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Second-hand smoke generated by combustion and electronic smoking devices used in real scenarios: Ultrafine particle pollution and age-related dose assessment

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ABSTRACT

Aerosol measurements were carried out in a model room where both combustion (conventional and hand-rolled cigarettes, a cigar and tobacco pipe) and non-combustion (e-cigarette and IQOS®) devices were smoked. The data were used to estimate the dose of particles deposited in the respiratory systems of individuals from 3 months to 21 years of age using the multiple-path particle dosimetry (MPPD) model. Regardless of the smoking device, the highest doses were received by infants, which reached 9.88×10^8 particles/kg bw during a cigar smoking session. Moreover, 60% to 80% of the particles deposited in the head region of a 3-month-old infant were smaller than 100 nm and could be translocated to the brain via the olfactory bulb. The doses due to second-hand smoke from electronic devices were significantly lower, below 1.60×10^8 particles/kg bw, than those due to combustion devices. Dosimetry estimates were 50% to 110% higher for IQOS® than for e-cigarettes.

1. Introduction

Particle matter (PM) pollution remains one of the most critical environmental risks to public health. Indeed, over the years, scientific evidence has shown an increasing number of adverse effects in humans linked to exposure to PM (PM_{10} and its subfractions), such as cardiovascular and pulmonary diseases (WHO, 2013), neurodegenerative diseases (Heusinkveld et al., 2016), and negative birth outcomes after intrauterine exposure (Lamichhane et al., 2015). In addition, the International Agency for Research on Cancer (IARC) recently classified PM in outdoor air pollution as a group 1 carcinogen to humans (IARC, 2015). Based on the growing evidence of human risks related to PM exposure, the World Health Organization (WHO) designated 50 and 25 μg/m^3 as reference values for outdoor PM_{10} and $PM_{2.5}$ concentrations (mean daily levels for general population exposure), respectively (WHO, 2006). However, even if these standards are met, the population is not completely protected against risks related to PM exposure because these guidelines consider only 2 PM fractions (PM_{10} and $PM_{2.5}$) and only outdoor PM exposure levels were provided (neglecting indoor environments). Several studies have shown that exposure to fine particles ($PM_{2.5}$) can generate many adverse effects on human health related to particle pollution (Dreher et al., 1996; Tsai et al., 2000; WHO, 2013; Feng et al., 2016). Moreover, the toxicity per unit mass of the particles has been demonstrated to increase as their sizes decrease. Consequently, scientific interest has focused on the particle surface area and number of particles rather than on the particle mass, underlining the relevance of submicronic particles (SMPs, < 1 μm) and ultrafine particles (UFPs, 0.01–0.1 μm) (Manigrasso et al., 2013; Oberdörster et al., 2005a, 2005b). Particles can be released from several heterogeneous sources, which are quite different for outdoor and indoor environments (Isaxon et al., 2015; Manigrasso et al., 2017). While the main source of outdoor PM in urban areas is vehicular traffic (Avino et al., 2016; Manigrasso and Avino, 2012), cooking activities and smoking are the most common sources of indoor PM levels, together with the ambient particles that infiltrate from the outdoors and the particles formed indoors from precursors emitted both indoors and outdoors (Morawska and Salthammer, 2015). In particular, indoor PM concentrations dramatically increase during smoking (Protano et al., 2014). To fully understand how smoking impacts the concentrations of indoor particles, comparisons between PM emissions from smoking and other combustion sources are necessary. De Marco et al. (2016), for example, reported PM levels from cigarette smoke that were 2–3 times higher than those released by heavy duty trucks. Furthermore, Protano et al. (2016) reported that spending 1 h in an indoor environment in

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which a single traditional cigarette had been smoked is equivalent to spending half an hour in a heavy traffic area in terms of SMPs exposure. To minimize exposure to air pollutants (including fine and ultrafine particles) generated by tobacco smoke, many countries have introduced smoking bans in public places. However, the smoke-free policy cannot be applied to household environments, where tobacco smoke remains an important source of pollution (Protano et al., 2012a, 2012b).

The aerosol size of the particles emitted by smoking is also an important issue. Becquemin et al. (2010) showed that a high percentage of particles emitted from cigarette smoke are UFPs. However, most studies published on this topic are limited to conventional cigarettes and do not include other ways of smoking, such as the use of cigars, pipes, and electronic and heat-not-burn devices. Notably, some previous studies have shown that the use of electronic cigarettes (e-cigs) indoors is not exempt from the emission of fine and ultrafine particles, though e-cigs result in much lower emissions of fine and ultrafine particles than conventional cigarettes (Pellegrino et al., 2012; Ruprecht et al., 2014). Furthermore, the results of a recent study showed that e-cig aerosols are a potential high-dose source of particles that can reach the deepest part of the respiratory system (Manigrasso et al., 2014). To our knowledge, these experiments, which were performed to assess the particle emission from all manners of smoking, were conducted using smoking machines. This kind of simulation allows the measurement of only the smoke produced by burning tobacco (the so-called sidestream smoke) and neglects the smoke exhaled by the smoker during active smoking (exhaled mainstream smoke). Exhaled mainstream and sidestream smoke are two different routes of gaseous and particulate pollutant generation that together characterize the phenomenon of “passive smoking” (also called environmental tobacco smoke, ETS) (Moldoveanu and St.Charles, 2007). Thus, contributions from both exhaled mainstream and sidestream smoke must be considered when evaluating pollutant emission during smoking. To further complicate this scenario, ETS has been recently demonstrated to result from the combination of two phenomena: second-hand smoke (SHS) and thirdhand smoke (THS). SHS is the environmental smoke near people who are smoking or just finished smoking, and THS is the environmental smoke that persist for a long period (up to weeks) and can be adsorbed and released by skin and hair, furnishings, clothing, etc. long after cigarettes, cigars or pipes are smoked. Therefore, it is essential that studies performed to evaluate exposure to ETS and its specific contaminants can assess the independent contributions of SHS and THS (Protano and Vitali, 2011).

The general aims of this study were 1) to evaluate the emissions of SMPs with diameters ranging from 5.0 to 560 nm arising from the “real” use (by already-smoker volunteers) of smoke products, including combustion (conventional and hand-rolled cigarettes, pipes, and cigars) and non-combustion products (e-cigs and IQOS®, a new electronic device that heats a cigarette-like stick without combustion), and 2) to estimate the exposure of individuals passively exposed to SHSs derived from the use of the above-mentioned smoke products, tracing specific exposure profiles for population groups according to age (infants, children, adolescents, and adults).

2. Materials and methods

2.1. Smoking devices and experimental plan

In the present study, two types of smoking devices were evaluated:

1) combustion devices: i) a conventional cigarette (Pall Mall® San Francisco; the nicotine, tar and carbon monoxide content was 0.7, 8.0, and 9.0 mg, respectively), ii) a hand-rolled cigarette (Golden Virginia® tobacco hand-rolled with a Rizla® Blue Regular Rolling Paper), iii) a cigar (Italian Toscanello® cigar), and iv) a pipe charged with tobacco (Amphora® Original Blend)
2) heat-not-burn electronic devices: i) IQOS®, a recently commercialized device that heats a cigarette-like stick without combustion used with a Marlboro® Balance stick, and ii) an e-cig (Smooke® E-SMART (L) e-cig) filled with Smooke® Light e-liquid containing nicotine at 9 mg mL^{-1}.

Six sets of experiments (one for each smoking device) were carried out in triplicate; each experiment was based on one or more smoking sessions, which were performed by volunteers who were currently smokers in a 52.7 m^3 test room with a door and window that were both closed.

Three smoking sessions at 1-h time intervals (Δt_1, Δt_2, Δt_3) for each smoking device (conventional cigarette, hand-rolled cigarette, e-cig and IQOS®) were performed. During each session, a single cigarette or IQOS® stick was smoked. For the e-cig, 12 puffs per session were taken because traditional smoking typically consists of 10–12 puffs per cigarette (Perkins et al., 2012). Since cigars and tobacco pipes are typically smoked differently than cigarettes, they were smoked in a single smoking session until the cigar or pipe tobacco was finished, which resulted in longer time intervals than for the other devices (approximately 30 and 45 min, respectively).

For each type of smoking device, aerosol measurement started 5 min before the first smoking session and lasted 200 min in order to follow the aerosol concentration decay. Before changing the smoking device, the door and window were opened to allow the atmosphere of the room to rebalance. It is well-known that the rebalance depends on several factors (ventilation, outdoor wind speed, temperature difference, indoor humidity, etc.); thus, door and window were opened overnight. Next experiment started two hours later to achieve stable conditions of test room temperature and relative humidity. Throughout the experiment, temperature and relative humidity were measured (mean values ± SD were equal to 22.2 ± 0.6 °C and 41.0 ± 5.6%, respectively).

2.2. Smoking volunteers

The volunteer smokers were four employees of the Sapienza University of Rome (three male and one female of 60, 58, 53 and 37 years of age that were already smokers). The study was non-sponsored and was approved by the local ethical committee (Policlinico Umberto I/Sapienza University of Rome; protocol code 3520).

2.3. Aerosol emission characterization

Aerosol number-size distributions were measured by using a TSI Fast Mobility Particle Sizer (model 3091, FMPS, Shoreview, MN, USA). The instrument counts and classifies particles according to their electrical mobility in 32 size channels in the range of 5.6 to 560 nm with a temporal resolution of 1 s. FMPS operates at high flow rate (10 L min^{-1}) to minimize diffusion losses and at ambient pressure to prevent the evaporation of volatile and semivolatile particles (Manigrasso et al., 2013; TSI, 2015).

The air exchange rate (λ) was calculated by using the tracer gas technique (Laussmann and Helm, 2011), where CO_2 was used as the tracer gas. The CO_2 was released from a cylinder into ambient air until a relatively stable concentration was reached; then, the decaying CO_2 concentration was measured over time (t). The temporal evolution of the CO_2 concentration is described by Eq. (1), where λ is the air exchange rate and $C_{in}(t)$, C_0 and C_{out} are the indoor and outdoor CO_2 concentrations (at $t = t$ and $t = 0$), respectively:

$$\ln(C_{in}(t) - C_{out}) = \ln(C_0 - C_{out}) - \lambda t \quad (1)$$

λ is equal to 0.67 h^{-1}, as calculated via linear regression analysis.

2.4. Age-specific dose evaluation

Dosimetry estimates were carried out using the multiple-path particle dosimetry (MPPD v2.1, ARA 2009, ARA, Arlington, VA, USA)

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