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Biological and Environmental Exposure Monitoring of Volatile Organic Compounds among Nail Technicians in the Greater Boston Area

Diana M. Ceballos[1,2,*], **Jessica Craig**[1], **Xianqiang Fu**[3], **Chunrong Jia**[3], **David Chambers**[4], **MyDzung T. Chu**[2], **Alai T. Fernandez**[4], **Victoria Fruh**[1], **Zoe E. Petropoulos**[1], **Joseph G. Allen**[2], **Jose Vallarino**[2], **Lydia Thornburg**[4], and **Thomas F. Webster**[1]

[1]Department of Environmental Health, Boston University School of Public Health, 715 Albany Street, Talbot 4th Floor West, Boston, MA 02118

[2]Department of Environmental Health, Harvard T.H. Chan School of Public Health, 401 Park Drive, 4th Floor West, Boston, MA 02215.

[3]School of Public Health, University of Memphis, 3825 DeSoto Avenue, Robison Hall 337, Memphis, TN 38152

[4]Volatile Organic Compounds Laboratory, Tobacco and Volatiles Branch, Centers for Disease Control and Prevention, 4770 Buford Highway NE, Building 103, Room 3105, Atlanta, GA 30341

Abstract

Nail technicians are exposed to volatile organic compounds (VOCs) from nail products, but no studies have previously measured VOC biomarkers for these workers. This study of 10 nail technicians aimed to identify VOCs in nail salons and explore relationships between air concentrations and biomarkers. Personal and area air samples were collected using thermal desorption tubes during a work shift and analyzed using gas chromatography/mass spectrometry (GC/MS) for 71 VOCs. Whole blood samples were collected pre- and post-shift, and analyzed using GC/MS for 43 VOCs. Ventilation rates were determined using continuous CO_2 measurements. Predominant air VOC levels were ethyl methacrylate (median 240μg/m^3), methyl methacrylate (median 205μg/m^3), toluene (median 100μg/m^3), and ethyl acetate (median 639μg/m^3). Blood levels were significantly higher post-shift than pre-shift for toluene (median pre-shift 0.158μg/L, post-shift 0.360μg/L) and ethyl acetate (median pre-shift <0.158μg/L, post- shift 0.510μg/L); methacrylates were not measured in blood because of their instability. Based on VOCs measured in these 7 nail salons, we estimated that emissions from Greater Boston area nail salons may contribute to ambient VOCs. Ventilation rates did not always meet the ASHRAE guideline for nail salons. There is a need for changes in nail product formulation and better ventilation to reduce VOC occupational exposures.

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*Correspondence to: Tel: +1 (617) 358 1911, ceballos@bu.edu.

CONFLICT OF INTEREST
The authors declare that they have no conflict of interest.

SUPPORTING INFORMATION
Additional Supporting Information found online in the supporting information tab for this article.

Keywords

nail salon; volatile organic compound; indoor air; biomarker; ventilation; toluene

INTRODUCTION

Nail services is an 8.5 billion-dollar business in the United States, with an estimated workforce of 380,000 nail technicians.[1] Nail salons are largely owned and staffed by female (94%), Vietnamese (51%), and young workers (43% age <40).[1] Most nail salons are small businesses, which usually provide limited knowledge and resources for health and safety, employing fewer than 10 nail technicians.[2] Limited English language skills in some nail technicians create additional occupational health and safety barriers.[3]

Nail technicians are exposed to a wide variety of chemicals during their work shift, while using products for doing manicures, pedicures, nail art, and artificial nails. Products common to the trade include those used for nail sculpting, as well as nail polishes and polish removers, which contain volatile organic compounds (VOCs) such as toluene, acetone, isopropyl acetate, ethyl acetate, and butyl acetate.[4,5] Although most of these chemicals are listed as ingredients in safety data sheets (SDS or MSDS), some are not, even if present in significant quantities.[6] Exposure to nail product related VOCs may occur through inhalation and dermal contact as technicians prepare, apply, or remove these products,[7] with the highest levels of exposure occurring during acrylic nail sculpting and gel nail polish procedures.[8,9] There is also potential for dermal absorption of nail product VOCs by direct contact and permeation through gloves, and to a lesser extent from air.[10]

Exposure assessment of nail technicians has been limited by a number of occupational constraints requiring control and characterization including numerous product formulations, limited accessibility to worker populations, and work environments that are often small, confined, and have client-visibility. Most research has involved assessing ventilation[11,12] and educating nail technicians.[13,14]These studies have found that nail salons with limited ventilation often have the highest levels of total volatile organic compound (TVOC, the sum of VOCs detected with a real time instrument).[15,16] Nail salons do not always provide appropriate personal protective equipment (PPE), and management and employees have limited knowledge of appropriate health and safety precautions.[14,15] Only a few studies have assessed worker exposure to VOCs, most finding strong odors and air levels well below occupational exposure limits (OELs) for individual VOCs or mixture of VOCs.[5,9,16–20] There has been one study measuring nail technicians' urinary VOC biomarkers.[21] In that study, urinary acetone and hippuric acid were found to be weakly correlated with acetone airborne concentrations (correlation coefficients of 0.49 and 0.45, respectively) and not significantly higher than those measured in a control group.[21] The authors concluded that these acetone biomarkers were not ideal for assessing exposures of nail technicians.

A few studies have examined possible respiratory, dermal, neurological, and reproductive health outcomes in nail technicians. [22–26] Negative health risks identified are the same as those typically associated with VOC exposure. [27–29] Because most of these epidemiological studies relied on self-reported measures of exposure such as job title or number of nail procedures, negative health outcomes cannot be confidently related to the actual exposures. This ambiguity could be abated through biomonitoring, a direct exposure measurement method that quantifies exposures resulting from multiple exposure routes.[30]

We performed an in-depth assessment of nail technicians' exposure to VOCs. The objectives of this pilot study were to: 1) characterize air concentrations of specific VOCs in salons and the breathing zone of nail technicians; 2) examine the relationship between personal VOC exposure and blood biomarker concentrations; 3) understand occupational contribution to exposures during the work shift; and 4) test the appropriateness of the exposure assessment methods used in this study for this worker population.

METHODS

Study Design

We assessed VOC exposure of 10 nail technicians over one work day during the period of November 2016 to June 2017. Nail technicians were recruited from seven nail salons in the Greater Boston area, Massachusetts, United States with the support of the Massachusetts Healthy Cosmetology Community (HCC). Nail salons included some located in the City of Boston and others in the Boston metropolitan area. Inclusion criteria for participation were: 1) female, 2) nonsmoker (smoking can be a source of VOCs), 3) >18 years of age, and 4) working full-time (at least 35 hours a week) in a nail salon. Vietnamese language services were provided when needed. Once a participant confirmed interest in participating, we coordinated a first visit to the nail salon with both the participant and salon owner. Potential participants read and signed a consent form. We scheduled sampling towards the end of a participant's work week when work load typically increases to capture highest exposure levels and following biomonitoring guidelines.[31] After collecting pre-shift biological (blood and breath) samples and setting up other sampling equipment, we performed a ventilation check and observed work practices. At the end of the shift, we collected post-shift biological samples and administered a survey. Study protocols were approved by the Institutional Review Boards of the Harvard T.H. Chan School of Public Health and Boston University School of Public Health.

Survey Instrument

We administered a short questionnaire to all participants to document occupational factors—work practices, work load, and controls used such as local exhaust ventilation (LEV) and PPE—and non-occupational factors—demographics, use of nail polish, health related behaviors—that may be have contributed to VOC exposure.

Nail Salon Observations and Ventilation Check

During a walkthrough on the day of sampling, we documented processes and controls, including nail procedures performed, nail products used, room ventilation, and PPE used. Temperature, relative humidity, number of salon occupants, and CO_2 levels indoors were continuously recorded at 1- min intervals during the work shift using a TSI Q-track indoor air quality monitor 7575, which was bump calibrated before the sampling day with a 400 ppm CO_2 gas standard. CO_2 levels outdoors were also measured for estimating ventilation rates. Any existing general and LEV was checked using a Gastec smoke tube kit (SKC Int., Pennsylvania, United States). Smoke generated with smoke tubes was effectively drawn into an LEV system and away from the nail technician's breathing zone when LEVs were operating adequately.

Nail Products Safety Data Sheet Review

We used Safety Data Sheets (SDS) to identify VOC ingredients in nail polish brands and other nail products found in the salons. Nail polish included two main products: standard defined as polish that lasts 1 to 2 weeks and does not require ultraviolet light to cure, and gel defined as polish that lasts 2 to 4 weeks and usually requires ultraviolet light to cure. Both nail polish products included a base, color, and top coat. Gel products also used a primer and a nail bonding agent. Other products included artificial nail sculpting ingredients, nail glues, nail cleaners, and nail polish removers. SDSs were obtained from online resources or directly from the nail product manufacturer as these were not found in the nail salons.

Personal and Area Air VOC Sampling and Analysis

VOC air monitoring used passive thermal desorption (TD) tube-type samplers during the work shift, following manufacturer instructions. The TD tubes were standard industrial tubes (89 mm L × 6.4 mm o.d. × 5 mm i.d) packed with 200 mg of Tenax TA (Catalog No. C1-AXXX- 5003, Markes International, Llantrisant, UK). For personal air sampling, a tube was fixed at the breast pocket of each nail technician using a proprietary pen clip with the sampling end turned up; sampling time averaged 493 minutes with a standard deviation (SD) of 86 minutes capturing their work shift. For area sampling, at least one tube per salon was fixed on a stand with the sampling end facing down in an area used during the day by the participant; sampling time averaged 531 minutes with a SD of 110 minutes. In two of the 7 salons, we placed replicate TD tubes side-by-side as part of quality control. These standard TD tubes have validated sampling rates ranging from 0.25 to 0.68 mL/min depending on the compound in occupational settings.[32]

After sample collection, tube samples were sealed with storage caps and stored in sealed aluminum containers. Samples were shipped with field blanks to the Environmental Analytical Laboratory at the University of Memphis within 2 days of collection. The samples were analyzed within 5 days upon receipt as previously described by Jia and Fu.[33] In brief, a tube was thermally desorbed at 260°C on an automated TD system (ULTRA 2+UNITY 2, Markes International, Llantrisant, United Kingdom), and the desorbed VOCs were then separated and analyzed on a gas chromatography/mass spectrometry (GC/MS) system (Agilent 7890A/5975C, Agilent, Santa Clara, California, U.S.A.). Data analysis were performed for 71 target VOCs, selected from EPA TO-15 Method and common compounds previously found in nail salons. Method detection limits (MDLs) were derived from the analytical limit of detection (LOD) of the instrument for 8-hr sampling (Supplemental Information (SI) Table S1). Samples below the MDL were imputed as $MDL/\sqrt{2})$[34].

Sampling and Analysis of VOC Biomarkers

Two grey top vacutainer tubes of whole blood (7mL) were collected from each participant at the work site, one at the beginning and one immediately at the end of the work shift.

Contaminant-free tubes were provided by the Centers for Disease Control and Prevention (CDC) VOC Laboratory. Trained nurses from the Beth Israel Deacons Medical Center performed venipuncture following the universal precautions for working with blood and blood products.[35] The tubes of whole blood were sent overnight (5ºC) to the CDC VOC Laboratory. Blood was analyzed within 5 days following headspace solid-phase microextraction with benchtop GC-MS CDC Method VOC54, as previously described.[36,37] MDLs were provided by the laboratory (SI Table S2). Concentrations below the MDL were imputed as $MDL/\sqrt{2}$.[34] Of the 43 blood VOCs tested, 8 were detected in blood; and of the 71 air VOCs that were screened, 22 were detected in air using TD tubes.

Sampled exhaled breath pre- and post-shift using 1L Tedlar bags were also measured at CDC. VOCs were analyzed using headspace solid phase micro extraction (SPME) GC/MS method for the analytes detected in blood, as previously described by Sampson et al.[38] However, semiquantative breath data (not shown) were below lowest calibration standard levels. For predominant blood VOCs detected, toluene and ethyl acetate, the lowest standard concentrations for exhaled breath measurements were 3.65 and 62.4 $\mu g/m^3$ (1.06 and 17.21 ppb_v), respectively.

Data Analysis

The work load was defined as the number of nail procedures a technician performed on the day of sampling. Data on work load was asked to technicians and verified by observations during the day. We estimated ventilation rates, or air exchanges per hour (ACHs), using CO_2 measurements and number of occupants in the space at steady state, and using a steady-state box model;[39–42] results were compared to ventilation guidelines for nail salons by the American Society of Heating, Refrigerating and Air-Conditioning Engineering (ASHRAE).[40] Details in SI 7.

Air VOC samples were not blank corrected because monitored compounds were non-detectable in field blanks. If there was more than one area air sample per salon during the same visit (i.e., replicate samples or 2 technicians sampled in the same salon), measurements were averaged. Salon 7 was visited twice for different participants, and the samples were treated as independent samples considering the large temporal variation.

We compared medians and ranges of blood concentrations with those from the 2013–2014 U.S. nonsmoking female general population.[43] We compared personal air and blood concentrations to the lowest OELs and biological exposure indices (BEIs).[31,44,45] For correlations between variables we used Spearman correlation coefficients; for contrasts between paired variables (e.g., pre- and post-shift blood VOCs) or to compare post-shift blood and NHANES blood levels we used Wilcoxon signed rank tests. Statistical analyses used AIHA IHstats V229, JMP 13.2.0 and SPSS 17.0.2, and statistical significance level, α, was set at 0.05.

RESULTS

Characteristics of Nail Salons and Nail Technicians

Table 1 describes the seven nail salons we studied. The salons were small (45 m^2) to medium size (279 m^2) and opened five to seven days per week. Salons had up to 9 manicure and 12 pedicure stations, although not all stations were occupied in some salons on the day of our visit. All but one of the salons performed acrylic nail enhancements. Salons kept temperatures throughout the work shift between 18–25°C and 32–53% relative humidity. Six salons had general exhaust ventilation while one relied on natural ventilation. The salon estimated general ventilation rates of 6.4–88 cfm/person, did not always meet the ASHRAE guideline for acceptable indoor air quality in nail salons of 25 cfm/person (equivalent to 7.5 m^3/min-person).[39] Two salons used LEV systems (extraction hoods to filter contaminants before recirculating the air indoors) over the manicure stations, which we verified were in good operating condition.

Table 2 summarizes demographic and employment characteristics of the ten nail technicians in our study. Six participants were Vietnamese and four were White non-Hispanic. The participants averaged nine years in the profession. Participants worked an average of nine hours on the day of our visit, and usually worked 39 hours per week. The work load for technicians ranged from 3–8 clients on the sampling day. A few nail technicians used limited PPE during their work shift, including gloves (thin latex and nitrile), uniforms, safety glasses, or respirators (disposable N95 with charcoal cartridges). Seven of the ten nail technicians reported washing their hands before eating and before leaving work. Additional information on the use of PPE and personal behaviors (e.g., hand washing) is in SI Tables S3 and S4, but was not further analyzed due to the small sample size.

Nail Products Safety Data Sheet Review

Nail polish was the most common nail product used in salons (typical nail salon carrying 4 to 5 different nail polish brands, while some carrying as many as 10). Of the 22 brands we reviewed, standard nail polish products reported higher SDS-disclosed percent by weight (% WT) content than gel products for ethyl acetate (<60% WT for standard vs <50% WT for gels) and toluene (<30% WT for standard vs 0% WT for gels). However, gel products had higher percent by weight content of acrylates (<100% WT for gels vs <30% WT for standard). Acrylates listed in nail polish SDSs included: hydroxyethyl methacrylate, isobornyl acrylate, tetrahydrofurfuryl methacrylate, and ethyl methacrylate. The nail bonding agent listed 100% ethyl acetate.

Nail products used for sculpting artificial nails, commonly known as acrylic nails or enhancements, included liquid, powder, or pre-mixed powder, composed of <100% acrylates. Acrylates listed in acrylic nail products' SDSs listed different polymerization fragments including: ethyl and methyl methacrylate, butyl methacrylate, and ethyl 2-cyanoacrylate. Other nail products used during nail procedures that contained VOCs in their ingredients included nail glue or superglue (<100% acrylates) and nail cleaners (i.e., 100% isopropyl alcohol). Further, nail polish removers used in the salons were all 100% acetone. Nail polish removers that do not contain acetone were not found in the salons studied.

VOCs in Personal and Indoor Air

Of the 71 monitored VOCs analyzed in air, 22 were detected in the nail salons studied (SI Table S1). The most abundant and frequently measured VOCs in air were toluene, ethyl acetate, ethyl methacrylate, methyl methacrylate, and d-limonene (Table 3). Other VOCs detected in more than 50% of the samples included: benzene, ethyl benzene, all the xylenes, styrene, p-isopropyltoluene (p- cymene), and carbon tetrachloride. Personal VOC air concentrations were significantly higher than area air ($p < 0.001$) for ethyl acetate, m,p-xylenes (not o-xylene), methyl methacrylate, and d-limonene. Conversely, personal VOC air concentrations were significantly lower than area air ($p < 0.001$) for benzene and ethyl methacrylate. All detected personal VOC levels were well below the lowest OELs, although OELs are not available for ethyl acrylate and p-isopropyltoluene (Table 3).

Ventilation (ACH) was significantly correlated with a reduction in toluene personal air levels (Spearman $r = -0.76$, $p = 0.017$). However, ACH was significantly associated with an increase in methyl methacrylate salon air concentrations (Spearman $r = 0.71$, $p = 0.034$); although unexpected, perhaps a higher air flow in the salon increases evaporation of the acrylic monomer when products were opened. Other VOCs in personal air, salon air, and blood were not significantly correlated with ventilation.

Work load (i.e., number of procedures during the work shift) was only significantly associated with ethyl acetate area air concentrations (Spearman $r = 0.84$, $p = 0.002$), similarly to that described by Quach et al.[13]

Blood VOCs

Of the 43 VOCs analyzed in blood, only two had detection rates above 50% in either pre- or post-shift samples from nail salon participants (SI Table S2). VOCs detected in air that were not quantified in blood and breath samples were methyl and ethyl methacrylate because they are not stable in blood and d-limonene and p-isopropyltoluene are not included in the blood VOC method because they have low toxicity[46,47]. Hazardous VOCs such as toluene and ethyl acetate were detected at >80% in post-shift blood samples. Median concentrations of these two compounds increased significantly from pre-shift to post-shift ($p < 0.02$, Figure 1). Nevertheless, there was variability among the nail technician blood levels. Table 4 and Figure 1 show that post-shift median blood concentrations of toluene (0.36 μg/L, maximum of 0.79 μg/L) and ethyl acetate (0.51 μg/L, maximum of 1. μg/L) significantly exceeded the levels estimated in the general female nonsmoking U.S. population for toluene (0.056 μg/L, 95th percentile of 0.225 μg/L) and ethyl acetate (<0.158 μg/L, 95th percentile of 0.158 μg/L), with $p < 0.002$.

Pre-shift blood concentrations and personal air exposures displayed significant associations for toluene (Spearman's $r = 0.68$, $p = 0.042$), but ethyl acetate was not significant (Spearman's $r = 0.27$, $p = 0.48$). Blood post-shift concentrations and personal air exposures displayed positive but insignificant associations: toluene $r = 0.53$, $p = 0.12$; ethyl acetate $r = 0.27$, $p = 0.46$.

DISCUSSION

Personal and Area Air VOC Levels Compared to Previous Studies

This pilot study documents the presence in nail salon air of several VOCs typically found in nail products: toluene, ethyl acetate, and ethyl and methyl methacrylates. Levels were similar to ranges previously documented in nail salons in the United States (Table 5). The levels of benzene, ethyl benzene, and the xylenes in our study were very low (non-detect to low μg/m^3) and comparable to ambient levels.[28]

While personal air concentration exceeded area air concentrations for four of the most frequently detected VOCs, the reverse was true for two VOCs, while there was no significant difference for the other 6 VOCs. Additional information (e.g., technician use of specific products) and a larger data set may be needed to understand such patterns.

Biomarkers of Nail Product Related VOCs

Most of the VOCs detected in the salon air were below detection limits of the blood analysis, but of the VOCs detected in the air and blood samples, toluene and ethyl acetate predominated. Post- shift blood concentrations of these two compounds increased significantly during the shift, suggesting that nail salon work made an important contribution to nail technician's exposures. Median post-shift blood samples concentrations exceeded those found in the female, nonsmoking U.S. population.

Half-lives for many stable VOCs such as toluene and ethyl acetate can extend up to 10 hours if the VOC has permeated into less polar tissues such as adipose,[48–51] making them able to be measured throughout a work shift. However, we found venipuncture to be challenging in this worker population (i.e., we failed to draw blood once after many attempts). Our attempt to use less invasive exhaled breath to measure VOCs was not successful at the low exposure levels (all non-detects). Development of a more sensitive breath analysis method with preconcentration or analysis of intact VOCs in urine may be worth pursuing.

Exposure Sources and Factors

Pre-shift blood levels may partly reflect work on previous days or non-work activities. Toluene was the only VOC measured in pre-shift blood at high detection rates (>89%). Toluene is ubiquitous[52] and air salon concentrations were relatively low (median personal air of 39 μg/m^3). Further, pre-shift blood samples were collected in the salon approximately 20–45min after the technician arrived before nail services were provided, which may have given time for toluene blood level to equilibrate with the salon environment.[53]

To control for other VOC sources such as tobacco smoke and personal use of nail salon products, we recruited only nonsmokers and asked participants to refrain from painting their nails during the week before the start of the sampling day. Only one participant reported alcohol consumption on the day before sampling and the laboratory did not report that ethanol interfered in the exhaled breath analysis. Nevertheless, there may be the potential for contributions from other VOC sources outside of work.

Of the four VOCs with the highest median concentrations in personal air—ethyl acetate highest median followed by methyl methacrylate, ethyl methacrylate and then toluene—ethyl acetate and toluene were also detected at high rates in post-shift blood. Methacrylates were not examined in blood because of their high instability in blood. Ethyl acetate, toluene and acrylates were also identified as ingredients of nail polish and artificial nail products using SDS information. This information suggests that nail products are a source of exposure for nail technicians, similarly to that confirmed by Zhong et al.[16]

Although d-limonene and p-isopropyltoluene occurred in the air of the nail salons, we did not identify these compounds as ingredients in the SDSs we reviewed. It is possible that they may be classified as a fragrance, or are present in other products used in the salons that we did not review, such as lotions, scrubs, waxes, and cleaning products. Both substances are irritating agents for both eyes and skin, and d-limonene may cause dermatitis.[46,47] Carbon tetrachloride was also found in most air samples but in very low levels typical of background indoor levels; this chemical is a legacy air contaminant that was previously used in industrial cleaning, dry cleaning, and aerosols.[54]

Besides environmental and occupational sources, other factors may affect VOC exposure of nail technicians such as ventilation, work load and use of PPE. We estimated ventilation rates to be 0.2 to 3.8 ACH (6.4 to 88 cfm per person), comparable to those in 7 nail salons in the Los Angeles area[55](ACH from 0.2 to 5.7) and 17 nail salons in Michigan[16] (ACH from 0.7 to 45.2) that also used CO_2 measurements in their studies. As reported above, we found an association between ventilation and toluene personal air concentration and work load and area air concentration for ethyl acetate, however more associations were not possible due to low statistical power or chance. Due to our small sample size, we could not adequately analyze the effect of PPE.

Significant Contribution to Ambient VOCs from Nail Salons

To understand the potential impact that the measured levels of VOCs in nail salons may have on annual emissions to the outdoor air, we estimated emissions per salon (calculation details described in SI5). If we make a series of assumptions: 1) the 7 nail salons studied were representative of a typical nail salon in the City of Boston, 2) City of Boston has 200 salons (data from the Boston Public Health Commission), and 3) salons operated all year, emissions from nail salons in the City of Boston (benzene 0.37, toluene 2.97, metric tons/year) would be comparable or higher than the emissions reported for all industrial facilities in Suffolk County in 2016 (benzene 0.58, toluene 1.2, metric tons/year).[56] In contrast, there were no emissions for these VOCs reported to the toxic release inventory for the City of Boston in 2016.[56] Nail salon emissions would be higher for the Greater Boston area but an accurate count of nail salons for the area was not available. Although individual salons are not required to report emissions, the nail salon industry collectively may be a non-negligible VOC emission source. Our rough estimates indicate that nail salon outdoor emissions would be important to explore in future studies because in the United States, urban air VOCs are increasingly derived from consumer products rather than industrial sites or transport related emissions.[57]

Nail salon VOCs and Nail Technician's Health

Salon air concentrations were below lowest OELs and nail technician blood levels were less than BEIs (Tables 3,4). These measured levels have not been identified to cause acute and chronic health effects.

Health effects typical of long-term toluene exposures in the ppmV range of a month, some of which are commonly reported by nail technicians, include the following: respiratory and eye irritation; irritated, dry, and cracked skin; nervous system dysfunction, headaches, dizziness, fatigue, and developmental impairment.[45,58,59]While many nail polish brands are eliminating toluene, [60] it may continue to be found as a residue in nail products.

Ethyl acetate is a major ingredient in many nail polishes. Chronic ethyl acetate exposure in the ppmV range on the order of a month has been associated with eye, skin, nose, and throat irritation, as well as nervous system depression, edema of the liver and kidney, corneal clouding, and even anemia.[61,62] There have been no studies of developmental toxicity to the unborn child,[63] which would be important for the high percentage of nail technicians in reproductive age.

Likely sources of methyl and ethyl methacrylate are nail polishes (especially gel products) and acrylic liquid or powder used for sculpting nails. Methyl methacrylate has been banned in 32 U.S. States, but not Massachusetts.[64]The Food and Drug Administration (FDA) has recommended since the late 1970s that methyl methacrylate not be used in pure liquid form because of adverse skin reactions (sensitizing),[65,66] but it is not listed as a prohibited or restricted substance.[66] Methyl and ethyl acrylates may occur as residues in products that only disclose the presence of acrylated oligomer or copolymers. The wide variety of acrylate formulations in nail products makes measuring and controlling exposure challenging. We found methyl methacrylate in salon air and listed as an ingredient in some nail products (i.e., acrylic powder SDS). The lowest air levels measured for both methacrylates were in salons that did not provide artificial nail procedures.

Potential health concerns for ethyl and methyl methacrylate include irritation of the nose and throat, coughing, shortness of breath, nervous system effects, drowsiness, light-headedness, dizzy spells, trembling of hands (suggested neurotoxicity), and skin sensitization or dermatitis.[45,67,68] Of particular concern was the listing of polyurethanes as an ingredient in one of the nail polish brands found in the salons studied. Polyurethanes have been well documented as potent sensitizers in the autobody industry[69]. This was particularly concerning, as the nail polish containing polyurethanes was labeled as non-allergenic.

Strengths and Limitations

Major strengths of our study include the measurement of the occupational contribution to VOC blood levels for nail technicians and the use of TD tubes. The latter proved to be an ideal sampling technique because they are easy to use, small, inconspicuous, had a 100% participation rate (i.e., all technicians in the study agreed to wear TD tubes as part of the study) in the client-oriented salon environment, and follow well defined sampling and analysis guidelines[32,70–72]TD tubes may serve for future studies to collect breath samples as it has been previously described.[73–75] We characterized exposure to more VOCs than previous studies at nail salons. Nevertheless, we were not able to measure all VOCs typically found in nail salons, as our methods did not include acetone, formaldehyde, ethanol, butyl acetate, isopropyl alcohol, and other acrylates beyond ethyl and methyl methacrylates. An important limitation of our study was the small sample size, preventing conclusions regarding many exposure factors such as PPE. Further, data from only 7 nail salons may not be representative of all nail salons in the Greater Boston area. However, the demographics of nail technicians we were able to recruit (60% Vietnamese and 40% Caucasian) were similar to the national statistics in the nail salon industry (56% Vietnamese and 36% Caucasian).[1]

Since October 2018, nail salons in the City of Boston need to mechanically exhaust air to the outside – instead of relying on air being passively exhausted through windows, doors, and cracks in the building like the salons in our study.[76] Even if the ventilation changes result in improved air quality indoors, nail salons would need to effectively filter exhausted air from VOCs to reduce current emissions to the ambient air. Thus, this study will serve as the basis for designing future studies to assess VOC exposure of nail technicians, the impact of safer alternatives in nail products, better controls including improved ventilation, and improved training and outreach to this worker population.

CONCLUSIONS

Nail technicians are exposed to a variety of VOCs throughout their work life. Higher concentrations of some VOCs in the post-shift blood of nail technicians compared to those measured pre-shift or in the general U.S. population indicate the importance of occupational exposure. Ethyl acetate and toluene found in air and blood were also listed as ingredients in nail products in the investigated salons. TD tubes were effective and easy to use for measuring a wide variety of VOC concentrations in indoor and personal air in nail salons. While blood was an effective VOC biomarker for investigating toluene and ethyl acetate exposures, venipuncture was challenging in this work environment, given that a whole tube of blood is needed for current analytical methods. While full-shift VOC air concentrations were well below established OELs (not available for ethyl acrylate and p- isopropyltoluene), they could still contribute to chronic health effects such as respiratory and skin irritation, headaches, dizziness, dermatitis, and neurocognitive and reproductive toxicity. Reducing VOC exposure among nail technicians may require change in nail product formulation, better ventilation, and more consistent and effective use of personal protective equipment.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Practical Implications

Nail technicians' elevated blood levels of toluene and ethyl acetate suggest occupational exposure to volatile organic compounds from nail products. Ventilation was found to be a key variable in the air levels found in the salons for these two volatile organic compounds. Thus, there is a need for changes in nail product formulation and better ventilation to reduce volatile organic compounds occupational exposures.

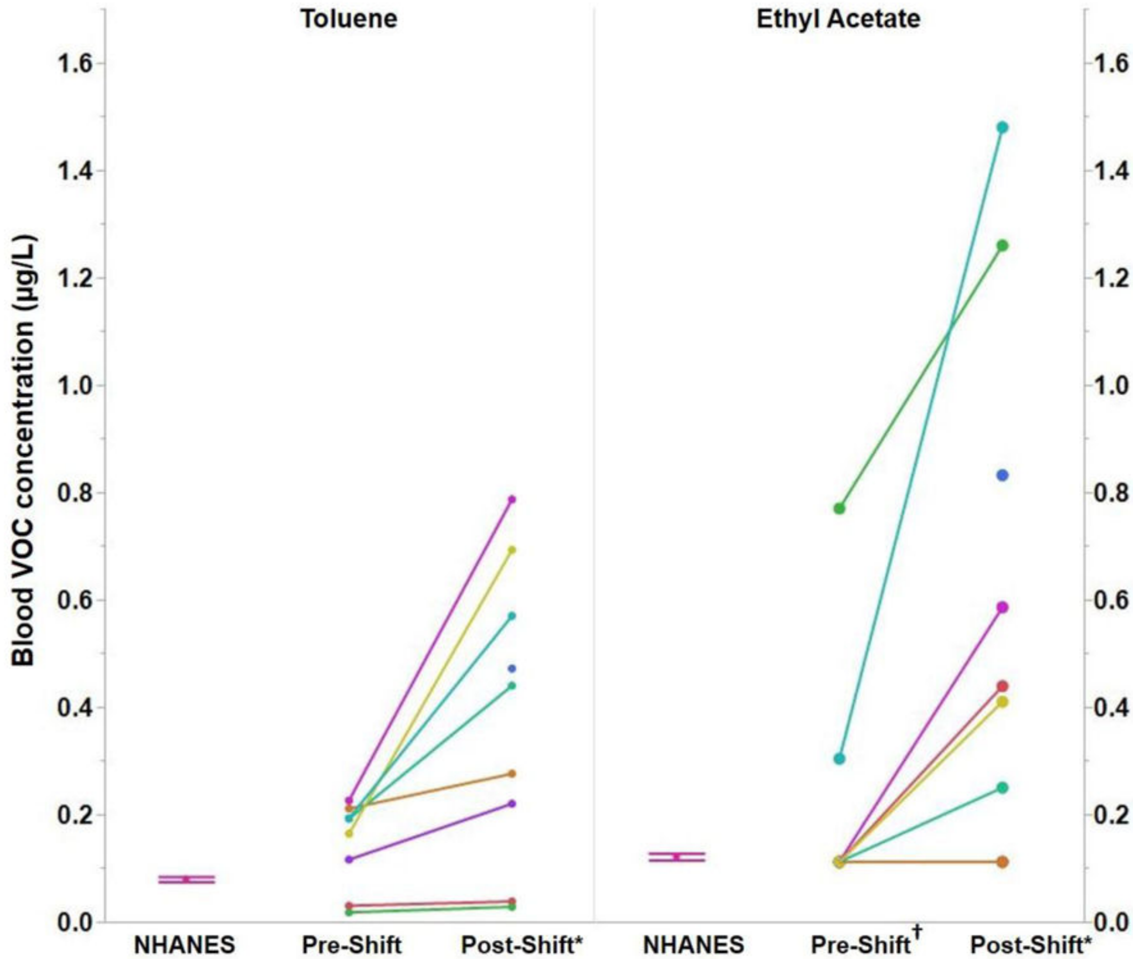

Figure 1.

Toluene and ethyl acetate blood levels measured before and after the work shift (2016–2017) and compared to the U.S. general population (NHANES 2013–2014 for female nonsmokers). *Post- shift blood levels significantly higher from pre-shift or NHANES. †All NHANES ethyl acetate and all but two pre-shift ethyl acetate samples were <MDL. Each color in the figure corresponds to the same participant.

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Table 1.

Nail salon characteristics (n = 7)

Nail salon ID	Area m^2	Number manicure stations	Number pedicure stations	General exhaust ventilation	Measured CFM Per person (m^3/min-person)	ACH	LEV	Typical services	Days per week open
1	55	3	2	No	7.0 (2.1)	0.32	Yes	Acrylic nails, natural care, hair (once a week without chemical treatments)	7
2	92	7	5	Yes	38 (11)	0.88	No	Acrylic nails, natural care, waxing	6
3	279	12	9	Yes	15 (4.5)	0.42	No	Acrylic nails, natural care (rarely done), waxing	6
4	124	10	8	Yes	ND	ND	No	Natural care, waxing	7
5	45	3	1	Yes	6.4 (1.9)	0.21	Yes	Acrylic nails, natural care (rarely done)	5
6	57	5	4	Yes	88 (26)	3.8	No	Acrylic nails, natural care, waxing	7
7	217	6	6	Yes	27 (8.1)	0.32	No	Acrylic nails, natural care, waxing	6

CFM = cubic feet per minute of ventilation (ft^3/min, equivalent to 0.3 m^3/min). ACH = air exchanges per hour of ventilation (#/hr). LEV = local exhaust ventilation. ND = Not determined. Data missing due to instrument logging failure. Natural care refers to using standard nail polish lines.

Table 2.

Demographic and employment characteristics of nail technician participants (n = 10)

Participant characteristics	No. of respondents	Mean (Std. Dev.)
Demographics		
Current age, years	10	45. 0 (10.8)
Country of origin (survey language)		
United States (English)	4	
Vietnam (Vietnamese)	6	
Employment		
Occupation at current salon		
Length, years		8.4 (6.4)
Nail technician	8	
Owner (also nail technician)	2	
Employment in nail industry		
No other job as nail technician	10	
Full time, years	10	10 (7.7)
Part time, years	8	10 (12.4)
Work schedule		
Weekly, hours		37.9 (6.1)
Day of sampling, hours		8.73 (1.4)
Nail procedures on day of sampling, by type		
Manicure, count	8	2.1 (1.3)
Pedicure, count	8	1.5 (0.6)
Types of manicure/pedicure reported, count	3	
Acrylic (i.e., new artificial nails)		6.0 (3.0)
Refill (i.e., redo of artificial nails)		1.0 (0.0)
Gel nail polish (i.e., UV light needed for curing)		4.0 (0.0)

Table 3.

Nail technicians full-shift personal and area air sampling results measured with thermal desorption tubes

	Nail Technicians Personal Air Concentrations (n = 10)				Nail Salon Area Air Concentrations (n = 8)			
Analyte[†]	MDL μg/m^3	%> MDL	Median μg/m^3	Range μg/m^3	%> MDL	Median μg/m^3	Range μg/m^3	ACGIH TLV TWA μg/m^3
BETX								
Benzene	0.16	90	0.46	<MDL-3.4	100	2.4[§]	1.6–4.7	1,600
Toluene	0.26	100	39	4.8–85	100	21	2.2–105	75,300
Ethyl benzene	0.16	80	0.32	<MDL-2.1	100	0.35	0.21–0.91	434,000
o-Xylene	0.23	60	0.33	<MDL-2.6	88	0.50	<MDL-0.74	434,000
m,p-Xylene	0.35	90	0.79[‡]	<MDL-7.8	100	0.43	0.52–1.8	434,000
Acrylates								
Ethyl methacrylate	0.28	70	24	<MDL-6,900	75	240[§]	<MDL-5,430	NA
Methyl methacrylate	0.37	80	190	<MDL-2,100	88	205	<MDL-2,580	410,000
Other VOCs documented in nail products								
Ethyl Acetate	0.28	100	760[‡]	140–2,800	100	639	142–2,630	1,440,000
Styrene	0.17	50	0.17	<MDL-0.50	88	0.39	<MDL-0.86	85,141
VOC likely as a fragrance in cleaning products, lotions, makeup, or waxes								
p-Isopropyltoluene	0.16	80	1.2	0.12–3.3	90	0.52	<MDL-2.52	NA
d-Limonene	0.53	100	9.3[‡]	5.3–180	100	6.4	4.2–130	110,000[¶]
Legacy VOC								
Carbon tetrachloride	0.14	70	0.76	0.10–1.5	90	0.29	0.1–1.0	1,078[¶]
Total measured VOCs								
Sum of 71 VOCs		100	2,750	677–7,910	100	1,970	584–6,280	

ACGIH TLV TWA = threshold limit values, American Conference of Governmental Industrial Hygienists,[46] for an 8-hr time weighted average. MDL = method detection limit. BETX = Benzene, toluene, ethyl benzene, and the xylenes. Sum of 71 VOCs = sum of all analytes identified and quantified by the analysis of the thermal desorption tubes.

[†] Analytes listed are those with at least 50% detected samples from SI Table S1.

[‡] Personal air significantly higher than area air.

[§] Area air significantly higher than personal air.

¶German limit is reported for d-limonene as TLV is not established; OSHA PEL was reported for carbon tetrachloride as is lower than the TLV.[45]

Table 4.

VOC concentrations in blood collected from nail technicians before and after the work shift and compared to the US general population

		Nail Technicians (n = 9[†]) Pre-shift Blood Concentrations μg/L			Nail Technicians (n = 10) Post-shift Blood Concentrations μg/L			United States General Population 2013–2014 NHANES Female Nonsmokers[#] Blood Concentrations μg/L					BEI μg/L
Analyte[‡]	MDL μg/L	%> MDL	Median	Range	%> MDL	Median	Range	n	MDL	Median	Range	95th Percentile	
Ethyl acetate	0.16	22	<0.16	<0.16–0.77	80	0.51[§]	<0.16–1.5	1,160	0.16	<0.16	<0.16–7.1	<0.158	NA
Toluene	0.025	89	0.16	<0.025–0.23	100	0.36[§]	0.028–0.79	1,147	0.025	0.056	<0.025–3.79	0.225	20

MDL = method detection limit. BEI = Biological Exposure Index ACGIH.[46] N = number of samples.

[†]One pre-shift sample was not collected because of challenges drawing blood during phlebotomy.

[‡]Analytes listed are those with >50% detect in at either pre- or post-shift samples from SI Table S2.

[§]Post-shift blood levels significantly higher from pre-shift blood levels.

Table 5.

Range of VOC concentrations detected in nail salons in this study compared to other studies

Country	Reference	Personal or area air (n)	# VOCs	Sampling Method	VOC Air Concentrations Range[†]				
					Toluene μg/m³	Ethyl methacrylate μg/m³	Methyl methacrylate μg/m³	Ethyl acetate μg/m³	d-Limonene μg/m³
US	**This study**	**Personal (10)**	**72**	**Passive**	**4.8–85**	**ND-6,900**	**ND-2,100**	**140–2,800**	**5.3–180**
		Area (8)	**72**		**2.2–105**	**ND-5,430**	**ND-2,580**	**142–2,630**	**4.2–130**
	Zhong 2019[16]	Personal (34)	12	Passive	ND-650	ND-1,920	ND-36,000	170–9,650	ND-300
		Area (34)			ND-380	ND-1,350	ND-34,200	84–6,900	ND-200
	Quach 2018[13]	Personal	3	Passive	ND-325[‡]	-	ND-41,000[‡]	-	-
	Garcia 2015[20]	Personal	3	Passive	188–640	-	82–27,880	-	-
	Alaves 2013[19]	Area (12)	7	Active	38–1,168	-	ND-16,810	180–7,200	-
	Quach 2011[5]	Personal (167)	3	Passive	75–3,766	-	-	72–19,800	-
		Area (3)	6	Active	38–226	-	492–5,330	72–540	-
	Marty 2007[79]	Personal	2	Active	-	187–145,000	615–21,320	-	-
	Spencer 1997[11]	Personal,LEV (8)	2	Active	-	1,870–7,013	ND	-	-
		Personal,no LEV (10)	3		-	32,725–65,450	ND	-	-
	Almaguer 1998[17]	Personal (1)	4	Active	-		ND	-	-
		Area (6)	4		-	ND-32,725	ND	-	-
	Almaguer 1992[80]	Personal (2)	2	Active	-	11,000–12,000	-	-	-
	Hiipakka 1987[81]	Personal (17)	4	Active	377–7,532	ND-79,475	-	-	-
	Froines 1986[8]	Area (≤25)	3	Active and passive	-	11,220–43,010	8610–27,880	-	-
Norway	Gjølstad 2006[4]	Area	70	Active	75–1,168	421–14,960	82–328	36–4,284	-
Korea	Park 2014[82]	Area		Passive	ND-1'849,000	ND-285,000	ND-2'500,000	720–608,000	-
	Yang 2010[21]	Area (≤25)	13	Active	490–5,300	-	-	756–9,000	-
				Active	-	-	41–492	-	-
Greece	Tsigonia 2010[18]	Area	3	Active	3.0–67	-	-	ND-44	ND-227

n = number of samples when available in the publication. ND = not detected. VOCs = volatile organic compounds.

[†] Range was chosen as the best comparison metric because of the different central tendencies reported across studies.

[‡] Approximate range deduced from statistics given in the publication.