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# Air, hand wipe, and surface wipe sampling for Bisphenol A (BPA) among workers in industries that manufacture and use BPA in the United States

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**ABSTRACT**

For decades, bisphenol A (BPA) has been used in making polycarbonate, epoxy, and phenolic resins and certain investment casting waxes, yet published exposure data are lacking for U.S. manufacturing workers.

In 2013–2014, BPA air and hand exposures were quantified for 78 workers at six U.S. companies making BPA or BPA-based products. Exposure measures included an inhalable-fraction personal air sample on each of two consecutive work days (n = 146), pre- and end-shift hand wipe samples on the second day (n = 74 each), and surface wipe samples (n = 88). Potential determinants of BPA air and end-shift hand exposures (after natural log transformation) were assessed in univariate and multiple regression mixed models.

The geometric mean (GM) BPA air concentration was 4.0 µg/m$^3$ (maximum 920 µg/m$^3$). The end-shift GM BPA hand level (26 µg/sample) was 10-times higher than the pre-shift level (2.6 µg/sample). BPA air and hand exposures differed significantly by industry and job. BPA air concentrations and end-shift hand levels were highest in the BPA-filled wax manufacturing/reclaim industry ($GM_{Air}$ = 48 µg/m$^3$, $GM_{Hand\text{-}End}$ = 130 µg/sample) and in the job of working with molten BPA-filled wax ($GM_{Air}$ = 43 µg/m$^3$, $GM_{Hand\text{-}End}$ = 180 µg/sample), and lowest in the phenolic resins industry ($GM_{Air}$ = 0.85 µg/m$^3$, $GM_{Hand\text{-}End}$ = 0.43 µg/sample) and in the job of flaking phenolic resins ($GM_{AIR}$ = 0.62 µg/m$^3$, $GM_{Hand\text{-}End}$ = 0.38 µg/sample). Determinants of increased BPA air concentration were industry, handling BPA containers, spilling BPA, and spending ≥50% of the shift in production areas; increasing age was associated with lower air concentrations. BPA hand exposure determinants were influenced by high values for two workers; for all other workers, tasks involving contact with BPA-containing materials and spending ≥50% of the shift in production areas were associated with increased BPA hand levels. Surface wipe BPA levels were significantly lower in eating/office areas (GM = 9.3 µg/100 cm$^2$) than in production areas (GM = 140 µg/100 cm$^2$).

In conclusion, worker BPA exposure was associated with tasks and conditions affecting both inhalation and dermal exposure. The potential for BPA-related health effects among these workers is unknown.

**KEYWORDS**
Endocrine disruption; exposure assessment; exposure determinants; occupational

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## Introduction

Bisphenol A (BPA) (CAS 80-05-7, 4,4′-isopropylidenediphenol) is a commercially-important chemical used as a monomer in the production of polycarbonate, epoxy, and phenolic resins, and as a reactant in making certain halogenated flame retardants;[1–4] residual BPA in these products is minimal. BPA is also used as a filler in certain investment casting waxes where BPA can comprise up to 45% of the wax, and as a developer in thermal paper;[5, 6] in both applications, BPA is unreacted.

Raw BPA is a white solid prill (dry sphere) or flake at room temperature. Handling raw BPA, such as when dispensing BPA from sacks or bags, can produce aerosols. Some resins made with BPA may also produce aerosols during handling, although these aerosols contain far less BPA because BPA is nearly consumed in the

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resin-forming reaction. The presence of BPA or BPA-based resin aerosols in the workplace can result in BPA-containing residues on surfaces and objects in production areas, along with the potential transfer of residues from production areas to eating and office areas via the hands, clothing or other objects. Thus, workers involved in manufacturing BPA or BPA-based products may be exposed to BPA by inhalation, skin contact, or ingestion.

The toxicity of BPA continues to be extensively studied and debated. BPA is weakly estrogenic with low acute toxicity.[7–9] A range of health effects in both animal and human studies, hypothesized to be related to endocrine system disruption, have been associated with BPA exposure.[10–15]

Published data on airborne occupational exposure to BPA are limited to manufacturing workers in China and Finland.[16–19] To our knowledge, no measurements of dermal exposure among workers handling BPA have been published. In a National Institute for Occupational Safety and Health (NIOSH) study conducted in 2013–2014, workers in U.S. industries making BPA or BPA-based products had geometric mean (GM) urinary BPA concentrations nearly 70 times higher than adults in the 2013–2014 National Health and Nutrition Examination Survey.[20] As a part of that study, BPA was quantified in personal air, hand wipe and surface wipe samples. Results of air and wipe sampling as well as the determinants of BPA air and hand exposures are reported herein.

## Methods

### *Company and participant recruitment*

Methods for recruiting companies and workers were described previously.[20] Briefly, participants were recruited from six companies listed on the 2010–2011 U.S. Environmental Protection Agency Toxic Release Inventory that made BPA or BPA-based products.[21] Participating companies were visited to identify BPA-related jobs, and workers performing these jobs were invited to participate in the study. Participants gave written informed consent. The study was approved by the NIOSH Institutional Review Board.

### *Sample collection*

A full-shift personal breathing zone air sample was collected on each worker for two consecutive work shifts. An IOM sampler (SKC, Inc.) with a 25-mm quartz fiber filter in a stainless-steel cassette was used at a nominal flow rate of 2 L/min to collect inhalable particles. Sampling pumps (Airchek® Model 224–52, SKC, Inc.) were pre- and post-calibrated. Completed filter-cassette units were placed in a 30-mL polypropylene wide mouth container for transport to the laboratory.

On the second day, a wipe sample of both hands was collected at the start and end of the work shift. Each hand was wiped with two Large Alpha® Swabs (polyester heads) (TX715, ITW Texwipe®) moistened with 100% HPLC grade isopropanol (IPA) (Thermo Fisher Scientific, Inc.). The palms and back of the hand were wiped with the first swab, then the surfaces between the fingers (in opposing directions) with the second swab. The process was repeated on the other hand. The four swabs were inserted into a 20-mL polypropylene vial (Thermo Fisher Scientific, Inc.) to form a single sample. Workers were instructed to delay final hand washing for the day until the end-shift sample had been taken. Hands were wiped on the second day to minimize interference with concurrent urine biomonitoring.

Workers were asked to identify surfaces and objects that they touched with ungloved hands. Two large Alpha® Swabs moistened with 100% IPA were used to wipe these surfaces/objects. The first swab was used to wipe the proscribed area horizontally then vertically, the second swab diagonally from right to left and then from left to right. The two swabs were inserted into a 20-mL polypropylene vial (Thermo Fisher Scientific, Inc.). For flat surfaces, a 10 cm × 10 cm paper template was used to proscribe the wiped area. For other objects, the dimensions of the wiped surface were measured and the total area computed.

Study staff wore nitrile gloves while handling air and wipe samples. All samples were kept cold (4°C) in the field and shipped and stored cold prior to analysis. Field blanks (10%) were prepared and handled in a manner similar to field samples.

### *Sample analysis*

The NIOSH contract laboratory, Bureau Veritas North America, quantified BPA in air, hand wipe, and surface wipe samples. Air sample filters were placed on a mechanical shaker and extracted with acetonitrile (2-mL) for 30 min. Extracts were diluted 1:1 with deionized water, and hand shaken to mix. Wipe sample swabs were extracted with acetonitrile (5-mL) then tumbled overnight on a rotary tumbler. De-ionized water (5-mL) was added to each wipe extract, hand shaken to mix, and filtered through a 13-mm polyvinylidene fluoride syringe filter. Air and wipe extracts were analyzed by high-performance liquid chromatography-ultraviolet detection (HPLC-UV) (run parameters in Supplemental Table SI). Laboratory quality control (QC) consisted of media blanks, lab-fortified matrix spikes, and replicate analyses. All sample results were corrected for recovery, media blanks, and field blanks. The limit of

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detection (LOD) across seven sample batches was 0.03–0.1 μg/sample (air), 0.05–0.3 μg/sample (hand wipe) and 0.05–0.2 μg/sample (surface wipe). The mean (±SD) recovery for matrix QC spikes was 90.9 ± 6.1% (air, n = 24), 85.2 ± 5.5% (hand wipe, n = 24), 90.2 ± 4.8% (surface, n = 14). Precision (relative percent difference ±SD) of duplicate analyses of field samples was 3.0 ±3.1% (air, n = 14), 2.5 ± 3.7% (hand wipe, n = 12), 1.3 ± 2.3% (surface wipe, n = 7).

### *Other information collected*

For each participant, demographic information was collected including sex, age, race/ethnicity, and job. On sampled days, participants were asked about BPA-related tasks performed, actual shift length worked, clothing and personal protective equipment worn, BPA spills, and hand-to-mouth behaviors.

Companies were grouped into five industry categories: (a) phenolic resin manufacturing (companies 1 and 2); (b) BPA and polycarbonate manufacturing (company 3); (c) BPA-filled wax manufacturing/reclaim (company 4); (d) BPA manufacturing (company 5); and (e) BPA-filled wax manufacturing/investment casting (company 6). Seven job categories were created across the six companies: (a) making BPA; (b) kettle/reaction/field operator making a BPA-based resin (hereafter referred to as "kettle operator"); (c) operator flaking a BPA-based resin; (d) maintenance work in a BPA or resin manufacturing area; (e) making BPA-filled wax; (f) working with solid BPA-filled wax; and (g) working with molten BPA-filled wax (e.g., wax reclaim and melt/burn out of BPA-filled wax from shells/molds).

### *Statistical analysis*

BPA concentrations in air, hand wipe and surface wipe samples were skewed to the right and a natural log transformation was applied. LOD/2 was assigned to samples where BPA was not detected.[21]

For air samples, summary statistics were computed by day, industry and job. Using the natural log of the BPA air concentration ($\ln(BPA_{AIR})$) as the dependent variable, 18 covariates were evaluated one-at-a-time in mixed models with worker treated as a random effect. Covariates included day (1 or 2), industry (5 levels), job (7 levels), age (continuous), smoking during work (yes/no), actual shift length (≤8, >8 and <12, ≥12 h, treated as ordinal), percent of work shift spent in production vs. offices/control rooms (<50, ≥50), handling bulk sacks, bags, drums, or buckets of BPA (yes/no), handling empty containers of BPA (yes/no), number of process/bulk samples taken containing BPA (≤3, >3), spilled BPA (yes/no), and cleaned up a BPA spill (yes/no). Covariates with a p-value ≤0.2 were included in a stepwise forward selection mixed model with worker treated as a random effect. Covariates were entered into the model one-at-a-time until all remaining covariates had p-values >0.05.

Hand wipe analyses were restricted to participants with both pre- and end-shift samples. Summary statistics were computed separately by shift time (pre- or end-shift) for all samples and by industry and job. A mixed model with worker as a random effect and shift time as a fixed effect was used to test for a shift-time difference (pre- vs. end-shift) in the overall sample. Industry (or job) was included as a fixed effect along with an interaction term for industry and shift time (or job and shift time) to test comparisons within industry (or job). Using the natural log of BPA on the end-shift hand wipe ($\ln(BPA_{HAND\text{-}END})$) as the dependent variable, and after adjusting for BPA at pre-shift ($\ln(BPA_{HAND\text{-}PRE})$), covariates described above for the air model, excluding day, but including body mass index (continuous), gloves (none, fabric or leather, chemical-resistant), eating during work excluding lunch or breaks (yes/no), chewing tobacco during work (yes/no), chewing gum during work (yes/no), and hand washing frequency during work (1–4, 5–7, >7 times) were evaluated one-at-a-time in mixed models with worker as a random effect. Covariates with p-values ≤0.2 were included in a stepwise forward selection mixed model as described previously.

Total variance was computed by fitting a model with worker-only as a random effect. For the final air model (two measurements per worker), the variance explained by the fixed effects was obtained by subtracting the within- and between-worker variances from the total variance. For the final hand model (one measurement per worker), the residual variance was subtracted from the total variance to obtain the variance explained by the fixed effects.

The wiped area for each surface sample was standardized to 100 $cm^2$ (reported as μg BPA/100 $cm^2$). After assigning surfaces/objects into seven groups with similar characteristics, summary statistics were computed by group. Groups were then dichotomized into "non-production" and "production" areas. A t-test was used on $\ln(BPA_{SURFACE})$ to compare the GMs of the two areas. Statistical analyses were performed in SAS v. 9.3 (SAS Institute, Inc., Cary, NC, USA). Significance testing was done at $\alpha = 0.05$.

## Results

### *Participants*

Participant recruitment results were described previously.[20] Briefly, of 199 workers in BPA-related jobs at six companies, 125 consented to participate and 78 could be scheduled for sampling. Study participants

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**Table 1.** Characteristics of study participants, N = 78.

| Characteristic | Frequency (%) |
|---|---|
| Sex | |
| Male | 76 (97.4) |
| Female | 2 (2.6) |
| Age, years | Mean ± SD = 43.6 (±11.0); Median = 44.0; Range = 20–63 |
| Race | |
| White | 70 (89.7) |
| Black | 6 (7.7) |
| More than one race | 2 (2.6) |
| Ethnicity | |
| Hispanic | 2 (2.6) |
| Not Hispanic | 76 (97.4) |
| BMI, kg/m$^2$ | Mean ± SD = 30.4 (±5.6); Median = 29.8; Range = 21.0–44.3 |
| Current Smoker | |
| No | 53 (68.0) |
| Yes | 25 (32.0) |
| Shift Type | |
| Fixed | 46 (59.0) |
| Rotating | 32 (41.0) |
| Company | |
| 1 (phenolic resin mfg.) | 15 (19.2) |
| 2 (phenolic resin mfg.) | 13 (16.7) |
| 3 (BPA & polycarbonate resin mfg.) | 18 (23.1) |
| 4 (BPA-filled wax mfg. & wax reclaim) | 14 (18.0) |
| 5 (BPA mfg.) | 7 (9.0) |
| 6 (BPA-filled wax mfg., wax patterns/molds, burn-out) | 11 (14.1) |
| Industry | |
| Phenolic resin mfg. (companies 1 & 2) | 28 (35.9) |
| BPA & polycarbonate resin mfg. (company 3) | 18 (23.1) |
| BPA-filled wax mfg. & wax reclaim (company 4) | 14 (18.0) |
| BPA mfg. (company 5) | 7 (9.0) |
| BPA-filled wax mfg., wax casting patterns/molds, wax burn-out (company 6) | 11 (14.1) |
| Job | |
| Flaker operator – resins | 12 (15.4) |
| Make/load BPA | 12 (15.4) |
| Kettle operator – resin mfg. (phenolic or polycarbonate) | 22 (28.2) |
| Maintenance – BPA & polycarbonate resin mfg. | 7 (9.0) |
| Molten BPA-filled wax work – reclaim, melt/burn-out | 6 (7.7) |
| Make BPA-filled wax | 14 (18.0) |
| Solid BPA-filled wax work: wax patterns, mold assembly, lab QC | 5 (6.4) |

*Notes*: BMI = body mass index; mfg. = manufacturing; QC = quality control.

were mostly male (97.4%) and white (89.7%); median age was 44.0 years (range 20–63 years) (Table 1). The number of sampled workers per company was 7–18, mean (± SD) 13 ± 3.7; the goal was 15 workers per company.

## Companies

Companies 1 and 2 added BPA and other ingredients to kettles, solidified molten resin, and converted it into a flake product. Participant jobs were kettle and flaker operators. Company 3 made BPA from acetone and phenol, then reacted BPA with phosgene to make polycarbonate resin. Participant jobs included operators, shift leads, and maintenance. Company 4 added BPA and other ingredients to kettles, then solidified molten wax into pastilles, billets or slabs. Company 4 also reclaimed the wax component from used wax using large hot boxes at ∼100°C to melt the wax, followed by removal of water and non-wax solids. Participant jobs included warehouse, wax preparation, blending and packaging, wax reclaim, and QC. Company 5 made BPA from acetone and phenol and then transferred BPA to the epoxy resin manufacturing unit via a closed system. Participant jobs included BPA operators, flakers, and loaders. Company 6 added BPA and other ingredients to kettles, solidified molten wax into pastilles, then used the wax in investment casting. Participant jobs included making wax, engineer, shift lead, lift-truck driver, wax injection, wax pattern/mold assembly, and wax removal from shells/molds in heated Boilerclaves® at ∼170°C followed by burn-out in ovens at ∼1000°C. Across companies, BPA was added to reaction or mixing vessels by a mix of manual/partly manual and automated methods. Chemical reactions (e.g., acetone with phenol) were carried out in closed systems, typically under negative pressure.

## Air sample results

Personal air samples were collected on 146 worker-days, 75 samples on Day 1; 71 samples on Day 2. BPA was detected in nearly all air samples (95.2%) with a GM BPA air concentration of 4.0 μg/m$^3$ (Table 2).

**Table 2.** BPA air sampling results, μg/m³.

| | n[a] | No. <LOD (%) | AM (SD) | Median | GM (GSD) | p-value | 25th, 75th % tiles | Range (Min, Max) |
|---|---|---|---|---|---|---|---|---|
| ALL | 146 | 7 (4.8) | 46 (130) | 6.0 | 4.0 (15) | | 0.61, 27 | 0.010, 920 |
| Day 1 (Ref.) | 75 | 2 (2.7) | 43 (150) | 6.9 | 3.7 (12) | Ref. | 0.61, 22 | 0.015, 920 |
| Day 2 | 71 | 5 (7.0) | 49 (100) | 5.6 | 4.2 (18) | 0.5465 | 0.59, 45 | 0.010, 650 |
| Industry | | | | | | <0.0001 | | |
| Phenolic resin mfg. | 53 | 6 (11.3) | 14 (51) | 0.86 | 0.85 (15) | Ref. | 0.095, 11 | 0.010, 350 |
| BPA & PC resin mfg. | 33 | 0 (0) | 49 (170) | 5.7 | 6.7 (6.2) | 0.0009 | 3.0, 13 | 0.13, 920 |
| BPA-filled wax mfg. & wax reclaim | 27 | 0 (0) | 100 (140) | 50 | 48 (4.0) | <0.0001 | 22, 110 | 1.8, 650 |
| BPA mfg. | 13 | 0 (0) | 18 (35) | 0.39 | 1.3 (12) | 0.5102 | 0.29, 4.5 | 0.12, 95 |
| BPA-filled wax mfg., wax casting patterns/molds, wax burn-out | 20 | 1 (5.0) | 66 (200) | 7.4 | 6.9 (11) | 0.0029 | 1.4, 32 | 0.015, 880 |
| Job | | | | | | 0.0002 | | |
| Flaker operator – resins | 23 | 3 (13.1) | 8.5 (24) | 0.63 | 0.62 (14) | Ref. | 0.059, 5.6 | 0.010, 120 |
| Make/load BPA | 22 | 0 (0) | 18 (32) | 1.2 | 2.2 (10) | 0.1268 | 0.30, 22 | 0.12, 95 |
| Kettle operator – resin mfg. (phenolic or PC) | 41 | 3 (7.3) | 47 (160) | 6.6 | 2.2 (19) | 0.1214 | 0.15, 15 | 0.013, 920 |
| Maintenance – BPA & PC resin mfg. | 13 | 0 (0) | 5.4 (3.7) | 4.9 | 4.2 (2.30) | 0.0680 | 3.1, 6.9 | 0.76, 13 |
| Molten BPA-filled wax work –reclaim, melt/burn-out | 11 | 0 (0) | 71 (54) | 56 | 43 (4.6) | 0.0002 | 30, 100 | 0.63, 170 |
| Make BPA-filled wax | 26 | 1 (3.8) | 130 (210) | 39 | 29 (11) | <0.0001 | 14, 110 | 0.015, 880 |
| Solid BPA-filled wax work: wax patterns, mold assembly, lab QC | 10 | 0 (0) | 5.9 (4.8) | 5.8 | 4.3 (2.4) | 0.0911 | 1.8, 8.0 | 1.2, 17 |

*Notes*: mfg. = manufacturing; PC = polycarbonate; QC = quality control; Ref. = referent group.
[a]Number of worker-days.

Variability was high (GSD = 15). Day 1 (3.7 μg/m³) and Day 2 (4.2 μg/m³) GM air concentrations were not significantly different ($p = 0.5465$). A kettle operator in the BPA/polycarbonate manufacturing industry had the highest air concentration (920 μg/m³).

BPA air concentrations differed significantly by industry ($p < 0.0001$) and by job ($p = 0.0002$) (Table 2, Figure 1). By industry, the GM BPA air concentration was highest in BPA-filled wax manufacturing/reclaim (48 μg/m³), a level significantly higher than in phenolic resin manufacturing, the industry with the lowest GM air concentration (0.85 μg/m³) ($p < 0.0001$). The GM BPA air concentrations in the next two highest industries, BPA-filled wax manufacturing/pattern and mold assembly/burn-out (6.9 μg/m³) and BPA/polycarbonate manufacturing (6.7 μg/m³), were also significantly higher than in phenolic resin manufacturing ($p = 0.0029$ and $p = 0.0009$, respectively). By job, the GM BPA air concentration was highest for those working with molten BPA-filled wax (43 μg/m³), followed by making BPA-filled wax (29 μg/m³). Both of these jobs had GM BPA air concentrations significantly higher than the lowest exposed job of flaking phenolic resins (0.62 μg/m³) ($p = 0.0002$ and $p < 0.001$, respectively).

## *Hand wipe results*

Seventy-four participants had both pre- and end-shift hand wipe samples. Work schedule changes (n = 3) and field error (n = 1) accounted for participants without both samples. One participant, who did not work on Day 2, had samples taken on Day 1. BPA was detected on 93.2% of pre-shift samples, 100% of end-shift samples (Table 3).

Hand wipe BPA levels are summarized in Table 3 and Figure 2. Pre-shift, hand wipe GM BPA levels were < 10 μg/sample for all industries and jobs. The end-shift BPA level (GM = 26 μg/sample, range 0.64–19,000 μg/sample) was 10-times higher than at pre-shift (GM = 2.6 μg/sample, range 0.025–72 μg/sample), a statistically significant difference ($p<0.0001$) (Table 3). End-shift GM BPA hand wipe levels were also significantly higher than pre-shift levels in all industries except BPA manufacturing (only 7 participants), and in all jobs (Table 3). A statistically significant interaction was found between industry and shift time ($p = 0.0040$) and between job and shift time ($p = 0.0248$), indicating that the magnitude of change in the BPA level from pre-shift to end-shift depended on type of industry (or job).

Pre-shift, the highest BPA hand level by industry was in BPA/polycarbonate manufacturing (GM = 8.7 μg/sample); by job for those making BPA (GM = 8.9 μg/sample). End-shift, by industry, the BPA hand level was highest in BPA-filled wax manufacturing/reclaim (GM = 130 μg/sample), followed by BPA-filled wax manufacturing/pattern and mold assembly/burnout (GM = 57 μg/sample), and lowest in phenolic resin manufacturing (GM = 5.8 μg/sample). By job, the end-shift BPA hand level was highest for those working with molten BPA-filled wax (GM = 180 μg/sample), followed by making BPA-filled wax (GM = 75 μg/sample) and working with solid BPA-filled wax (GM = 74 μg/sample). The high end-shift GM (and GSD) hand level for the job of working

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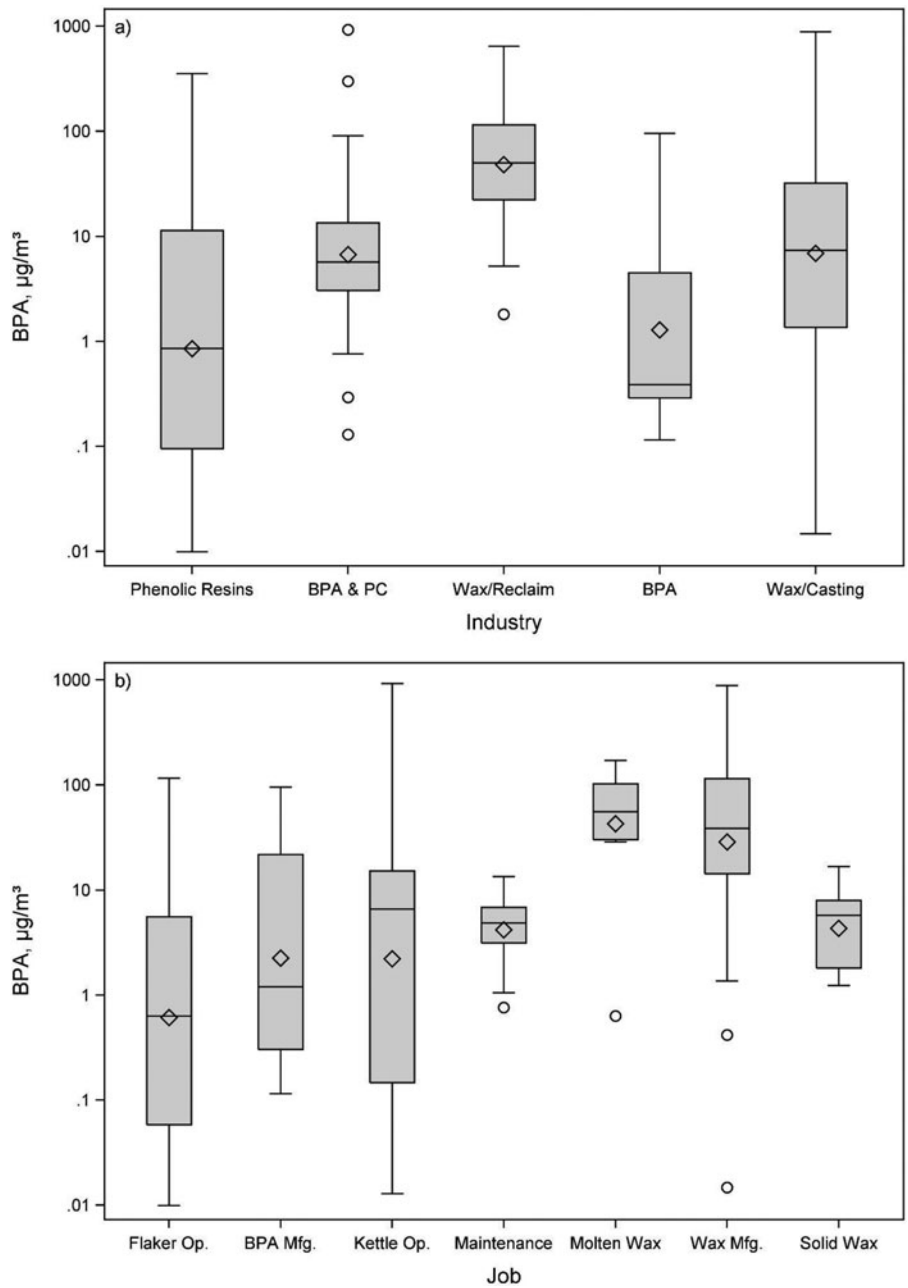


**Figure 1.** Box plots of BPA air concentrations (n = 146) by (a) industry and (b) job. The box represents the interquartile range and the large circle represents the geometric mean. Abbreviations: PC = polycarbonate; Mfg. = manufacturing; Op. = operator.

with molten BPA-filled wax was influenced by high levels (19,000 and 12,000 µg/sample) for two wax reclaim workers who cleaned hot boxes used to melt wax. While these two samples were considered valid, hand wipe summary statistics were re-computed excluding these two participants (Supplemental Table SII).

### *Surface wipe results*

Across six companies, BPA was detected on 96.6% of 88 surface/object wipe samples. GM BPA levels were lowest in eating areas (6.5 µg/100 $cm^2$) followed by offices/control rooms (12 µg/100 $cm^2$), door handles/knobs/buttons (31 µg/100 $cm^2$), hand tools (88 µg/100 $cm^2$), production area objects (140 µg/100 $cm^2$), work benches/tables (150 µg/100 $cm^2$), and BPA-filled wax (13,000 µg/100 $cm^2$) (Table 4, Figure 3). The surface wipe GM BPA level in "production" areas (140 µg/100 $cm^2$, n = 34) was 15-times higher than in "non-production" areas (9.3 µg/100 $cm^2$, n = 54, $p < 0.0001$); when the three BPA-filled wax samples were excluded, GM BPA levels in "production" areas (89 µg/100 $cm^2$) remained nearly 10 times higher than in "non-production" areas (9.3 µg/100 $cm^2$) ($p < 0.0001$) (Table 4).

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**Table 3.** BPA hand wipe results for participants with both pre- and end-shift samples, µg/sample.

| | n | No. <LOD (%) | AM (SD) | Median | GM (GSD) | Range (Min, Max) | p-value |
|---|---|---|---|---|---|---|---|
| ALL | | | | | | | |
| Pre | 74 | 5 (6.8) | 8.6 (13) | 3.3 | 2.6 (6.4) | 0.025, 72 | Ref. |
| End | 74 | 0 (0) | 520 (2600) | 22 | 26 (7.9) | 0.64, 19000 | <0.0001[a] |
| INDUSTRY | | | | | | | |
| Phenolic resin mfg. | | | | | | | |
| Pre | 25 | 5 (20) | 1.2 (2.0) | 0.52 | 0.43 (4.9) | 0.025, 9.0 | Ref. |
| End | 25 | 0 | 15 (31) | 6.1 | 5.8 (3.9) | 0.64, 150 | < 0.0001 |
| BPA & PC resin mfg. | | | | | | | |
| Pre | 17 | 0 | 12 (9.3) | 9.7 | 8.7 (2.6) | 1.5, 35 | Ref. |
| End | 17 | 0 | 100 (190) | 43 | 45 (3.6) | 4.1, 810 | < 0.0001 |
| BPA-filled wax mfg./reclaim | | | | | | | |
| Pre | 14 | 0 | 15 (22) | 6.6 | 6.2 (4.3) | 0.56, 72 | Ref. |
| End | 14 | 0 | 2300 (5800) | 97 | 130 (10) | 8.1, 19000 | < 0.0001 |
| BPA mfg. | | | | | | | |
| Pre | 7 | 0 | 14 (19) | 3.9 | 6.8 (3.6) | 2.2, 47 | Ref. |
| End | 7 | 0 | 75 (120) | 7.1 | 16 (7.4) | 2.1, 280 | 0.1069 |
| BPA-filled wax mfg., wax casting patterns, mold assembly, wax burn-out | | | | | | | |
| Pre | 11 | 0 | 7.3 (6.6) | 6.1 | 4.5 (3.2) | 0.52, 20 | Ref. |
| End | 11 | 0 | 290 (670) | 72 | 57 (7.3) | 1.7, 2300 | < 0.0001 |
| JOB | | | | | | | |
| Flaker operator – resins | | | | | | | |
| Pre | 11 | 2 (18) | 0.68 (0.71) | 0.52 | 0.38 (3.7) | 0.025, 2.5 | Ref. |
| End | 11 | 0 | 6.8 (6.9) | 4.1 | 4.0 (3.2) | 0.83, 21 | < 0.0001 |
| Make/load BPA | | | | | | | |
| Pre | 11 | 0 | 15 (15) | 9.7 | 8.9 (2.9) | 2.2, 47 | Ref. |
| End | 11 | 0 | 150 (240) | 26 | 33 (8.1) | 2.1, 810 | 0.0032 |
| Kettle operator – resin mfg. | | | | | | | |
| Pre | 20 | 3 (15) | 5.3 (7.6) | 1.3 | 1.2 (8.6) | 0.025, 25 | Ref. |
| End | 20 | 0 | 33 (44) | 12 | 12 (4.8) | 0.64, 150 | < 0.0001 |
| Maintenance – BPA & PC resin mfg. | | | | | | | |
| Pre | 7 | 0 | 9.7 (12) | 4.3 | 5.6 (3.0) | 1.5, 35 | Ref. |
| End | 7 | 0 | 42 (40) | 26 | 31 (2.2) | 10, 130 | 0.0023 |
| Molten BPA-filled wax work – reclaim, melt/burn-out | | | | | | | |
| Pre | 6 | 0 | 26 (32) | 11 | 7.0 (8.2) | 0.52, 72 | Ref. |
| End | 6 | 0 | 5200 (8300) | 89 | 180 (42) | 1.7, 19000 | < 0.0001 |
| Make BPA-filled wax | | | | | | | |
| Pre | 14 | 0 | 9.4 (5.6) | 7.9 | 7.6 (2.1) | 1.3, 20 | Ref. |
| End | 14 | 0 | 280 (590) | 100 | 75 (5.4) | 7.4, 2300 | < 0.0001 |
| Solid BPA-filled wax work – wax patterns, mold assembly, lab QC | | | | | | | |
| Pre | 5 | 0 | 1.8 (1.3) | 1.1 | 1.5 (2.1) | 0.56, 3.4 | Ref. |
| End | 5 | 0 | 98 (90) | 51 | 74 (2.2) | 37, 250 | < 0.0001 |

*Notes*: mfg. = manufacturing; PC = polycarbonate; QC = quality control; Ref. = referent group.
[a]Compared end-shift GM to pre-shift GM.

**Table 4.** BPA levels by surface/object and by area, µg/100 cm$^2$, n = 88.

| | N | No. < LOD | AM (SD) | Median, | GM (GSD) | Range (Min, Max) |
|---|---|---|---|---|---|---|
| By Surface/Object | | | | | | |
| Eating areas | 22 | 2 | 19 (30) | 6.1 | 6.5 (5.7) | 0.1, 130 |
| Offices/control rooms | 32 | 1 | 57 (110) | 15 | 12 (9.0) | 0.05, 580 |
| Door handles/knobs/buttons | 8 | 0 | 81 (89) | 52 | 31 (6.5) | 0.96, 260 |
| Hand tools | 5 | 0 | 250 (250) | 210 | 88 (8.0) | 4.8, 590 |
| Objects in production areas | 10 | 0 | 4400 (9400) | 79 | 140 (29) | 1.6, 29,000 |
| Work benches/tables | 8 | 0 | 450 (530) | 150 | 150 (6.5) | 8.5, 1200 |
| BPA-filled wax | 3 | 0 | 16,000 (13,000) | 12,000 | 13,000 (2.4) | 5,600, 31,000 |
| By Area | | | | | | |
| [a]Non-production (Ref.) | 54 | 3 | 41 (89) | 11 | 9.3 (7.6) | 0.05, 580 |
| [b]Production | 34 | 0 | 2900 (7500) | 110 | 140[c] (16) | 0.96, 31,000 |
| Production, excluding BPA-filled wax | 31 | 0 | 1600 (5500) | 81 | 89[C] (12) | 0.96, 29,000 |

*Notes*:
[a]Non-production includes eating areas and offices/control rooms.
[b]Production includes door handles/knobs/buttons, hand tools, objects in production areas, work benches/tables, BPA-filled wax.
[c]Significantly different than non-production, $p < 0.0001$.

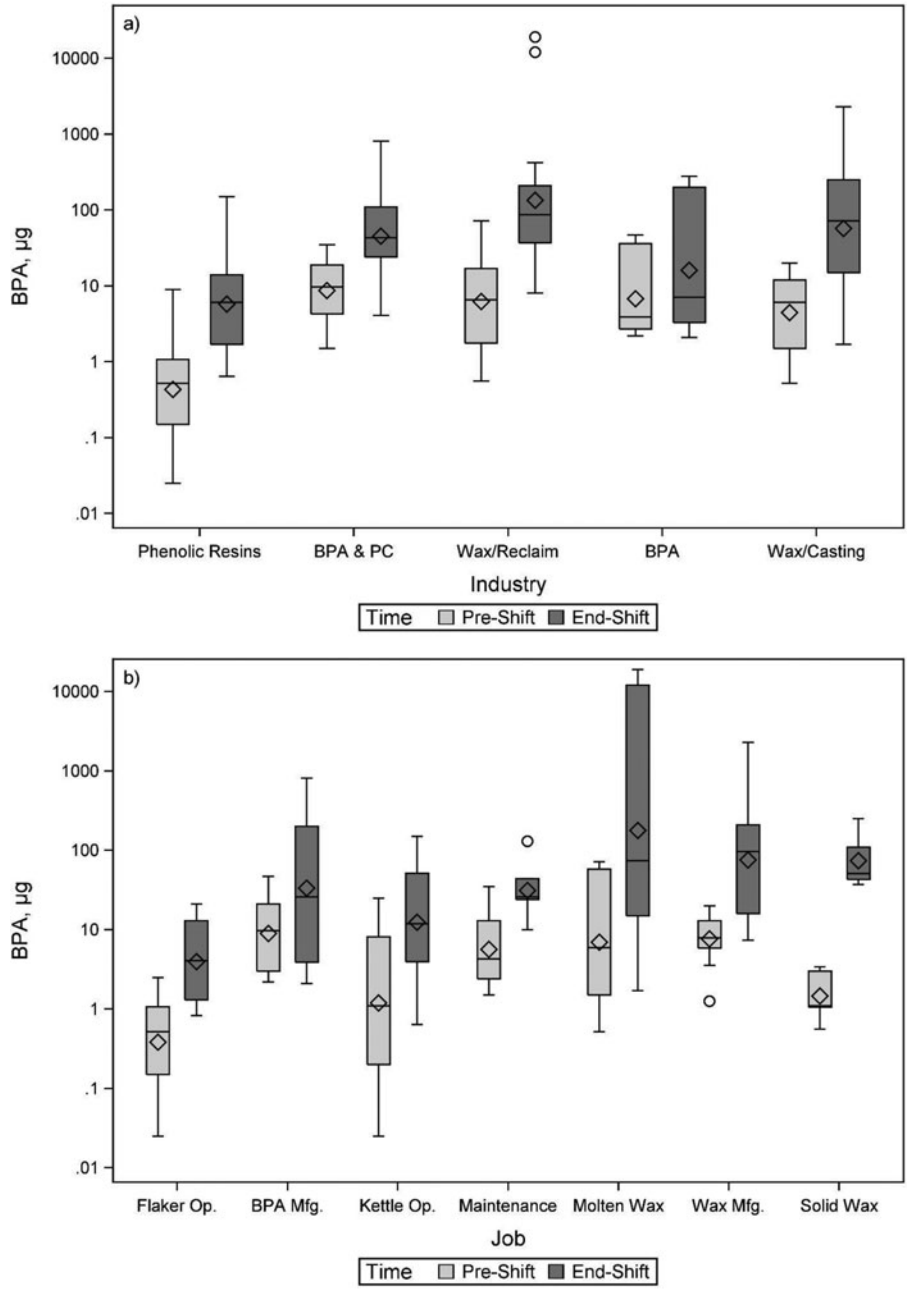


**Figure 2.** Box plots of BPA levels on hand wipes pre- and end-shift (n = 74 each) by (a) industry and (b) job. The box represents the interquartile range and the large circle represents the geometric mean. Abbreviations: PC = polycarbonate; Mfg. = manufacturing; Op. = operator.

### *Air and hand wipe exposure determinant modeling*

Covariates for air and hand wipe models are summarized in Tables 1 and 2. For air, sample size is given as worker-days (n = 146 for 78 workers); for hand wipes as number of workers with both pre- and end-shift samples (n = 74). Frequency of covariate responses for worker-days and workers was similar (Table 5). Because all covariates applied to hand wipe but not necessarily to air samples, frequencies described below are for the 74 workers with both hand wipe samples.

By industry, the number of workers was highest in phenolic resin manufacturing (33.8%), followed by BPA/polycarbonate manufacturing (23.0%), BPA-filled wax manufacturing/reclaim (18.9%), BPA-filled wax manufacturing/pattern and mold assembly/burnout (14.9%), and BPA manufacturing (9.5%). By job, the number of workers was highest for kettle operator making a BPA-based resin (27.0%), followed by the jobs of making BPA-filled wax (18.9%), flaking a BPA-based resin and making BPA (14.9% each), maintenance work in

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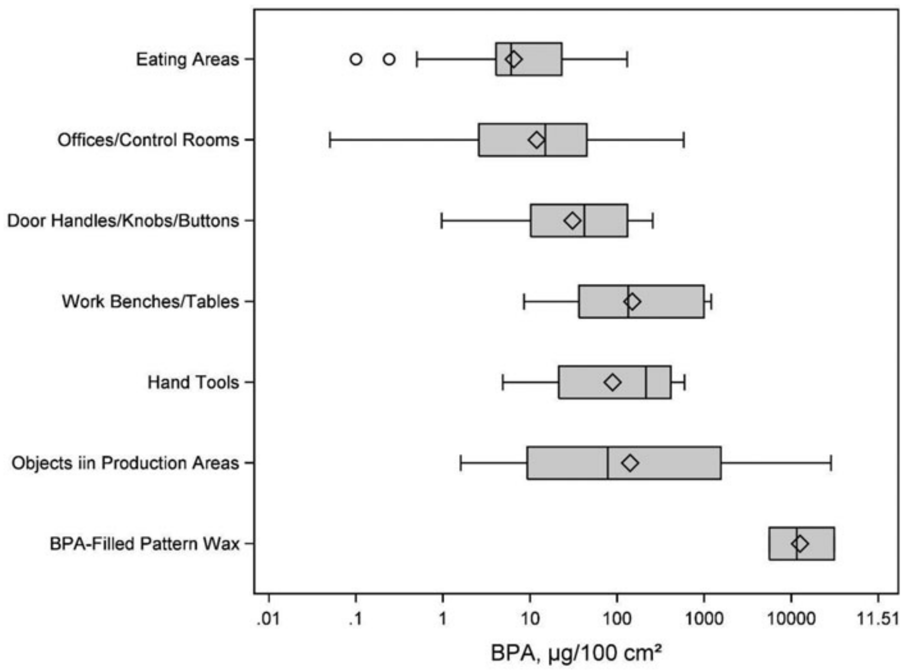


**Figure 3.** Box plots of BPA surface wipe levels (n = 88) by surface/object category. The box represents the interquartile range and the large circle represents the geometric mean.

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BPA/polycarbonate manufacturing (9.5%), working with molten BPA-filled wax (8.1%), and working with solid BPA-filled wax (6.8%). Nearly half (48.6%) of the participants worked a 12-hr shift or longer. Approximately 70% of the workers spent 50% or more of their shift in production vs. control rooms/offices. Sacks, bags, buckets, or drums of BPA were handled by 12.2% of the workers, 9.5% handled empty BPA containers, while taking ≥3 process or bulk samples containing BPA, spilling BPA and cleaning up a BPA spill were each performed by 8.1% of the workers. Because of small numbers, we could not examine process sample types separately. Some type of glove was worn by nearly 88% of the workers during their shift; a chemical-resistant glove by 47.3% of the workers, fabric or leather glove by 40.5%. Eating during work, excluding lunch or breaks, was the most commonly reported hand-to-mouth activity, 59.5% of workers (Table 5). Self-reported hand washing frequency was highest at 5–7 times per shift (41.9%).

Covariates positively associated with $\ln(BPA_{AIR})$ at $p \le 0.2$ in univariate analyses were industry ($p < 0.0001$), handling sacks, bags, buckets or drums of BPA ($p < 0.0001$), handling empty BPA containers ($p = 0.0001$), job ($p = 0.0002$), smoking during work ($p = 0.0017$), spilling BPA ($p = 0.0023$), working ≥50% of the shift in production vs. offices/control rooms ($p = 0.001$), and cleaning up a BPA spill ($p = 0.0917$); covariates inversely associated with $\ln(BPA_{AIR})$ at $p \le 0.2$ were shift duration ($p = 0.0153$) and age ($p = 0.0165$) (Table 6). After including these covariates in a stepwise model, industry ($p < 0.0001$), handling sacks, bags, buckets or drums of BPA ($p < 0.0001$), spilling BPA ($p = 0.0249$) and working ≥50% of the shift in production vs offices/control rooms ($p = 0.0491$) remained positively associated with $\ln(BPA_{AIR})$, while age remained inversely associated ($p = 0.0068$) (Table 7). Compared to phenolic resin manufacturing, the adjusted GM BPA air concentration in BPA-filled wax manufacturing/reclaim was 24-times higher, BPA filled wax manufacturing/pattern and mold assembly/burnout was 20-times higher, and BPA and polycarbonate manufacturing was 15-times higher (Table 7) ($p < 0.0001$ each) (Table 7). Fixed effects explained 44.9% ($_{Fixed}S^2 = 3.25$) of the total variance ($_{Total}S^2 = 7.23$), within-worker component 23.5% ($_{Within}S^2 = 1.70$, $_{Within}GSD = 3.68$), and the between-worker component 31.7% ($_{Between}S^2 = 2.29$, $_{Between}GSD = 4.54$).

Covariates positively associated with $\ln(BPA_{HAND\text{-}END})$ at $p \le 0.2$ in univariate analyses were working ≥50% of the shift in production areas vs. offices/control rooms ($p = 0.0033$), smoking during work ($p = 0.0064$), industry ($p = 0.0085$), job ($p = 0.0305$), handling sacks, bags, buckets, or drums of BPA ($p = 0.0836$, wearing gloves ($p = 0.1361$), spilling BPA ($p = 0.15$), cleaning up a BPA spill ($p = 0.1510$), and taking more than three process samples ($p = 0.1868$) (Table 6). Eating during work was inversely associated with $\ln(BPA_{HAND\text{-}END})$ ($p = 0.1295$) (Table 6). When these covariates were included in a stepwise model and after adjusting for $\ln(BPA_{HAND\text{-}PRE})$, the adjusted GM BPA end-shift hand level was 2.5 times higher for those working ≥50% of

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**Table 5.** Work-related covariates pertaining to air and/or hand wipe samples.

| Covariate | Frequency (%) Air N = 146 worker-days[a] | Hand N = 74 workers |
|---|---|---|
| Industry | | |
| Phenolic resins mfg. | 53 (36.3) | 25 (33.8) |
| BPA & PC resin mfg. | 33 (22.6) | 17 (23.0) |
| BPA-filled wax mfg. & wax reclaim | 27 (18.5) | 14 (18.9) |
| BPA mfg. | 13 (8.9) | 7 (9.5) |
| BPA-filled wax mfg., wax casting patterns/molds, wax burn-out | 20 (13.7) | 11 (14.9) |
| Job | | |
| Flaker operator – resins | 23 (15.8) | 11 (14.9) |
| Make/load BPA | 22 (15.1) | 11 (14.9) |
| Kettle operator – resin mfg. | 41 (28.1) | 20 (27.0) |
| Maintenance – BPA & PC resin mfg. | 13 (8.9) | 7 (9.5) |
| Molten BPA-filled wax work – reclaim, melt/burn-out | 11 (7.5) | 6 (8.1) |
| Make BPA-filled wax | 26 (17.8) | 14 (18.9) |
| Solid BPA-filled wax work – wax patterns, mold assembly, lab QC | 10 (6.8) | 5 (6.8) |
| **Work Activities** | | |
| Actual shift length worked, hr | | |
| ≤8 | 29 (19.9) | 18 (24.3) |
| >8 and <12 | 41 (28.1) | 20 (27.0) |
| ≥12 | 76 (52.0) | 36 (48.6) |
| Percent of shift in production areas (vs. offices/control rooms) | | |
| <50 | 45 (30.8) | 22 (29.7) |
| ≥50 | 101 (69.2) | 52 (70.3) |
| Handled bulk sacks, bags, drums or buckets of BPA | | |
| No | 128 (87.7) | 65 (87.8) |
| Yes | 18 (12.3) | 9 (12.2) |
| Handled empty bulk sacks, bags or drum liners of BPA | | |
| No | 131 (89.7) | 67 (90.5) |
| Yes | 15 (10.3) | 7 (9.5) |
| Number of process/bulk samples taken containing BPA | | |
| ≤3 | 136 (93.2) | 68 (91.9) |
| >3 | 10 (6.8) | 6 (8.1) |
| Spilled BPA | | |
| No | 137 (93.8) | 68 (91.9) |
| Yes | 9 (6.2) | 6 (8.1) |
| Cleaned up a BPA spill | | |
| No | 136 (93.2) | 68 (91.9) |
| Yes | 10 (6.8) | 6 (8.1) |
| **PPE/Clothing**[b] | | |
| Wore gloves | | |
| No | NA | 9 (12.2) |
| Fabric or leather | | 30 (40.5) |
| Chemical-resistant | | 35 (47.3) |
| **Hygiene** | | |
| Smoked during work shift | | |
| No | 124 (84.9) | 63 (85.1) |
| Yes | 22 (15.1) | 11 (14.9) |
| Ate food during work shift, excluding lunch & breaks | | |
| No | NA | 30 (40.5) |
| Yes | | 44 (59.5) |
| Chewed gum during work shift | | |
| No | NA | 61 (82.4) |
| Yes | | 13 (17.6) |
| Chewed tobacco during work shift | | |
| No | NA | 61 (82.4) |
| Yes | | 13 (17.6) |
| Number of times washed hands during work shift | | |
| 1–4 | NA | 24 (32.4) |
| 5–7 | | 31 (41.9) |
| >7 | | 19 (25.7) |

*Notes*: mfg. = manufacturing; NA = not applicable; PC = polycarbonate; QC = quality control.
[a]For 78 workers.
[b]Wore a respirator: for N = 146 worker-days, no = 118, yes = 28; for N = 74 workers, no = 62, yes = 12.

the shift in production areas vs. offices/control rooms ($p < 0.0115$) and 3.1 times higher for those who smoked during work ($p = 0.0221$) (Table 7). When the two participants with the highest end-shift hand levels were excluded, two task-related determinants, taking ≥3 BPA-containing process samples (3.6 times higher than < 3 samples) and handling BPA containers (2.7-times higher than no handling), became significant while smoking

**Table 6.** Univariate regression models for BPA in air and hand wipe samples.

| | Air (n = 146) | | Hand[a] (n = 74) | | Hand[a, b] (n = 72) | |
|---|---|---|---|---|---|---|
| | ln(BPA Air Conc., μg/m$^3$) | | ln(BPA end-shift hand wipe, μg/sample) | | | |
| Dependent variable | B (SE) | p-value | B (SE) | p-value | B (SE) | p-value |
| INDUSTRY | | **< 0.0001** | | **0.0085** | | **0.0427** |
| Phenolic resin mfg. | Ref. | Ref. | Ref. | Ref. | Ref. | Ref. |
| BPA & PC resin mfg. | 2.058 (0.595) | 0.0009 | − 0.265 (0.565) | 0.6406 | 0.152 (0.534) | 0.7770 |
| BPA-filled wax mfg. & wax reclaim | 4.037 (0.684) | < 0.0001 | 1.089 (0.561) | 0.0565 | 0.920 (0.520) | 0.0815 |
| BPA mfg. | 0.550 (0.831) | 0.5102 | − 1.107 (0.676) | 0.1060 | − 0.724 (0.632) | 0.2562 |
| BPA-filled wax mfg., casting patterns/molds, wax burn-out | 2.164 (0.702) | 0.0029 | 0.485 (0.572) | 0.3991 | 0.809 (0.535) | 0.1352 |
| Handled bulk sacks, bags, drums or buckets of BPA (Yes/No = Ref.) | 2.581 (0.593) | **< 0.0001** | 0.917 (0.523) | **0.0836** | 0.950 (0.466) | **0.0454** |
| Handled empty bulk sacks, bags or drum liners of BPA (Yes/No = Ref.) | 2.395 (0.608) | **0.0001** | 0.536 (0.585) | 0.3624 | 0.651 (0.524) | 0.2186 |
| JOB | | **0.0002** | | **0.0305** | | **0.0576** |
| Flaker operator – resins | Ref. | Ref. | Ref. | Ref. | Ref. | |
| Make/load BPA | 1.324 (0.857) | 0.1268 | − 0.270 (0.687) | 0.6957 | 0.139 (0.633) | 0.8271 |
| Kettle operator – resin mfg. (phenolic or PC) | 1.178 (0.751) | 0.1214 | 0.277 (0.536) | 0.6063 | 0.425 (0.488) | 0.3878 |
| Maintenance – BPA & PC resin mfg. | 1.850 (0.998) | 0.0680 | 0.0139 (0.734) | 0.9850 | 0.364 (0.674) | 0.5913 |
| Molten BPA-filled wax work-reclaim, melt/burn-out | 4.195 (1.052) | 0.0002 | 1.596 (0.774) | 0.0432 | 0.456 (0.760) | 0.5507 |
| Make BPA-filled wax | 3.788 (0.824) | < 0.0001 | 0.669 (0.650) | 0.3077 | 1.057 (0.600) | 0.0826 |
| Solid BPA-filled wax work – wax patterns, mold assembly, lab QC | 1.889 (1.102) | 0.0911 | 1.910 (0.763) | 0.0148 | 2.084 (0.695) | 0.0039 |
| Smoked during work shift (Yes/No = Ref.) | 2.151 (0.668) | **0.0017** | 1.380 (0.491) | **0.0064** | 0.801 (0.484) | **0.1022** |
| Spilled BPA (Yes/No = Ref.) | 2.488 (0.800) | **0.0023** | 0.911 (0.626) | **0.1500** | 1.140 (0.557) | **0.0446** |
| Percent of shift in production areas vs. offices/control rooms (≥50/ < 50 = Ref.) | 1.785 (0.530) | **0.0010** | 1.076 (0.354) | **0.0033** | 0.923 (0.322) | **0.0056** |
| Actual shift length worked (treated as ordinal), h | − 0.720 (0.293) | **0.0153** | − 0.209 (0.224) | 0.3549 | − 0.265 (0.201) | **0.1917** |
| Age, years | − 0.0600 (0.0245) | **0.0165** | 0.000603 (0.0157) | 0.9694 | 0.00896 (0.0143) | 0.5332 |
| Cleaned up a BPA spill (Yes/No = Ref.) | 1.413 (0.832) | **0.0917** | 0.914 (0.630) | **0.1510** | 1.175 (0.560) | **0.0395** |
| Number of process/bulk samples taken containing BPA (>3/≤3 = Ref.) | − 0.708 (0.839) | 0.3997 | 0.848 (0.636) | **0.1868** | 0.826 (0.571) | **0.1525** |
| Day (2/1 = Ref.) | 0.178 (0.294) | 0.5465 | NA | | | |
| BMI, kg/m$^2$ | NA | | − 0.00427 (0.0311) | 0.8912 | 0.0135 (0.0284) | 0.6371 |
| Glove worn | NA | | | **0.1361** | | **0.1081** |
| None | | | Ref. | Ref. | Ref. | Ref. |
| Fabric or Leather | | | 0.828 (0.551) | 0.1376 | 0.704 (0.496) | 0.1597 |
| Chemical Resistant | | | 1.101 (0.544) | 0.0470 | 1.034 (0.488) | 0.0379 |
| Chewed tobacco during work shift (Yes/No = Ref.) | NA | | 0.375 (0.450) | 0.4080 | − 0.342 (0.438) | 0.4374 |
| Ate food during work shift, excluding lunch & breaks (Yes/No = Ref.) | NA | | − 0.531 (0.346) | **0.1295** | − 0.519 (0.315) | **0.1043** |
| Chewed gum during work shift (Yes/No = Ref.) | NA | | − 0.425 (0.453) | 0.3513 | − 0.350 (0.408) | 0.3947 |
| Number of times washed hands during work shift | NA | | | 0.3109 | | **0.1478** |
| 1–4 | | | Ref. | Ref. | Ref. | Ref. |
| 5–7 | | | − 0.456 (0.400) | 0.2575 | − 0.650 (0.359) | 0.0743 |
| >7 | | | 0.147 (0.451) | 0.7456 | − 0.0776 (0.408) | 0.8498 |

*Notes*: BMI = body mass index; mfg. = manufacturing; NA = not applicable; PC = polycarbonate; QC = quality control; Ref. = referent group.
[a]Adjusted for ln(BPA in the pre-shift hand wipe), $p < 0.0001$.
[b]Excludes two participants with highest end-shift BPA levels.
Bolded values: covariates with p-values ≤0.2.

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during work did not enter the model (the two excluded workers smoked during work) (Table 7). In the hand model with all 74 participants, fixed effects (${}_{Fixed}S^2$ = 2.44) explained 57.2% of the total variance (${}_{Total}S^2$ = 4.270). In the hand model excluding the two participants, fixed effects (${}_{Fixed}S^2 = 1.818$) explained 56.5% of the total (reduced) variance (${}_{Total}S^2 = 3.216$).

## Discussion

In this study, BPA air and hand exposures were quantified among U.S. workers making BPA or products made with BPA. BPA was readily detected in full-shift personal air samples (95.2%) and on worker's hands (pre-shift 93.2%; end-shift 100%). All BPA air concentrations were < 1 mg/m$^3$ with a GM of 4.0 μg/m$^3$. Similar to urinary BPA concentrations among these workers,[19] personal air concentrations were highest in the wax manufacturing/reclaim industry and in the job of working with molten BPA-filled wax, while lowest in the phenolic resin manufacturing industry and in the job of flaking phenolic resins.

High BPA air concentrations in the molten BPA-filled wax job were unexpected. Airborne particles were not

**Table 7.** Forward stepwise regression models for air and hand wipe samples.

| Model | B (SE) | p-value | Factor[a] | Adj. GM[b] | 95% CI |
|---|---|---|---|---|---|
| **Air** | | | | | |
| **Dependent variable: ln(BPA Air Conc., μg/m³), n = 146** | | | | | |
| Intercept | 1.138 (0.988) | 0.2528 | | | |
| Industry | | < 0.0001 | | | |
| Phenolic resin mfg. | Ref. | | | 3.2 | 1.2, 8.4 |
| BPA & PC resin mfg. | 2.705 (0.541) | < 0.0001 | 15[c] | 47 | 16, 140 |
| BPA-filled wax mfg. & wax reclaim | 3.194 (0.606) | < 0.0001 | 24 | 77 | 23, 260 |
| BPA mfg. | 1.730 (0.775) | 0.0285 | 5.6 | 18 | 4.0, 80 |
| BPA-filled wax mfg., casting patterns/molds, wax burn-out | 3.004 (0.689) | < 0.0001 | 20 | 64 | 16, 260 |
| Handled bulk sacks, bags, drums or buckets of BPA | | | | | |
| No | Ref. | | | 6.7 | 3.2, 14 |
| Yes | 2.737 (0.523) | < 0.0001 | 15[d] | 100[e] | 32, 330 |
| Age, years | − 0.0589 (0.0211) | 0.0068 | 0.94 | | |
| Spilled BPA | | | | | |
| No | Ref. | | | 12 | 6.5, 23 |
| Yes | 1.537 (0.678) | 0.0249 | 4.7 | 57 | 14, 220 |
| % of shift in production areas vs. offices/control rooms | | | | | |
| <50 | Ref. | | | 17 | 6.0, 48 |
| ≥50 | 0.902 (0.453) | 0.0491 | 2.5 | 41 | 18, 96 |
| **Hand**[f] | | | | | |
| **Dependent Variable: ln(BPA end-shift hand wipe, μg/sample), n = 74** | | | | | |
| Intercept | 1.771 (0.300) | < 0.0001 | | | |
| ln(BPA pre-shift hand wipe, μg/sample) | 0.708 (0.0911) | < 0.0001 | 2.0[g] | | |
| % of shift in production areas vs. offices/control rooms | | | | | |
| <50 | Ref. | | | 20 | 9.9, 42 |
| ≥50 | 0.911 (0.351) | 0.0115 | 2.5 | 51 | 32, 82 |
| Smoked during work shift | | | | | |
| No | Ref. | | | 18 | 13, 26 |
| Yes | 1.128 (0.482) | 0.0221 | 3.1 | 57 | 23, 140 |
| **Hand**[h] **(excludes two participants with highest end-shift BPA levels)** | | | | | |
| **Dependent Variable: ln(BPA end-shift hand wipe, μg/sample), n = 72** | | | | | |
| Intercept | 1.416 (0.294) | < 0.0001 | | | |
| ln(BPA pre-shift hand wipe, μg/sample) | 0.752 (0.0804) | < 0.0001 | 2.1 | | |
| % of shift in production areas vs. offices/control rooms | | | | | |
| <50 | Ref. | | | 25 | 13, 49 |
| ≥50 | 1.130 (0.312) | 0.0006 | 3.1 | 76 | 39, 150 |
| Number of process/bulk samples taken containing BPA | | | | | |
| ≤3 | Ref. | | | 23 | 14, 36 |
| >3 | 1.290 (0.531) | 0.0177 | 3.6 | 83 | 29, 230 |
| Handled bulk sacks, bags, drums or buckets of BPA | | | | | |
| No | Ref. | | | 27 | 16, 45 |
| Yes | 0.986 (0.427) | 0.0239 | 2.7 | 71 | 29, 170 |

*Notes*: adj. GM = adjusted geometric mean; mfg. = manufacturing; PC = polycarbonate; Ref. = referent group.
[a] $e^{\beta}$.
[b] Adjusted GMs were computed for categorical variables using the LSMEANS statement in the PROC MIXED procedure in SAS.
[c] Indicates a 15-times increase in BPA air concentration compared to phenolic resins.
[d] Indicates that participants who reported "Yes" had a 15-times increase in BPA air concentration as compared to those who reported "No".
[e] If model re-run with age as a categorical variable dichotomized at the median (44 yr), then for ≤44 yr, adj. GM = 32 (95%CI = 12–82); >44 yr: adj. GM = 19 (95%CI = 7.3–51).
[f] Handled bulk sacks, bags, drums, or buckets of BPA (yes/no = ref.) was borderline significant at p = 0.0516
[g] Indicates a 2-times increase in amount of BPA in end-shift hand sample when the amount of BPA on the pre-shift hand sample increases by a factor of e.; this is equivalent to a 5.1-times increase in the BPA level on the end-shift hand wipe for every 10-times increase in BPA level on the pre-shift hand wipe.
[h] Spilling BPA (yes/no = ref.) was borderline significant at p = 0.0673.

visible during melting (which was enclosed) or when hot box/oven doors were opened. At standard conditions, BPA has a low vapor pressure ($3.96 \times 10^{-7}$ to $8.7 \times 10^{-10}$ mm Hg) and a high boiling point (398°C at 760 mm Hg);[23] therefore, BPA vapor would not be expected at these conditions. We are not aware of data on the potential for vapor formation from BPA-filled wax at temperatures ≥100°C (approximate temperature used to melt wax for reclaim). If BPA vapor was released from the wax during melting, then it is possible that the vapor rapidly condensed to small particles that were subsequently captured on the sampling filter. The filter-only air sampling method used in this study would not capture any BPA that remained as a vapor. Under experimental conditions, BPA

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has been detected in the exhaust effluent from extruders processing polycarbonate at ∼300°C;[24] BPA in polycarbonate is present at much lower levels (i.e., ppm) than in wax (i.e., percent). Because these are the first reported data on BPA air concentrations in industries that melt BPA-filled wax and the sample size is small, additional investigation into the nature of the exposure is warranted.

Important predictors of increased BPA air concentrations included activities expected to produce BPA-containing aerosols, such as handling sacks or bags of BPA or spilling BPA. The association of younger age with increased BPA air concentrations suggests that younger workers performed the "dustier" jobs. The finding that those who spent ≥50% of their work shift in control rooms or offices had lower BPA air concentrations, on average, than those who spent ≥50% of their work shift in production areas confirmed the importance of isolating the worker from the exposure as an exposure control. The above determinants along with industry type explained nearly 45% of the air concentration total variance. The largest proportion of the unexplained variance was in the between-worker component; therefore, efforts to identify additional air exposure determinants should focus on tasks and behaviors that differ between workers.

BPA air sampling data have been reported for two Chinese worker populations, the first in BPA and epoxy resins manufacturers[17, 18] and the second in epoxy resin factories.[16] In both populations, BPA was detected in >90% of full-shift inhalable fraction personal air samples. Reported median BPA air concentrations of 6.7 μg/m$^3$ (n = 161)[17] and 4.57 μg/m$^3$ (n = 180)[18] in the first population were comparable to our study median (6.0 μg/m$^3$). A dose-response relationship between cumulative exposure and reduced male sexual function (self-reported) for several functional domains was also found in this group of workers.[18] Findings from this study have not yet been confirmed. Median BPA air concentrations in the second population were 0.27–1230 μg/m$^3$ across jobs described as "definitely" using BPA; health outcomes were not examined.[16] In Finland, personal BPA air concentrations were reported for workers in a liquid paint factory and a thermal paper factory (two workers each). BPA was detected only in the sample from the worker in each factory who added pure BPA to a container during manufacturing.[19]

Occupational exposure limits (OEL) for BPA in air (8-hr inhalable fraction) have been recommended or established by the European Commission's Scientific Committee on Occupational Exposure Limits (SCOEL) (2 mg/m$^3$) and a few European countries (5 or 10 mg/m$^3$).[25, 26] All workers in our study had BPA air concentrations below these OELs. Neither NIOSH, the U.S. Occupational Safety and Health Administration, nor the American Conference of Governmental Industrial Hygienists have established or recommended OELs for BPA in air. SCOEL based its OEL on liver and kidney effects in orally-dosed rats and mice after concluding that additional studies were needed to confirm reports of male reproductive dysfunction in workers.

The highest and lowest end-shift GM BPA hand and air exposures were in the same industries and jobs. Nearly all workers had BPA detected on their hands pre-shift even though all workers sampled on Day 2 reported showering or bathing between Day 1 and Day 2, suggesting either incomplete BPA removal with showering/bathing and/or possible contact with BPA residues on surfaces/objects in homes or vehicles. In the hand model with all 74 participants, fewer determinants were associated with hand exposure than with air exposure; however, when the two participants with the highest hand levels were excluded from the model, additional task-related determinants emerged. The two participants with the highest BPA hand levels did not have air samples with unusually high concentrations.

Working ≥50% of the shift in production areas as compared to offices/control rooms was associated with increased hand exposure, a finding consistent with significantly higher BPA levels on surface/objects in production areas than in non-production areas. The association of smoking during work with increased hand exposure in the hand model was likely driven by the two participants with the highest end-shift BPA hand levels as this association did not remain when the two participants were excluded from the model. Smoking during work was not associated with increased urinary BPA concentrations among these workers.[20]

*In vitro* studies have shown that BPA can be absorbed into the skin, generally in the range of 9–13%.[27–29] Using the end-shift BPA hand level, a 10% dermal absorption factor,[30] and skin contact durations of 2-, 4-, 8-, and 12-hr, plus actual shift duration, dermal doses were estimated for workers in our study (hand wipe level in μg × 0.1 absorption factor × fraction of 24-hr day exposed) (Supplemental Table SIII). Dermal dose estimates (n = 74) ranged from 0.0053–160 μg/day (GM = 0.22 μg/day) for a contact duration of 2 hr; 0.032–950 μg/day (GM = 1.3 μg/day) for 12 hr. If body parts other than the hands were also exposed, computed values would underestimate dermal exposure.

Rough estimates of inhalation intake (μg/day) were computed as follows: BPA air concentration (μg/m$^3$) × inhalation rate (m$^3$/hr) × actual shift duration (h/day) × lung absorption factor. Estimates were computed for inhalation rates of 1.2 m$^3$/hr (light activity) and

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0.45 $m^3$/hr (resting state),[31] with an absorption factor of 1 (100% absorption)[32, 33] Inhalation exposure away from work was assumed to be negligible. Inhalation intake estimates (n = 146) ranged from 0.16–13,300 μg/day (GM = 49.0 μg/day) for an inhalation rate of 1.2 $m^3$/hr and from 0.06–4890 μg/day (GM = 18.4 μg/day) for an inhalation rate of 0.45 $m^3$/hr. On average, GM inhalation intake estimates were about 10–30 times higher than the GM dermal intake estimate for a 12-hr day, suggesting that for these workers BPA intake by inhalation was substantially greater than by dermal absorption. By contrast, in the only other study with hand wipe, air and urine samples, BPA exposure to children was estimated to be almost entirely due to ingestion.[34]

Surface wipe results indicated that BPA transfer from production to non-production areas (i.e., eating areas, offices/control rooms) was likely; however, BPA levels by surface/object were in an encouraging direction, with the lowest levels in eating and office areas and the highest levels in production areas. BPA was recovered at a high level from the surface of solidified BPA-filled wax, although the sample size was small (n = 3). Those in the job of working with solid wax, however, had the second lowest urinary BPA concentrations of seven jobs evaluated.[19] The efficiency of BPA transfer from the wax to the hand and the efficiency of BPA removal from the hand using IPA-moistened swabs are unknown. Low efficiency of wax-to-skin transfer and/or slow dermal uptake of BPA could reduce or delay the appearance of BPA in urine. We are not aware of published reports of BPA levels on workplace surfaces or objects. Median BPA levels in surface wipe samples from study workplaces were 3–4 orders of magnitude higher than levels reported for wipe samples from windows, floors, and food preparation areas in homes.[34, 35]

Some study limitations should be noted. The inhalable aerosol fraction was collected anticipating that large particles would result from handling raw BPA; therefore, it was not possible to determine if respirable-sized particles were associated with jobs involving molten BPA-filled wax. End-shift hand wipes do not provide a cumulative (shift-long) measure of BPA hand exposure nor information on skin residence time. Skin hydration and condition, factors not evaluated in this study, could also influence dermal uptake, as well as ambient temperature and humidity. In computing dermal dose estimates, a fixed fractional absorption factor was used that does not account for certain conditions that might affect estimates.[36] Therefore, hand wipe data should be used cautiously as an indicator of potential BPA dermal exposure. Finally, surface wipe data are difficult to relate to individual exposure without information on contact frequency and duration; however, surface wipe data may indicate where housekeeping interventions should be targeted.

## Conclusion

Air, hand wipe, and surface wipe sampling for BPA in industries that make BPA or BPA-containing products indicated workers were exposed to BPA by both inhalation and dermal routes, with intake estimates suggesting that inhalation, on average, was the dominant exposure route for these workers. Full-shift worker exposures to BPA in air were all <1 $mg/m^3$, well below current European OELs of 2–10 $mg/m^3$. As found previously for urinary BPA among these workers, workers in industries or jobs involving molten BPA-filled wax had, on average, the highest BPA air and hand exposures. Tasks that generated BPA aerosols and spending most of the work shift in production areas were important determinants of BPA air exposure. Determinants of BPA hand exposure were influenced by high values for two workers; however, in general, tasks involving direct contact with BPA-containing materials and a higher proportion of the shift spent in production areas were associated with increased BPA hand exposure. Surface wipes indicated potential BPA exposure in non-production areas although at lower levels than in production areas. Because BPA air concentrations in this study were similar to those of manufacturing workers in China where male reproductive health effects were reported, additional health studies are needed among BPA-exposed workers.

## Disclaimer

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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