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Occupational exposure to volatile organic compounds and health risks in Colorado nail salons☆

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ABSTRACT

Nail salon technicians face chronic exposure to volatile organic compounds (VOCs), which can lead to adverse health outcomes including cancer. In this study, indoor levels of formaldehyde, as well as benzene, toluene, ethylbenzene and xylene, were measured in 6 Colorado nail salons. Personal exposure VOC measurements and health questionnaires ($n = 20$) were also performed; questionnaires included employee demographics, health symptoms experienced, and protective equipment used. Cancer slope factors from the United States Environmental Protection Agency (US EPA) and anthropometric data from the Centers for Disease Control and Prevention were then used to estimate cancer risk for workers, assuming 20-yr exposures to concentrations of benzene and formaldehyde reported here. Results show that 70% of surveyed workers experienced at least one health issue related to their employment, with many reporting multiple related symptoms. Indoor concentrations of formaldehyde ranged from 5.32 to 20.6 $\mu g\ m^{-3}$, across all 6 salons. Indoor concentrations of toluene ranged from 26.7 to 816 $\mu g\ m^{-3}$, followed by benzene (3.13–51.8 $\mu g\ m^{-3}$), xylenes (5.16–34.6 $\mu g\ m^{-3}$), and ethylbenzene (1.65–9.52 $\mu g\ m^{-3}$). Formaldehyde levels measured in one salon exceeded the Recommended Exposure Limit from the National Institute for Occupational Safety and Health. Cancer risk estimates from formaldehyde exposure exceeded the US EPA *de minimis* risk level (1×10^{-6}) for squamous cell carcinoma, nasopharyngeal cancer, Hodgkin's lymphoma, and leukemia; leukemia risk exceeded 1×10^{-4} in one salon. The average leukemia risk from benzene exposure also exceeded the US EPA *de minimis* risk level for all demographic categories modeled. In general, concentrations of aromatic compounds measured here were comparable to those measured in studies of oil refinery and auto garage workers. Cancer risk models determined that 20-yr exposure to formaldehyde and benzene concentrations measured in this study will significantly increase worker's risk of developing cancer in their lifetime.

1. Introduction

Studies have documented that workers in nail salons are regularly exposed to volatile organic compounds (VOCs), including acetone, toluene, ethyl acetate, methyl methacrylate, and formaldehyde (Quach et al., 2011; Alaves et al., 2013), which are ingredients in many nail salon products. These chemicals are known to cause skin, eye, and respiratory irritation as well as headaches, neurological issues (US EPA, 2007), reproductive complications (John et al., 1994), and cancer (Swenberg et al., 1980; Swenberg et al., 2013).

Despite the serious risks associated with exposure to these compounds, current regulations to protect U.S. workers from VOCs

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are often insufficient. The Occupational Safety and Health Administration (OSHA) issues a disclaimer along with its Permissible Exposure Limits (PELs) for workers, acknowledging that many of its PELs are “outdated and inadequate for ensuring protection of worker health” (OSHA, 2017). OSHA also advises businesses to supplement PELs with internal corporate guidelines and to utilize other Occupational Exposure Limits (OELs) such as Recommended Exposure Limits (RELs) published by the National Institute for Occupational Safety and Health (NIOSH) and Threshold Limit Values (TLVs) published by the American Conference of Government Industrial Hygienists (ACGIH). This poses a challenge for the U.S. salon industry, where 91% of all establishments are small businesses (Professional Beauty Association, 2014) that often lack the knowledge and resources to develop workplace guidelines capable of supplementing OSHA regulations. Consequently, salon technicians commonly report symptoms like eye irritation, skin irritation, respiratory irritation, headaches, reduced cognitive function, asthma, and work-related allergies (Kreiss et al., 2006; Roelofs et al., 2008; Quach et al., 2011).

Poor working conditions in nail salons may also contribute to health disparities since they disproportionately impact women and minority groups who constitute the majority of the industry's workforce. According to the Bureau of Labor Statistics, the “Miscellaneous Personal Appearance Workers” subgroup, which is comprised of manicurists, pedicurists, makeup artists, shampooers, and skin care specialists, is approximately 62% Asian, 9% Latino, 8% African American, and 82% female (BLS, 2018).

Previous research studies (Table 1) have examined various aspects of nail salon environments including VOC exposure (Quach et al., 2011), OEL compliance (Alaves et al., 2013), and ventilation (Roelofs & Do, 2012; Pavilonis et al., 2018). These studies provided characterizations of nail salon environments but did not attempt to estimate long-term health risks for nail salon workers based on VOC exposure.

In this study, an assessment of occupational VOC exposure was conducted in 6 Colorado nail salons between July 2017 and January 2019. The study included measurements of indoor levels of formaldehyde and the aromatic compounds benzene, toluene, ethylbenzene, and xylenes (BTEX), as well as personal exposure concentrations for 9 VOCs (BTEX, acetone, ethyl acetate, n-butyl acetate, methyl methacrylate and 2-butanone). These compounds were selected because they are common ingredients in nail products, have been reported by other nail salon studies (Quach et al., 2011; Alaves et al., 2013), or are especially harmful to human health (IARC, 2000; IARC, 2012a; IARC, 2012b). Worker health questionnaires were also completed by 20 nail salon technicians, and self-reported health symptom data were correlated to exposure factors (e.g. age, years worked, VOC exposure concentrations). Formaldehyde and benzene concentration measured here were then used to estimate cancer risks along with modeling data published by the US EPA and Centers for Disease Control and Prevention (CDC).

2. Material and methods

2.1. Recruitment of salons and technicians

Six nail salons located along the Colorado Front Range and within a radius of 100 km were recruited for this study through referrals from members of our research team and other collaborators. An initial contact was made to assess interest in participating in the study and a second visit was made to obtain informed consent. Five of the participating salons offered standard services, including acrylic nail services, and utilized popular product lines. Salon 6 was marketed as a “non-toxic” nail salon that used a custom product line and did not offer any acrylic nail services. Salons 3 and 4 also provided hair styling, although it represented a small percentage of services performed. All salons were equipped with mechanical ventilation systems, which were operational during the sampling period. The salons ranged in size from 90 to 260 m^2. All were located in attached storefronts near highways with 4 or more traffic lanes. Salons 1, 3, and 5 were located within 100 m of a gas station.

Three to 5 nail technicians from each salon participated in the study ($n = 20$). All participants, aged 23 to 57, identified as non-smokers and were primarily of Vietnamese descent. Sixteen participants (80%) were female, and 4 (20%) were male. The study was approved by the University of Colorado Boulder Institutional Review Board. All participants were presented with information outlining the scope of the research and required to provide informed consent prior to participating in the study. Upon completion, participating businesses and subjects were provided a report that included a summary of study results as well as instructions for finding additional guidance on healthy workplace practices.

2.2. Questionnaires

Two brief questionnaires were utilized in this study. The manager questionnaire contained questions regarding the size and location of the salon, salon practices, products used, and services offered. Technician questionnaires included questions about demographics, employment history, business and safety practices, and work-related health symptoms. Neither questionnaire inquired about potential VOC exposure at home or other locations outside of the workplace. Both questionnaires were made available in English and Vietnamese and were administered by a research team member fluent in both languages. The full questionnaires can be found in the Supplementary Materials.

2.3. Air sampling

Air quality measurements were performed during regular business hours (between 9 a.m. and 7 p.m.), over 4 business days (3 weekdays and 1 weekend day) for 8 continuous hours each day.

Table 1
Published studies examining the nail salon environment.

STUDY	LOCATION	N	FINDINGS
Quach et al. (2011)	San Francisco, CA	20	VOC exposure among 80 workers in 20 nail salons was assessed. Average concentrations of ethyl acetate, toluene, and MMA were 530 ppb, 150 ppb, and 1.3 ppm, respectively.
Roelofs and do (2012)	Boston, MA	22	Fourteen of 22 nail salons (64%) did not have functional mechanical ventilation systems, and 73% had CO_2 levels over 700 ppm.
Alaves et al. (2013)	Salt Lake County, UT	12	Fifty-eight percent of a randomly selected set of nail salons in Salt Lake County, UT exceeded NIOSH REL for formaldehyde (16 ppb)
Pavilonis et al. (2018)	New York City, NY	10	Mean and maximum Total VOC (TVOC) concentrations of 12 ppm and 67 ppm, respectively. Large increases in TVOC concentrations were observed when ASHRAE target CO_2 concentrations were exceeded.

Researchers were present in the salons during the entire 8 h measurement period and recorded the location, start time, end time, and type of every service performed.

2.3.1. Formaldehyde

Indoor formaldehyde levels were measured using DNPH-Silica cartridges analyzed with High-Performance Liquid Chromatography (HPLC), according to US EPA Method TO-11A (US EPA, 1999a). DNPH-silica cartridges were deployed on 1 day in each nail salon, and 1–2 LPM of air was drawn through the cartridges for 8 h using a GAST DOA P704-AA vacuum pump (Gast Manufacturing Inc., Benton Harbor, MI, Max flow: 3200 LPM, Max pressure: 4.2 bar). The flow rate at the inlet of each cartridge was measured 3 times over the course of each 8 h sampling period using a TSI 4100 flow meter (TSI Inc., Shoreview, MN, Range: 0–20 LPM, Accuracy: ±0.05 LPM). Following collection, samples were stored at 4 °C for up to 4 weeks prior to analysis.

HalTech HFX-205 electrochemical formaldehyde monitors (Hal Technologies, Fontana, CA, Range 0.00–10.00 ppm, Resolution 0.01 ppm) were also used to measure formaldehyde concentrations and to determine whether air inside salons was well-mixed. Two electrochemical monitors were deployed on 4 consecutive days in each salon and sampled at 1 min intervals. Both monitors were within 1 year of manufacturer calibration at the time of the study. They were positioned along interior walls, adjacent to electrical outlets and at heights ranging from 0.6 m to 1.2 m (the typical range of heights for pedicure and manicure stations). These monitors were deployed at 2 separate locations: one near manicure or pedicure stations (location A), and the other at the opposite end of the salon, 3.5–10 m away (location B). Supplementary Fig. S1 shows a typical salon floor plan, including A and B locations. On days when DNPH-Silica cartridges were used, they were collocated with one of the electrochemical monitors.

2.3.2. BTEX

Indoor air samples were also collected to quantify concentrations of benzene, toluene, ethylbenzene, and xylenes (BTEX), according to methods similar to US EPA TO-15 (US EPA, 1999b). Samples were captured using 6 L Silonite-coated whole air sample canisters equipped with an Entech Toxic Organics Valve (TOV-2) and a CS1200ES flow controller (Entech Instruments, Simi Valley, CA). A single 8 h, time-integrated sample was collected at each salon.

Prior to each deployment, the canisters were cleaned and evacuated using an Entech Instruments 3100D Canister Cleaning System following US EPA Compendium Method TO-15. Flow controllers were also cleaned using UHP nitrogen and calibrated for flow accuracy prior to deployment. Whole air sampling canisters were placed at location A along with a formaldehyde monitor. After sampling, the valve for each canister was closed, and the canister was stored at room temperature for up to 7 weeks prior to analysis.

2.3.3. Personal exposure VOCs

Personal VOC exposure sampling was performed during regular business hours on 1 weekday and 1 weekend day using 3M OVM 3520 passive diffusive samplers (3M, Maplewood, MN) following manufacturer's protocol. Three technicians at each salon wore a sampler on each measurement day. Sampling badges were attached to the workers' collars, near the breathing zone, and worn throughout the worker's shift (7–8 h). Field blanks were collected on every sampling day, and results were blank-corrected during data analysis. Following sample collections, samples were stored at 4 °C until the time of analysis.

2.4. Chemical analyses

2.4.1. HPLC

Formaldehyde was extracted from the DNPH-Silica cartridges with 3 mL of high-purity acetonitrile using a Waters extraction manifold operated at 457 mmHg. Extracted samples were then diluted to 5 mL with additional acetonitrile. Samples were analyzed using an Agilent 1260 Infinity HPLC system (Waters, Milford, MA) equipped with a Waters Nova-Pak C18 column (Waters, Milford, MA, Particle Size: 4 μm, ID: 3.9 mm, Length: 150 mm). The diode array detector was operated at 360 nm. Formaldehyde concentrations were determined using standard calibration curves and total volume of air sampled. A field blank, stored alongside the formaldehyde samples, was used for blank correction.

2.4.2. GC-FID-ECD-MS

Whole air samples were analyzed for BTEX using a 5-channel Gas Chromatography (GC) system coupled with 3 flame-ionization detectors (FID), an electron capture detector (ECD), and a mass spectrometer (MS). The system and its components are described in detail in Benedict et al. (2019). The 5-channel GC system was comprised of a 30 cm stainless steel cryogenic preconcentration loop packed with 1 mm diameter glass beads, a splitter box, and an excess volume reservoir, which was connected to the combination of GCs and detectors. One of the GC-FIDs was used to quantify benzene and toluene, whereas the GC-MS was used to quantify ethylbenzene and xylenes. Throughout the analysis, US EPA's TO-15 methods were followed, where applicable.

The 5-channel GC system was challenged using ultra high purity (UHP) nitrogen for baseline verification, and 8 dilutions of a high pressure 1 ppm BTEX standard (Airgas, Fort Collins, CO) were used for system calibration. During canister cleaning, a canister from each batch was selected as a batch blank and filled with UHP nitrogen and analyzed to ensure that the cleaning system was operating properly; blank correction was applied as needed.

BTEX concentrations (ppm) were determined using the calibration curve slopes for each compound and accounting for the difference in pressure between the sample and the calibration standard. Concentrations were calculated from the area under the peak obtained from the GC-FID or GC-MS system.

2.4.3. GC-MS

Personal exposure VOC samples were prepared following the procedures in the 3M Organic Vapor Monitor Sampling and Analysis Guide (3M, 1993), and analyzed using GC-MS. These samples were analyzed for 9 compounds: acetone, 2-butanone (MEK), ethyl acetate, methyl methacrylate (MMA), benzene, n-butyl acetate, toluene, ethylbenzene, and xylene (m-xylene used to quantify all isomers). Samples were eluted with 1.4 mL of carbon disulfide (CS_2), which was tested for purity before use. Samples were then placed on a Cole Parmer OR-100 orbital shaker (Cole Parmer, Vernon Hill, IL) for 30 min at 180 RPM. Samples were decanted into 2 mL glass autosampler vials, sealed with a Teflon® screw cap, and immediately analyzed with GC-MS. The instrument operated in single ion monitoring mode for the following ions: 51, 56, 58, 61, 69, 70, 72, 73, 91, 100, and 106. Reported results are the average of 3 injections per sample (n = 3). Four standard solutions, prepared in CS_2, were used to calibrate for all 9 compounds. Samples were also analyzed once by GC-MS in scan mode to qualitatively screen for the presence of other compounds.

Personal exposure VOC concentrations were determined using the methods outlined in the 3M Organic Vapor Monitor Sampling and Analysis Guide (3M, 1993). The OVM 3520 model utilizes 2 adsorbent carbon pads, which are analyzed separately and then combined to obtain a total concentration for each sample. 3M guidelines state that the lower limit of quantitation (LLOQ) for a single compound measured using this method is 2–3 μg per sample. Any compound below the LLOQ (Supplementary Table S1) was reported as 0 ppm.

2.5. Data analysis

2.5.1. Questionnaires

Data from the questionnaires were analyzed according to data type; results for numerical values (e.g., age, years employed, length of shift) are reported as the median and range. Work-related health symptoms and use of personal protective equipment (PPE) were reported as binary answers (yes/no). Results are reported as percentages of technicians responding "yes" to each question. In addition, place of birth and language(s) spoken at home were reported.

2.5.2. Comparison to air quality standards/guidelines

Formaldehyde concentrations measured in salons using DNPH-Silica cartridges were compared to the 8-h NIOSH REL for workplace formaldehyde exposure (16 ppb).

BTEX concentrations were first converted from ppm to mass-based concentrations (μg m^{-3}) using the average salon temperature and theoretical surface pressure. The latter was calculated for each salon location using the compact barometric formula (Jacob, 1999):

$$P(z) = P(0)e^{-z/H} \quad [1]$$

where H (atmospheric scale height) is 7400 m, and z is the altitude at each salon location (m).

Where applicable, BTEX concentrations were compared to US EPA Reference Concentrations for Inhalation Exposure (RfCs) (US EPA, 2005). RfCs are recommended exposure limits to avoid specific non-carcinogenic health complications and are currently available for 104 compounds.

Personal exposure VOC concentrations were compared to both odor threshold values and US EPA RfCs. Odor threshold values for acetone (832 ppb), ethyl acetate (245 ppb), n-butyl acetate (4.3 ppb), MMA (210 ppb), and MEK (440 ppb) were obtained from previous studies (Nagata, 2003; Cometto-Muñiz et al., 2008; Cometto-Muñiz and Abraham, 2009).

2.5.3. Health symptoms versus exposure factors

Health symptoms data from the questionnaires were compared with exposure factors, including VOC concentrations and demographic data. For each health symptom, exposure factors were compared between workers experiencing that symptom versus those who were not, and a t-test was used to determine if the population means differed significantly. Welch's unequal variances t-test was used to account for the relatively small and unequal population sizes. VOC exposure concentration data was assumed to be log-normal and a log transformation was performed prior to testing.

2.6. Cancer risk estimation

Cancer risk estimates for benzene and formaldehyde exposure were calculated using cancer slope factors published by the US EPA in their Integrated Risk Information System (IRIS) (US EPA, 2005) as well as proposed cancer slope factors for formaldehyde exposure that were outlined in US EPA's draft reassessment of formaldehyde-inhalation (US EPA, 2010). These 2 compounds were the only ones measured in this study for which cancer slope factors are presently available from US EPA. Estimates were based on a 20-yr occupational exposure duration and incorporate average body weight provided by the CDC as well as inhalation rates provided by US EPA. Worker chronic daily intake (CDI) for each compound was calculated according to the following equation (Tunsaringkarn et al., 2012):

$$CDI\left(\mu g\ kg^{-1}d^{-1}\right) = (CA \times IR \times ET \times EF \times ED)/(BW \times AT) \quad [2]$$

where CA is the concentration of each compound in the salon air (μg m^{-3}), IR is the worker inhalation rate (m^3 h^{-1}), ET is the exposure time (h wk^{-1}), EF is the exposure frequency (wk yr^{-1}), ED is the exposure duration (20 yr), BW is the average body weight of the technician (kg), and AT is the averaged time (70 yr × 365 d yr^{-1}).

Lifetime cancer risks were calculated by multiplying CDI values by the cancer slope factors for formaldehyde and benzene (Tunsaringkarn et al., 2012):

$$Lifetime\ Risk = CDI \times CSF_i \quad [3]$$

where CSF_i is the cancer slope factor for each compound calculated from US EPA's unit risk estimates. CSF values are calculated as (US EPA, 2005):

$$CSF_i = URE_i/CDE \quad [4]$$

where URE_i is the unit risk estimate for pollutant exposure published in IRIS, and CDE is the continuous daily exposure (given as 0.143 μg kg^{-1} d^{-1}). A 90% absorption factor for inhalation exposure was applied to each CDI for both benzene (Colman Lerner et al., 2012; Gong et al., 2017; Zhang et al., 2018) and formaldehyde (US EPA, 2010).

Cancer risks were calculated for the 3 demographics represented in this study population: Asian Females, Asian Males, and White Females, who all differ in terms of average body weight (BW) and inhalation rate (IR). Cancer risk values were compared to the US EPA threshold for *de minimis* cancer risk (1×10^{-6}); a cancer risk $>10^{-6}$ was considered a carcinogenic effect of concern.

Values for BW and IR were obtained from Tables 3 and 5 of the CDC Anthropometric Reference Data Handbook (CDC, 2016) and Tables 6–28 of The US EPA Exposure Factors Handbook (US EPA, 2011), respectively. IR for Asian males was 0.8 m^3 h^{-1}, while IR for both Asian and White females was 0.5 m^3 h^{-1}. BW values used for

Table 2
Worker health-related symptoms and PPE use.

Symptom Experienced	Number of Respondents n (%)
Nose irritation	4 (20%)
Throat irritation	2 (10%)
Lung irritation	1 (5%)
Skin irritation	6 (30%)
Eye irritation	5 (25%)
Headaches	8 (40%)
Nausea	0 (0%)
Coughing	2 (10%)
Increased pulse rate	1 (5%)
Confusion	2 (10%)
Shortness of breath	3 (15%)
Chest tightness	3 (15%)
Type of PPE Used	**Number of Respondents n (%)**
Latex Gloves	13 (65%)
Nitrile Gloves	3 (15%)
Surgical Mask	11 (55%)
N95 Dust Mask	0 (0%)
N95 w/Odor ctrl.	2 (10%)
Air purifying respirator	1 (5%)

Table 3
Formaldehyde concentrations from nail salons (8-h average).

Salon ID	Concentration (μg/m^3)
Salon 1	10.6
Salon 2	7.85
Salon 3	5.32
Salon 4	13.1
Salon 5	20.6[a]
Salon 6	7.29

[a] Exceeded NIOSH 8-h REL for formaldehyde exposure (16 ppb, 19.6 μg m^{-3}).

Asian Males (73.20 kg) and White Females (76.20 kg) are for individuals aged 40–59 and 20–39, respectively. The BW value selected for the Asian Females (60.75 kg) is a weighted average that assumes 30% between ages 20–39 and 70% between ages 40–59. These values were determined using the demographic data captured in the worker questionnaires. The ET used was the median number of hours worked per week, as reported by nail technicians in this study. EF was set at 50 weeks.

3. Results

3.1. Questionnaires

Results indicated that the median age of the technicians was 42 yr old (range: 23–57). Similarly, the median values for the time they had been employed in the nail salon industry, the number of hours they worked per week, and the number of hours per shift were 7.5 yr (range: 0.17–19), 52.5 h/wk (range: 33–80), and 9 h d^{-1} (range: 7–11), respectively. Seventy percent of participants were born in Vietnam and speak primarily Vietnamese at home, while 25% reported being U.S. born and speaking English at home.

Table 2 lists the health-related symptoms reported by the participants as well as their PPE use. Seventy percent of all workers reported wearing either nitrile or latex gloves, with 65% wearing latex gloves. Sixty-five percent reported wearing some type of facemask when performing nail services, with 55% wearing surgical style facemasks. No workers reported wearing N95 dust masks.

Workers across all 6 salons reported headaches as the most common symptom (40%), followed by skin irritation (30%), eye irritation (25%), and nose irritation (20%). Seventy percent of technicians reported experiencing at least one of the health symptoms listed (Supplementary Fig. S2). Of those respondents reporting symptoms, 57% experienced multiple health-related symptoms, and nearly 30% reported 4 or more of them.

3.2. Formaldehyde

A comparison of formaldehyde concentrations measured with both electrochemical monitors and DNPH-Silica cartridges

Table 4
Personal exposure VOC concentrations (ppm).

SALON ID	ACETONE	MEK	ETHYL ACETATE	MMA	N-BUTYL ACETATE
SALON 1	8.0 (6.0–14)	0.00 (0.00–0.00)	0.34 (0.19–0.59)	0.19 (0.070–0.33)	0.14 (0.080–0.21)
SALON 2	17 (12–32)	0.00 (0.00–0.00)	0.42 (0.23–0.68)	0.00 (0.00–0.00)	0.10 (0.060–0.28)
SALON 3	14 (10–27)	0.00 (0.00–0.080)	0.23 (0.090–0.51)	0.00 (0.00–0.00)	0.040 (0.00–0.12)
SALON 4	14 (3.6–24)	0.00 (0.00–0.00)	0.21 (0.14–0.33)	0.00 (0.00–0.00)	0.080 (0.00–0.16)
SALON 5	19 (13–31)	0.00 (0.00–0.13)	0.31 (0.19–0.95)	0.52 (0.16–1.1)	0.10 (0.060–0.16)
SALON 6	30 (25–45)	0.00 (0.00–0.00)	0.55 (0.39–1.4)	0.00 (0.00–0.00)	0.28 (0.18–0.67)

Table 5
Lifetime cancer risk increases due to measured benzene and formaldehyde levels[a].

Demographic	SCC[b]	NPC[c]	Hodgkin Lymphoma[c]	Leukemia (Formaldehyde)[c]	Leukemia (Benzene)[b]
Asian Female					
Salon 1	1.47×10^{-5}	1.01×10^{-5}	1.56×10^{-5}	5.23×10^{-5}	1.21×10^{-5} – 4.30×10^{-5}
Salon 2	1.09×10^{-5}	7.49×10^{-6}	1.15×10^{-5}	3.88×10^{-5}	1.05×10^{-6} – 3.72×10^{-6}
Salon 3	7.37×10^{-6}	5.08×10^{-6}	7.83×10^{-6}	2.63×10^{-5}	1.39×10^{-6} – 4.94×10^{-6}
Salon 4	1.81×10^{-5}	1.25×10^{-5}	1.93×10^{-5}	6.48×10^{-5}	7.33×10^{-7} – 2.60×10^{-6}
Salon 5	2.85×10^{-5}	1.96×10^{-5}	3.02×10^{-5}	1.02×10^{-4}	2.97×10^{-6} – 1.05×10^{-5}
Salon 6	1.01×10^{-5}	6.96×10^{-6}	1.07×10^{-5}	3.60×10^{-5}	1.03×10^{-6} – 3.65×10^{-6}
Average	1.65×10^{-5}	1.13×10^{-5}	1.75×10^{-5}	5.87×10^{-5}	3.22×10^{-6} – 1.14×10^{-5}
Asian Male					
Salon 1	1.95×10^{-5}	1.34×10^{-5}	2.07×10^{-5}	6.95×10^{-5}	1.61×10^{-5} – 5.71×10^{-5}
Salon 2	1.44×10^{-5}	9.95×10^{-6}	1.53×10^{-5}	5.15×10^{-5}	1.39×10^{-6} – 4.94×10^{-6}
Salon 3	9.79×10^{-6}	6.75×10^{-6}	1.04×10^{-5}	3.49×10^{-5}	1.85×10^{-6} – 6.56×10^{-6}
Salon 4	2.41×10^{-5}	1.66×10^{-5}	2.56×10^{-5}	8.60×10^{-5}	9.73×10^{-7} – 3.45×10^{-6}
Salon 5	3.78×10^{-5}	2.61×10^{-5}	4.02×10^{-5}	1.35×10^{-4}	3.95×10^{-6} – 1.40×10^{-5}
Salon 6	1.34×10^{-5}	9.24×10^{-6}	1.42×10^{-5}	4.79×10^{-5}	1.37×10^{-6} – 4.85×10^{-6}
Average	2.18×10^{-5}	1.51×10^{-5}	2.32×10^{-5}	7.80×10^{-5}	4.27×10^{-6} – 1.52×10^{-5}
White Female					
Salon 1	1.17×10^{-5}	8.05×10^{-6}	1.24×10^{-5}	4.17×10^{-5}	9.67×10^{-6} – 3.43×10^{-5}
Salon 2	8.67×10^{-6}	5.97×10^{-6}	9.20×10^{-6}	3.09×10^{-5}	8.37×10^{-7} – 2.97×10^{-6}
Salon 3	5.88×10^{-6}	4.05×10^{-6}	6.24×10^{-6}	2.10×10^{-5}	1.11×10^{-6} – 3.94×10^{-6}
Salon 4	1.45×10^{-5}	9.97×10^{-6}	1.54×10^{-5}	5.16×10^{-5}	5.84×10^{-7} – 2.07×10^{-6}
Salon 5	2.27×10^{-5}	1.57×10^{-5}	2.41×10^{-5}	8.11×10^{-5}	2.37×10^{-6} – 8.41×10^{-6}
Salon 6	8.05×10^{-6}	5.55×10^{-6}	8.55×10^{-6}	2.87×10^{-5}	8.21×10^{-7} – 2.91×10^{-6}
Average	1.31×10^{-5}	9.04×10^{-6}	1.39×10^{-5}	4.68×10^{-5}	2.57×10^{-6} – 9.10×10^{-6}

[a] Based on 20-year exposure to measured concentrations at 52.5 h/wk.
[b] Cancer slope factor derived from current US EPA IRIS inhalation risk values (US EPA, 2005).
[c] Cancer slope factor derived from proposed US EPA inhalation risk values (US EPA, 2010).

analyzed with HPLC (US EPA Method TO-11A) showed that there was low correlation between the 2 sampling methodologies (Supplementary Table S2 and Fig. S3). Consequently, data from the electrochemical monitors were only used to verify well-mixed conditions for the indoor air in the salons. Results showed that air was well-mixed inside each nail salon (Supplementary Fig. S4).

Table 3 shows the 8 h average formaldehyde concentration for each salon measured with the DNPH-Silica cartridges as well as the 8 h formaldehyde REL published by NIOSH. Only Salon 5 exceeded the NIOSH 8 h REL (16 ppb) for formaldehyde with a concentration of 20.6 $\mu g\ m^{-3}$ (21.5 ppb).

3.3. BTEX

The LLOQ for benzene and xylenes was determined to be approximately 0.03 $\mu g\ m^{-3}$; the LLOQ for toluene and ethylbenzene was approximately 0.07 $\mu g\ m^{-3}$. Fig. 1 shows 8 h average BTEX concentrations measured inside each nail salon. Toluene was detected in the highest concentrations, ranging from 26.7 $\mu g\ m^{-3}$ to 816 $\mu g\ m^{-3}$, followed by benzene (3.13 $\mu g\ m^{-3}$ - 51.8 $\mu g\ m^{-3}$), xylenes (5.16 $\mu g\ m^{-3}$ - 34.6 $\mu g\ m^{-3}$), and ethylbenzene (1.65 $\mu g\ m^{-3}$ - 9.52 $\mu g\ m^{-3}$). Average BTEX levels from 2 published studies that measured occupational BTEX exposure are also shown. Singh et al. (2013) investigated BTEX exposure inside the distribution terminal of an oil refinery, while Badjagbo et al. (2010) documented BTEX exposure among mechanics and painters in auto garages. In most cases, the BTEX levels measured in this study fell between those reported by Badjagbo et al. (2010) and Singh et al. (2013). Salon 1 also exceeded the RfC for benzene (30 $\mu g\ m^{-3}$).

3.4. Personal exposure VOCs

Of the 9 analytes quantified by GC-MS, only acetone, ethyl acetate, and n-butyl acetate were detected at all 6 salons. The other 6 analytes were detected infrequently or not at all. Table 4 summarizes the blank corrected personal exposure results for each salon. The median of 6 personal exposure measurements for each analyte is reported along with the minimum and maximum personal exposure concentrations measured in each salon.

The VOC with the highest concentration measured at every salon was acetone, ranging from 3.6 to 45 ppm. Ethyl acetate ranged from 0.090 to 1.4 ppm, and n-butyl acetate ranged from 0 to 0.67 ppm. MEK and MMA were also detected in some salons. MMA concentrations in Salon 5 were exceptionally high, exceeding 1 ppm on one occasion. Benzene, toluene, ethylbenzene, and xylene concentrations were below limits of quantitation (53, 39, 55, and 54 ppb, respectively) for this method.

Average acetone and n-butyl acetate concentrations exceeded odor threshold values by more than an order of magnitude in all 6 salons. Average concentrations of ethyl acetate exceeded the odor threshold value in 5 out of 6 salons and the average MMA concentrations exceeded the odor threshold value in one salon. MEK concentrations were relatively low and never exceeded the odor threshold concentration. Salons 1 and 5 exceeded the RfC for MMA (~171 ppb) on several occasions.

A qualitative analysis of personal exposure samples was also performed from GC-MS scans of each sample. This analysis found ethyl methacrylate in salons 1 through 5, styrene in Salons 1 and 2, and Butane in Salons 4, 5, and 6. Samples from Salons 1 and 6 also showed significant levels of ethanol, which is known to interfere with the type of electrochemical formaldehyde sensor used in this study (Hal Technology, 2015). These ethanol levels likely caused the discrepancies observed between the two formaldehyde sampling methods at salons 1 and 6.

3.5. Health symptoms versus exposure factors

Results from Welch's unpaired *t*-test are shown in Supplementary Table S3 and Fig. S5. Due to the small sample size (n = 20), few correlations were found to be significant. Of the 252 comparisons performed, only 16 had p-values below 0.05. The full list of p-values for each comparison is shown in Supplementary Table S3. Supplementary Fig. S5 shows boxplots from all comparisons that were statistically significant. A comparison of PPE used vs total number of symptoms experienced was also performed; however, there were no statistically significant results.

3.6. Cancer risk estimates

Table 5 shows the estimated increase in lifetime cancer risk for workers in each of the participant salons based on 20 years of exposure to the benzene and formaldehyde levels observed in this study. These estimates are based on cancer risk slope factors proposed by US EPA for Squamous Cell Carcinoma (SCC), nasopharyngeal cancer (NPC), and Hodgkin's lymphoma from formaldehyde exposure as well as leukemia from both benzene and formaldehyde exposure. All cancer risk values (or range of values) estimated in this study exceeded the US EPA *de minimis* risk level of 1×10^{-6}. Elevated lifetime risk for SCC from formaldehyde exposure ranged from approximately 6 in 1,000,000 (5.88×10^{-6}) to

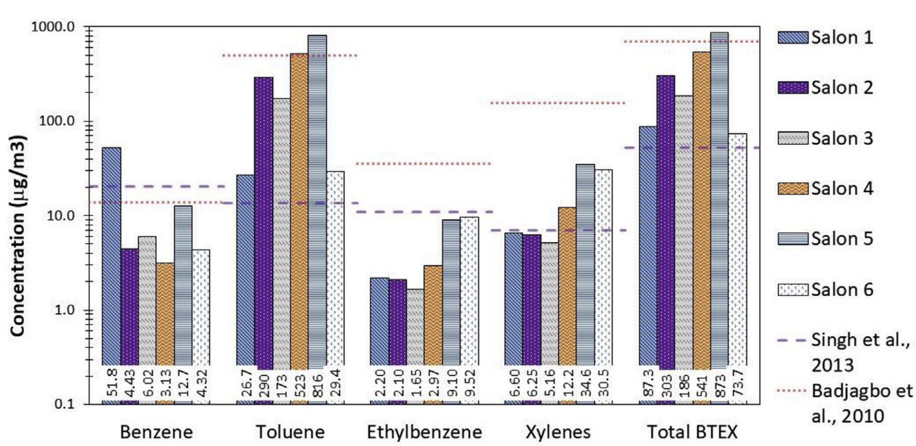

Fig. 1. BTEX concentrations at each salon. Dash lines represent average BTEX concentrations (ppb) measured at the distribution terminal in an oil refinery (Singh et al., 2013) and at auto garages (Badjagbo et al., 2010).

almost 4 in 100,000 (3.78×10^{-5}). Average lifetime risk of SCC for Asian females, Asian males, and White females across all salons were 1.65×10^{-5}, 2.18×10^{-5}, and 1.31×10^{-5}, respectively. Elevated lifetime risk for NPC ranged from 4.05×10^{-6} to 2.61×10^{-5}, with average risk increases of 1.13×10^{-5}, 1.51×10^{-5}, and 9.04×10^{-6} for Asian females, Asian males, and White females, respectively. Elevated lifetime risk for Hodgkin's lymphoma ranged from 6.24×10^{-6} to 3.02×10^{-5}, with average risk increases of 1.75×10^{-5}, 2.32×10^{-5}, and 1.39×10^{-5} for Asian females, Asian males, and White females, respectively.

Leukemia risk from formaldehyde exposure ranged from 2.10×10^{-5} to 1.35×10^{-4}, with average risk increases of 5.87×10^{-5}, 7.80×10^{-5} and 4.68×10^{-5} for Asian females, Asian males, and White females, respectively. Increased cancer risk from benzene exposure is presented as a range of values based on US EPA's published unit risk. The lowest range observed in this study was $5.84 \times 10^{-7} - 2.07 \times 10^{-6}$, and the highest was $1.61 \times 10^{-5} - 5.71 \times 10^{-5}$. The average range of lifetime cancer risk for Asian Females, Asian Males, and White Females was $3.22 \times 10^{-6} - 1.14 \times 10^{-5}$, $4.27 \times 10^{-6} - 1.52 \times 10^{-5}$, and $2.57 \times 10^{-6} - 9.10 \times 10^{-6}$, respectively.

4. Discussion

Seventy percent of workers in this study reported experiencing health symptoms, similar to the 62% reported by Quach et al. (2008). Their study ($n = 201$) also found that 47% of participants experienced health symptoms potentially related to solvents. Occupational exposure to odors has previously been linked to several symptoms commonly reported in our health questionnaire (Carrer & Wolkoff, 2018). Of the 252 health-related correlations that were tested (Supplementary Table S3), 16 were found to be significant ($p < 0.05$). Of these, 13 were related to VOC exposure concentrations. The majority of these findings (8 of 13) were negative associations between symptoms and exposure concentrations (Supplementary Fig. S5). This result may have been due to the small sample size ($n = 20$). It is also likely that workers who were frequently exposed to higher concentrations of VOCs were desensitized based on their exposure. For example, based on the exceedance of RfC values for MMA, workers in Salons 1 and 5 were at risk of olfactory epithelium degeneration, which affects sensitivity to smell (US EPA, 2005).

Workers in Salon 1 were at risk of decreased lymphocyte count due to benzene exposure (based on RfC exceedance). Chronic exposure to low-level concentrations of BTEX has also been reported to alter central nervous system sensory and motor function (de Oliveira et al., 2017) and cause oxidative stress and genotoxicity in humans (Xiong et al., 2016).

Measurable levels of MMA in 2 nail salons were unexpected because MMA is banned by the Colorado Office of Barber and Cosmetology Licensure (CDORA, 2018). Several nail salon owners in this study reported that despite this ban, MMA can still be purchased from Colorado nail supply stores. It is also frequently requested by technicians in their shops, who prefer it to safer ethyl methacrylate alternatives because they find it easier to apply. Similar findings were published by Quach et al. (2011), Alaves et al. (2013), and Zhong et al. (2019). Discouraging technicians from requesting these products will likely require additional education regarding statutes and safety.

Salon 6 had the highest personal exposure concentrations of acetone, ethyl acetate, and n-butyl acetate, but the BTEX and formaldehyde levels were similar to those measured in other salons in this study. Since this salon was marketed as “non-toxic”, these results may have implications regarding product labeling regulations and practices in the cosmetics industry. The U.S. Food and Drug Administration (US FDA) is not required to approve cosmetic products or ingredients, with the exception of color additives, before marketing; instead, it defers to manufacturers to ensure product safety. The US FDA has limited power to recall hazardous cosmetic products (US FDA, 2013). Limited oversight of the cosmetics industry has led to product mislabeling and misbranding. California EPA investigated nail products labeled “toluene-free” or “three-free” (i.e., free of toluene, formaldehyde, and dibutyl phthalate) and found that 10 out of the 12 products tested contained toluene in concentrations as high as 177,000 ppm (17.7%) (Guo et al., 2012). Additionally, products containing the “three-free” label were found to contain dibutyl phthalate in higher concentrations than regular products. Such misrepresentation effectively negates the ability of nail professionals to mitigate exposure to harmful ingredients and creates a false sense of safety in their working environment. The safety of nail products should be independently assessed before any recommendations can be made regarding their use.

Formaldehyde is designated by both US EPA and the International Agency for Research on Cancer (IARC) as a known human carcinogen (US EPA, 2010; IARC, 2012a; IARC, 2012b). Estimated lifetime risk of SCC, NPC, Hodgkin's lymphoma, and leukemia from formaldehyde exposure in this study exceeded the US EPA *de minimis* risk level of one-in-a-million (1×10^{-6}) for all categories of worker at every salon; leukemia risk in one salon exceeded 1×10^{-4}. Although risk levels were considered significant, formaldehyde concentrations measured in this study were similar to those previously measured in homes (Francisco et al., 2016), early childhood education environments (Bradman et al., 2016), and other nail salons (Alaves et al., 2013; Zhong et al., 2019). Additional research is needed to determine whether formaldehyde levels measured in salons are impacted by emissions from building materials and other indoor sources. Similarly, exposure to formaldehyde and VOCs in other locations, like home, should be assessed but was not included in this study. Additional exposure to these compounds in these other locations would effectively increase the cancer risk for these participants. Determination of formaldehyde exposure should adhere to established methodology, and the use of electrochemical formaldehyde monitors should be discouraged in environments where interfering VOCs, like ethanol, may also be present.

The National Academy of Sciences (NAS) stated in their review of US EPA's draft Reassessment of Formaldehyde Inhalation Exposure that proposed cancer slope factors for SCC, NPC, and Hodgkin's lymphoma were reasonable (NAS, 2011). However, the NAS also stressed the need to: (1) determine the mode of action by which formaldehyde exposure causes Leukemia and Hodgkin's lymphoma and (2) validate the dose-response models used in US EPA's unit risk estimate calculations. Starr and Swenberg (2016) suggested that top-down approaches to modeling formaldehyde cancer risk with linear dose-response models can lead to over-estimation, and that bottom-up models may provide improved accuracy. Also, since CDI depends on body weight, cancer risk estimates were higher for all Asian workers due to their low average body weight compared to other ethnic groups. Additionally, higher inhalation rates for Asian males result in consistently higher estimated cancer risk versus Asian females. These factors must be considered when setting exposure limits, in order to avoid one-size-fits-all approaches that fail to account for diverse populations.

The upper estimate of increased leukemia risk from benzene exposure exceeded 1×10^{-6} for all demographics and salons in this study. Similarly, for each demographic, the average leukemia risk across all salons also exceeded 1×10^{-6}. This finding is noteworthy since no previous study of nail salon VOC exposure reported significant benzene concentrations. The source of this pollutant in the nail salon environment was not identified; however, it was observed in all 6 salons and is likely linked to activities performed inside these businesses.

In this study, 65–70% of workers reported using basic PPE, reflecting a culture of safety in these salons; this fact provides a foundation for improvements. It should be noted, however, that 10% of respondents reported using an in-table ventilation system, 10% reported using N95 face masks with odor control, and 5% reported using air purifying respirators; however, none of them were observed by researchers during the study or were reported by the salon managers in their questionnaire responses. This suggests that approximately 10% of respondents were either confused by the questionnaire or unfamiliar with the technologies described therein. When questioned about their knowledge of best practice guidelines for healthier nail salons, most salon managers indicated that they were unaware of educational materials published by US EPA (US EPA, 2007), OSHA (OSHA, 2012), NIOSH (NIOSH, 1999), and the California Healthy Nail Salon Collaborative (CHNSC, 2014). Therefore, in addition to improving the regulatory structure surrounding the nail salon industry, nail technicians and managers should be trained in established best practices and safety technologies.

Results from this study provide new evidence of environmental health disparities among minority populations. It is well-documented that individuals from some ethnic minority groups experience higher air pollution exposure compared to majority groups (Apelberg et al., 2005; Hun et al., 2009; Wang et al., 2009; D'Souza et al., 2009). Asian and Pacific Islander populations experience some of the largest cancer risks from air toxics of any racial or ethnic group in the U.S. (Morello-Frosch and Jesdale, 2006). This study also found that BTEX exposure among nail salon workers closely resembles that of workers in oil refineries (Singh et al., 2013) and auto garages (Badjagbo et al., 2010). Similar BTEX exposure in beauty salons was also reported in Baghani et al. (2018). These findings conflict with the public perception that cosmetology is safer than other industrial occupations.

5. Conclusions

This study contributes to growing evidence suggesting nail salons are hazardous working environments, where chronic exposure to VOCs can lead to negative health effects and increases in lifetime cancer risk. This exposure may contribute to minority health disparities, affect employee performance (Collins et al., 2005), and lead to higher employee turnover rates (Huang et al., 2016). The current regulatory structure meant to protect workers and consumers does not address these issues and creates a need for interventions that reduce occupational VOC exposure in the nail salon industry. Results from this study are comparable to previous studies that investigated individual aspects of the larger nail salon issue. Further research, including longitudinal and cross-sectional studies of nail salon worker health, is needed to better understand and evaluate the health risks associated with employment in this industry.

Conflicts of interest

The authors declare they have no actual or potential competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.03.086.

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