Indoor Nanoparticle Emissions and Exposures during Heat-Based Hair Styling Activities

Jianghui LIU[1]*, Jinglin JIANG[1], Satya S. PATRA[1], Xiaosu DING[1], Chunxu HUANG[1], Jordan N. CROSS[1], Brandon E. BOOR[1], Nusrat JUNG[1]*

[1]Purdue University, Lyles School of Civil Engineering,
West Lafayette, IN, United States

* Corresponding Author
E-mail address: nusratj@purdue.edu

ABSTRACT

Exposure to indoor gas- and particle-phase emissions were demonstrated to have adverse impact to both human health and indoor environment. Our recent study has revealed that indoor hair styling activities using hair care products (HCPs) can release large quantity of volatile organic compounds (VOCs) that can be inhaled by occupant with high mass intake. Besides VOCs, HCPs may also emit organic compounds with different degree of volatility, such as semi-, intermediate-, and low-volatility compounds (SVOCs, IVOCs, and LVOCs). These compounds have the potential to nucleate and condense to primary nanoparticles. During hair styling, HCPs are often used in combination with heat-based appliances, such as hair straighteners, hair curlers, hair wavers, and blow dryers. The combination of chemically complex HCPs and heat may generate particle-phase contaminants that can be subsequently inhaled into the respiratory system. To evaluate indoor nanoparticle emissions and exposures during heat-based hair styling activities in residential buildings, realistic hair care routines were simulated in a mechanically ventilated residential building – the Purdue zero Energy Design Guidance for Engineers (zEDGE) Test House. Particle concentrations and size distributions from 6 to 10000 nm were measured in real-time (1 Hz) with a high-resolution electrical low-pressure impactor (HR-ELPI+) and nanoparticles (6 – 500 nm) were evaluated in this study. During the measurement campaign, siloxane-based HCPs were used in tandem with different heat appliances. Occupant exposures were evaluated through size-resolved respiratory tract deposited doses and dose rates ($RTDD_N$ and $RTDDR_N$).

Our results revealed that heat-based hair styling activities can produce significant amounts of airborne nanoparticles, with number concentrations often in the range of 10^4 to 10^5 particles cm^{-3}. Indoor nanoparticle number size distributions were generally bi-modal with peak diameter between 10 to 100 nm for styling activities using hair straighteners. The emitted nanoparticles are likely formed during heat-based processes involving the vaporization and thermal decomposition of chemical constituents in the HCPs. For human exposure analysis, sub-100 nm nanoparticles exhibited higher size-resolved $RTDDR_N$ and the total $RTDD_N$ during hair care routines can reach 10^{10} particles cm^{-3} across the head airways, tracheobronchial region, and pulmonary region per occupant. Our results demonstrate that heat-based hair styling activities represent a major yet unknown source of airborne nanoparticles in bathrooms and bedrooms of residential buildings.

1. INTRODUCTION

Personal care products (PCPs) are usually fragranced and are well known to emit organic compounds with different degrees of volatility into the indoor atmosphere when in an application (Wei et al., 2022; Yeoman et al., 2020). Hair care products (HCPs), including shampoos, lotions, gels, oils, waxes, sprays and other arrays, are popular PCPs that consumers could use routinely during hair cleaning and styling activities (Biesterbos et al., 2013; Comiskey et al., 2015; Loretz et al., 2006; Wu et al., 2010). Our recent study using a Proton Transfer Reaction Time-of-Flight Mass Spectrometer (PTR-TOF-MS) discovered that application of HCPs results in major emissions and exposures to various toxic and persistent species of volatile organic compounds (VOCs), including siloxanes, terpenes and glycols (Jiang et al., 2023). Although VOC emissions from PCPs and HCPs have been studied in previous research, there is currently a lack of research on the nanoparticle emissions from use of HCPs with heating appliances.

He et al. (2004) and Zhao et al. (2021) have demonstrated that heat-based indoor activities, such as candle burning, fan heating and toasting can produce large number of sub-micrometer particles. In theory, heat-based hair styling activities, including hair straightening, curling, and waving, have the capacity to emit nanoparticles into the indoor environment. Additionally, use of HCPs would emit organic compounds with different degrees of volatility, including semi-, intermediate-, and low-volatility compounds (SVOCs, IVOCs, and LVOCs) that also have the potential to condense into ultrafine particles (Patoulias et al., 2015). Other indoor chemical reactions, such as VOC/ozone (O_3) and VOC/free radical reactions, may also form secondary organic aerosols (Avery et al., 2023; Camredon et al., 2007; Han et al., 2022; Waring et al., 2011). According to a survey conducted in Europe, 97% of the participants revealed the use of HCPs, 80% of the HCP consumers revealed that they apply products more than once per week and around 40% of the HCP consumers apply products more than once per day (Biesterbos et al., 2013). As individuals engage in routine hairstyling, they may unknowingly expose themselves to airborne particles, potentially inhaling these particles into their respiratory systems given thje proximity of the hair styling activity to their breathing zone. Previous research indicated that airborne nanoparticles can enter the human respiratory tract (Yang et al., 2019), and ultrafine particles with aerodynamic diameter (D_a) < 100 nm can even deposited in the alveolar region (Hoet et al., 2004). Long-term exposure to these particles can lead to adverse impacts on human health including the accumulation of excessive lung burden (Oberdorster, 1995). With rising concern in indoor air quality and home environment, it is important to evaluate the potential nanoparticle doses from hair styling activities via modelling of respiratory tract deposited dose rates (RTDDRs) and respiratory tract deposited doses (RTDDs) (Jiang et al., 2021; Rosales et al., 2022; Wu et al., 2018). It has been demonstrated that RTDDs can provide an estimation for the total deposition pattern of aerosol particles in different regions of the respiratory system (Hussein et al., 2015). As humans interact with a wide size of particles present in the air, understanding the intricate dynamics of how these particles deposit in the respiratory tract is crucial for assessing potential health risks and evaluating the impact of air quality on human well-being.

To enable the modelling of RTDDRs and RTDDs, a real-time measurement instrument is needed to measure the particle size distribution in a wide particle range, such as the new version of Electrical Low-Pressure Impactor (ELPI+, Dekati Ltd.). ELPI+ is popular and is widely used for real-time measurement of particle size distribution in the range 6 nm – 10000 nm (Brachert et al., 2014; Fang et al., 2022; Mertens et al., 2014). However, the particle size resolution is limited to the number of impactor stages (Saari et al., 2018). To conduct a more detailed analysis of particles in different size ranges, a recently launched new ELPI instrument was adopted in this study, which is called as the High-Resolution Electrical Low-Pressure Impactor (HR-ELPI+, Dekati Ltd.). In advance of the conventional discrete cut-point diameter concept of ELPI+, HR-ELPI+ used an advanced iterative inversion calculation method to improve particle size resolution and data analysis quality (Lee et al., 2021; Saari et al., 2018). The high resolution of HR-ELPI+ allows researchers to gain a more comprehensive understanding of the complex dynamics within a given aerosol or particulate sample. This dynamic capability is particularly advantageous when studying dynamic systems, such as industrial processes, combustion sources, or atmospheric aerosols (Dibaji et al., 2022; Ehtezazi et al., 2021; Park et al., 2021; Patra et al., 2024).

To date, there is no research on online measurements of nanoparticle emissions from using HCPs with heat-based styling techniques. Also, there are no prior studies on the real-time evaluation of potential human exposure during heat-based hair styling activities in residential buildings. This study contributes valuable insights into the risks associated with heat-based hair care practices via the use of a real-time measurement instrument - HR-ELPI+ in a single zone building with real-participants. The objectives of this study are to investigate the temporal change of nanoparticle number size distribution during an actual hair styling event and evaluate associated human exposure via RTDDR and RTDD modelling.

2. MATERIALS AND METHODS

2.1 Study Site

Realistic hair care routines were conducted in a single zone mechanically ventilated residential architectural engineering laboratory built on a mobile trailer – the Purdue zero Energy Design Guidance for Engineers (zEDGE) Test House located on the Purdue University campus in West Lafayette, Indiana, U.S.A. The zEDGE is designed according to the Recreational Vehicle Industry Association (RVIA) guideline with an interior volume 60.35 m^3 and holds a National Organization of Alternative Housing (NOAH) certificate. To ensure a controllable indoor environment, the outdoor air exchange rate was maintained at approximately 6.5 h^{-1} by a powered ventilator fitted with two MERV 13 filters to supply filtered outdoor air to indoors, and a portable air conditioner with an exhaust duct to eliminate indoor air to outdoors (QPCA08JAMWG1, Haier, Louisville, KY, U.S.A.). The nominal indoor air temperature was also maintained at 20 °C (68 °F) by a single-zone ductless heating and cooling system (FTX12NMVJU, Daikin North America LLC, Houston, TX, U.S.A.).

2.2 Real-time Measurement of Nanoparticle Size Distributions, VOCs and O_3 in zEDGE Test House

A HR-ELPI+ (Dekati Ltd., Kangasala, Finland) were used to measure the particle size distribution with D_a from 6 to 10000 nm at 1 Hz. The HR-ELPI+ consists of a corona charger, a low-pressure cascade impactor that includes 14 stages, and sensitive electrometers. Oil-soaked sintered collection plates were used to eliminate particle bounce and impactor overloading. A 1.2 m conductive silicone tube was connected to the inlet of the HR-ELPI+ to sample air in the loft area of zEDGE. The HR-ELPI+ uses an advanced iterative inversion algorithm to improve the size resolution beyond the standard ELPI+, increasing the number of size bins from 14 to 100. Additional details regarding the operational principle of ELPI+ can be found in other studies (Järvinen et al., 2014; Marjamäki et al., 2000).

A PTR-TOF-MS (PTR-TOF 4000, Ionicon Analytik Ges.m.b.H., Innsbruck, Austria) was used to measure the VOC mixing ratios at 1 Hz with inlet sampling rate at 100 sccm using hydronium (H_3O^+) as the reagent ion. Major detected compounds in this study are siloxanes ($C_6H_{18}O_3Si_3$, $C_8H_{24}O_4Si_4$, $C_{10}H_{30}O_5Si_5$, $C_{12}H_{36}O_6Si_6$, $C_8H_{24}O_2Si_3$, $C_{10}H_{30}O_3Si_4$, and $C_{12}H_{36}O_4Si_5$), terpenes ($C_{10}H_{16}$, and $C_{10}H_{14}O$, $C_{10}H_{16}O$, $C_{10}H_{18}O$, $C_{10}H_{20}O$ and $C_{10}H_{22}O$) and glycols ($C_3H_8O_2$, $C_3H_8O_3$, and $C_6H_{14}O_2$). A perfluoroalkoxy (PFA) sampling line (3/8 in. OD) coupled with a polytetrafluoroethylene (PTFE) membrane filter (1 µm pore size) at the intake, was located in the center of zEDGE. Additional information regarding the PTR-TOF-MS daily calibration, raw signal/mixing ratio conversion and data analysis can be found in our previous studies (Jiang et al., 2021; Liu et al., 2024). A photometric analyzer based on non-dispersive ultraviolet (UV) absorption of O_3 at 254 nm (Serinus 10, ACOEM Ecotech, Melbourne, Australia) was adopted to measure indoor mixing ratios of ozone (O_3) at 60 Hz.

2.3 Experimental Protocol

In this study, participants were invited to conduct realistic hair styling experiment in zEDGE with their own choice of HCPs. In this paper, we are reporting dataset from the two participants who conducted realistic hair styling experiments using a siloxane-based hair cream in combination with hair straightener. The hair length of both participants was longer than shoulder (considered as long hair), and two hair straighteners were used in this study. Participants were instructed to perform this experiment in five steps: (1) divide hairs into four sections (left rear, left front, right rear, right front) before the experiment starts; (2) enter zEDGE and stay for a period of time to provide background emissions; (3) set the temperature of hair straightener and preheat the flat iron; (4) apply 2 pumps of HCPs to one hair section and heat this hair section with hair straightener, then repeat this step for the rest of the three hair sections; (5) after finishing step (4), wrap up and exit zEDGE. The experimental sequence is illustrated in **Figure 1**.

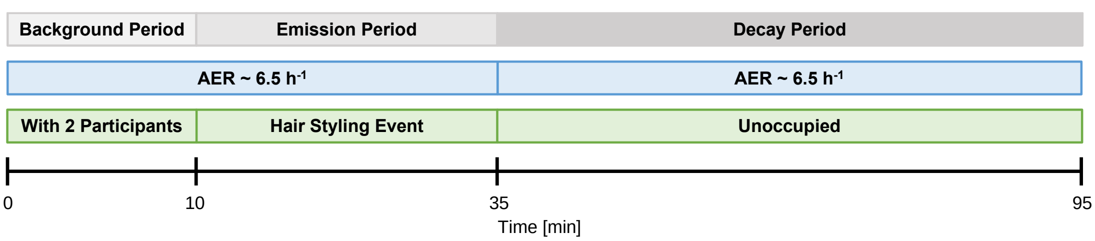

Figure 1. Experimental sequence for real-life heat-based hair care activity in zEDGE.

This experiment was designed with a 10-minute background period with two participants in zEDGE to account for human-related particle and VOC emissions followed by a 25-minute emission event and a 60-minute decay period. The outdoor air exchange rate (AER) of zEDGE was controlled at approximately 6.5 h^{-1} throughout the experiment. During the 25-minute emission event, participants need to set the temperature of the hair straightener to 370 F and then preheat the flat iron for 3 minutes. Participants would then apply HCP to one hair section and heat this hair section for 5 minutes in the order: left rear, left front, right rear, and right front. After finishing their heat-based hair styling activity, participants have 2 minutes to wrap up the tools and leave zEDGE unoccupied for 60 minutes for concentration decay. This experimental protocol was approved by Purdue University Institutional Review Board (IRB-2022-157).

2.4 Calculation of Respiratory Tract Deposited Doses and Dose Rates

Respiratory tract deposited doses (RTDDs), or inhaled deposited doses, were analyzed to evaluate human exposure to aerosols generated using hair care products. RTDD is the cumulative number ($RTDD_N$) of inhaled aerosols that deposit in the human respiratory tract over a specific period. The Multiple-Path Particle Dosimetry (MPPD) model (v3.04, Applied Research Associates Inc., Albuquerque, NM, U.S.A.) describes the human respiratory tract into three regions: head airways, tracheobronchial region, and pulmonary region (Anjilvel & Asgharian, 1995; Miller et al., 2016). Size-resolved regional deposition fractions were obtained from the MPPD model. To obtain the cumulative size-integrated RTDD during the period $t_1 - t_2$, we need to first calculate the size-resolved respiratory tract deposited dose rates in number ($RTDDR_N$) over a particle size range, D_{a1} - D_{a2} for each respiratory tract region as shown in Eq. (1).

$$RTDDR_N = \int_{D_{a1}}^{D_{a2}} Q \times DF \times \frac{dN}{dlogD_a} \qquad (1)$$

where Q is the human inhalation rate ($m^3\ h^{-1}$), DF is the size-resolved deposition fraction for each respiratory tract region and $dN/dlogD_a$ is the particle number size distribution function. Both DF and $dN/dlogD_a$ are functions of particle diameter, D_a. The integrated size range was the sample range of the HR-ELPI+ (D_a: 6 to 500 nm). The $RTDD_N$ can then be calculated by integrating the $RTDDR_N$ during period $t_1 - t_2$ as shown in Eq. (2).

$$RTDD_N = \int_{t_1}^{t_2} (RTDDR_N)\, dt \qquad (2)$$

3. RESULTS AND DISCUSSIONS

3.1 Time-resolved Evaluation of Nanoparticle Emissions During a Real-life Indoor Heat-based Hair Styling Activity

Figure 1 illustrates the temporal variation of nanoparticles, VOCs and indoor O_3 levels during a realistic hair straightening event with the application of HCP and use of a hair straightener. The nanoparticle number size distribution and size-integrated nanoparticle number concentrations (6 – 500 nm) are shown in **Figure 1 (a)** and **(b)**, respectively. A sudden change in the nanoparticle size distribution and number concentrations was observed after 1 minute of flat iron preheating. The nanoparticle number concentrations were then observed at a high level (3×10^5 ~ 5×10^5 particles cm^{-3}) throughout the hair styling activity. According to **Figure 1 (a)**, even without a direct hair heating event, abundant of sub-100 nm particles can be produced while preheating the flat iron of the hair straightener. Larger particles with D_a ranging from 100 – 500 nm can be produced in the magnitude of 10^4 ~ 10^5 particles cm^{-3} when flat iron was heating actual hairs, but particles ranging from 10 nm – 100 nm still contribute distinctly higher concentration at 10^5 ~ 10^6 particles cm^{-3}. According to **Figure 1 (b)**, four peaks five minutes apart from each other with spikes were observed in the temporal variation of number concentrations. The presence of four peaks matches the hair heating sequence of each hair section. As hair straightening activity requires participants to heat the hair in each section repeatedly, the presence of spikes may be due to each time of hair heating. The highest spike during this hair styling activity can reach the magnitude ~ 1.2×10^6 particles cm^{-3}. It was found that particle emitted from heat-based hair styling activity is similar in magnitude compared to other none heat-based indoor activities, such as cleaning with disinfectant products (Jiang et al., 2021; Rosales et al., 2022). It should be noted that while the magnitude of particle number concentration is comparable, the particle size ranges are vastly different. Particle emissions from cleaning activity using disinfectants were considered as secondary sources, in which the sub-50 nm particles dominates the number concentration.

To further investigate the correlation between indoor chemistry and nanoparticle emissions, mixing ratios of identified VOCs and indoor O_3 are reported in **Figure 1 (c)** and **(d)**, respectively. VOCs identified during this realistic hair straightening event included variety of siloxanes ($C_6H_{18}O_3Si_3$, $C_8H_{24}O_4Si_4$, $C_{10}H_{30}O_5Si_5$, $C_{12}H_{36}O_6Si_6$, $C_8H_{24}O_2Si_3$, $C_{10}H_{30}O_3Si_4$, and $C_{12}H_{36}O_4Si_5$), terpenes ($C_{10}H_{16}$, and $C_{10}H_{14}O$, $C_{10}H_{16}O$, $C_{10}H_{18}O$, $C_{10}H_{20}O$ and $C_{10}H_{22}O$), and glycols ($C_3H_8O_2$, $C_3H_8O_3$, and $C_6H_{14}O_2$). The HCP used in this study was a siloxane-based product, in which siloxanes are identified to be the dominant VOC with a peak mixing ratio of 824 ppb. Compared with the high siloxane concentrations, the contribution of terpene and glycol emissions is minor, and the peak mixing ratios of terpenes and glycols are only 11 and 42 ppb, respectively. Different from the particle emission profile, four peaks with significant emission and decay were observed in the VOC emission profile, which refers to the emissions from heating the four sections of hairs. **Figure 1 (c)** indicated that only the first 2 minutes of the hair heating event contributes to VOC emissions, hair heating after 2 minutes will no longer emit VOCs which allows the concentration of VOCs to have a short decay period before heating the next section of hair. This means the HCP on each section of hair may be completely vaporized after 2 minutes of heating. The vaporized VOCs with lower volatility may further condense and nucleate to form nanoparticles. It is interesting to note that there is no significant change in sub-100 nm particle concentrations during flat iron preheating and actual hair straightening which suggests that sub-100 nm particle emissions might be heat-dependent.

Besides nanoparticle and VOC emissions, depletion of indoor O_3 levels were also observed as illustrated in **Figure 1 (d)**. The O_3 depletion is around 10 ppb which suggests there could be a new particle formation event due to the ozonolysis of terpenes. As the HCP used in this study is a siloxane-based product and the concentration of terpenes during the hair straightening event is relatively low, the new particle formation due to ozonolysis could be very limited. Moreover, no significant HO_2 and RO_2 radicals were observed during the experiment (data not shown). Thus, new particle formation due to terpene/O_3 and siloxane/HO_2/RO_2 radicals were considered to have a minimal contribution to the particle size distribution.

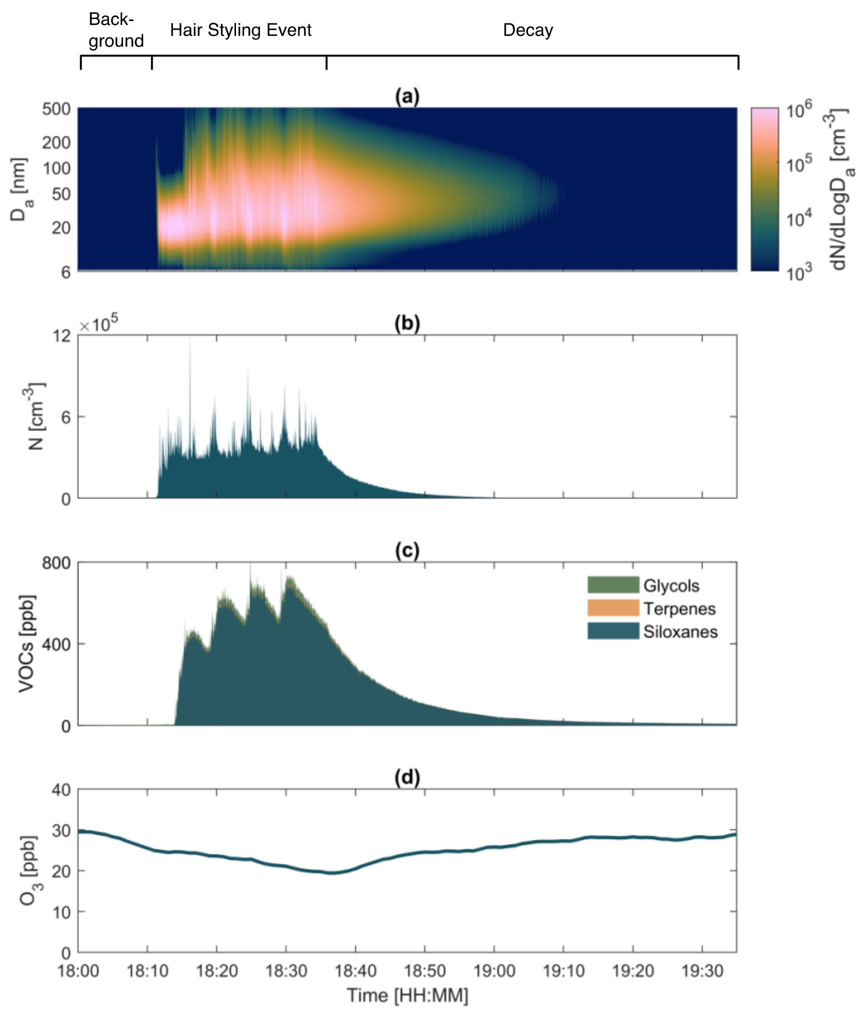

Figure 2. Time series profiles for heat-based hair styling experiment using a siloxane-based HCP and a hair straightener with flat iron temperature set to 370 F. (a) Particle number size distribution for D_a ranging from 6 to 500 nm. (b) Size-integrated particle number concentration for D_a ranging from 6 to 500 nm. (c) Mixing ratios of siloxanes (sum of $C_6H_{18}O_3Si_3$, $C_8H_{24}O_4Si_4$, $C_{10}H_{30}O_5Si_5$, $C_{12}H_{36}O_6Si_6$, $C_8H_{24}O_2Si_3$, $C_{10}H_{30}O_3Si_4$, and $C_{12}H_{36}O_4Si_5$), terpenes (sum of $C_{10}H_{16}$, and $C_{10}H_{14}O$, $C_{10}H_{16}O$, $C_{10}H_{18}O$, $C_{10}H_{20}O$ and $C_{10}H_{22}O$), and glycols (sum of $C_3H_8O_2$, $C_3H_8O_3$, and $C_6H_{14}O_2$). (d) Mixing ratios of indoor ozone.

3.2 Human Exposure Analysis via Size Resolved $RTDDR_N$ and $RTDD_N$ Modelling

The size distribution of nanoparticles measured in the hair styling activity (**Figure 1 (a)**) were used to estimate the participant-normalized respiratory tract deposited dose rates and total respiratory tract deposited doses in number ($RTDDR_N$ and $RTDD_N$) for head airways, tracheobronchial and pulmonary regions. **Figure 3** illustrates the modelling of $RTDDR_N$ and $RTDD_N$ from size-resolved particle size distribution. The size distribution of this heat-based hair styling event (**Figure 3 (a)**) displays a bi-model log-normal distribution, exhibiting a prominent peak observed between 20 – 30 nm, while a shoulder peak observed between 40 – 60 nm. With this size-resolved lognormal size distribution, and the size-resolved DF determined via the MDDP model (**Figure 3 (b)**), the size-resolved $RTDDR_N$ (**Figure 3 (c)**) can then be determined based on Eq. (1). We considered hair styling to be a light activity, which inhalation rate for light activity (1.25 m^3 h^{-1}) was used for calculation (Liu et al., 2024). The peak $RTDDR_N$ for head airways, tracheobronchial and pulmonary regions were between 30 – 40 nm particles, and the values are 1.87×10^7, 3.02×10^7, and 5.81×10^7 particles per minute per person, respectively. The size-integrated $RTDD_N$ for the three regions can be calculated as the integration of $RTDDR_N$ during the hair styling event as shown in Eq. (2) (**Figure 3 (d)**). Higher $RTDDR_N$ would yield higher $RTDD_N$, which the size-integrated $RTDD_N$ for head airways, tracheobronchial and pulmonary regions are 1.36×10^{10}, 2.07×10^{10}, and 3.25×10^{10} particles per person, respectively. The $RTDD_N$ in pulmonary region is the highest among the three regions because the majority of particles falls between size 10 – 100 nm, where the DF for particles ranging 20 – 100 nm in pulmonary region are higher than head airways and tracheobronchial regions. The AER of zEDGE was set to approximately 6.5 h^{-1} throughout the experiment, which means the indoor air was replaced by outdoor air 6.5 times per hour. Under this well-ventilated condition, it still takes around 35 min for nanoparticles to decay to background concentration level (**Figure 2 (a)** and **(b)**), and occupant could still inhale in total 6.69×10^{10} number of nanoparticles after 25 minutes of hair straightening. This result emphasis the importance of conducting heat-based hair styling activity in a well-ventilated residential building to minimize human exposure to nanoparticles.

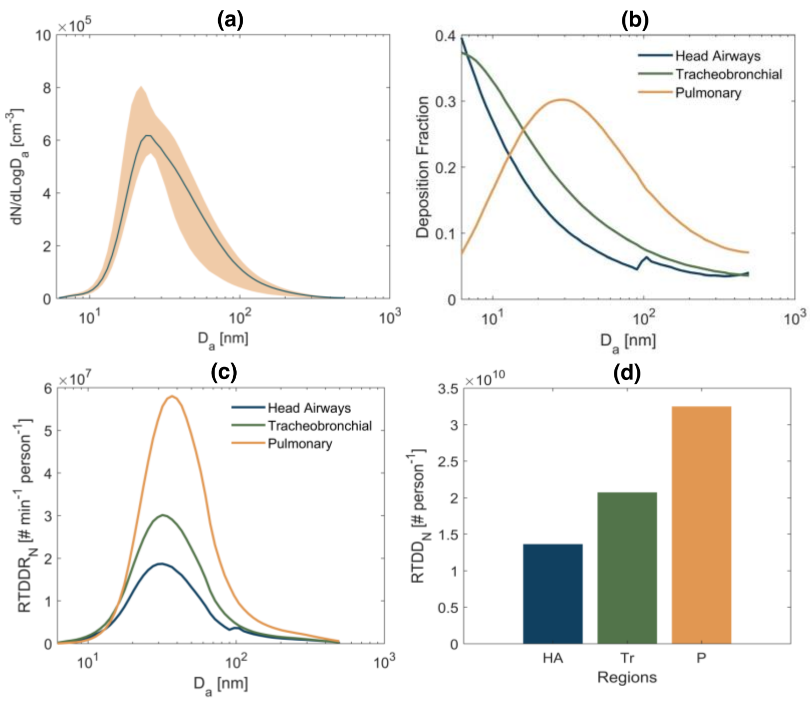

Figure 3. (a) Size-resolved particle size distribution for D_a ranging from 6 nm to 500 nm (solid line represents the median values of each size bin while shaded region represents the 25th and 75th percentile of each size bin). (b) Size-resolved deposition fraction for D_a ranging from 6 nm to 500 nm in head airways, tracheobronchial and pulmonary regions determined by the Multiple-Path Particle Dosimetry (MPPD) model. (c) Size-resolved respiratory tract deposited dose rates for D_a ranging from 6 nm to 500 nm in head airways, tracheobronchial and pulmonary regions (solid lines represents the median dose rate of each size bin). (d) Size-integrated respiratory tract deposition dose ($RTDD_N$) for inhaled particles (D_a from 6 nm to 500 nm) in head airways ("HA"), tracheobronchial ("Tr") and pulmonary regions ("P").

4. CONCLUSION

In conclusion, this study has shed light on the indoor environmental exposure and its impact on human's that is associated with routine use of HCPs with heat-based appliances. High magnitude of nanoparticle emissions (~10^6 particles cm^{-3}) were observed, and the $RTDD_N$ modelling results indicated that occupant could still inhale in abundant of nanoparticles during a hair straightening event in a well-ventilated indoor space. At this stage, we cannot draw direct conclusions suggesting that nanoparticle emissions are directly correlated with VOC emissions as the time-series profiles showed that nanoparticle emissions might be heat-dependent. Further experiments, such as change of outdoor ventilation rate, use of different HCPs and heating appliances, change of heating temperature, and measurment of particle compositions using PTR-TOF-MS coupled with CHARON inlet are required for a more comprehensive evaluation on the impact of HCP use and heat-based hair styling activity to indoor occupational health and environment.

ACKNOWLEDGEMENT

Financial support was provided by Purdue University (start-up funds to N.J.), the Alfred P. Sloan Foundation (G-2018-11061 to P.S.S. and B.E.B), and the National Science Foundation (CBET-1847493 to B.E.B.).

REFERENCES

Anjilvel, S., & Asgharian, B. (1995). A multiple-path model of particle deposition in the rat lung. *Fundamental and Applied Toxicology*, *28*(1), 41-50.

Avery, A. M., Alton, M. W., Canagaratna, M. R., Krechmer, J. E., Sueper, D. T., Bhattacharyya, N., Hildebrandt Ruiz, L., Brune, W. H., & Lambe, A. T. (2023). Comparison of the Yield and Chemical Composition of Secondary Organic Aerosol Generated from the OH and Cl Oxidation of Decamethylcyclopentasiloxane. *ACS Earth and Space Chemistry*, *7*(1), 218-229. https://doi.org/10.1021/acsearthspacechem.2c00304

Biesterbos, J. W., Dudzina, T., Delmaar, C. J., Bakker, M. I., Russel, F. G., von Goetz, N., Scheepers, P. T., & Roeleveld, N. (2013). Usage patterns of personal care products: important factors for exposure assessment. *Food Chem Toxicol*, *55*, 8-17. https://doi.org/10.1016/j.fct.2012.11.014

Brachert, L., Mertens, J., Khakharia, P., & Schaber, K. (2014). The challenge of measuring sulfuric acid aerosols: Number concentration and size evaluation using a condensation particle counter (CPC) and an electrical low pressure impactor (ELPI+). *Journal of Aerosol Science*, *67*, 21-27. https://doi.org/10.1016/j.jaerosci.2013.09.006

Camredon, M., Aumont, B., Lee-Taylor, J., & Madronich, S. (2007). The SOA/VOC/NO_x system: an explicit model of secondary organic aerosol formation. *Atmos. Chem. Phys.*, *7*(21), 5599-5610. https://doi.org/10.5194/acp-7-5599-2007

Comiskey, D., Api, A. M., Barratt, C., Daly, E. J., Ellis, G., McNamara, C., O'Mahony, C., Robison, S. H., Safford, B., Smith, B., & Tozer, S. (2015). Novel database for exposure to fragrance ingredients in cosmetics and personal care products. *Regul Toxicol Pharmacol*, *72*(3), 660-672. https://doi.org/10.1016/j.yrtph.2015.05.012

Dibaji, S. A. R., Oktem, B., Williamson, L., DuMond, J., Cecil, T., Kim, J. P., Wickramasekara, S., Myers, M., & Guha, S. (2022). Characterization of aerosols generated by high-power electronic nicotine delivery systems (ENDS): Influence of atomizer, temperature and PG:VG ratios. *PLoS One*, *17*(12), e0279309. https://doi.org/10.1371/journal.pone.0279309

Ehtezazi, T., Evans, D. G., Jenkinson, I. D., Evans, P. A., Vadgama, V. J., Vadgama, J., Jarad, F., Grey, N., & Chilcott, R. P. (2021). SARS-CoV-2: characterisation and mitigation of risks associated with aerosol generating procedures in dental practices. *Br Dent J*, 1-7. https://doi.org/10.1038/s41415-020-2504-8

Fang, X., Wu, L., Zhang, Q., Zhang, J., Yang, Z., Zou, C., Ma, C., Zhang, Y., & Mao, H. (2022). Study on Particle Size Distribution Characteristics in Urban Roadside Microenvironment Using an ELPI+. *Water, Air, & Soil Pollution*, *233*(11). https://doi.org/10.1007/s11270-022-05942-w

Han, C., Yang, H., Li, K., Lee, P., Liggio, J., Leithead, A., & Li, S. M. (2022). Secondary organic aerosols from OH oxidation of cyclic volatile methyl siloxanes as an important Si source in the atmosphere. *Atmos. Chem. Phys.*, *22*(16), 10827-10839. https://doi.org/10.5194/acp-22-10827-2022

He, C., Morawska, L., Hitchins, J., & Gilbert, D. (2004). Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmospheric Environment*, *38*(21), 3405-3415.

Hoet, P. H., Bruske-Hohlfeld, I., & Salata, O. V. (2004). Nanoparticles - known and unknown health risks. *J Nanobiotechnology*, *2*(1), 12. https://doi.org/10.1186/1477-3155-2-12

Hussein, T., Wierzbicka, A., Löndahl, J., Lazaridis, M., & Hänninen, O. (2015). Indoor aerosol modeling for assessment of exposure and respiratory tract deposited dose. *Atmospheric Environment*, *106*, 402-411. https://doi.org/10.1016/j.atmosenv.2014.07.034

Järvinen, A., Aitomaa, M., Rostedt, A., Keskinen, J., & Yli-Ojanperä, J. (2014). Calibration of the new electrical low pressure impactor (ELPI+). *Journal of Aerosol Science*, *69*, 150-159. https://doi.org/10.1016/j.jaerosci.2013.12.006

Jiang, J., Ding, X., Patra, S. S., Cross, J. N., Huang, C., Kumar, V., Price, P., Reidy, E. K., Tasoglou, A., Huber, H., Stevens, P. S., Boor, B. E., & Jung, N. (2023). Siloxane Emissions and Exposures during the Use of Hair Care Products in Buildings. *Environ Sci Technol*, *57*(48), 19999-20009. https://doi.org/10.1021/acs.est.3c05156

Jiang, J., Ding, X., Tasoglou, A., Huber, H., Shah, A. D., Jung, N., & Boor, B. E. (2021). Real-Time Measurements of Botanical Disinfectant Emissions, Transformations, and Multiphase Inhalation Exposures in Buildings. *Environmental Science & Technology Letters*, *8*(7), 558-566. https://doi.org/10.1021/acs.estlett.1c00390

Lee, M.-H., Yang, W., Chae, N., & Choi, S. (2021). High resolution size characterization of particulate contaminants for radioactive metal waste treatment. *Nuclear Engineering and Technology*, *53*(7), 2277-2288. https://doi.org/10.1016/j.net.2021.01.029

Liu, J., Jiang, J., Ding, X., Patra, S. S., Cross, J. N., Huang, C., Kumar, V., Price, P., Reidy, E. K., & Tasoglou, A. (2024). Real-time evaluation of terpene emissions and exposures during the use of scented wax products in residential buildings with PTR-TOF-MS. *Building and Environment*, 111314.

Loretz, L., Api, A. M., Barraj, L., Burdick, J., Davis, D. A., Dressler, W., Gilberti, E., Jarrett, G., Mann, S., & Pan, Y. L. (2006). Exposure data for personal care products: hairspray, spray perfume, liquid foundation, shampoo, body wash, and solid antiperspirant. *Food and Chemical Toxicology*, *44*(12), 2008-2018.

Marjamäki, M., Keskinen, J., Chen, D.-R., & Pui, D. Y. (2000). Performance evaluation of the electrical low-pressure impactor (ELPI). *Journal of Aerosol Science*, *31*(2), 249-261.

Mertens, J., Brachert, L., Desagher, D., Thielens, M. L., Khakharia, P., Goetheer, E., & Schaber, K. (2014). ELPI+ measurements of aerosol growth in an amine absorption column. *International Journal of Greenhouse Gas Control*, *23*, 44-50. https://doi.org/10.1016/j.ijggc.2014.02.002

Miller, F. J., Asgharian, B., Schroeter, J. D., & Price, O. (2016). Improvements and additions to the Multiple Path Particle Dosimetry model. *Journal of Aerosol Science*, *99*, 14-26. https://doi.org/10.1016/j.jaerosci.2016.01.018

Oberdorster, G. (1995). Lung particle overload: implications for occupational exposures to particles. *Regulatory Toxicology and Pharmacology*, *21*(1), 123-135.

Park, J., Song, W., Gweon, J., Seo, H., Lee, J. J., & Jang, H. (2021). Size effect of zircon particles in brake pads on the composition and size distribution of emitted particulate matter. *Tribology International*, *160*. https://doi.org/10.1016/j.triboint.2021.106995

Patoulias, D., Fountoukis, C., Riipinen, I., & Pandis, S. N. (2015). The role of organic condensation on ultrafine particle growth during nucleation events. *Atmos. Chem. Phys.*, *15*(11), 6337-6350. https://doi.org/10.5194/acp-15-6337-2015

Patra, S. S., Jiang, J., Ding, X., Huang, C., Reidy, E. K., Kumar, V., Price, P., Keech, C., Steiner, G., Stevens, P., Jung, N., Boor, B. E., & Grassian, V. (2024). Dynamics of nanocluster aerosol in the indoor atmosphere during gas cooking. *PNAS Nexus*, *3*(2). https://doi.org/10.1093/pnasnexus/pgae044

Rosales, C. M. F., Jiang, J., Lahib, A., Bottorff, B. P., Reidy, E. K., Kumar, V., Tasoglou, A., Huber, H., Dusanter, S., & Tomas, A. (2022). Chemistry and human exposure implications of secondary organic aerosol production from indoor terpene ozonolysis. *Science Advances*, *8*(8), eabj9156.

Saari, S., Arffman, A., Harra, J., Rönkkö, T., & Keskinen, J. (2018). Performance evaluation of the HR-ELPI+inversion. *Aerosol Science and Technology*, *52*(9), 1037-1047. https://doi.org/10.1080/02786826.2018.1500679

Waring, M. S., Wells, J. R., & Siegel, J. A. (2011). Secondary organic aerosol formation from ozone reactions with single terpenoids and terpenoid mixtures. *Atmospheric Environment*, *45*(25), 4235-4242. https://doi.org/10.1016/j.atmosenv.2011.05.001

Wei, W., Little, J. C., Ramalho, O., & Mandin, C. (2022). Predicting chemical emissions from household cleaning and personal care products: A review. *Building and Environment*, *207*. https://doi.org/10.1016/j.buildenv.2021.108483

Wu, T., Taubel, M., Holopainen, R., Viitanen, A. K., Vainiotalo, S., Tuomi, T., Keskinen, J., Hyvarinen, A., Hameri, K., Saari, S. E., & Boor, B. E. (2018). Infant and Adult Inhalation Exposure to Resuspended Biological Particulate Matter. *Environ Sci Technol*, *52*(1), 237-247. https://doi.org/10.1021/acs.est.7b04183

Wu, X. M., Bennett, D. H., Ritz, B., Cassady, D. L., Lee, K., & Hertz-Picciotto, I. (2010). Usage pattern of personal care products in California households. *Food Chem Toxicol*, *48*(11), 3109-3119. https://doi.org/10.1016/j.fct.2010.08.004

Yang, Y. F., Wang, W. M., Chen, C. Y., Lu, T. H., & Liao, C. M. (2019). Assessing human exposure risk and lung disease burden posed by airborne silver nanoparticles emitted by consumer spray products. *Int J Nanomedicine*, *14*, 1687-1703. https://doi.org/10.2147/IJN.S171510

Yeoman, A. M., Shaw, M., Carslaw, N., Murrells, T., Passant, N., & Lewis, A. C. (2020). Simplified speciation and atmospheric volatile organic compound emission rates from non-aerosol personal care products. *Indoor Air*, *30*(3), 459-472. https://doi.org/10.1111/ina.12652

Zhao, J., Birmili, W., Hussein, T., Wehner, B., & Wiedensohler, A. (2021). Particle number emission rates of aerosol sources in 40 German households and their contributions to ultrafine and fine particle exposure. *Indoor Air*, *31*(3), 818-831. https://doi.org/10.1111/ina.12773