31.9	16.2	27.2	127.0	21.0	13.1	12.3
Fe	6669.0	2402.0	3771.0	1666.0	3149.0	1131.0	585.0
K	<1000.0	<1000.0	<1000.0	<1000.0	<1000.0	<1000.0	<1000.0
La	<0.1	0.3	0.3	1.9	0.5	0.2	0.2
Mg	112.0	356.0	299.0	130.0	189.0	105.0	<100.0
Mn	149.0	84.0	57.7	24.8	66.5	<5.0	<5.0
Mo	15.5	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Na	<1000.0	3492.0	2610.0	<1000.0	<1000.0	<1000.0	<1000.0
Ni	668.0	216.0	213.0	151.0	356.0	8.1	19.8
Pb	10.1	5.7	5.8	6.8	3.2	10.9	<3.0
Sb	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
Sn	<5.0	7.1	8.6	<5.0	<5.0	<5.0	<5.0
Ti	24.7	52.2	42.8	40.5	33.1	30.6	<20.0
Tl	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
V	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0	<10.0
Zn	<500.0	<500.0	<500.0	<500.0	<500.0	<500.0	<500.0

[a] Metal background concentrations determined without e-cigarette the day before first vaping session.

are responsible for the apparent euphoria and relaxation, but also for addiction to nicotine consumption (Benowitz, 2010). Nicotine has a higher affinity for acetylcholine receptors in the brain than those in skeletal muscle; at toxic doses (adults: 30–60 mg, children: 6–10 mg) it causes death by respiratory paralysis (Katzung, 2006). Our results confirm that liquids contain amounts of nicotine that are potentially lethal for adults and children. As nicotine readily passes into the bloodstream following dermal contact, spilling of 5 ml of e-cigarette liquid (equivalent to 110 mg nicotine) onto the skin can cause severe intoxications or even death. There is a considerable health risk, if young children accidentally touch or swallow nicotine solutions, especially when liquids are not sold in child-safe containers. Moreover, the tested e-cigarette solutions contained several sensitizing chemicals including benzylalcohol and L-limonene. Clinical data show that these substances can produce allergic contact dermatitis and immediate contact reactions, characterized by itching and the appearance of wheals, erythema, and pruritus (Chow et al., 2013; Nardelli et al., 2011). Recent studies also reported the presence of carcinogenic nitrosamines in e-cigarette solutions (Goniewicz et al., 2013a; Trehy et al., 2011).

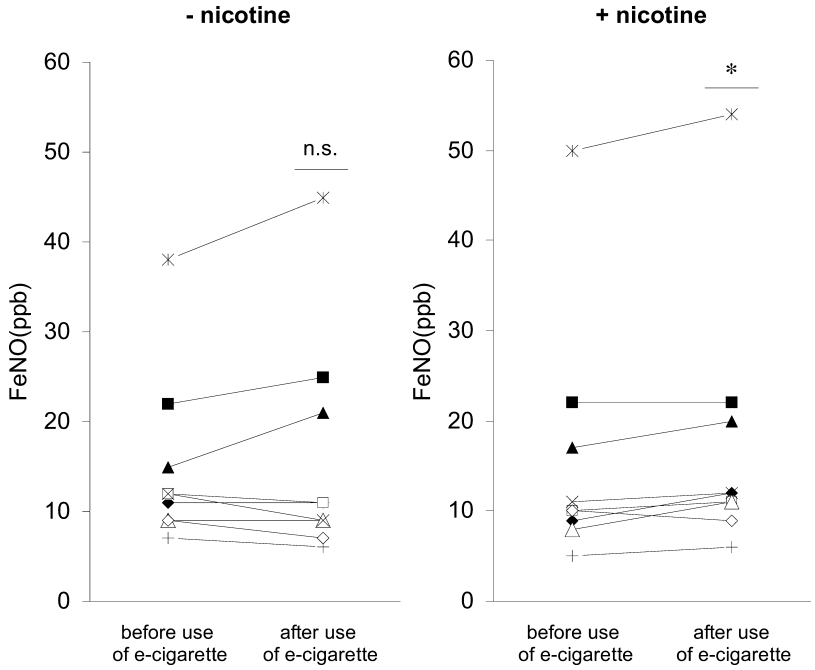

Fig. 1. Seven out of nine volunteers showed increased FeNO levels after vaping an e-cigarette with nicotinic liquid (right panel) but only three with nicotine-free liquid (left panel). Each symbol represents NO (ppb) in the exhaled air of each of the subjects before and after vaping an e-cigarette with (+, right panel) or without (−, left panel) nicotine for 2 h. *$p = 0.030$; n.s., not significant in pre-post comparison.

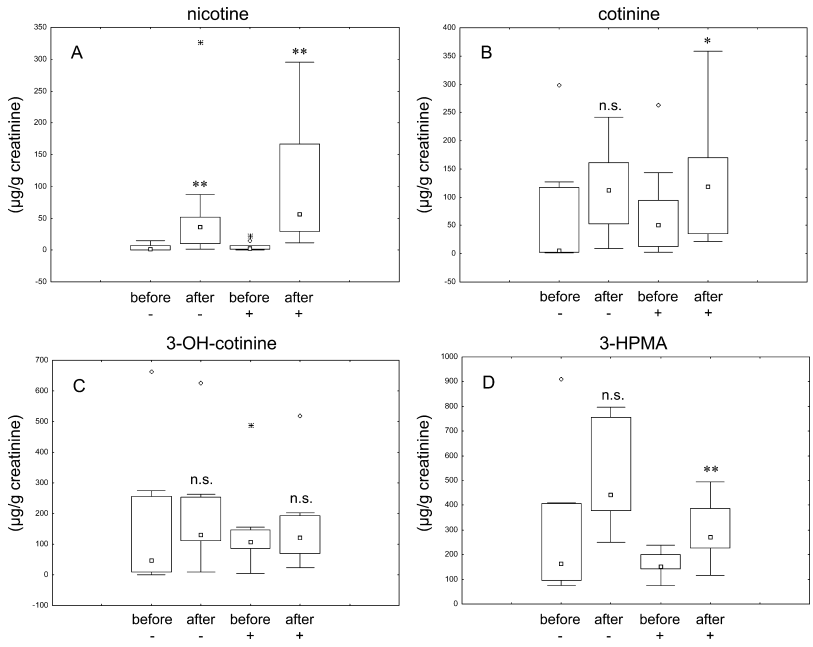

Fig. 2. Box plots show the concentrations of (A) nicotine, (B) cotinine, (C) trans-3′-hydroxycotinine (3-OH-cotinine), and (D) 3-hydroxypropylmercapturic acid (3-HPMA) measured in urine samples of nine subjects collected before and after vaping an e-cigarette with (+) or without (−) nicotine. $^{*}p < 0.05$; $^{**}p < 0.01$; n.s., not significant in pre-post comparison.

Our analyses, however, did not confirm this observation in the liquids used by us. These considerations indicate that e-cigarette solutions should be labeled with appropriate warnings of potential health effects, particularly regarding children.

Analysis of indoor air quality during vaping sessions showed that e-cigarettes are not emission-free. We found substantial amounts of 1,2-propanediol, glycerine and nicotine in the gas-phase as well as high concentrations of $PM_{2.5}$ (mean 197 µg/m^3), which is consistent with previous findings in indoor air (McAuley et al., 2012; Pellegrino et al., 2012). With regard to the seven PAH classified as probable carcinogens by the IARC (IARC, 2002, 2010), their concentration increased by 20% to 147.3 ng/m^3 during the vaping sessions. Similarly, aluminum showed a 2.4-fold increase in indoor air, which has also been reported by Williams and co-workers (Williams et al., 2013). PNC ranged from 48,620 to 88,386 particles/cm^3 (median) with peaks between 24 and 36 nm. For comparison, the particle size distribution of a conventional filter cigarette peaks at 100 nm and shows a higher total number concentration (Schripp et al., 2013). The fine and ultrafine particles related to the use of e-cigarettes are probably formed from super-saturated 1,2-propanediol vapor and should be partially deposited in the human lung.

There are few data on adverse physiologic effects after short-term use of e-cigarettes (Vardavas et al., 2012). Using an e-cigarette and liquids containing < 10% nicotine for only 5 minutes led to an immediate decrease in FeNO and an increase in airway resistance. This effect may be attributed to nicotine (see below) and/or 1,2-propanediol that is capable of causing acute ocular and upper airway irritations in healthy individuals (Wieslander et al., 2001). Recently, a case report even described the occurrence of exogenous lipoid pneumonia due to inhalation of glycerine present in e-cigarette solutions (McCauley et al., 2012). In our study, seven out of nine subjects showed a rise of FeNO after nicotinic but not non-nicotinic e-cigarette consumption.

FeNO is commonly considered as a marker of eosinophilic airway inflammation but also depends on other factors. As it is well known, a reduction of the bronchial area due to smooth muscle action or an impairment of NO transfer from the mucosa into the lumen due to mucosal fluid imbalance, or an interaction with inhaled oxidants can lead to a decrease of FeNO. Such factors might have been active in the acute response observed after 5-min e-cigarette vaping (Vardavas et al., 2012), and the increase in airway resistance would be consistent with the decrease in FeNO, without invoking inflammatory mechanisms, as the increase could be associated with a reduction in bronchial area. In contrast, subjects consumed e-cigarettes for as much as two hours in our study, and this could well have led to different or even opposite responses. Literature findings on bronchial effects of nicotine are not consistent but there are some data on acute bronchoconstrictor effects, with subsequent time-dependent bronchodilator action in cats (Thompson et al., 1990). These data seem of interest as cats are sometimes considered to be better suited for the physiological comparison with humans than rats or mice.

For the interpretation of our results is seems of interest that nicotine has been shown to enhance NO production by activation of the endothelium nitric oxide synthase (eNOS) and the inducible NO synthase (iNOS) (Chen et al., 2004). NO from eNOS is known to act as neurotransmitter in the central nervous system or as potent vasorelaxant though modulation of muscular tone (Moncada et al., 1989). It could be possible that vasodilation increases the total amount of NO transported into the lumen of the respiratory tract. In contrast, NO from iNOS is generally defined as a deleterious molecule within the processes of inflammation (Southan and Szabo, 1996) and seems to predominantly transcriptionally activated. It is not clear from the literature at which time scale these different mechanisms work, however direct physiologic effects, e.g. by vasodilation or changes in bronchial area, after a 2-h exposure would be more plausible than direct effects on iNOS via common transcription factors (Ahn and Aggarwal, 2005). Comparing with the results by Vardavas et al. (2012), the issue of FeNO in response to e-cigarette vaping seems interesting and worth of further study.

In contrast to FeNO, there were no changes in eCO. We measured eCO not because we expected a significant CO load from e-cigarettes, in contrast to conventional cigarettes or Shisha, but because CO is considered as a potential marker of oxidative stress (Babusikova et al., 2008). Exhaled CO is, however, notoriously

difficult to attribute to pathophysiological alterations due to disturbances arising from the CO contained in inhaled air.

The data on urinary metabolites confirm the uptake of nicotine and acrolein through e-cigarette consumption. Nicotine is metabolized in the liver by cytochrome P450 (CYP) enzymes, primarily CYP2A6 (Benowitz et al., 2006). The major metabolite is cotinine. Other primary metabolites include nicotine N′-oxide, nornicotine or trans-3′-hydroxycotinine, which is formed from cotinine by hydroxylation (Hukkanen et al., 2005). We observed a significant increase of nicotine and cotinine levels in urine samples of subjects who consumed e-cigarettes with nicotinic liquids. Interestingly, 3-HPMA, the mercapturic acid metabolite of acrolein, was also elevated, although in indoor air no acrolein could be observed. Acrolein is a strong irritant for the skin, eyes, and nasal passages and is commonly associated with the risk of lung cancer (Feng et al., 2006).

Overall, our data underline that e-cigarettes are not emission-free and impair indoor air quality. Exposure to e-cigarette pollutants might be a health concern, as fine and ultrafine particles formed from supersaturated 1,2-propanediol vapor can be deposited in the lung. Physiologic effects in consumers, though difficult to interpret, are suggested by the slight increase of FeNO after vaping nicotine-containing liquids. Whether effects also occur in passive smokers, is uncertain. Recent data on leukocyte populations in the blood and parameters of conventional spirometry did not indicate alterations induced by passive or even active vaping of e-cigarettes (Flouris et al., 2013, 2012) but these measures are not likely to be the most sensitive markers. Further research is needed to address particularly the issue of potential long-term effects of e-cigarette use. This is relevant because e-cigarettes are used by many consumers in order to facilitate withdrawal from cigarette smoking. It is currently not clear whether and in which specific circumstances this strategy works (Odum et al., 2012) and, more importantly, whether subjects stop the e-cigarette use after some time or continue with it instead of conventional cigarettes. In view of consumer protection, e-cigarettes and especially nicotine-containing liquids, as extremely toxic substances, should be officially regulated and labeled with appropriate warnings on health risks, particularly toxicity in children. Recently, a corresponding draft law regarding better regulation of e-cigarettes was also passed by the European Parliament.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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